A Review on Energy harvesting from roads (Piezoelectric Roads)

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Abstract: The agenda of this review paper is to review current methods of energy harvesting and also focusing on piezoelectric energy harvesting. The piezoelectric energy harvesting technique is based on the materials property of generating an electric field when a mechanical force is applied. This phenomenon is known as the direct piezoelectric effect. Energy harvesting technologies from road infrastructure is a new research territory that encompasses technologies that capture the wasted energy occurred at pavements, accumulate and store it for later use. The concept is very compatible with current traffic trends and the ongoing depletion of natural resources. This review write-up outlines the current state of the art in road energy harvesting technology, with a focus on piezoelectric Systems, including an analysis of the impact of the technology from environmental and social stance. Based on an extensive desktop review study, this article provides an extensive insight towards roadway energy harvesting technologies. Specifically, this write-up discusses the societal and environmental benefits of road energy harvesting technologies, as well as the challenges. The study outlined the meaningful benefits that positively align with the concept of sustainability. Overall, the literature findings indicate that the expansion of the roadway energy harvesting technology to a large practical scale is feasible, but such an undertaking should be wisely weighed from broader perspectives. Ultimately, the article provides a positive outlook of the potential contributions of road energy harvesting technologies to the ongoing energy and environmental challenges of human society.

Keywords: Piezoelectric Sensors, Environment, Sustainability, Energy Collection, Engineering application.

Introduction: Energy surrounds us and is available in many different forms, such as wind and solar energy or thermal and mechanical energy. Mankind's trends are characterized by an ascending energy consumption profile that has its detrimental consequences on energy security and the environment's viability. These matters have highlighted the need for novel and cutting edge methods for energy harvesting that also includes energy conservation and its final utilization. Energy Harvesting or scavenging is the process of capturing the wasted energy from naturally occurring energy sources, accumulating and storing it for later use. With the rapid development of society, the increasing energy consumption leads to the shortage of non-renewable energy resources. To solve this problem, many countries pay attention to the collection and use of renewable energy. Pavement will bear millions of times of the axle loadings from traveling vehicles in its service life, resulting in deformation and vibration. Great mechanical energy is wasted during this process. It will be a breakthrough for energy conservation and emission reduction if the mechanical vibration energy is transformed into electric energy. Interestingly, the capability of harvesting the energy wasted through braking, the mechanical pulses of traffic, roadway insolation, etc., are now feasible. Indeed, road energy harvesting represents a promising option for clean energy efficiency and environmental conservation. While the energy sources available for harvesting from the roadway systems include solar, vibration, acoustic waves, temperature gradients, etc., this article focuses mainly on road vibration energy-harvesting systems. Actually, the most common energy harvesting technologies are designed to harness either the mechanical stresses or strains generated by traffic, or the heat energy that the roadways receive through exposure to solar radiation. In either case, the energy is converted into electricity or heat, which is considered as an alternative to conventional energy sources or auxiliary energy stored for delayed uses.

The piezoelectric energy harvesting technology has been studied for many years. Priya (2005) invented a pocket piezoelectric windmill which was attached to a rotating cam [1]. When the cam rotates, the motivated piezoelectric material will convert the mechanical energy into electric energy. Alexander et al. (2010) developed a system to collect vibration energy generated by pedestrians walking on the roads [2]. Yoshiyasu (2008) developed an energy collection device which was embedded in the pavement [3]. It had been tested at subway entrance, shopping malls, etc. An Israel company INNOWATTECH (2010) announced that they had developed a pavement energy harvesting systems: Innowattech Piezo Electric Generator (IPEG), which is based on a piezoelectric transducer. According to reports, when traffic volume of vehicles is more than 500 in the single lane per hour, up to 250 kW of electrical energy can be collected per kilometer per lane [4]. Guan et al. (2010) studied the cement-based piezoelectric materials for road power generation, where the cement-based piezoelectric composites are manufactured by pre-embedding piezoelectric ceramics [5]. Zhao et al. (2011) designed the piezoelectric materials using the finite element analysis [6]. Xiong et al. (2012) show that the pavement deformation by vehicle processing and the vibration caused by moving vehicles on the road can be used for the collection of electric energy, and the best power acquisition system is discussed in the study [7]. Xiang et al. (2013) considered the piezoelectric road model as the Bernoulli–Euler beam model with pavement damping [8]. Yuan et al. (2014) studied the use of piezoelectric transducers in the collection of track vibration energy for railway safety driving and found that the piezoelectric energy harvester could generate 30 mW powers [9]. Zhang et al. (2014) studied the performance of a concrete-piezoelectric cantilever beam transducer in a single vehicle using ANSYS simulation [10]. In all, most of the research on the piezoelectric harvesting technology in pavement engineering is still in the exploratory stage. Although the previous studies have conducted preliminary theoretical analysis and laboratory tests, lack of engineering practice still limits the promotion of this new innovative green technology. The concept and breadth of applications of piezoelectric materials have evolved over time. Thus, considering one of the most recent definitions of such phenomenon,"Piezoelectricity is a property for some materials which lies in generating electrical voltage when mechanical force is subjected into it and vice versa". Currently, there are various studies for the use of this phenomenon, ranging from special bricks on the sidewalk for pedestrians, pressure points in roadways and railroads [5], up to specialized breakwaters for coastal zones [5, 6]. Hence, the literature in this regard seems to show some glimpse of the use of piezoelectric materials, indicating that they could have an interesting future for supporting power generation. The above, the purpose of this paper is to summarize methods of energy harvesting and their socio-economic implications, of applying such methods of power generation, which does not completely alter urban spaces.

