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A critical review of roadway energy harvesting technologies

Mohammadreza Gholikhani[a], Hossein Roshani[b], Samer Dessouky[a,*], A.T. Papagiannakis[a]

[a] Department of Civil and Environmental Engineering, University of Texas at San Antonio (UTSA), San Antonio, TX, USA
[b] Lockwood, Andrews & Newnam Inc. (LAN), 10101 Reunion Pl, San Antonio, TX, USA

HIGHLIGHTS

- A comprehensive review of energy harvesting technologies in roadways is provided.
- Mechanism and efficiency of laboratory and commercial products are summarized.
- All technologies were compared on the basis of cost, output energy and readiness.
- Thermoelectric and Piezoelectric technologies are the most readily available methods.

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ABSTRACT

Energy harvesting from roadways has the potential to generate electricity for a multitude of roadside data collection and communication applications. Roadside energy harvesters are broadly grouped into three categories on the basis of the energy source tapped: mechanical energy from vehicles, pavement heat, and solar radiation. In terms of harvesting technology, harvesters are grouped into electromagnetic, piezoelectric, thermoelectric, pyroelectric, photovoltaic, and solar heat collector involving liquid or air circulation. This paper provides a comprehensive state-of-the-art review of the literature on each of these energy harvesting technologies. It includes information on the harvesting principle, prototype development, implementation efforts, and economic consideration for each harvesting technology. It concludes that several of these harvesting technologies are sufficiently developed to generate self-sustainable roadside electrical power.

1. Introduction

Sustainable development and roadway infrastructure are essential elements of future life quality [1]. Powering and monitoring this infrastructure in a sustainable fashion are challenging problems that have been the subject of considerable recent research [2]. Research areas range from data collection to smart communication and signage to structural health monitoring. Their common characteristic is the need for electrical power generated sustainably at the roadside that is independent from the electrical grid [3]. Sustainable roadside power generation for such applications can be done through energy harvesting, which converts ambient energy sources into electricity [4]. These sources include solar, thermal, and mechanical energy [5]. The technologies used are solar panels, thermoelectric generators, and electromagnetic, or piezoelectric, harvesters, respectively. Each of these technologies is in a different stage of development and has distinct advantages and disadvantages [6]. Regardless of the technology type, energy harvesting has the obvious advantage of eliminating carbon emissions associated with fossil-fuel-generated power [7]. Another important advantage is the decentralization of the electric power source that eliminates the need for power lines to bring the power to the roadside [8].

Roadway pavements cover millions of urban and rural square kilometers and are continuously exposed to various types of energy, such as solar radiation, heat, and traffic-induced stresses [9]. Harvesting these forms of energy and converting them to a usable format, such as electricity, can supplement currently available energy sources [10]. More importantly, harvested electrical energy can power equipment, signage, and other applications in remote rural areas without relying on the electrical grid [11]. Powering signage and lighting in remote areas can improve safety, while powering data acquisition systems roadside can decentralize traffic data and structural health monitoring data collection [12].

Solar energy harvesting technology is well developed. Commercially

* Corresponding author.
E-mail addresses: mohammadreza.gholikhani@utsa.edu (M. Gholikhani), HRoshani@lan-inc.com (H. Roshani), samer.dessouky@utsa.edu (S. Dessouky), at.papagiannakis@utsa.edu (A.T. Papagiannakis).

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available solar panels are proven electricity generators that make supplying the electrical grid financially viable [13]. A variety of roadside solar panel installation examples exist in different countries [14]. The main limitation of current solar panel technology is the physical space installation requirements. Applications have emerged that use solar panels installed at the top of pavements serving as the driving surface [15]. This technology, although solving the physical space requirement, has considerable structural capacity and safety challenges [13].

Harvesting heat energy from pavements is driven by the differential temperature gradients between the surface and the lower pavement layers [16]. In hot climates, daytime pavement surface temperatures are typically higher than the temperatures found in the lower layers, while the opposite is true in cold climates. A variety of applications that use these temperature gradients to either drive thermoelectric generators [17] or simply store heat to be used later for specific applications (e.g., deicing) exist [18]. A secondary benefit of heat harvesting from asphalt pavements in hot climates is their potential surface cooling, which to some extent mitigates urban heat island (UHI) effects [19]. Such practices may also result in a marginal reduction in the operating temperature of asphalt concrete surfaces, which can improve their rut resistance [20].

Harvesting mechanical energy from pavements is possible through either electromechanical means (i.e., Faraday's principle) or piezoelectric means (Curie's principle). Faraday's principle states that a time-varying magnetic field generates a corresponding electrical field, and vice versa [21]. Curie's principle states that piezoelectric materials generate a charge across their boundaries when a stress is applied to them, and vice versa [22].

The range of energy harvesting technologies in roadway pavements calls for a critical review of their potential for powering roadside applications. This paper offers a critical review of the literature on energy harvesting from roadway pavements. It is divided by technological principle and addresses details on operating principle, design, output, and economic feasibility. Technologies with high potential for energy harvesting from pavement are divided into three main groups: mechanical energy harvesting, heat harvesting, and solar radiation harvesting. They encompass technologies that harvest mechanical energy impacted by roadway vehicles, pavement heat, and solar radiation, respectively. Mechanical energy harvesters include piezoelectric and electromagnetic systems, heat harvesters include thermoelectric (i.e., Curie) and convection-based harvesters, and solar radiation harvesters include the variety of systems fragmented by photovoltaic effects.

2. Objective

The aim of this paper is to present a critical review of the various technologies available for harvesting energy from roadway pavements in order to evaluate the applicability of these energy harvesting processes. The specific objectives are to:

- Describe the various energy harvesting technologies available.
- Compare their technical characteristics.
- Provide estimates of their cost and economic feasibility.

3. Mechanical energy harvesting using electromagnetic means

Electromagnetic energy harvesting technology captures the mechanical energy of vehicles on the roadways and generates electricity [23]. Each day, roadways are subjected to numerous loads of passing vehicles. Generally, the mechanical energy from passing vehicles dissipates as heat and pavement deformation. To harvest this energy from pavements, new electromagnetic technologies have been proposed and developed recently. Typically, devices absorb the mechanical energy from passing vehicles and convert it to a movement that actuates an electrical motor that functions on Faraday's principle. This technology has been exploited to harvest energy from other sources [24], such as mechanical energy from vehicle suspensions [25], railroads [26], ocean waves [27], and backpacks [28].

3.1. Principle and basic features

Faraday's principle states that the relative movement of an electric conductor with respect to a magnetic field induces an electric current [21]. The amount of electricity generated depends on the velocity of relative movement, the strength of the magnetic field, and the number of coils [29]. In practice, mechanical energy from a moving vehicle applies a force/displacement to a mechanical system that leads to relative movements between a magnet and coil, thereby generating electrical power [30]. These mechanical systems can be divided into three categories, as discussed next.

In the first category, passing vehicles apply vertical displacements into the system through a plate flush with the pavement or a bump protruding from the pavement. This vertical displacement is converted to a movement that actuates an electromagnetic generator. These mechanical systems include rack and pinion [31], cam and arm [32], hydraulic [33], and chain and sprocket [34]. In some cases, two mechanisms are combined, such as the rack-and-pinion and hydraulic mechanisms [35]. One of the most popular electromagnetic harvesting mechanisms is the rack-and-pinion system. This type of energy harvester consists of a top plate capable of carrying vehicular loads and transferring them into a rack-and-pinion system. The rack receives loads and moves vertically, while the pinion translates it into a rotational movement that activates the generator. In such systems, high vertical displacement input is needed [35]. In the cam-arm system, the top plate moves downward and then upward after each vehicle passes. In this system, the follower arm captures loads and pushes one side of the cam down, causing a rotation of the cam, which then activates the electric generator [32]. A variation of these systems is a servo-hydraulic means of activating the electric generator, whereby traffic loads generate pressure in a hydraulic cylinder that activates the electric generator through a crank transmission [36]. Fig. 1 shows examples of servo-hydraulic systems and rack and pinion systems.

In the second category, the vertical displacement input from passing vehicles is a direct input to the relative movement between a coil and a

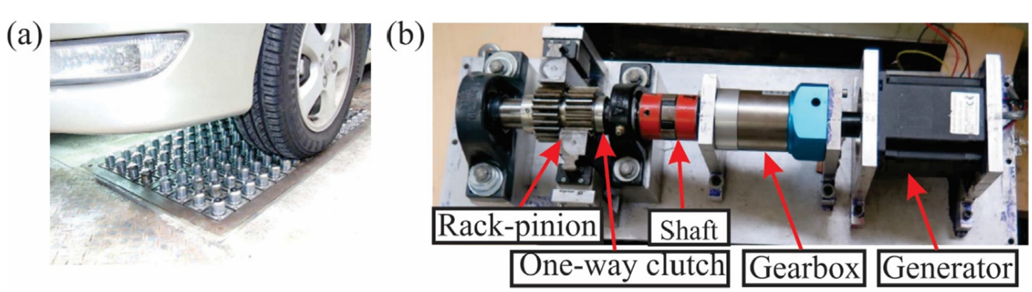


Fig. 1. (a) Passing vehicle pushing downward on hydraulic pistons in a servo-hydraulic system (annotated from Ting et al. prototype [36]); (b) Design and prototype of a proposed rack-and-pinion energy harvester (annotated from Wang et al. [42]).

