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Prospective of Societal and Environmental Benefits of Piezoelectric Technology in Road Energy Harvesting

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Abstract: Road energy harvesting is an ingenious horizon for clean and renewable energy production. The concept is very compatible with current traffic trends and the ongoing depletion of natural resources. Yet, the idea of harvesting roadway energy is still in its genesis, and only a few real-time implementation projects have been reported in the literature. This review article summarizes 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 social and environmental standpoints. Based on an extensive desktop review study, this article provides a comprehensive insight into roadway energy harvesting technologies. Specifically, the article 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: transportation; piezoelectric sensors; society; environment; sustainability

1. Introduction

In transportation systems, innovative ideas often aim for efficiency in regard to areas such as safety, practicality, mobility, durability, maintainability, and resource optimization [1,2]. However, the evidence of energy waste is a notable fact of road transportation systems. Regrettably, there are still some inherent economic, social, and environmental challenges impeding the useful harnessing of this energy. These challenges are, in part, exacerbated by the raising concerns of climate change and environmental impairment [3]. Interestingly, the capability of harvesting the energy wasted through braking, the mechanical pulses of traffic, roadway insolation, etc., is 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 [4,5].

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 [6]. Nonetheless, the number of studies in the literature reporting the practicality of road energy harvesting technologies is insufficient. The documentation of relevant aspects such as cost efficiency, energy storage, or energy demand/supply is also limited. These aspects are probably among the factors limiting the application and usage of road energy harvesting systems at an industrial or commercial scale. Nonetheless, the willingness to diversify energy sources is a social reality that aligns with the imperative of sustainability. Herein, this article is a relevant contribution, since it comparatively reviews the latest advances in roadway energy harvesting and discusses the potential opportunities of the technology from a social and environmental perspective.

In particular, the article reviews and analyzes the use of piezoelectric sensors in the road energy harvesting systems, then it expounds the potential benefits, merits, challenges, and limitations. As the title infers, the article focused on societal and environmental impacts with limited discussions on the economic facets of the technology. Actually, an adequate cost efficiency assessment of the road harvesting technology would require a minimum amount of information for the life cost analyses, which unfortunately are not reported in the literature. In fact, the road energy harvesting technology is still a novel field in transportation research. A realistic completion of a life cycle cost analysis of the technology would require an example of its implementation at the society level [7]. At the present stage, there is no documented example of such large-scale implementation, and this is a sign that further feasibility research is needed. Following this introductory section, the subsequent two sections address the existing road energy harvesting technologies, and the piezoelectric energy harvesting system, respectively, as reviewed from the extensive literature. The subsequent section examines the benefits and merits of the road energy harvesting systems within a multilevel framework of social and environmental aspects, followed by the limitations and challenges. The article then concludes with a discussion and summary of key findings.

2. Existing Technologies for Road Energy Harvesting

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, the three technologies reported in this section are promising, and 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, which is hereby discussed in the next section.

3. The Piezoelectric Energy Harvesting System

3.1. The Concepts of the Piezoelectric Technology

At the state-of-the-art level, there are three major categories of road vibration harvesters, including the piezoelectric, electromagnetic, and electrostatic sensors [6–10]. However, the available literature on piezoelectric energy clearly outbalances the other two categories [4–6], which indicates the promising potential of the piezoelectric technology in the road energy harvesting systems. The principle is to transfer mechanical energy, ambient vibration, into usable electrical power [15,16]. According to the literature, the mechanism of the piezoelectric energy system was first discovered in 1880 by Pierre and Jacques Curies [17,18]. The mechanism is fundamentally based on the ability of piezoelectric materials to generate a voltage in response to the application of a mechanical stress or strain [19]. Actually, the piezoelectric device captures the ambient mechanical vibrations from which useful electrical energy capable to power other devices is generated [10]. The most frequently used piezoelectric materials include crystalline materials, piezoceramics, and polymers [6–20]. However, piezoceramics have had much research attention because of their comparatively high performance characteristics. Nonetheless, it is a derivative of the piezoceramics—namely, lead zirconate titanate—that is widely used in piezoelectric energy harvesting systems due to its comparatively high cost effectiveness [20]. Aligning with this tendency in road energy harvesting research, this paper focused on the piezoelectric technology [15]. Precisely, the piezoelectric technology has been addressed for its reported high performance and high cost-effectiveness [7]. Thus, the outcomes of the study are expected to sustain initiatives for a large-scale implementation of the technology.