Technology for road energy harvesting - Energy harvesting or energy scavenging technologies refer to applications that capture and exploit the unused and depleted energy so as to convert it to a more usable form. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. Moreover, thermal energy due to temperature gradients and ambient vibrations constitute some of the major sources of energy that has a lot of potential for being harvested. Harvesting energy stands alone as one of the most promising techniques for approaching the global energy problem without depleting natural resources. The hierarchy at the energy harvesting procedure is firstly, the capture of energy; secondly, the storage of energy that includes its condition before its final use.

The term Energy Harvesting or Renewable Energy, such as solar panels or wind turbine, is a method of producing electrical energy by utilizing the energy surrounding the environment from the sun and wind. However, energy formed from various vibration machines, objects in motion, or any other source of mechanical energy is not being captured. Therefore, this source of energy is dispersed and thus wasted. As an effective method to utilize this loss, piezoelectric material is used to absorb the wasted mechanical energy and convert it to electrical energy.

The most known technologies used for road energy harvesting include the piezoelectric sensors, asphalt solar collectors, photovoltaic sensors, phase change materials (PCMs), and electromagnetic generators [8,9]. The piezoelectric sensors are devices that are placed within a pavement layer to collect the mechanical stresses and strains caused by vehicle movements and convert them into electrical energy [6–10]. Hence, the energy output from the piezoelectric sensors is generated from vehicle weight, motion, and vibrations. The asphalt solar collector is designed to take advantage of the dark color of the asphalt surfacing layer that has a low albedo (i.e., high solar absorption coefficient), allowing the solar energy to be absorbed. The absorbed solar energy accumulates in the pavement layers in the form of heat. In order to harness this heat, special pipes with circulating fluid inside are embedded in the asphalt layer [11]. During the mechanism, the fluid is heated by the higher temperature of the surrounding pavement, and the energy is harvested using the low-temperature geothermal heat pumps.

In the case of the photovoltaic technology, the surface of the pavement structure is incorporated with solar cells (i.e., photovoltaic sensors). The incident sunlight received by the solar cells is converted into electricity through a photovoltaic effect [9]. As for the PCMs, the energy harvesting process is much simpler. Indeed, PCMs are products capable of controlling temperature in such a way that they store and release thermal energy during their process of melting and freezing (changing from one phase to another). When the PCMs are coupled within the asphalt pavements, they can also serve to control cracking through asphalt self-healing. Regarding electromagnetic generators, the principles of road energy harvesting are similar to the ones with piezoelectric systems [12, 13]. The electromagnetic generators are made of magnets that harness low ambient vibrations and generate voltage [13]. In the case of bridges, the electromagnetic generators seem adequate to harvest the vibrations created by passing traffic [14]. In this case, the harvested energy can be used to monitor the structural health of bridges [14]. Although the list of road energy harvesting technologies is longer but represent sustainable options for renewable energy harvesting and power generation from roadways. In order to provide a concise understanding of the societal and environmental aspects of the road energy harvesting systems, this article primarily focused on the piezoelectric technology.

Piezoelectric working principle - The principle of piezoelectricity lies behind the crystals. The electrical voltage is induced when crystalline materials are subjected to external force, pressure, or strain. There are several types of natural crystals, found at the surface or deep within the earth, which can be used today to apply piezoelectricity effect such as clear quartz and amazonite. A variety of artificial crystals are formed by chemical compounds, as well. These include Barium Titanate, Lead Titanate, and Lead Zirconate Titanate, etc. [7]. The efficiency of piezoelectric devices is influenced by the type of crystals due to the variety of their properties. However, Lead Zirconate Titanate (PZT) crystals are being used widely to achieve a high piezoelectric effect. The ease of fabrication to any complex shape, high material strength and long-life service, resistant to humidity and heat temperature over 100°C, are all distinctive factors of PZT [8].