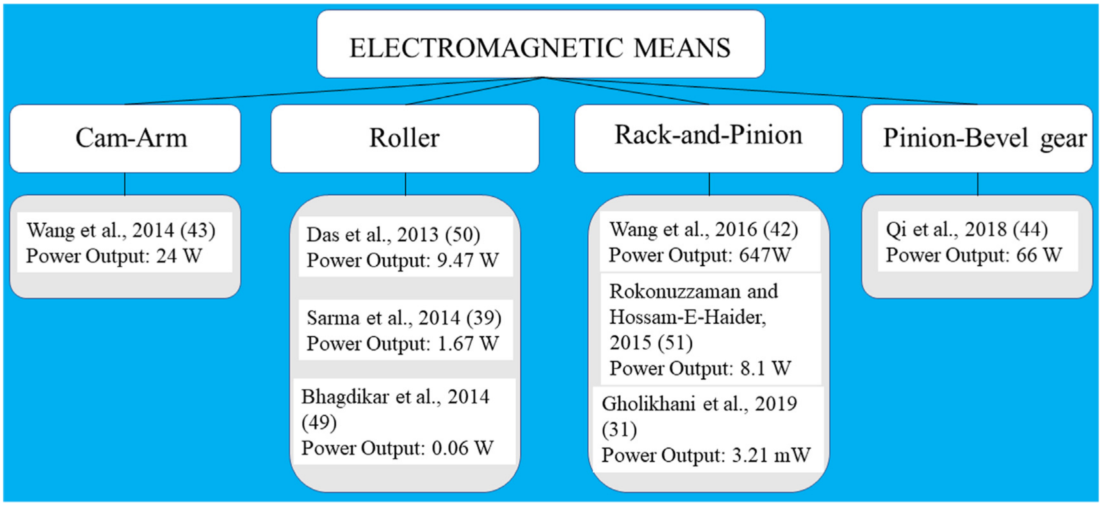


Fig. 2. List of generated power outputs by electromagnetic means.

magnet [37]. Such systems are referred to as linear generators. In these systems, either the coil or the magnet is fixed and is referred to as the stator; the other part is free to move and is referred to as the translator. When a vehicle passes over this system, the translator moves vertically and results in relative movements between the translator and the stator. These relative movements induce electricity in the coil [38]. Such systems generally include multiple sets of coils and magnets to maximize the output power.

In the third category, passing vehicles directly generate rotational input to the harvester, which is applied to the generator through a chain-and-sprocket mechanism [39]. There are also some proposed technologies that parallel the electromagnetic energy harvester that capture passing vehicles' energy, but instead of generating electrical power, they perform other activities, such as providing high-pressure air. Pneumatic mechanisms translate vehicular forces into compressed air through a pneumatic configuration. The mechanism involves a plate that pressurizes air in a cylinder equipped with a one-way valve and stores it in a high-pressure storage tank [40]. The compressed air can be used directly in applications where high-pressure air is needed (e.g., industrial applications) [41]. For instance, Goodey et al. [40] developed a pneumatic energy harvesting device to produce compressed air for industrial consumption. The desired max air pressure of 200 psi was achieved through a pressure regulator.

3.2. Output and efficiency

Some researchers have determined output power based on various types of electromagnetic energy harvesters. For instance, Wang et al. developed a mechanical energy harvesting prototype using a speed-bump type of actuator and a rack-and-pinion system. The highest output power achieved was 200 W. In a subsequent study, Wang et al. were able to generate a 647 W peak power for each passing axle [42]. Wang et al. conducted a study to test a new type of energy harvesting device working with a cam-arm mechanism to harvest the energy from passing vehicles at high speeds. They tested the prototype at different vehicle speeds. The highest obtained power was reported as 24 W, and a voltage of 5 V was recorded when the vehicle was passing at 5 mph and external resistance was set at 10 Ohm [32]. A study conducted in China developed a harvester using a pinion and bevel gear. Laboratory and field testing of this system produced a maximum output of 66.025 W under a 2 Hz loading cycle [43]. Gholikhani et al. developed and tested a simple rack-and-pinion device under different loading conditions. The maximum output power of their devices was 3.21 mW [31]. Another device with a rack-and-pinion mechanism was proposed by Ahmad and Massod [44]. It generated maximum voltage outputs of 13.8 V under an axle load of 10 kN moving at a speed of 7 m/s. Sailaja et al. [45] and Aswathaman and Priyadharshini [34] introduced prototypes based on rack-and-pinion mechanisms and chain-and-sprocket mechanisms. Aswathaman and Priyadharshini studied the output voltage by testing variable vehicle speeds and axle loads; the maximum output voltage they reported was 7.93 V for a speed of 10 km/h and 11.81 V for a load of 2650 N [34], while the maximum voltage reported by Sailaja et al. was 23.5 V. Moreover, these systems were proven cost effective [45]. Azzouz et al. [46] designed a prototype with a set of pneumatic cylinders that was installed in pavement and extended slightly above the surface to harvest energy from passing vehicles. The results showed that their prototype generated 798 J per vehicle tire pass. They claimed an output of 83 kWh/day for a roadway with 37,400 vehicle/day. Rao et al. [47] developed a prototype based on a crankshaft and gears and tested it by applying different loads. The prototype generated a voltage of 11.23 V under a load of 2000 N [47].

The literature reports some power output results for mechanical harvesters such as the ones described above. Sarma et al. used a roller mechanism to capture vehicle mechanical energy [39]. The device output power for one axle passing load was 1.67 W. They estimated an output of 2.3 kW during a 24-hour period. Another roller mechanism energy harvester was introduced by Bhagdikar et al. [48]. It employed a chain mechanism to transmit mechanical energy to the generator. The power output for a single pass of a motorcycle was reported as 0.06 W. Das et al. developed a similar prototype capable of generating 9.47 W [49]. Rokonuzzaman and Hossam-E-Haider compared two mechanisms of the energy harvester, namely a rack-and-pinion and a roller. They found that one vehicle passing over the rack-and-pinion mechanism prototype generated 19.62 W, while one passing over the roller mechanism generated 8.1 W. They concluded that both mechanisms have potential for harvesting energy from roadways [50]. Power outputs reported by studies are briefly presented in Fig. 2.

3.3. Cost considerations

Some of the studies described above provided analysis of the economic feasibility of the mechanical energy technologies developed. The study with the pneumatic mechanism [40] evaluated the prototype's financial feasibility. Researchers calculated the cost of the device to be about $7000. They found that their device could produce sufficient compressed air at a competitive cost compared to conventional air pressure generation systems and required minimal maintenance [40]. The economic feasibility of some other energy harvesting systems was considered in railroad applications. A rack-and-pinion type of harvester costing $2135 (including materials and labor) was deemed financially feasible for railroad applications [51]. This system was very similar in design to some of the rack-and-pinion systems installed on roadway pavements. Although this technology is still evolving, it appears that harvesting roadway mechanical energy by electromagnetic means produces sufficient electrical energy to make such devices cost effective.

4. Mechanical energy harvesting using piezoelectric materials

Several efforts have been made to use piezoelectric technology in harvesting energy across a variety of applications [52]. Piezoelectric materials have been embedded in shoes [53], knee replacement [54], and tires of automobiles [55]. Another emerging field for piezoelectric materials is energy harvesting from various energy sources in the environment, such as water- and wind-exerted stresses [56] and the vibration of structures [57]. Some studies investigated the use of piezoelectric technology to produce energy from human movements [58]. Another application of piezoelectric materials is in powering transducers and sensors to detect signals by generating voltage out of vibrations [59].

Piezoelectric materials have shown potential in harvesting mechanical energy from roadway pavements due to their simplicity [60] and high power density [61]. The power generated has been applied to powering wireless sensors [62], health monitoring systems [63], signage, and lighting [8]. According to the literature, piezoelectric materials are the best choice for powering “smart road” sensors independently of the electrical grid [64].

4.1. Principle and basic features

Piezoelectric materials generate electric energy in response to an applied stress/strain, and vice versa [65]. They can be used for generating electricity under stress or, conversely, used as stresses/strain sensors that are given an electric excitation. The electrical energy stored in piezoelectric materials is released by connecting their poles to an external resistance [66]. The direct piezoelectric effect is described in Eq. (1) and Eq. (2).

$$D = \varepsilon^{\sigma}E + d\sigma \tag{1}$$

$$S = s^{E}\sigma + dE \tag{2}$$

where D and S are electric displacement and strain, E is the electric field, d is the piezoelectric coefficient, σ is stress, $\varepsilon^{\sigma}$is dielectric permittivity in a constant stress status, and s^{E} is the material’s mechanical compliance matrix.

Two piezoelectric coupling modes, referred to as 31 and 33, are associated with piezoelectric coefficients d_{31} and d_{33}, respectively [67]. In the first, the direction of stress and polarity are perpendicular to each other, while in the second, they are parallel to each other. The literature suggests that the latter is more efficient for energy harvesting applications [68]. Priya studied the productivity of an energy harvester under the 31 and 33 modes and concluded that the piezoelectric materials with the 33-mode configuration have better performance when subjected to moving vehicle loads in pavements [69].

Piezoelectric materials are available in nature as a single crystal, such as quartz. There are also several synthetic piezoelectric materials, including crystals that are quartz analogs, ceramics, polymers, and composites [70]. Two of the most common piezoelectric materials are lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF). PZT is in the piezo-ceramic family, and PVDF is a polymer. PZT-based piezoelectric elements have been used extensively in industrial applications. For energy harvesting, the following transducers can be used: cymbal [71], moonie [71], multilayer, biomorph, reduced and internally biased oxide wafer (RAINBOW) [72], thin layer unimorph ferroelectric driver and sensor (THUNDER), and macro-fiber composite (MFC) [73].

Each piezoelectric material has different parameters that affect its performance and efficiency. PZT is an inorganic fragile ceramic material with a large piezoelectric coefficient. On the other hand, the PVDF composite has excellent flexibility and thermal stability, is chemical resistant, and is a durable polymer material, but it has a much smaller piezoelectric coefficient [74].

A piezoelectric energy harvesting device includes two fundamental elements: the mechanical part that generates electricity, and the electrical circuitry that conditions the electricity produced. Both of these elements’ integration and interaction have a significant effect on device efficiency [75]. In addition, several factors affect piezoelectric device performances in energy harvesting [76], such as piezoelectric constants, distribution of electrical permittivity, geometry, tolerance of a ceramic, and delamination of a ceramic [77].