The piezoelectric energy harvesting system presents multiple technical advantages, including its high power density, architectural simplicity, and scalability [4–17]. Under the stress or strain caused by vehicles traveling over the roadways, the piezoelectric devices embedded in the roadway produce a voltage. The voltage generated is proportional to the stresses and strains produced by the vehicles [21]. Kazmierski and Beeby [21] reported the constitutive equations for the mechanical response characteristics of a piezoelectric material and electrical energy estimation in a simplified form, as follows:

$$\delta = \sigma / Y + d\,E \tag{1}$$

$$D = \varepsilon\,E + d\,\sigma \tag{2}$$

where δ is the mechanical strains, σ is the mechanical stress, Y is the Young's modulus of the material, d is the piezoelectric strain coefficient, E is the electric field, D is the electrical displacement (charge density), and ε is the dielectric constant of the piezoelectric material. In a more complex tensor form, the above equations can be represented as follows [9]:

$$S_{ij} = s^{E}_{ijkl}\,T_{kl} + d_{kij}E_k \tag{3}$$

$$D_i = d_{ikl}T_{kl} + \varepsilon^{T}_{ik}E_k \tag{4}$$

In Equations (3) and (4), each of the terms i, j, k, and l take values of 1, 2, and 3. S represents the strain tensor (dimensionless), while T stands for the stress tensor with a unit of $\mathrm{N/m^2}$. D is in $\mathrm{C/m^2}$ and represents the electric displacement. E is in V/m and represents the electric field vectors.

In Equation (3), s^E is in m^2/N, d is a matrix of the piezoelectric strain coefficients with a unit of m/V, and ε^T is a matrix of the permittivity values that are evaluated at a constant stress with a unit of N/V^2. Note that d represents the charge created by a given force in the absence of an electric field (short circuit electrical condition), or the deflection caused by an applied voltage in the absence of an applied force (stress-free mechanical condition). However, in light of the growing interest in the road energy harvesting systems, research is warranted to substantiate the validity and accuracy of these constitutive equations for estimating the productivity of electricity from the piezoelectric energy harvesting systems.

3.2. The Highway Sensing and Energy Conversion (HiSEC)

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. Sodano et al. [10] reported a potential power generation of 1 µW for a 50-µm 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. Figure 1 presents a prototype of a piezoelectric module, namely Highway Sensing and Energy Conversion (HiSEC), which was experimented in a laboratory at TTI. The HiSEC 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. Figure 2 presents the power generation capacity of the HiSEC device at an excitation frequency of 1 Hz at room temperature (20 °C).