Typically, an energy harvesting system has three parts [6]:

1. The energy source: represents the energy from which the electrical power will be scavenged—this energy can be ambient (available in the ambient environment, e.g., sunlight, ambient heat or wind) or external (energy sources that are explicitly deployed, e.g., lightning, human heat or vibrations) [7];
2. The harvesting mechanism: consists of the structure which converts the ambient energy into electrical energy;

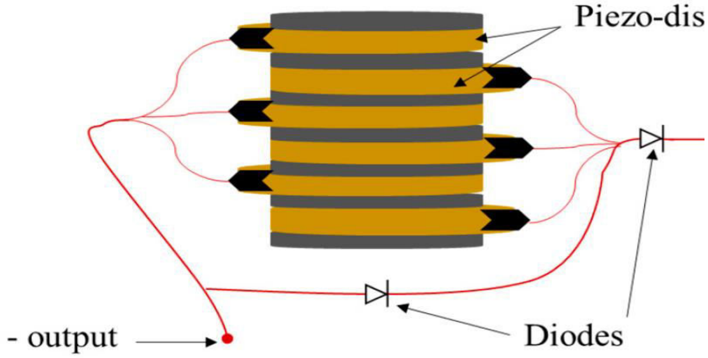
3. The load: the sink which consumes or stores the electrical output energy.

The most common small-scale energy sources are sunlight, electromagnetic radiation, environmental mechanical energy, human body heat, and human body mechanical energy. Unlike solar energy, electromagnetic radiation, and environmental mechanical energy, which are highly dependent on the environment, human body energy harvesters can be integrated into daily human activities to power a variety of devices [3, 8]. Human body heat can be harvested using the principle of thermoelectric power generators, based on the Seebeck effects of materials. Using this material's principle, one can generate electrical energy using the difference between the human body and the ambient temperature. The inconvenience is that a considerable difference in temperature is needed to have a stable system [3]. Human body mechanical energy and environmental mechanical energy are widely exploited due to their abundance in daily life. Every motion in nature can be a potential source of kinetic energy. Therefore, mechanical energy is the most prevalent form of energy [9]. Using mechanical energy scavenging, sufficient power can be provided to ensure long-term autonomy for self-powered systems.

Piezoelectric Materials - Non-centrosymmetric materials are materials lacking a center of inversion. There are 32 crystal classes of which 20 possess direct piezoelectricity, and 10 of these are polar crystals (in the absence of mechanical stress, they exhibit spontaneous polarization). These polar crystals will show pyroelectricity—in the presence of an oscillating thermal gradient, they will generate a charge. Moreover, the materials are ferroelectric if the dipole moment is reversible when a sufficiently large electric field is applied. Therefore, ferroelectric materials are also piezoelectric, but they exhibit semiconductor properties that are similar to the properties found in mechanically stressed piezoelectric materials [41]. There are around 200 piezoelectric materials used in energy harvesting applications [44], found in four main categories:

1. Single crystals (Rochelle salt, lithium niobite, quartz crystals);
2. Ceramics (barium titanate (BaTiO3), lead-zirconate-titanate (PZT), potassium niobate (KNbO3));
3. Polymers (polylactic acid (PLA), polyvinylidene fluoride (PVDF), co-polymers, cellulose and derivatives);
4. Polymer composites or nanocomposites (polyvinylidene fluoride-zinc oxide (PVDF-ZnO), cellulose BaTiO3, polyimides-PZT).

Energy Conversation - The number of experimental tests reported in the literature provides substantive information on the real-time electricity production from piezoelectric sensors [9–21]. In the road energy harvesting systems, piezoelectric sensors are embedded in the pavement structure [22]. The sensors are designed to harvest mechanical stresses and strains, which are then converted into electrical voltage. The output voltage depends on the traffic loading, the frequency of vehicles passing, and the vehicle moving speed [21]. In conditions of dense traffic, there is a capability to reach electricity production at an industrial scale[10] reported a potential power generation of 1_W for a 50-_m deflection at an excitation frequency of 70 Hz. However, an experimentation study carried by the Teaxs A&M Transportation Institute (TTI) portends a higher energy generation capacity for a piezoelectric device. The energy conservation module is made up of three pairs of piezo discs stacked and connected with two diodes. The mountage is thereafter enclosed in a metal case covered on the top with an impact cap.