Effective energy harvesting in pavements requires piezoelectric devices that satisfy stringent requirements for stiffness, durability, and strength [78]. To protect piezoelectric elements from vehicular loads and adverse environment conditions, they need to be encased in a properly designed enclosure made of suitable materials, such as concrete, steel, or engineered plastic [79]. Several studies were conducted on designing piezoelectric element enclosures, and many of them focused on cantilever beam configuration [80]; researchers concluded that the cantilever beam is too fragile for handling loads from in-service vehicles [81]. On the other hand, Ye et al. found that energy harvesting from pavement using a piezoelectric cantilever system can be feasible [82]. Experimental results showed that an arch bridge had higher energy production efficiency than arc and trapezoidal bridge designs, while trapezoidal bridge designs sustained higher loads [83]. Two research groups examined the applicability of piezoelectric elements in harvesting energy from pavements. They evaluated different configurations based on stiffness [78], efficiency [84], and brittleness [78]. Both groups found neither of their configurations was suitable for energy harvesting in pavement. Zhao et al. introduced a cymbal-shaped piezoelectric transducer made of a composite piezoelectric ceramic disk sandwiched between two metal end caps and claimed the transducer performed satisfactorily in pavement applications [68].

In summary, there is no unique configuration that favors piezoelectric energy harvesters for pavement applications. Researchers have chosen designs based on their intuition and past successful designs found in the literature. Fig. 3 presents two piezoelectric-based energy harvesting prototype examples.

4.1.1. Installation and implementation

Factors such as piezoelectric material, element configuration, depth of embedment of the piezoelectric enclosure, position of vehicle wheels with respect to the enclosure, vehicle speed, vehicle class, and traffic volume can affect the generated electrical power [67]. The vertical stress dissipates along the depth, which means that the closer the energy harvesting device is to the pavement surface, the more mechanical energy it receives [22]. There are some considerations, such as the need to be able to repair the topmost pavement surface (e.g., removal of the top 50 mm (2 in.) of an asphalt concrete layer), that dictate that piezoelectric harvester enclosures should be placed below that depth to allow pavement rehabilitation [9]. At that depth, they experience about 90% of the stresses applied to the surface, but they allow unfettered routine rehabilitation [86]. It has been suggested that the center of the device be located along the wheel path, which is 45–60 cm from the edge of the traffic lane. Zhang et al. concluded that if the distance between the wheel and transducer exceeds 4 m, the output power will drop to zero [67]. Wischke et al. studied the installation of piezoelectric harvesters in roadway tunnels and concluded that the vibrations from vehicles did not generate sufficient energy to make harvesting feasible [87]. Maximum output power was achieved at a particular vehicle speed and for certain pavement damping properties [88]. Finally, the literature suggests that the harvester enclosure stiffness should be the same as the stiffness of the surrounding pavement to minimize the

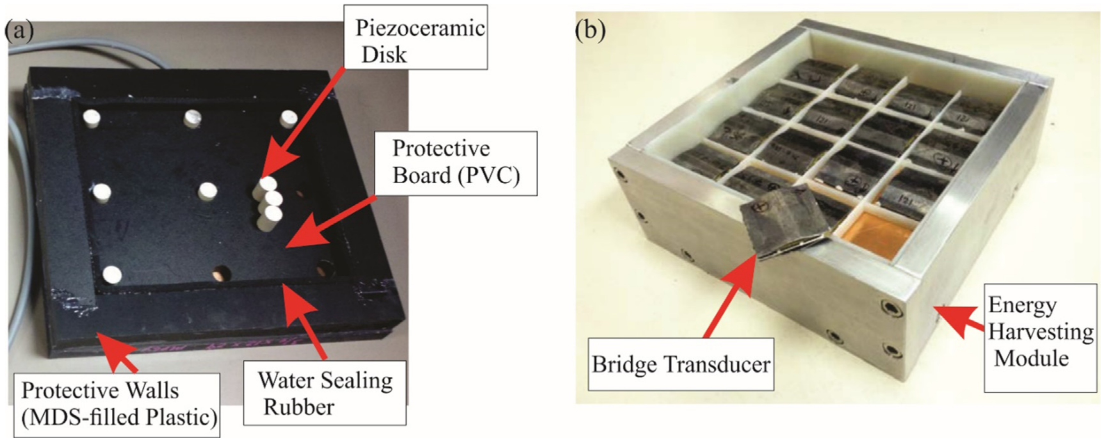


Fig. 3. (a) Assembled energy harvester without the cover (annotated from Xiong et al. [79]); (b) Prototype, top cover removed, showing the top layer of transducers, nylon spacers, and lined walls (annotated from Yesner et al. [85]).

differential deflections at the interface of the device and the pavement to control the reflective cracking. Furthermore, to prevent cracking around the device, designing sharp edges on the device should be avoided [89].

4.1.2. Storing the generated electricity from piezoelectric materials

The electrical energy generated by piezoelectric harvesters is relatively low, so it is necessary to store it in order to power infrastructure applications [90]. There are two methods to store electrical energy, namely using supercapacitors or rechargeable batteries [91]. Sodano et al. found that rechargeable batteries perform better than traditional capacitors when a constant power is needed. Their results showed compatibility between the battery and the piezoelectric devices, and a charge of 40 mAh was obtained from the piezoelectric device in less than an hour [92]. In 2019, Xiong studied the applicability of rechargeable batteries to store the energy generated from piezoelectric devices. According to the results, the charging speed of the battery was initially high. However, subsequently, the charging rate dropped drastically until the battery was fully charged [93]. Recent studies show that supercapacitors are efficient and durable and have high energy densities and low self-discharge rates. They are often coupled with a diode rectifier to maximize the output power [92]. Several studies confirmed that due to the recent developments in supercapacitors, they are a better choice to store piezoelectric output energy [94,95].

4.2. Output and efficiency

The output energy of piezoelectric harvesting devices depends on many variables, such as materials, shape, dimensions, and number of installed piezoelectric elements. Therefore, electrical energy output can vary significantly between harvesters. Table 1 summarizes the main design element, testing method, electrical output, and conclusions drawn for piezoelectric energy harvesters in the literature.

There has been some commercial development of piezoelectric harvesters, such as the one from JR East. JR East of Japan developed an energy harvesting device using a piezoelectric array and installed it in a Tokyo railway station. The output energy could light a 100 W lightbulb for 80 min. However, energy generation decreased after three weeks due to system degradation [122].

4.3. Cost considerations

Energy harvesting needs to be cost effective in order to be accepted and widely utilized. Few of the studies reviewed evaluated the cost effectiveness of the harvesters developed. Moure et al. assessed the value of the energy harvested by the cymbal-shaped harvester described earlier under in-service traffic conditions [78]. They found that the initial cost of this technology—when considering a 15-year service life—is 1.98 €/kWh [78]. Papagiannakis et al. applied the levelized cost of energy (LCOE) concept to estimate the cost of energy generated by several piezoelectric energy harvester prototypes and compared it to the LCOE of other energy sources [108]. LCOE is expressed as the ratio of the annualized harvester cost divided by the power generated annually. They compared two different prototypes under four traffic composition scenarios [108]. The LCOE estimates obtained for Prototype 1 ranged from 8.7 $/kWh to 34.7 $/kWh and for Prototype 2 ranged from 4.8 $/kWh to 19.4 $/kWh, assuming a 20-year service life [108]. Guo et al. evaluated the cost effectiveness of a PZT energy harvesting system and presented LCOE estimates ranging from 35.66 $/kWh to 106.97 $/kWh for service lives of 5 to 15 years, respectively [91]. Another study by Roshani et al. estimated their harvester's LCOE at 27.90 $/kWh for a service life of 10 years [86].

In comparing the cost of conventional electric grid power—which is approximately $0.15 to $0.30 per kWh in the United States—with the cost of piezoelectric technology, one can conclude that the cost of harvesting energy using piezoelectric technology is too high. However, it is important to point out that this technology is still in its infancy and has not benefited yet from economies of scale in manufacturing. Additionally, this sustainable energy resource could be more effective in remote areas where there is no power grid to supply energy for facilities.

There are plenty of factors that influence the cost of energy generated using piezoelectric materials. By improving the efficiency of the devices and considering the increasing amount of passing vehicles, the generated power value should increase and, consequently, the cost of produced energy should decrease [123].

5. Heat harvesting using liquid circulation

Another method of harvesting roadway energy is by collecting and conveying heat through a network of fluid pipes embedded into the pavement structure [124]. These systems are often referred to as asphalt solar collectors (ASCs), road pavement solar collectors, or hydronic asphalt pavements. Popular applications of this technology include melting pavement surface ice in the winter and reducing pavement surface temperature from hot pavement in the summer. Another application of these systems is utilizing the warm fluid to heat buildings [125].

5.1. Principle and basic features

Generally, this technology is based on exchanging the heat between

Table 1
Piezoelectric energy harvesters in pavements.

