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Road Energy Harvesting

A Tutorial Overview

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***Abstract*— The technological revolution experienced by modern society is accompanied by a growing demand for energy. Though energy cannot be created or destroyed, it often dissipates in forms that are technologically useless in daily life. In addition, energy dissipation in the form of heat, motion, and light contributes to the environmentally dangerous greenhouse effect. Thus, an ideal solution is to identify hubs of ambient energy and convert it into more useful forms. Researchers have determined that roadway systems contain substantial levels of ambient energy. To utilize this energy and lessen the demand for energy produced by way of fossil fuels, engineers have developed roadway energy harvesters. This paper discusses the current developments in road energy harvesting as well as the future viability of the technology.**

Keywords*— *Energy Harvesting, Renewable, Implementation, Photovoltaic, Piezoelectric, Thermoelectric, Electromagnetic, Roadway System

I. INTRODUCTION

Society's demand for electrical energy has drastically increased with its progressive dependence on electronic technology. This demand calls for advanced levels of energy production and, consequently, the consumption of non-renewable resources such as fossil fuels [1-3]. The accelerated consumption of fossil fuels threatens the health and sustainability of future generations through its depletion of finite resources and production of harmful greenhouse gases [3]. Therefore, an infrastructural transition that harnesses renewable resources for electrical generation is necessitated. The optimal remedial approach is energy harvesting. Although renewable or "clean" energy processes can harvest useful levels of energy from the natural environment, systems remain in which significant energy exists unutilized [5]. The most prominent of these systems are roadways.

Roadway systems contain three significant forms of energy: solar energy from sunlight, heat energy from the environment, and kinetic or mechanical energy from vehicle motion [1]. Under normal conditions with the current lack of implemented harvesting methods, these energy variants dissipate and remain unused. In pursuit of renewability, sustainability, and overall energy efficiency, engineers are developing harvesters for each of the unused roadway energy variants. Thus, there are four fundamental forms of harvesters that correspond to the respective forms of energy: photovoltaic for solar, thermoelectric for heat, and piezoelectric and electromagnetic for kinetic or mechanical vehicle loads [1]. While the harvesters differ in operation, they all convert previously unutilized energy into the useful form of electricity. However, most harvesters output less than one joule of energy, which restricts their applications and practical viability [1]. Hence, a main objective of harvester research and development is to substantially increase the harvesters' electrical yield.

An additional purpose of road energy harvesters, in conjunction with environmental consciousness, is to aid in creating autonomous "smart" roadway systems [2]. Roadways contain a myriad of signaling and data acquisition components that require modest levels of electricity to function. If the components' little needed electricity could be produced passively by road energy harvesters, the roadway's electronic system would effectively be autonomous, and would allow for supplementary energy demands [2].

The ideal implementation of road energy harvesters is a convoluted matter. As with all engineering projects, especially those with the implications of macroscale energy harvesting, all aspects of implemented technology must be considered. Consequently, deviations between harvesters in cost, material availability, installation ease, and required maintenance are all significant viability factors beyond raw electrical output [3]. Regardless of the leading harvester options, it is certain that improvements are needed before wide-spread installations occur. This paper provides an overview and comparison of the research and development of the fundamental road energy harvesting technologies. Each harvesting method is broken into its mode of generation, standard implementation, and experimental performances during implementation.

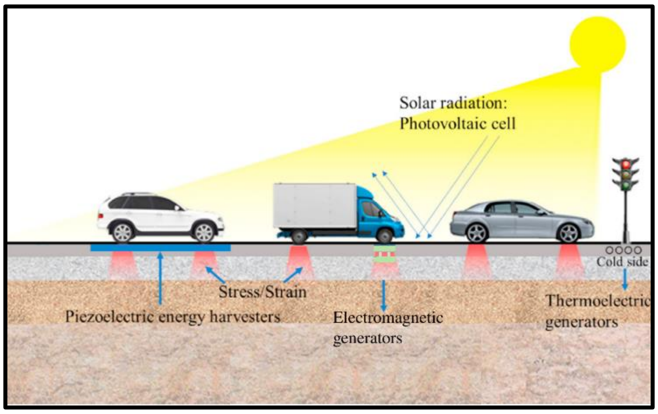

Figure 1. Depiction of the four fundamental road harvesting technologies in application [3].