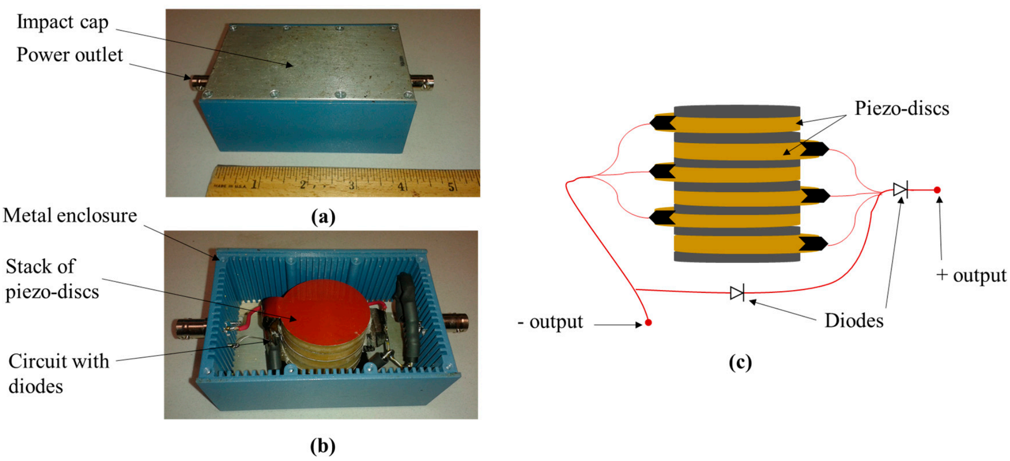

Figure 1. Prototype of the Highway Sensing and Energy Conversion (HiSEC) piezoelectric sensor, (**a**) the external view of the device; (**b**) the internal view; (**c**) a schematic representation of the electric mountage of the stack of piezo discs.

The curve in Figure 2 shows that the responsive power generation of the HiSEC device increases gradually as the load/stress is increased. This responsive power generation capacity of the HiSEC module aligns with previous experiences of piezoelectric sensors, and portends the potential feasibility of a large-scale road energy harvesting system. Notably, one example of a piezoelectric energy harvesting system was designed by Innowattech®, Tel Aviv, Israel [23]. The implementation framework proposed by Innowattech seems very consistent and useful for a large-scale adoption of this concept, as well as energy harvesting technology. In the design, the piezoelectric devices are mounted about 50 mm below the pavement surface, such that any slight deformation resulting from vehicles traveling on the road produces an electrical current [22]. Also, the sensors are installed at a spacing of 300 mm apart from each other in the wheel paths. Based on the data reported by Innowattech®, a traffic volume of 600 vehicles/h moving at 70 km/h over a 1-km long pavement with sensors as described above is capable of generating approximately 200 kWh of electrical energy [23].

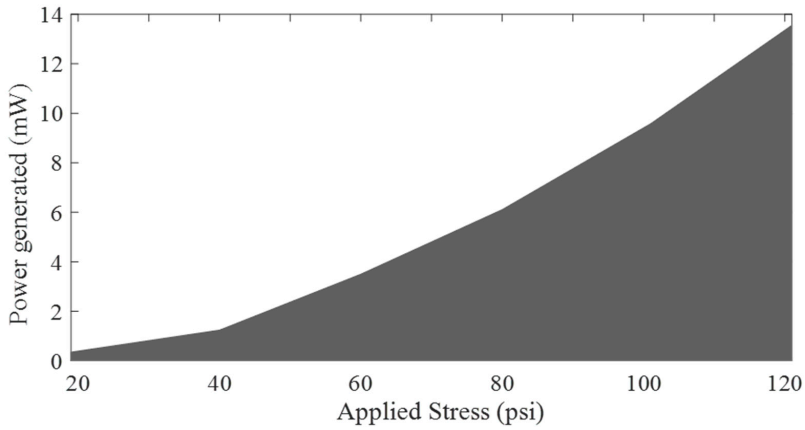

Figure 2. Power generation capacity of the prototype of HiSEC when submitted to various loads in a moderate environmental condition.

4. Benefits and Merits of the Road Energy Harvesting System

This section presents a multilevel analysis of road energy harvesting using piezoelectric sensors. Specifically, the section discusses the social and environmental facets of the technology. Although the study did not intend to carry out economic and financial analyses of the technology, it reports a brief summary of cost comparisons for the common energy sources used in the United States (USA).