Author(s)	Specimen materials and design	Test	Electric output	Study conclusion
Yao et al., 2012 [96]	PZT—arc and trapezoidal bridge transducers	Universal Testing Machine (UTM) under different loads and frequencies	232 V for arc bridge and 106 V for trapezoidal	Piezoelectric technology in roadways is practical.
Kim et al., 2012 [97]	PZT—some cantilever plates installed in a speed-bump device and underneath a pavement layer	In field with real vehicle road	7.61 mW for speed-bump device and 63.90 mW for underneath device	Increasing the number of piezoelectric cantilevers is useful to generate more energy.
Cafiso et al., 2013 [98]	PZT material—circle plate	Direct compression test	2.43 mW and 1.6 V for voltage	Output power was very low. It can be improved by changing the size and network connection of transducers.
Zhao and Erturk [99]	PZT-5H—multilayer stack	Horizontally compressed by a long-stroke shaker at low frequency	0.6 mW/cm^3	Introduced analytical and numerical tools to predict piezoelectric harvester performance.
Xiong et al., 2012 and 2016 [79,100]	PZT—disk-shape with nine different configurations	Material Testing System (MTS)	3.1 mW electrical energy per passing vehicle [79]; 300 µW/cm^3 [100]	The generated power decreased significantly after one year of operation. The product is suitable for small electronics' infrastructure.
Jiang et al., 2014 [75,101]	PZT-8—device that consisted of groups of piezoelectric units, including three multilayer stacks	Using shake table to input the vibration excitations	One single-unit 85 mW DC power [101]; 200 mW [75]	The output energy was sufficient to power low-power equipment.
Zhao et al., 2015 [83]	PZT disks—arch bridge and trapezoidal bridge	MTS provided distributed half-sine loads in certain frequency	Arch bridge transducer generated 286 V under 0.7 MPa and stored 0.6 mJ electrical energy	The arch bridge had a higher efficiency of energy conversion, while the trapezoidal bridge had more pressure resistance. The arch bridge generated less electrical potential while its thickness increased.
Kim et al., 2015 [102]	Two different piezoelectric materials	Asphalt Pavement Analyzer (APA)	2.67 mW at 72 km/h simulated traffic speed	Self-supporting energy capability of highways in remote areas is practical.
Li, 2015 [103]	PZT and phosphor- bronze end cap—arc and rectangular bridge transducer	MTS provided the necessary half-sine wave load with frequencies of 1 Hz and 5 Hz and amplitude of 0.1–0.7 MPa for the experiment	Arc transducer generated 220 V, while rectangular transducer produced 160 V	The rectangular transducer could tolerate higher stress than the arc bridge.
Song et al., 2016 [104]	PZT-PZNM ceramic attached to stainless steel—piezoelectric cantilever beams	UTM under different loads and frequency	One-fourth of the harvesting module output power was 184 µW, and power density was 8.19 mW/m^2	By installing the prototype in a road with 600 passing vehicles per hour, 4.91 Wh/m^2 electrical power could be generated.
Yesner et al., 2016 [85]	Transducer PZT ceramic and hardened steel end cap—cymbal design based bridge	For load simulation, using a pneumatic piston with an impact force of 2670 N (600 lb) that can be repeated at a frequency up to 5 Hz	Each simulated vehicle loading of the transducer generated 0.83 mJ energy; under simulated traffic conditions at 5 Hz loading, the device generated 2.1 mW	The transducer output was sufficient to run low-power sensors, electronics, and LEDs.
Kim et al., 2017 [105]	PZT-PZNM as a piezoelectric material and stainless steel for substrate—fixed-fixed beam type piezoelectric plate in a box	Connect shaker to fixed-fixed beam to make a frequency load	112.937 V	Output voltage increased from 92.312 V to 112.937 V when the piezoelectric energy harvester's mass decreased from 6.035 g to 5.386 g.
Xiao et al., 2017 [106]	PZT transducer	Automatic rutting test machine—the frequency is 0.7 Hz and wheel pressure is 0.7 MPa	16.8 mW	The system has the potential to improve pavement preservation, management, and maintenance.
Yang et al.,2017 [107]	PZT-PZNM ceramic and stainless steel used for piezoelectric cantilever	UTM and a third-scale mobile loading simulator (MMLS3)	625 mW for UTM test in 15 Hz loading frequency, 280 mW for MMLS3 test, and about 330 mW for APA machine test; maximum power density 21.47 W/m^2	The prototype could work as an energy source for sensors in smart roads and autonomous vehicles.
Papagiannakis et al., 2017 [108]	PZT-4 prototype—three layers of piezoelectric were connected in series, a stack of six PZT-5A ceramic disks, 21 rectangular PZT elements, composite of three of 21 rectangular PZT elements	UTM loading system	Electrical power generated from a single pass of truck tire load was between 1.0 and 1.8 W	Connecting piezoelectric elements in parallel avoids generating unmanageably high voltages.
Wischke et al., 2011 [87]	PZT ceramic plate fixed to box—piezoelectric sensors at road and railway tunnels cantilever-based piezoelectric generator	In field, under real traffic of railway and roadway loads	Showed output energy from railway vibration, at least 135 µJ from 85% of all trains was higher than road tunnel's output	Vehicle vibrations at any location in the road across the pavement and tunnel walls were not enough for energy harvesting. Harvesting the vibrations using more cantilevers can be a solution to increase the output energy.

(*continued on next page*)

Table 1 (*continued*)

Author(s)	Specimen materials and design	Test	Electric output	Study conclusion
Hou et al., 2017 [109]	PZT—biomorph cantilever beam		Generated and stored 1.68 mW power	Output was sufficient for the acceleration sensor for data collection and RF communication.
Xu et al., 2017 [110]	PZT materials—stack– cantilever composite piezoelectric cylinder pieces were installed in a box	Instron 8874 fatigue testing machine for fatigue test; in field, under real traffic loads for output	Maximum voltage was 70 V for PZT-5H in 10 Hz loading with 1000 kg load;	Using piezoelectric technology in roadway pavement energy harvesting is feasible. Fatigue test showed the possibility of piezoelectric box installation in pavements.
Yang et al., 2017 [111,112]	PZT-5H—piezoelectric box prototype consisted of 12 piezoelectric units	In field, under real traffic loads	Output voltage range was between 250 and 400 V for vehicle speed from 20 km/m to 80 km/h	The output power was enough to operate LED boards [112]. The results also showed reliable performances of the prototype in fatigue, waterproof, anticorrosive, and antiwear tests. The transducer operation did not change significantly after 100,000 loading cycles.
Guo and Lu, 2017 [113]	PZT disks—harvesting prototype consisted of two conductive asphalt layers and one layer of piezoelectric	Simulation of traffic loads on specimens by an MTS	Maximum electrical power output was 300 mW under 30 Hz vibration frequency	More flexible conductive asphalt mixture and arranging more piezoelectric materials with higher piezoelectric stress constant increased the output electricity.
Jasim et al., 2017 [114]	PZT-5X square plates— piezoelectric layered bridge transducers, 64 transducers in an aluminum casting in four layers	Vehicular loading was simulated using a pneumatic piston; loading pressure was 70 kPa repeated at 5 Hz	Maximum output power was 2.1 mW at 5 Hz and 400 kΩ resistive load	The output power is greater at high resistive loads due to the high impedance of bridge transducers.
Roshani et al., 2017 [86]	PZT—piezoelectric prototype consisted of a stack of 11 piezoelectric elements connected in parallel	The durability of the prototype with APA machine	Output was 64.12 mW for each passing tire with 64 km/h	The output power remained constant throughout the loading repetition test.
Wang et al., 2018 [115]	PZT—area of the device was 100 mm × 100 mm	MTS—0.2 to 0.7 MPa loads were applied	Maximum output was 11.67 mW at 0.7 MPa load and 15 Hz	Maximum output power of the energy harvesting units is positively correlated to the load size and frequency.
Jasim et al., 2018 [116]	PZT-5X—64 transducers in four layers, with 17.8 × 17.8 × 7.6 cm dimensions	Maximum load of 3.56 kN (800 lb) at a frequency up to 5 Hz	26.6–30.1 mW under 0.7 MPa loading stress at 5 Hz	The energy harvesting performance is affected by vehicle weights, speed, and embedment location of the energy module.
Shin et al., 2018 [117]	PVDF—two connected 15 × 30 × 10 cm^3 modules	In field test under real traffic conditions	620.2 mW (13.8 W/m^2) at 15 cm × 30 cm^2 area with a passenger vehicle at 80 km/h	The output power has a linear relation to the vehicle speed and weight.
Rui et al., 2018 [118]	MFC-M8514-P2 cantilever beam with new bandwidth—101 mm × 20 mm × 0.21 mm dimensions	Laboratory set up with shaker, signal generator, power amplifier, and oscillograph	Maximum output power 3.277 mW under the harmonic excitation of 4 m/s^2	The harvester has high performance with enhanced output power in wide operating frequency range.
Yesner et al., 2019 [119]	PZT—bridge transducer with 2 mm × 32 mm × 32 mm dimensions	Pneumatic system used to simulate vehicle	Output energy for a single loading cycle was 0.83 mJ	Technology can monitor traffic levels and distinguish between a light vehicle and a heavy truck.
Guo and Lu, 2019 [120]	PZT—bulk piezoelectric elements inside the piezoelectric layer, including piezo cylinder, piezo curved roof, and piezo ball	MTS with 40 kN uniformly distributed over 0.2 m × 0.2 m	Maximum output voltage was 85 V for piezo ball configuration	The voltage outputs from the PZ-EHPS with a rigid piezoelectric layer are generally higher than those from the PZ-EHPS with a flexible piezoelectric layer.
Wang et al., 2019 [121]	Stacked piezoelectric have two kinds of structures: the separation-type piezoelectric chip stack structure uses a multilayer adhesive, and the integral stack co-firing structure uses a monolithic co-firing	MTS applied cyclic loading, 0.7 mPa with 10 Hz	Output power was 22.80 mW	Multilayer units exhibit good structural stability and weatherability.

the pavement and fluid in pipes embedded into the pavement and storing the harvested heat in a suitable heat sink [16]. For cooling purposes, cooler fluid from lower layers or from bodies of water (e.g., a river or sea) is circulated near the pavement surface to reduce its temperature. It is in turn circulated back to the lower layers where heat can be suitably dissipated. For heating, warmer fluid from the lower layers is circulated to the surface to prevent ice formation [126]. Some studies have tried variations of this system by relying on the porosity of the layers to conduct the fluid instead of pipes for instance study conducted by Pascual-Muñoz et al. [127] and Garcia and Partl [128].