II. HARVESTER TECHNOLOGIES

Photovoltaic (Solar)

Photovoltaic technology converts light into electricity. The parent form of a photovoltaic harvester is a solar panel. A solar panel consists of an array of solar cells, connected both in parallel and series to increase current and voltage, that individually perform the energy conversion with polarized semi-conductors [3]. When one side of the conductor is exposed to light, the free electrons within the conductive material move to complement their negative charge. This movement creates an electrical current and completes the conversion process. As such, the maximum electrical yield from any solar cell will occur when the cell is entirely exposed to sunlight. This gives photovoltaic technology viability as an energy harvester on well-lit roadway systems.

Given that solar cells commonly require an ample flat surface to properly function, their current optimal placement is on either the road itself or surrounding compatible structures. Engineers and developers suggest that panels be used as the driving surface, which satisfies their geometric constraint for placement, but also forces consideration of the vehicles' need for traction with the driving surface [2,3]. Because the exterior of solar cells is typically transparent to allow the penetration of sunlight, a surface augmentation must be applied to meet the roadway's friction demands [2,3,5]. Panels that have replaced asphalt as the driving surface were also structurally modified to support the mechanical loads of vehicles [2,3,5]. Current modifications are layers of polymers and porous rubber that cover or encase the panels to enhance their mechanical rigidity [2,3].

There have been several experimental solar harvester implementations that exercised these approaches. One study concerning SolaRoad, a solar panel system designed to function as a driving surface, found that a 70 m paneled bike path generated roughly 3 MWh of electricity over a period of six months [1,2]. Rather than place the solar panels on the road itself, the solar company Soluxio developed cylindrical panels that cased the exterior of roadside light posts. Their power output was enough to sustain the connected lights and isolate their demand from the electrical grid [1]. In a 2014 study of roadway heat mitigation, it was determined that replacing asphalt with solar panels for roadway surfaces could reduce pavement temperatures by up to 15%, which would contribute to overall environmental sustainability in addition to electrical generation [2].

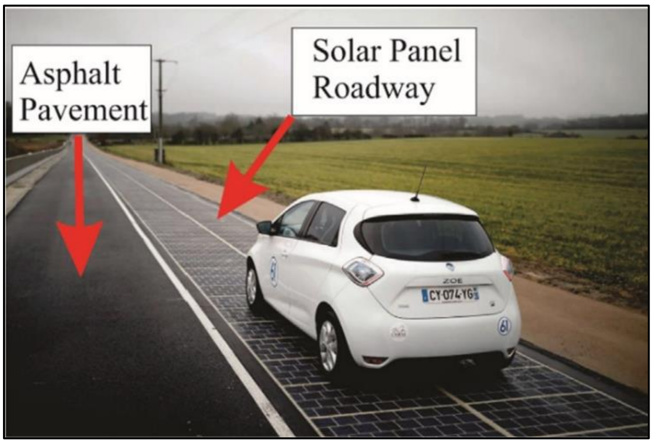

Figure 2. Solar panel roadway beside a normal asphalt roadway [2].

Piezoelectric

Piezoelectric energy harvesting has also been heavily researched and developed. Piezoelectric materials, or crystalline ceramics manipulated to have unidirectional dipoles, generate electricity when mechanically strained [7]. Through this passive property, they can convert the mechanical loads from vehicle traffic into electricity [1-8,10]. The electrical output from piezoelectric materials depends on many factors, of which the most significant are the strain or elastic deformation of the material, the shape, orientation and arrangement of the material, and the material's piezoelectric constant, or the electrical polarization that occurs under strain [6,7].

The current implementations of piezoelectric harvesters have a standard configuration. The piezoelectric material is evenly arranged in a grid and supported with a casing or frame. The entire system is then placed directly under the roadway surface to ensure protection and proximity to vehicle pressure [1-8,10]. With this nominal arrangement, the developments in piezoelectric harvesters are produced by variations in the previously listed factors of electrical output. Noticeable output differences are observed between these variations in material shape and composition.

There are four basic piezoelectric material variants identified by their shape or state: solid cylinder, stacked cylinder or disk, cymbal or bridge, and cementitious (See Figures 3 and 4 for graphic). A study that featured two housings of 18 solid cylinders found that, under the volume of 4000 vehicle passes in one day, each housing generated between 0.08 and 2.1 W [7]. Two separate studies by Khalili et al. and Sherren et al. determined that a singular stacked harvester could yield 1.5W and 1.2W of power with practical conditions, respectively [1,4]. Similarly, a 2010 experiment with a cymbal-shaped harvester concluded with the harvester generating 1.2 mW under a load frequency of 20Hz [8]. The cementitious harvester deviates from the standard harvester configuration as the piezoelectric material is mixed with cement to dually function as the driving surface. It is the least developed of the four main piezoelectric harvester variants and therefore lacks noteworthy experimental data [1].