4.1. Benefits for the Society

4.1.1. Equity and Sustainability

While energy (heat and electricity) plays an essential role in human society, there is a blurring discrepancy between the contributions of renewable energy sources compared to conventional non-renewable sources. Figure 3 depicts this discrepancy; it also shows that a paradigm shift is needed to reduce the dependency on fossil energy sources. The reduction of the dependency on non-renewable energy sources may be achieved through the promotion of new renewable energy sources that include road energy harvesting systems. Despite road harvesting technologies constituting new territory for research and engineering, their social benefits can be realistically portended. For instance, road energy harvesting offers an alternative energy source for roadway lighting. Furthermore, this energy source can likely pioneer and aid in promoting the use of electric and hybrid vehicles. The road energy harvesting technology is one of the new visions for energy efficiency in the transportation sector and society at large. However, at the present stage, this area is poorly documented, which is partly due to the infancy of the road energy harvesting technologies. Rather than seeing this as a negative feature, it should instead be considered as a beneficial factor for enticing new research horizons on road energy harvesting. Therefore, the educative component of the technology is fairly limited, since research activities still need to be carried out on different aspects of road energy harvesting.

At the societal level, the use of road energy harvesting technology is likely to improve the social awareness regarding the importance of renewable energy, particularly within the framework of climate change adaptation [24,25]. In addition, the implementation of road energy harvesting technology should help reduce air pollution and subsequently improve public health. The use of this energy can also positively affect social well-being and convenience by making cheap and clean energy available and directly useable for various purposes including domestic use, charging portable electronic devices, public safety signalization, monitoring traffic mobility, etc. The energy may help enlighten roadways and improve pedestrians' safety in low luminosity conditions.

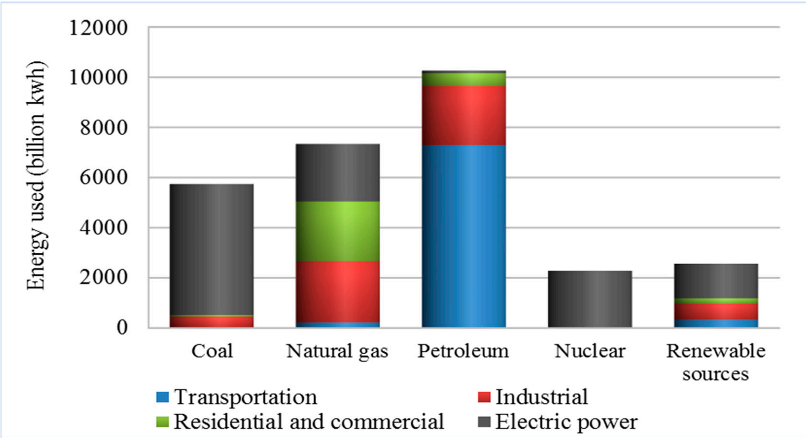

Figure 3. Energy sources and consuming sectors in the United States (USA) during the year 2011 (www.eia.gov).

In smart roads, piezoelectric sensors serve as healthy monitors for the road conditions, among other factors, to improve roadway and motorist safety. In winter, for instance, the same sensors can serve as heating elements to heat up and de-ice the roads, for the ultimate benefit of the traveling public and community. In adverse weather conditions such as fog, storms, and snow, driving can also be highly risky. Although road signals are helpful to drivers, they cannot efficiently inform on the magnitude of the risks, since these risks depend highly on the actual weather conditions. Actually, at a specific time, the driving risk level depends on several parameters, including the weather condition and their adversity [26]. Therefore, the level of alert is not expected to always be the same along the road network. Opting for road energy sensors may help devise and operate traffic devices that can detect the risk level in time and space along the road. The risk level can then be communicated adequately to the drivers by installing automated signals that would function based on the harvested road energy.

Besides the potential for traffic safety applications, the piezoelectric sensors can also be employed to monitor traffic characteristics. In practice, the energy generated by the piezoelectric sensors may serve to monitor traffic loads by providing real-time and continuous measurement of traffic parameters including volume, speed, weight, occupancy, etc. [27]. The energy can also be used to monitor traffic violations such as speeding, overweight, and abnormal driving behaviors. This later function is likely to improve road safety and significantly reduce the risk of accidents. Moreover, the energy generated may find an ecological application. Particularly for highways and rural roadways, this energy can be included in the strategy for reducing wild animal mortalities. For this application, the energy may be utilized to operate specific automated signals devised accordingly to provide real-time warnings on the presence of wildlife on the road (i.e., animals crossing the road), and thereby helping to prevent vehicle collisions with these animals. Indeed, roadway collisions represents a major cause of wildlife mortality in the USA [28,29], and the frequency of vehicle-related animal mortality has increased with the increase in traffic and road density.