Several factors affect the performance of ASCs, such as ambient temperature, wind speed, solar radiation intensity, cloud cover, pavement material properties, and exchange system design specifics [129]. ASC pipe materials play an important role because they control the heat transfer process. In addition, these pipes are subjected to traffic loads and therefore need to have sufficient strength. Early ASC designs involved metal pipes [130], but they were shown to be prone to leaks and subject to corrosion. Subsequent designs involved plastic or polyethylene pipes that exhibited better performance [126]. Additional work established that other pipe parameters, such as pipe length, diameter, spacing, and installation depth, affect ASC system efficiency [16]. Larger-diameter pipes resulted in better performance by increasing the rate of heat exchange [131]. The closer to the surface the installation of the pipes, the higher the efficiency of ASC systems. A study conducted by Bobes-Jesus et al. concluded that the optimum embedment depth of pipes was 20 mm [124]. The efficiency of the system increases with closer spacing between pipes [132]. Two studies by Chen et al. [133] and Bob-Jesus et al. [124] concluded that a serpentine arrangement of pipes performs better than a parallel arrangement. There is disagreement about the effect of fluid flow rate on ASC system efficiency. Some studies concluded that a higher flow rate leads to higher efficiency [134], while others suggest that flow rate effect is negligible [131]. In most ASC systems, water is the fluid of choice due to its low cost and environmental friendliness, although commercially, antifreeze has been chosen for some deicing applications [16].

Mallick et al. evaluated the effect of pavement materials on the performance of ASC systems and found that aggregates with higher conductivity, such as quartzite, can improve the heat transfer efficiency better than aggregates with lower conductivity, like limestone [135]. They suggested that increasing the heat transfer with highly conductive aggregates is preferable to adding high conductivity additives such as copper powder. Other solutions for increasing the efficiency of ASC systems are painting the asphalt surface with black acrylic [19], increasing the thermal conductivity of pavement materials [136], and adding graphite to pavements to increase thermal conductivity [137]. In contrast, Pascal-Munoz et al. found that adding materials such as graphite does not significantly affect system performance [127]. In conclusion, ASC systems need to be custom designed to meet the particular application requirements and environmental conditions at a particular site [138]. Examples of ASC system prototypes are shown in Fig. 4.

5.2. Output and efficiency

In general, the efficiency of the ASC system is the ratio of collected solar energy by the system to the whole input solar energy. The earliest documentation on ASC efficiency comes from a 1981 UK study by Sedgwick and Patrick [140]. They used a network of plastic pipes spaced at a 0.02 m depth under a tennis court to heat a swimming pool. Their results showed that the system generated sufficient thermal energy to heat the swimming pool water to between 20 and 27 °C. They found that the system was cost effective and practical for UK climatic conditions. Zhou et al. developed an ASC system capable of absorbing 2821 kWh heat from the pavement and storing in the soil during 69 days in the summer. The system also was able to take out 4598 kWh heat from the soil during 104 days of cold weather. The harvested energy was higher than the consumed energy in both cases. The results demonstrated that a 24-hour operation of the system could increase the pavement temperature and reduce the freezing time (when the pavement temperature is lower than 0 °C) by about 32%. The freezing time reduction ratio increases if the system works only in snowy weather. They also found that the system could absorb 46% of heat generated by solar radiation, which was absorbed by the pavement in summer. In addition, they concluded that the pavement temperature decreases by 2 °C when it works at night, which is an additional solar heat absorption benefit of the system [141]. Pascual-Munoz et al. conducted laboratory testing to determine the efficiency of ASC systems. They used a lamp to simulate solar radiation. The results showed high thermal efficiency for a multilayered pipe collector ranging from 75% to 95% depending on the solar lamp's radiation and intermediate layer porosity [127]. They described the thermal efficiency as the ratio of the energy transferred to the fluid to the energy absorbed by the system. Meanwhile, Wu et al. observed that their system reduced the pavement surface temperature around 19.4 °C compared to the control condition [134]. Furthermore, Gao et al. investigated the maximum percentage of heat-collecting capacity of the pipe system embedded in the asphalt pavement top layer with three different serpentine pipe configurations. They concluded that the system with the highest pipe density achieved the maximum heat-collecting capacity (250 W/m^2) [132].

Some ASC systems have been installed on bridges in various states, such as Texas, Virginia, New Jersey, Wyoming, Oregon, and Nebraska [142]. In addition, ASC systems have been installed in several airport runways, such as at Norway [143], Sweden, [144] and Poland. Furthermore, in Switzerland, a solar energy collector system called SERSO was installed in the pavement for melting snow and deicing the roadway's surfaces [145]. The system collected about 20% of solar radiation

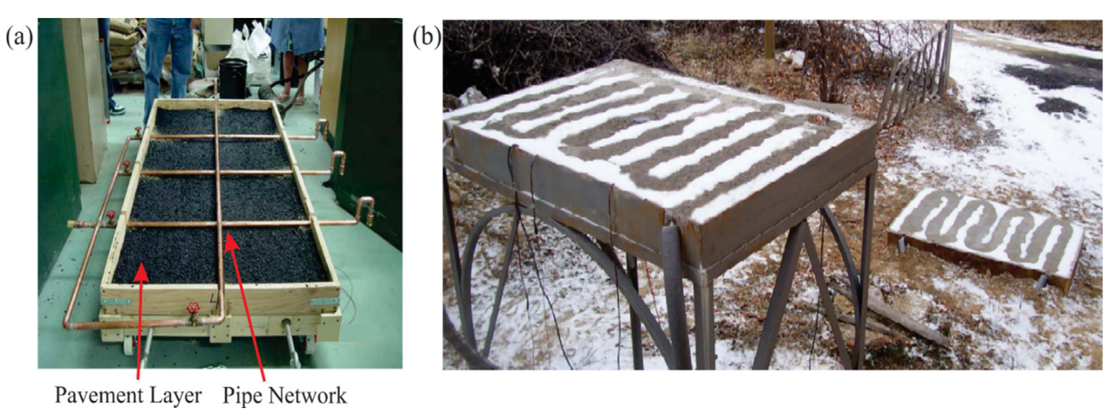


Fig. 4. (a) ASC prototype pipe network configuration (annotated from Mallick [131]); (b) Snow-melting process on slabs after 30 min with ASC prototype (annotated from Balbay and Esen [139]).

energy, and around 65% of this energy was stored in the heat sink during the summertime. In the winter, the stored energy was used to deice pavement surfaces [146]. The SERSO system performed better when a continuous fluid flow was used rather than using it only during snowstorms [147]. ICAX, a UK company, installed an ASC system and used it to store heat during the summer and then used the stored heat to heat a building through the winter [12]. Another ASC project, was developed and implemented on Japan's roadways to prevent ice and snow formation in the winter. Using water pipes cost 20% less than a system relying on electric wires embedded in the pavement, and its efficiency was much higher [132]. Another study in Japan showed that a pipe heating system with underground water storage can effectively keep pavement surfaces at temperatures higher than 0 °C [148]. Ooms Company, based in The Netherlands, also implemented an ASC system in different areas of The Netherlands and other countries, such asScotland [149]. Several other commercial systems have been installed around the world, including systems in Netherlands [150], Sweden [151] and China [152].

5.3. Cost considerations

Cost analysis of ASC systems typically involves comparing the material and installation costs with the operating expenses of a similar system functioning with electrical power. It is recognized that the cost of materials and installation is a function of the scale of the installation and the particular local requirements [16]. Factors that increase system efficiency increase the system return and promote the financial performance of the system. For example, in lower latitudes, more solar energy is available for harvesting, so the payback period for installing such systems is reduced. A preliminary economic analysis of ASC systems conducted in Sweden suggests that ASC systems are cost effective, despite the fact that additional study of their economic feasibility is required [153]. Mallick et al. stated that the payback period of the ASC system they developed was 10 years. Their estimation was based on the heat harvested by hour throughout the year, which was translated into equivalent electrical energy at 10c/kWh [131].

6. Heat harvesting using air circulation

A variation on systems that use a liquid fluid as the heat exchange medium is systems that utilize air. Their distinct advantage is that they cannot compromise the pavement structure by leaking [154].

6.1. Principle and basic features

Heat harvesters using air as the exchange medium consist of pipes capable of circulating air embedded into the pavement surface. The air either absorbs or emits heat from/to the pavement surface depending on the temperature differential [155]. Air circulation may be possible through convection, so there is no need for a circulating pump. Such systems may be able to use the air flow to activate a wind turbine and produce electricity [156]. Different types of pipe material have been used, such as stainless steel and copper. Alternatively, some researchers have tried replacing copper pipes with corrugated concrete pipes. Concrete pipes are more cost effective but have inferior performance due to their high specific heat and high friction surfaces [157]. The speed of the air outflow through the chimney depends on the fluid-dynamic and thermodynamic effects of the piping, as well as the shape and material of the chimney. The chimney material is polyvinyl chloride (PVC), which is covered with a thin layer of insulation material [154]. Its dimensions (diameter and height) vary from one study to another. Long chimneys tend to emit air closer to the ambient temperature, while short chimneys reduce air flow speed [128]. The circulating pipes and the chimney are connected through elbow connectors to a junction box [157]. Fig. 5 shows examples of prototype air exchange ASC systems.

6.2. Output and efficiency

The reduction in pavement surface temperature fluctuations is an indicator of the effectiveness of air-exchange ASC systems [128]. The system that Chiarelli et al. developed reduced pavement surface temperatures by more than 6 °C [159]. However, its maximum efficiency was only 4.80% [154]. It was concluded that these systems are not practical for generating electrical energy. Another study by Chiarelli et al. [157] compared the performances of different pipe configurations. The results showed that the system with pipes in a single row was most efficient, and the higher the air speed, the lower the pavement surface temperature [157].

6.3. Cost considerations

The cost of this technology has not been documented in the literature. However, the very low efficiency of the prototypes described above suggests that this technology in its current state of development is not cost effective.