Environmental Benefits - If there is something common to all methods of implementation of piezoelectric materials as a means of generating energy, it is that they obtain electricity from structures or activities forming part of the current routines of human beings. Such materials have come a long way, and recently, they had a huge impact on the scientific community, considering that the first paper in which the term "nano piezoelectric generator" was used is of ZL Wang, who is the father of this concept. From an environmental perspective, the road energy harvesting technology represents a promising innovation in road transportation systems. The technology is viable, and appears as a solution for the growing global energy problems and the actual depleting trend of natural resources [8]. Hence, the opportunity of harvesting energy from mechanical vibrations is becoming an area of interest that has enticed a growing amount of attention from researchers [4–9]. Although the application of road energy harvesting systems at the large scale is still at an embryonic stage, the potential benefits of the technology are significant. The technology is devised for energy efficiency (i.e., harvest and reuse the energy wasted as mechanical stresses or strains), and is therefore environmentally friendly. Conventionally, from the energy budget of vehicles using fossil fuels, only 15% of the energy generated by the burnt fuels is used to move the vehicles [32, 33]. Most remarkably, the energy lost mechanically represents 27.2% of the energy budget. These mechanical losses include idling losses (17.2%), rolling resistance (4.2%), overcoming inertia, and braking losses (5.8%). With regard to details on energy losses, road energy harvesting is an important option for improving transportation efficiency. The road energy harvesting technology is generally safe, environmental friendly, and reliable within the realm of increasing traffic trends. The energy generated is entirely clean, with zero green house gas (GHG) emissions. This type of energy source is relevant for air pollution management, and is therefore advantageous for human health [34]. Furthermore, the road energy harvesting opportunity is in phase with the actual adaptation strategies for global climate change [24–35]. In addition, the functionality of the system is free of noise emission. The system produces a ready-to-use energy that may also be employed for continuous environmental monitoring strategies. However, many of the advantages of the road energy harvesting technologies should be found in their applications, where practical estimates can be inferred. For instance, the United States' Environmental Protection Agency (EPA) estimates the carbon dioxide (CO2) and energy production of fossil fuel (gasoline) as 8.887 kg of CO2 and 33.7 kWh per gallon. Considering the information by EPA in combination with the aforementioned Innowattech's estimates, it can be inferred that 1 km of pavement length with piezoelectric sensors should be able to contribute to the reduction of an equivalent of 53 kg of CO2 per hour. This quantitative value is an estimate of the tremendous potential environmental benefits associated with the road energy harvesting system, especially considering the severe environmental effects of excessive CO2 emission, including the current trends of climate change and global warming. The use of road energy with zero atmospheric emissions may thus aid in minimizing global warming and contribute to stabilizing the climate. Unlike other energy sources, such as wind farms or solar power, road energy harvesting does not require any additional land space, as it utilizes the existing road network infrastructure. Furthermore, not much land space is needed either for electric poles/pylon installation and power transmission lines, as the end users and potential applications will naturally be within the road proximity. This in itself constitutes a huge contribution towards natural resource optimization and environmental conservation. That is, the road network will not only serve as transportation media, but also simultaneously serve as a renewable energy source. Developing and clarifying public policy play a decisive role for the methods of harvesting energy not only for being innovative but friendly to all parts involved, in order to be positioned successfully

Conclusion - The capability of the piezoelectric materials to convert mechanical energy into electric power is the fundamental basis for road energy harvesting systems using piezoelectric sensors [19, 20]. Although this article focuses on the piezoelectric technology, it is important to recall the possibility of using alternative techniques to harvest road energy [7]. In practice, a rational choice of a road harvesting technique must take into account the relevant economic, environmental, and social factors. From a technological prospective, this choice must also depend on the expected use of the generated current. In the case of piezoelectric systems, large-scale application can be envisaged on a highway[6] asserted that the piezoelectric system has a high ability to convert mechanic vibrations into electricity. This unique feature is relevant for projecting a large-scale implementation of road energy harvesting. However, the technology is still in its infancy, and proper evaluation of its economic, social, and environmental impacts is critical before this technology can be feasibly implemented on a practical scale. In this paper, the piezoelectric-based road energy harvesting systems were comparatively evaluated against other common renewable and non-renewable energy sources with respect to their social and environmental merits. The literature findings, as discussed in the preceding sections of this paper, indicated that the piezoelectric road energy harvesting technology can be a horizon for clean and renewable energy production. The technology offers multiple alternatives for additional improvements in the transportation system. In addition, it meets the contemporary challenges of global resource depletion. Road energy is a renewable source that is safe, clean, simple, reliable, sustainable, and environment friendly. The technology has zero GHG emissions, and is an irrefutable asset for promoting the use of hybrid and electric vehicles. However, substantial research still needs to be conducted in order to address the various challenges that are currently associated with this emerging technology, including the efficient design of the energy harvesting modules, energy transfer and storage devices, etc. In comparison to other conventional energy sources, cost competitiveness is also another challenge to be addressed, partly because the piezoelectric energy harvesting technology is in its infancy.

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