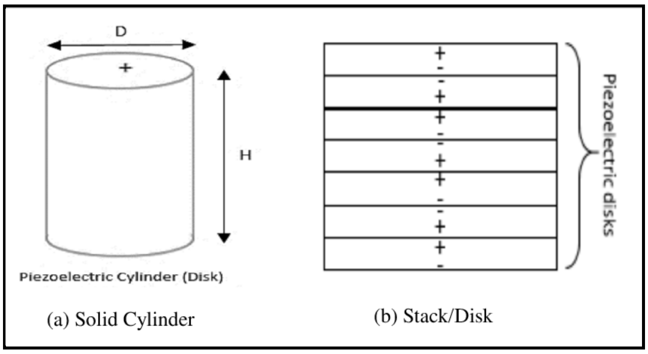

Figure 3. Side view of solid cylinder harvester (a) and stacked disk harvester (b) [1].

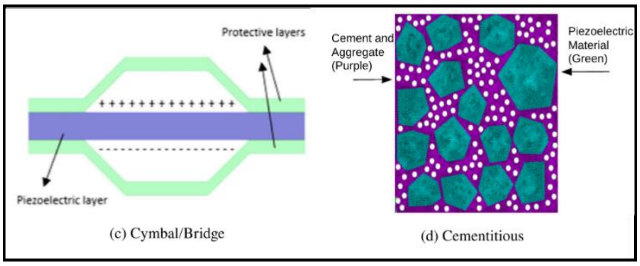

Figure 4. Side view of cymbal/bridge (c) harvester and cementitious harvester (d) [1].

Thermoelectric

Thermoelectric harvesting is another primary mode of energy harvesting from roadway systems. Thermoelectric properties allow the conversion of heat gradients into electricity via semi-conductors. This is also known as the Seebeck Effect [1-3,5,8]. Roadways present the opportunity to apply such phenomenon, as they contain substantial differences in temperature between their exposed surfaces and underground layers from both the natural environment and constant vehicle traffic. The power generated by a thermoelectric system is directly proportional to the thermoelectric material's heat gradient [1]. Thus, most thermoelectric generators (TEGs) utilize materials that insulate heat and conduct electricity [1-3]. These materials, such as silicon germanium, maintain temperature grades while allowing electrical potential, and in doing so, maximize electrical output [2].

The format for a metal-based thermoelectric harvester consists of a thermally conductive metal strip that is partially exposed on the roadway's surface and extended into the cooler subsurface regions [1-3,5,8]. From this setup, the necessary heat differential can be obtained either naturally or by hydrocooling. A natural heat gradient is completely passive, only relying on the natural temperature difference that exists between the roadway and its subsequent layers. In contrast, hydrocooling utilizes water pipelines and active bodies of water to sustain cool-side temperatures lower than those underground. As with piezoelectric materials, engineers have also developed a cementitious thermoelectric mix designed as a harvester with the properties of a construction material. The addition of carbon nanotubes (CNTs) and composite fibers transforms ordinary cement into a thermoelectric substance with electric production capabilities [1].

Metal-based thermoelectric harvesters have had a multitude of tests and implementations. In a 2012 study, researchers Wu and Yu found that a naturally cooled thermoelectric harvester could generate a maximum of 0.02 mW from a heat gradient of 6.44 °C [2]. The efficiency of the harvester in this experiment was calculated to be 1.6% [5]. A preceding study in 2006 produced more favorable results, as Hasebe et al. implemented a pipe-based hydrocooling harvester that yielded 5 W from a 40.5 °C temperature grade. The same system yielded 0.9 W under a 11.5 °C differential, which is far more realistic for practical application [5]. Significantly less experimental data exists for cementitious thermoelectric harvesters. While the material's energy conversion output is unclear, researchers have confirmed that nano additives substantially improve the mix's mechanical strength [1].

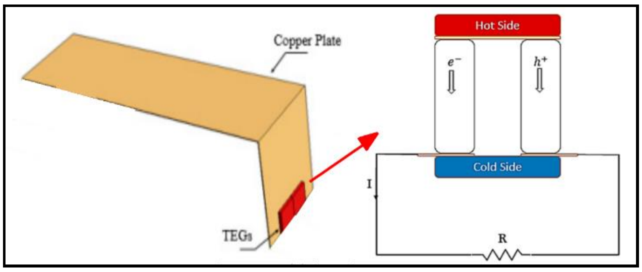

Figure 5. A metal strip harvester and diagram of its thermoelectric generator [1,2].