7. Heat harvesting using thermoelectric generators

The thermal gradient between pavement layers can be used to generate electrical energy through thermoelectric generators (TEGs) that function on the Seebeck effect [69], which is described as electrical voltage generated between two points of an open circuit made from two heterogeneous semiconductors, an N-type and a P-type, joined at one end. The thermal electromotive force generated is a function of the temperature gradient and the number of N-type an P-type semiconductors [160]. The produced power can be controlled by arranging semiconductors and covering them with a thermally conductive but electrically insulating ceramic plate [69]. Rowe [161] indicated that a 5 °C temperature difference could generate 250 mW of electrical power. Researchers used TEGs to generate electrical power from automobile exhaust pipes [162], soils, and building walls [163]. The results showed potential to convert heat into electrical power. A few studies have been conducted to investigate the performance of these technologies in pavements.

7.1. Principle and basic features

Appropriate thermoelectric materials must have low thermal conductivity and high electrical conductivity to perform effectively in converting the temperature gradient into electric energy [164]. Silicon germanium (SiGe), bismuth telluride (Bi2Te3), and lead telluride (PbTe) are three semiconductors that have these properties [164].

Thermal energy harvesters consist of a TEG, a heat sink, and a heat-conducting plate [17]. There are several commercial TEGs that are applicable to the energy harvesting systems. TEGs in the system are subjected to a large number of thermal cycles, so their thermal cycle resistance must be high. For heat conductivity plates, metal is an ideal option [165]. The metal plate absorbs the heat from the surface of the pavement and transfers it to the point where the TEGs are installed. This plate must be insulated properly to minimize the heat loss in the transferring process. The plate can have different shapes, such as a Z-shape or an L-shape. The whole system should be isolated and waterproof to increase efficiency [164].

Kim et al. evaluated a TEG module system powered by the temperature gradient between the pavement surface and the ambient air that was installed on the surfaces of both a Portland concrete and an asphalt concrete pavement. The results showed that the Portland concrete pavement performed better at generating voltage than the asphalt concrete pavement. The reason cited was that the temperature difference between the Portland concrete and the ambient air was 1.7 times higher than the corresponding difference for the asphalt concrete pavement. The researchers also found that copper performed better as a

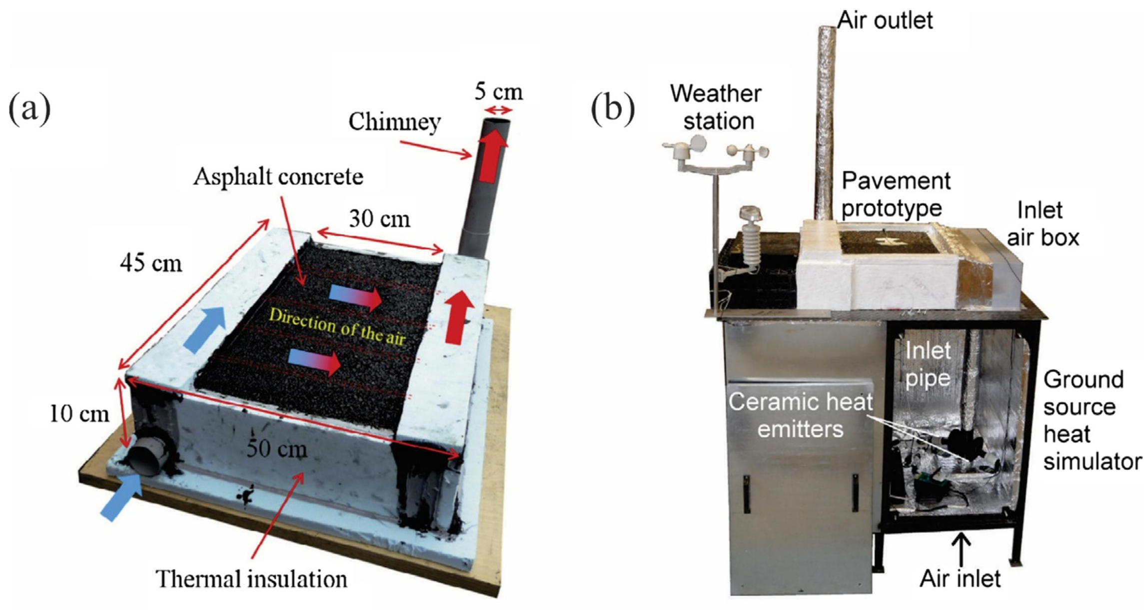


Fig. 5. (a) Scheme of the ASC with air prototype [128]; (b) Ground source heat simulator built at the Nottingham Transportation Engineering Centre that includes ASC with air [158].

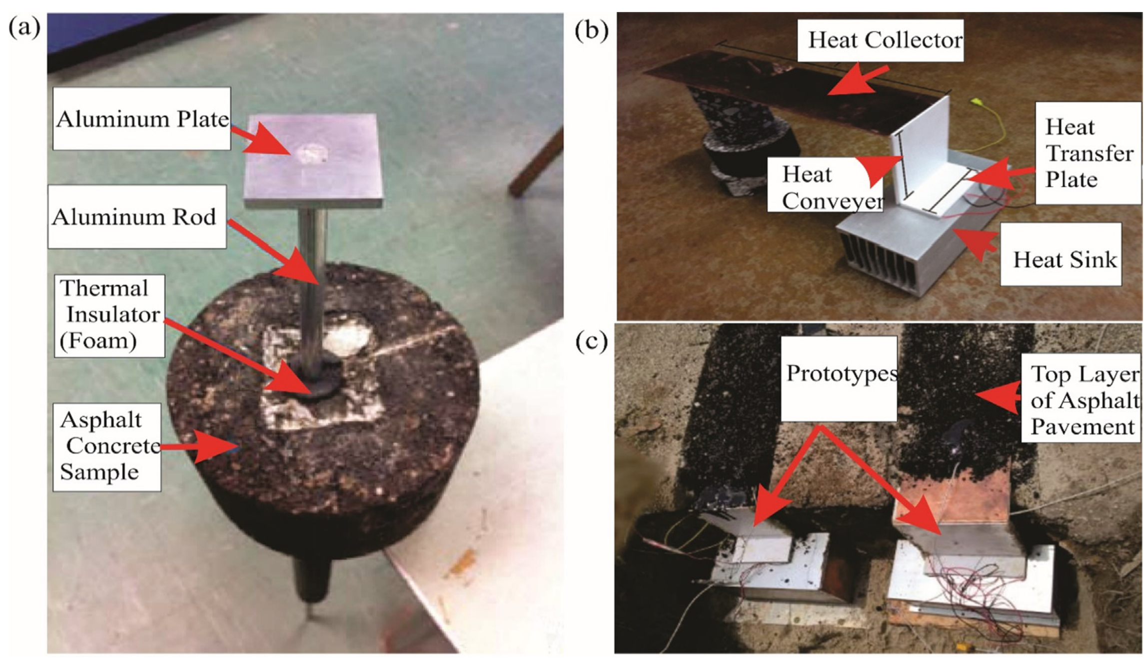


Fig. 6. (a) Thermoelectric prototype parts (annotated from Wu et al. [167]); (b) Harvester prototype components (annotated from Datta [164]); (c) Installation of prototype in the field (annotated from Datta [164]).

heat transfer material than aluminum. Furthermore, they found that a black-colored TEG performed better than a red- or white-colored TEG [166]. Fig. 6 shows the components of the two prototypes.

7.2. Output and efficiency

Wu and Yu evaluated the energy harvesting performance of TEGs installed in pavement structures. They installed the TEG module on the surface of the pavement and thermally connected its lower side to the lower pavement layers using an aluminum rod. This system produced a voltage of 300 mV and 0.05 mW of power under a temperature gradient between top and lower pavement layers of 20 °C. The power produced was sufficient to power a blinking LED light. The maximum output power of a 4 cm × 4 cm × 0.5 cm TEG unit under a 6.44 °C thermal gradient was 0.02 W, and its energy output was 1000 J per day, which was deemed sufficient for powering a road monitoring system. According to their study[168], they concluded that the efficiency of the electronic system was 41.3%, which resulted in an overall TEG efficiency of 1.6%. Jiang et al. also developed a pavement-surface-installed TEG prototype. They used thermal gradients between the pavement surface and the ambient air. The tests were performed both outside and indoors using lamps. The results showed that the output voltage for a 15 °C gradient during the winter was 0.4 V, and 0.6–0.7 V during the summer with a 25–30 °C thermal gradient. They claimed that a road 1 km long and 1 m wide could generate 160 kWh in 8 h [169]. Jiang et al., in another study, introduced a new road thermoelectric generator system (RTEGS). The output of this system in field tests was 0.564 V. They estimated that the RTEGS would generate about 33 kWh in a single day if it covered an area of 10,000 m^2 [170].

Tahami et al. developed a prototype and tested it in the field. They obtained an average power output of 29 mW per day while observing a maximum power output of 34 mW under the highest thermal gradient experienced (i.e., 34 °C during a hot Texas summer day) [17]. Lee et al. tested a TEG installed on top of a pavement surface and simulated the conditions in the lab. The maximum output voltage generated was only 0.123 V [171]. Another study by Datta et al. developed a TEG harvester situated lower in the pavement layers. It was equipped with a Z-shape copper heat transfer plate connected to the warm side of the TEG and a heat sink connected to the cool side of the TEG. This prototype could generate a sustained average of 6.5 mW of electrical power over an eight-hour period per day. The power density was about 16 mW per square meter of pavement, and the daily energy accumulation of the prototype was about 0.5 kWh [164].

In another study, Hasebe et al. developed a hybrid TEG-ASC system. The TEG was installed between two heat exchanger tubes carrying water. One of these tubes was heated by solar radiation, while the other was cooled with water pumped from a nearby river. Electrical power values of 5 W, 2.9 W, and 0.9 W were obtained by this system in response to temperature gradients of 40.5 °C, 25.9 °C, and 11.5 °C, respectively. They observed that the electrical power generated increased linearly with the water flow rate. The output power was sufficient to power the water-circulating pump [172]. Fig. 7 illustrates generated power outputs by difference studies.