In addition, road energy has the potential to provide society with continuous and sustainable power as long as vehicles are moving on the road, thus giving people much needed peace of mind. This is particularly critical in most third-world countries, where hydro-electric or thermal (coal) power supplies for instance are not only costly, they are also very erratic. Lastly, the application of the road energy technology in society may confer the prestige to the community for being pioneers for adapting an advanced technology in their transportation systems.

4.1.2. Energy Diversification and Source of Income for the Society

In the USA, the existing energy sources are used for transportation, production (industry, manufacture, mining, agriculture), domestic, and commercial purposes (See Figure 3). Overall, these energy sources may be classified into two major categories, namely renewable and non-renewable sources. Figure 4 exemplifies the levelized estimated cost of production for each of these energy sources based on data collected from the USA Energy Information Administration (EIA). The levelized cost reflects all of the costs, including initial capital, return on investment, continuous operation, fuel, and maintenance, as well as the time required to build a plant and its expected lifetime (EIA 2015). However, data on the levelized cost of piezoelectric energy harvesting systems are not consistently established. Hill and Tong [30] used vendor-supplied data and reported an estimate of the levelized cost of piezoelectric systems to be within the range of 0.08 to 0.20 USD/kWh. However, this range should be greatly narrowed down in order to support a realistic provision. Recently, Wang et al. [7] used a theoretical framework to estimate the levelized cost of piezoelectric power, and found it to be $106.38 USD/kWh. Notice that in this estimation by Wang et al. [7], the equivalent monetary benefits of the road are not taken into account, justifying the high value obtained. Hence, at the present stage, it is difficult to portend exactly what would be the levelized cost of a piezoelectric road energy harvesting system. This is mainly due to the lack of real time large-scale implementation, since the road energy harvesting technology is very new. Nonetheless, several studies support the practicability of the energy generation capacity of the roads. For instance, Zuo and Zhang [31] analyzed a series of experiments for the road energy harvesting system, and reported a harvestable power ranging from 100 watts to 400 watts, with a middle-size vehicle moving at 97 km/h over a road in average condition. However, the data reported by Zuo and Zhang [31] are merely experimental and based on theoretical frameworks. Thus, more practical cases are essential for a better understanding of the functionality of the road energy harvesting systems. Similarly, few cases of the road energy harvesting system installation have been reported across the globe.

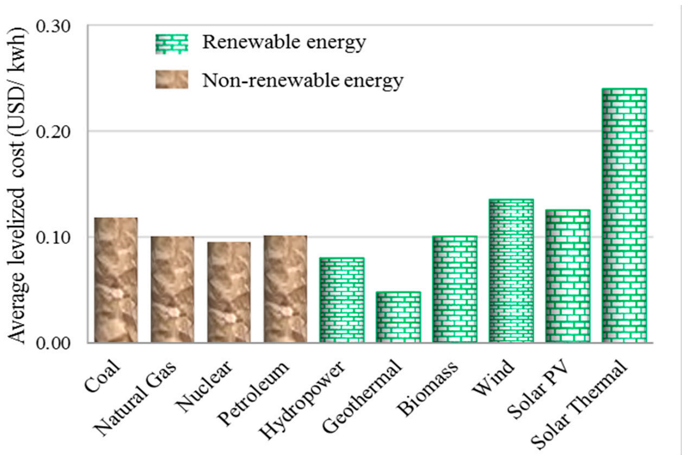

Figure 4. Comparing the levelized production costs for different energy sources in USA for the year 2014 (www.eia.gov).