7.3. Cost considerations

Two studies have analyzed the economic feasibility of the TEG-powered harvesters. The first study [164] used the LCOE approach described earlier to compare TEG harvesters to the more developed photovoltaic (PV; i.e., solar panel) harvesters. The corresponding LCOE estimates were 0.89 \$/kWh for a 7 °C thermal gradient and 0.344 \$/kWh, respectively. Although there is still a considerable gap in cost, TEG technology shows promise as an alternative to PV technology. Another study also used the LCOE concept for estimating the cost feasibility of TEG systems [91]. It compared the cost of TEG and PZT harvesting technologies. For TEG harvesters, the LCOE estimate was 2.31 \$/kWh, which was lower than the LCOEs of PZT systems.

8. Thermal energy harvesting using pyroelectric materials

Some piezoelectric materials have pyroelectric ability. Pyroelectricity is the ability of materials to convert thermal energy to electrical energy when heated or cooled. The pyroelectric current is directly proportional to the rate of change in temperature [173]. The difference between thermoelectric energy harvesting and pyroelectric energy harvesting is that the latter does not rely on temperature gradients and can be achieved by simply exposing the material to environmental changes. As described earlier, thermoelectric energy harvesting relies on temperature gradients across thermocouples. Limited studies exist on harvesting pyroelectric energy from pavements.

8.1. Principle and basic features

Pyroelectric materials are a subset of piezoelectric materials; that is, some of the piezoelectric materials exhibit pyroelectric properties as well (e.g., PZT [174], PVDF [175], and MFC [176]). Several studies were conducted to evaluate the pyroelectric effects of selected piezoelectric materials and examine their relative suitability in harvesting energy. Bhattacharjee et al. studied lithium tantalate and cement composites with nanofibers and concluded that both could be used for harvesting energy from pavements [173]. Wen and Chung evaluated a cement composite and found that steel/carbon nanofibers increased its dielectric properties [177]. Dietze and Essouni combined PZT and polyvinylidene-trifluoroethylene (PVDF-TrFE) and found that the dielectric and pyroelectric constants of the composite increased compared to the PVDF-TrFE material [178]. Another study determined that the pyroelectric constant of a Lead Zirconate Titanate powder and polyvinylidene fluoride-hexafluoropropylene (PZT-PVDF-HFP) composite increased at high temperatures [179]. Yang et al. developed a self-powered sensor with pyroelectric effect [180]. Batra et al. claimed that pyroelectric effects depend on the electromechanical properties of the materials and that a few of them—for example, PVDF and its co-polymers, modified PZT, lithium tantalite, barium strontium titanate, and the triglycine sulfate family—are suitable for powering devices [181]. Pyroelectric energy harvesters require a full bridge diode arrangement to produce useful electrical power because the polarity of the generated electricity changes in response to heat flux direction changes [173].

8.2. Output and efficiency

All the research that has focused on the pyroelectric effect has considered it part of a hybrid energy harvesting technology that combines pyroelectric and piezoelectric effects. Coupling these effects requires defining their synergistic characteristics. Hu et al. found that these two effects are additive without being coupled to each other [175]. Another experimental study compared alternative pyroelectric materials, including PZT, PMN-PT, PVDF, and thin films [182]. That study involved measuring the harvested energy from rapid temperature increases—that is, from 45 °C to 140 °C in 10 sec. The results showed that the PZT material had the best performance, and its maximum power density was 0.23 $\mu W/cm^2$.

8.3. Cost considerations

Because some piezoelectric materials exhibit pyroelectric effects, there is no additional cost involved with the latter. Therefore, piezoelectric materials that have pyroelectric properties offer harvesting through both mechanisms at no extra cost.

9. Solar energy harvesting using solar panels

Scavenging solar energy is not a new concept. Modern applications of solar energy harvesting invariably involve a PV panel technology. PV panels are used in a wide range of applications, from aerospace to transportation. Where installation space is not an issue, PV panels can

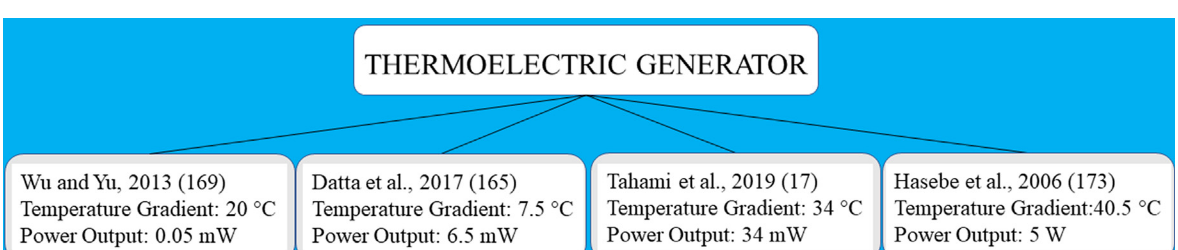


Fig. 7. (a) List of generated power outputs by academic studies.

be cost effective in generating electrical power, which is, in fact, currently taking place and supplying a portion of the electricity distributed through the electrical grid. However, when pavement surface is the only installation space available, adapting PV panels to become driving surfaces poses a unique set of challenges and will require considerable additional research and development.

9.1. Principle and basic features

PV cells consist of two types of semiconductors: an N-type and a P-type. A flow of free electrons occurs in response to solar exposure, whereby positively charged electrons move toward the P-type semiconductor while negatively charged electrons move toward the N-type semiconductor [183]. Developing PV panels that serve as driving surfaces poses a number of significant challenges in terms of material selection and design.

A variety of PV materials, such as polycrystalline silicon cells, dye-sensitized cells, thin film and organic thin film solar cells, and monocrystalline silicon cells, are commonly available [184]. Among these materials, the highest output energy was obtained from monocrystalline silicon cells. It should be mentioned that shading on cells leads to degraded PV panel performance, so the internal structure of the cells and their arrangement should be such as to avoid shading the PV surfaces [184].

Another consideration is the structural properties of these PV panels—their transparent surfaces and their underlying support. A PV cell surface must be supported by a structural frame capable of withstanding vehicular traffic. Limited choices for structural material—such as steel, aluminum, and fiberglass reinforced polymers—exist. Another issue is that the surface of the PV panels must have sufficient friction to enable vehicular braking [13], which suggests the need for surface texture, but that conflicts with the need for surface transparency [183]. Some options for the transparent surface layer are acrylic, tempered glass, and polycarbonate, all of which could be textured, assuming that their transparency can be maintained. These materials have compressive strength higher than that of concrete, but it is questionable whether their tensile strength is sufficient to withstand tensile stresses from traffic and environmental loading. The tensile strength of the panel support system is also of concern due to the tensile stresses imposed by traffic [13]. Additional consideration should be given to waterproofness and flexibility under variable foundation support [184]. Furthermore, the surface should have sufficient cross-slope to allow rapid water removal from driving surfaces to prevent hydroplaning [13].

Fig. 8 presents examples of a photovoltaic system and a roadway surface equipped with PV solar panels. Fig. 8(a) shows the Solar Roadways company product. This product's performance in different environmental conditions was evaluated by Nussbaum et al. [185]. Fig. 8(b) displays a "solar road" produced by Colas that was installed at a test site in the French town of Tourouvre in an effort to prove the potential of solar roads to generate electrical power [186]. This solar road was comprised of 2800 square meters of resin-coated solar panels. It was claimed the electricity generated by the solar roadway was sufficient to power streetlights.

9.2. Output and efficiency

PV solar panel installations involve connecting multiple panels in series or in parallel to meet certain voltage or current generation requirements. In 2014, Efthymiou et al. developed PV pavement prototypes, referred to as P_1 and P_2. The dimensions of these two prototypes were the same, 3.5 m × 1.3 m, but they generated different amounts of power, namely $P_1 = 145$ W and $P_2 = 220$ W. The P_1 and P_2 panels produced 1.4 kWh/day and 2.1 kWh/day, respectively. The efficiency of these prototypes was about 14%. The researchers also found that the PV pavement temperature was 11–15 °C lower than the conventional asphalt pavement temperature [15]. Dezfooli et al. also conducted a study on two prototypes, a solar panel and a solar pavement. They measured voltage and current output to determine power conversion efficiency (PCE). The maximum amount of output current and voltage for the solar panel was 39.1 mA and 3.16 V; for the solar pavement, it was 24.5 mA and 3.04 V. The PCE of the solar pavement was 5.336% higher than that of the solar panel [13].

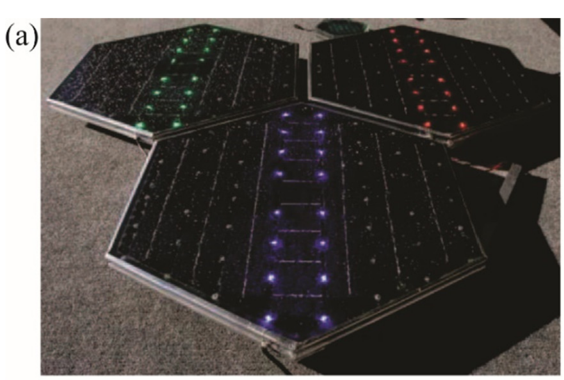
Furthermore, SolaRoad product is another commercially available PV panel suitable for roadway surfaces. It was developed by a consortium of Dutch companies. In 2014, SolaRoad constructed a 70 m bike path as a test site. The company reported that the prototype was working after six months, but some deterioration in the anti-slip surface coating was observed. This project was evaluated after one year in operation by Shekhar et al. [187]. The annual energy yield from the project for 2015 was 78 KWh/m^2.