As mentioned above, the Innowattech® reported in approximation a power generation capacity of 200 kWh for a 1-km long pavement with piezoelectric sensors [23]. Since the average monthly energy consumption in the USA is 909 kWh per household per month [32], the energy generated by a 1-km length of road with piezoelectric sensors can satisfy the energy demand of 158 average households in the USA. Yet, pending realistic case studies, these estimates remain arguable. Nevertheless, it is reasonable to assert that roads with piezoelectric energy harvesting systems have the potential to generate revenue and thereby become capable of financing themselves (i.e., construction/installation, operations, and maintenance), at least even partially. From this perspective, roads with piezoelectric energy harvesting systems can be anticipated to be more sustainable than conventional roads, subject to the optimism that the technology becomes viably successful. Unlike conventional roads, they will also simultaneously serve as sustainable power and revenue-generating infrastructural facilities. The other benefit of this technology is that the same piezoelectric sensors can monitor the structural health and road conditions, and timely detect any potential defects or road failures before they become terminal; a concept commonly known as smart roads.

4.2. Environmental Benefits

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. Particularly, the environmental benefits of this technology (Table 1) complement its social advantages. Indeed, compared to conventional energy sources, the road energy harvesting system represents a clean source of renewable energy. 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 (CO_2) and energy production of fossil fuel (gasoline) as 8.887 kg of CO_2 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 CO_2 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 CO_2 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.

Table 1. Comparing the advantages and disadvantages of various energy sources used in the USA.

Energy Source		Advantages	Disadvantages
Non-Renewable Energy	Coal	-Relatively cheap -Easy to store and transport -Convenient for trade	-Fossil energy -Greenhouse gases (GHGs) emission/source of pollution -Threat for public health and environment
	Natural gas	-Relatively cheap -Convenient for trade	-Fossil energy -GHGs emission/source of pollution -Threat for public health and environment
	Petroleum	-Relatively cheap -Easy to store and transport -Convenient for trade -Leading energy in transportation systems	-Fossil energy -GHGs emission/ source of pollution -Threat for public health and environment -Depleting resource
	Nuclear	-Cheap energy source -Produced on demand	-Requires high technicity, high cost of installation -High risks for the public and the environment -Social reluctance
Renewable Energy	Hydro-power	-Cheap energy source -Zero GHGs emission	-Relies on water resources availability -Not necessarily environmental friendly/ risks of floods
	Biomass	-Environmental friendly -Alternative for fossil energy/ reduces GHGs emission (45–65% less) -Easy to store and biodegradable	-Requires land for biomass production -Cause of deforestation when produced at a large scale
	Geothermal	-Probably the cheapest in the USA -Safe and clean, zero GHGs emissions -Environment friendly	-Risk of groundwater depletion -Risk of harmful gases released in the air -Requires high technicity, high installation cost
	Solar	-Environmental friendly -Zero GHGs emissions, safe, and clean -Adequate with climate change	-Storage problem
	Wind	-Environmental friendly -Zero GHGs emissions, safe, and clean	-Storage problem
	Road energy (piezoelectric)	-Environmental friendly -Zero GHGs emissions, safe and clean -Innovative technology	-Storage problem -Lack of research efforts