9.3. Cost considerations

The literature reviewed showed limited analysis of the cost of the PV panel roadway surface installations and the value of the electrical energy produced. The SolaRoad test site, which was only 70 m long, was built at a cost of \$3.7 million. Clearly, the cost of such PV panel installation is much higher than conventional PV panel installations due to the special structural requirements highlighted earlier [187]. Furthermore, the cost of such test sites is not indicative of the cost of installing roadway surfaces on an industrial scale. Thus, no meaningful benefit-cost comparisons of this technology are possible at present.

10. Comparison of technologies

This section provides a summary comparison of the energy harvesting technologies reviewed in this paper. It consists of two parts; the first part summarizes the advantages and disadvantages of each type of harvesting energy technology (Table 2). The second part summarizes peak-power and power-density output for the most efficient system



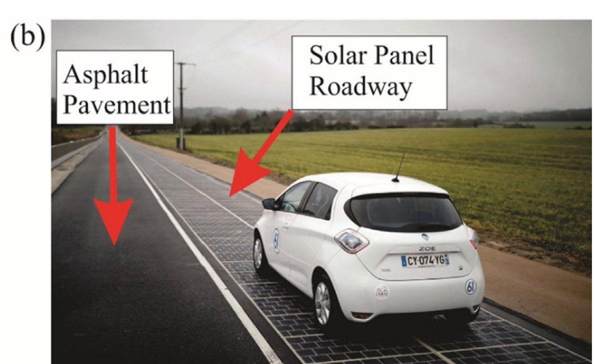


Fig. 8. (a) Nussbaum solar panel for roadways, with LEDs, shown in full daylight [185]; (b) First pilot solar panel roadway in France (annotated from [186]).

Table 2
Advantages and disadvantages of technologies.

Technology	Advantage	Disadvantage	Output
Electromagnetic	Has high electrical power output (appropriate for most road devices), uses several techniques to capture the energy, does not affect roadway's maintenance, and is independent from weather conditions	Has high maintenance because of mechanical components and the effect on traffic stream; is not applicable for all roads	Electrical energy, compressed air, and hydraulic pressure
Asphalt Solar Collector with liquid	Has high energy saving	Has negative effect on pavement construction and maintenance, is weather dependent, needs energy for operation, and has leakage problems	Deicing, reduced pavement temperature, UHI mitigation, decreased thermal distresses, and cold or hot water generation for buildings
Thermoelectric	Has wide applicability and is easily combined with other technology	Has low efficiency and high cost per unit, and is weather dependent	Electrical energy, decreased thermal distresses, and UHI mitigation
Piezoelectric	Can be installed in all roadways, is independent from weather conditions, and can be designed in a vast range of sizes and shape, has no adverse effects on pavement life	High cost for high energy output, and needs a support package to tolerate traffic loads	Low-power electrical energy and deicing
Photovoltaic Panels	Has high energy output	Has high cost, is susceptible to traffic loading, has low skid resistance, is weather dependent, depends on direct solar radiation and shadow situation, and is vulnerable to dust and dirt	Electrical energy, UHI mitigation, and decreased thermal distresses
Pyroelectric	Adds output energy to a piezoelectric material output	Is fully dependent on piezoelectric technology and has very low efficiency	Low-power electrical energy and deicing
Asphalt Solar Collector with Air	N/A	Is weather dependent, has very low efficiency, and does not work in cold weather	Deicing, UHI mitigation, and decreased thermal distress; can be used for building air conditioning (development inefficiency)

reported in the literature for each energy harvesting technology type (Table 3). For this purpose, efficiency is defined in terms of benefit-cost ratio [10]. In addition, Table 3 summarizes the LCOE of the electrical power being produced by each of these systems and its technology readiness level (TRL). The TRL ranges from 1 to 9, where 1 is the lowest level of readiness and 9 is the highest [6].

11. Summary

Most of the energy harvesting technologies reviewed show potential for harvesting energy from roadways. Clearly, some are more suited than others and some are more developed than others. Some of these technologies can complement each other, such as piezoelectric and pyroelectric materials. The most promising technologies are summarized below:

1. Electromagnetic systems are capable of generating high amounts of energy output in all weather conditions. According to the literature, the electromagnetic energy harvesting technology with different mechanisms shows a high potential to be applied in roadway pavement and provides cost-effective, renewable energy sources, especially in remote areas where the power grid is not available [191]. However, the various mechanisms used to transfer vehicular input into movements in electric motor may limit the general application in roadway pavements. This technology can generate electrical power, which is much higher than other on-road energy harvesting technologies, and as a result, it could power devices that cannot be handled with other existing energy harvesting methods [32].
2. Asphalt solar collector technology, involving either a liquid or air, has varied applications, such as scavenging energy for nearby building cooling/heating, preventing ice formation or snow accumulation, and dissipating heat from pavements, thus reducing UHI effects. ASC efficiency depends on system design, including the pipe network configuration, installation depth, pipe size, fluid materials, and flow rate [192]. Careful design of ASC components is needed to meet objectives [193]. Unlike air-circulating ASC systems, liquid-circulating ASC systems require power for a circulation pump. The air-circulating ASC systems require a minimum of 2 m/s airspeed to generate electricity, which is possible only in hot weather [155].
3. Thermoelectric technology shows a high potential for harvesting energy; however, its efficiency is low. This technology absorbs heat from the pavement surface and could potentially mitigate UHI effects. Improvements in design, such as better heat dissipation from the lower layers though improved heat sink design and better isolation between TEG ends to preserve temperature gradients, can significantly improve efficiency [164]. The system can be used for low-powered communications and health-monitoring devices, especially in remote areas away from the power grid [167]. One drawback to this technology is that it could reduce pavement surface life and potentially interfere with pavement maintenance activities.
4. Piezoelectric materials generate electrical power from vibrations or stresses caused by passing vehicles. Typically, they produce high voltages by low amperage, resulting in relatively lower power output. According to the literature, this technology can supply electrical energy to operate low-power roadway systems, such as LED lights and embedded sensors [9]. The literature suggests that such systems have shown considerable promise for harvesting energy. Their power output and efficiency depends on the type of piezoelectric material—its shape, size, and dimensions; the mechanism of operation; and the electric circuitry used [75]. The scavenged energy depends not only on the device's characteristics but also the external factors. The magnitude and frequency of vehicle loads affect the output power so that higher load values and higher frequencies lead to actuating more dipoles and, as a result, the output power increases. Also, higher speeds of passing vehicles lead to higher excitation frequencies, which affect the energy produced [84]. However, piezoelectric energy harvesting devices do have some drawbacks. First, their power output is low, so they require careful management. Second, they need to be placed near the pavement surface where vehicular stresses are maximum, which may interfere with pavement maintenance operations. Finally, although piezoelectric materials have high compressive strength, they exhibit low tensile strength and can be damaged by eccentric compressive or bending stresses. As a result, the design of the box encasing them and its placement need to be carefully considered [194].
5. The pyroelectric properties of piezoelectric materials can be used in

Table 3
Comparison of energy harvesting technologies.

Technology	System configuration	Peak-power output	Power density	Manufacturing cost of each prototype ($)	Levelized cost of electricity ($/kWh)	Technology readiness level	Efficiency
Electromagnetic	Rack-and-pinion mechanism with top plate 1 m^2 area [42]	647 W [42]	647 w/m^2 [42]	5000–7000 [40] and based on calculation of [42]	NA	2	Medium to high
Asphalt Solar Collector with liquid	NA	NA	NA	129,000 [188]	4.21 [6]	3	Medium to high
Thermoelectric	Prototype with four TEGs and heat collector with 562 cm^2 area [164]	42 mW [189]	41 μW/cm^2 [164]	190 [164]	0.89 [164]	3	Medium to high
Piezoelectric	Stack of six PZT-5A, 43 mm diameter and 6.2 mm height, connected parallel by two sets [108]	1.8 W [108]	5 mW/cm^2 [108]	240 [86]	27.90 [190]	4	Medium
Photovoltaic Panels	Solar panel with 4.55 m^2 surface area [15]	220 W [15]	48 W/m^2 [15]	1700 [184]	0.45 [6]	3	Medium to high
Pyroelectric	0.98 cm^2 PMN-PT plate [182]	0.33 μW [182]	0.33 μW/cm^2 [182]	No additional cost to piezoelectric technology	No additional cost to piezoelectric technology	3	Low
Asphalt Solar Collector with Air	NA	NA	NA	NA (cheaper than ASC)	NA	1	Low

conjunction with piezoelectricity to generate additional electrical power. Their effects are not coupled [175]; thus, their output can be superimposed. This technology seems especially attractive for roadway surface applications, given their exposure to heat throughout the year.

6. PV panel technology is highly developed but not quite ready for roadway pavement surface installations. The main challenges are structural capacity to sustain vehicular loads, sufficient friction to ensure safe movement for vehicles, and surface transparency to capture maximum solar radiation exposure [15]. PV panels also require periodic cleaning to keep their surface clean of dust and debris [185]. Furthermore, PV performance is largely a function of environmental conditions, so installing panels such that they maximize direct sunray exposure and avoid shading is very important. Properly designed PV panel supports can protect the pavement surface by reducing plastic deformation and cracking [195].

12. Conclusion

All these energy harvesting technologies generate green renewable energy that can be used in roadside applications to power LED lights, sensors, and microprocessors for a multitude of data collection applications. Their advantages are obvious: no greenhouse gas emissions associated with fossil fuel combustion and no need for electric power transmission lines to bring grid electricity roadside. Since the demand for smart highway features such as connectivity and signage are expected to increase, harvesting energy technology will soon become a necessity. The technologies that seem closest to implementation appear to be the thermoelectric and the piezoelectric harvesters. Although their power generation potential is lower than that of the better developed PV technology, they can be installed unobtrusively by simply embedding them into the pavement layers. The economic efficiency of these harvesting technologies needs to be revaluated as they become implemented on a wider scale to ensure that wider distribution will reduce their unit cost.

Declaration of Competing Interest

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

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