5. Limitations and Challenges

The technology of road energy harvesting produces renewable, clean, and safe energy that is ready to use. However, compared to conventional energy sources, the piezoelectric energy harvesting system suffers from several limitations, including the storage problem and the lack of detailed information on its economic merits. In addition, it is important to mention the toxicity of lead zirconate titanate, which is the most widely used material for piezoelectric sensors [36]. Even though this material is highly valued for its high cost-effectiveness, it also presents health risks due to lead toxicity [37]. Interestingly, for large-scale piezoelectric energy projects, several studies have suggested the advantages of using lead-free or mixed materials, which are likely biocompatible [36]. However, the environmental friendly properties of these alternative materials are not sufficiently established, and more research is needed to outline the cost benefits [38]. Frequently, the energy-harvesting devices are designed in such a way that the power harnessed from an ambient energy source is used to recharge the batteries incorporated within the system [9]. For instance, the piezoelectric sensors are often equipped with batteries that are capable of storing electrical voltage. However, the energy conversion efficiency of the batteries is generally variable, and is sometimes low [39]. Therefore, the efficiency of the piezoelectric energy system depends highly on the available battery technologies. Although the option for recharging depleted batteries is a crucial alternative for battery replacements [39], it is fair to recognize that rechargeable batteries have also a lifespan. From that standpoint, it would somehow be difficult to address defective batteries, since the sensors are themselves embedded within pavement layers.

Nonetheless, the dependence on batteries can be minimized or eliminated by opting for a self-sustaining approach in the road energy harvesting system. This approach should emphasize the direct use of the electric energy produced by the system. It seems more efficient and reasonable for operating this type of energy production system, as the energy should be used as it is produced. In the other case, batteries often have a limited storage capacity; they can only store a part of the energy produced. With the self-sustaining approach, the energy losses can be minimized, or even totally avoided, by synchronizing the energy supply to the actual demand. This option is feasible, because the density of the sensors under the pavement layers can be adjusted accordingly in order to release the adequate amount of energy [19–22]. However, the effectiveness of this approach requires an understanding of the societal energy demands.

Another challenge of the piezoelectric energy harvesting system is the maintenance of the road energy sensors. Unlike most energy harvesting systems, the piezoelectric system is operated using the sensors installed within the pavement layers. Thus, whenever the sensors need to be repaired or replaced, the pavement layers should be removed and resurfaced. Such repair will require additional cost, along with the usual costs. However, that later challenge can partially be overcome by improving the durability of the sensors. In addition to the power storage issues, the lack of practical research on the piezoelectric energy harvesting systems itself represents a challenge. Indeed, the current contours of the production and maintenance costs are vague, i.e., the projected costs of installation, operation, management, and maintenance of the road energy sensors are not clearly established. Ultimately, research efforts on the life cycle cost of the piezoelectric energy system constitute a prominent step towards a broad adoption of the technology in the roadway systems. Hence, the authors encourage future studies to thoroughly address the economic and financial contours of the technology.

6. Summary—Synthesis and Discussions

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 technics to harvest road energy [7]. In practice, a rational choice of a road harvesting technic 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. For instance, electromagnetic generators are shown to be practical when used on bridges to self-power structural health monitoring systems [14]. In the case of piezoelectric systems, large-scale application can be envisaged on a highway. Kim et al. [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.

Based on the 2013 federal estimations, the total USA public roads were in excess of four million lane miles [40]. This mileage is an indicator for the huge potential of roadways in the energy harvesting technologies. In consideration of this potential and the alternative of incorporating energy sensors in the roads, road energy harvesting systems and the related technologies are supposed to play a significant role in the future of human society, particularly regarding resource optimization, climate change, and environmental conservatism. In order to envision a large-scale implementation of the road energy system, the benefits (i.e., environmental, societal, etc.) of the road energy harvesting system must outbalance its risks, especially economic and financial risks. This scheme is critical for decision-making, and will thereby be determinant for the societal enticement for a large-scale implementation of the road energy harvesting technology. In terms of the energy production capacity, the case of the HiSEC reported in this article confirms the energy production potential of piezoelectric sensors. Additionally, consistent results aligning the HiSEC performance are also reported in the literature [31].

However, in order to propose a feasible framework for the road energy harvesting systems, their energy production capacity needs to be justified from economic and financial angles, including pilot field studies. Such stages of justification are critical in decision-making on a large scale. It may be fully addressed by involving notions such as the carbon cost through a life cycle assessment [41]. Thus, the authors encourage future research initiatives to carry out a rigorous economic and financial appraisal of the road energy harvesting system (piezoelectric sensors), including pilot field trial studies.

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