Electromagnetic

Electromagnetic energy harvesting, an asset to macro energy generation, also has applications for micro energy harvesting within roadway systems. Electromagnetic systems convert mechanical or kinetic energy into electricity. They rely on electromagnetic generators, or motors, to produce an electrical current from the rotation of a magnetic field (Faraday's Principle) [1-3,5,8]. Via mechanical systems, electromagnetic harvesters implemented in roadways convert the vehicles' linear force into the rotational motion needed to generate electricity. The following are the possible mechanical systems used to obtain rotational motion: rack and pinion, hydraulic, pneumatic, roller, cam and arm, and chain and sprocket [1,3]. Alternatively, some researchers suggest that electromagnetic harvesters can be physically minimized and fixed to a singular vehicle's suspension [2,3].

Stationary harvesters are implemented directly below the driving surface with the exception of a roadway surface plate or protrusion, similar to a speed bump, to capture kinetic vehicle motion and initiate the conversion process. Once electricity is generated, there are several storage options. The energy can remain in the form of electricity and be stored in a battery or a capacitor, or can be converted yet again into alternatives such as hydraulics and compressed air [1]. Storage units can be located underground, adjacent to the harvester, or simply near the roadway [1].

There is an abundance of experimental data concerning electromagnetic harvesters. Wang et al. created a harvester with a rack and pinion mechanical system. The initial energy was retrieved through a speed bump, and the final output power was 200 W [2]. A project focused on downhill deceleration featured a hydraulic mechanical system that yielded on average 600 W at an efficiency of 41%. The harvester's output was produced from a 3 cm displacement of the hydraulic pistons on the roadway surface [1]. A pneumatic-based harvester developed by Azzouz et al. is said to produce 83 kWh per day given a volume of 37,400 vehicles per day [2].

The significant magnitude of output energy from electromagnetic harvesters further supports the development of energy storage systems. Though hydraulic and compressed air mechanisms have proven to be effective, engineers are striving to create storage systems that are mechanically similar to the roadway itself [1]. Examples of these efforts are geopolymer and cement and graphene capacitors. The geopolymer capacitor had a power density of 0.33 kW/m² and the cement and graphene had an estimated capacitance of nearly 19.5 F/g [1].

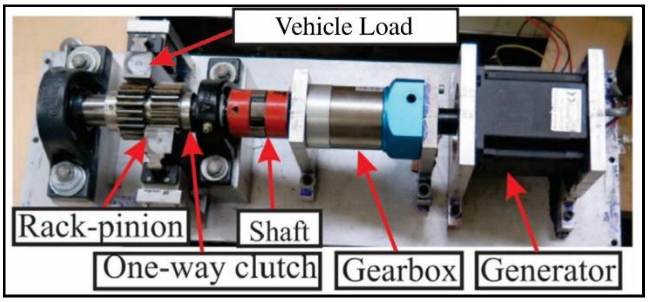

Figure 6. Electromagnetic rack and pinion harvester [2].

III. COMPARISONS AND CONCLUSION

Normalized comparisons and scales are used to account for the various factors that determine the viability of technology. For energy harvesters, these significant values are the technology readiness level (TRL) and levelized cost of electricity (LCOE) [1-3,5]. The TRL scale assigns a technology a value from 1 to 9 according to its ability to perform in practical application.

Concerning the four main harvesting technologies, photovoltaic is currently most applicable (TRL of 9) due to its wide array of successful implementation [1-3,5]. Along with thermoelectric systems, it has the advantage of kinetic passivity. Solar cells and thermoelectric generators require no internal or external mechanical energy to generate electricity, unlike piezoelectric and electromagnetic systems. However, current roadway solar technology is far more fragile than the technology of the other harvesting methods and is therefore relatively expensive. The additional costs of solar cell reinforcements and maintenance reduce the viability of photovoltaic harvesting on roadways. Yet, its cost effectiveness remains high (LCOE between 0.45 $/kWh and 19.8 $/kWh) compared to other systems [1-3].

Piezoelectric harvesters have an advantage in installation ease and system simplicity. They contain no moving parts and are independent of environmental conditions, unlike solar and thermal mechanisms. With a current maximum TRL of 5 and LCOE range of 19 $/kWh to 60 $/kWh, their immediate viability is slightly less than solar [1-3]. In general, their outputs and efficiencies are lower than the those of the other harvester options. Piezoelectric harvesters appear to have the greatest potential for mass implementation out of the four harvester modes, given the extensive research that has been performed on them.

Thermoelectric harvesters can be summarized in similar fashion to photovoltaic harvesters. Their electrical generation is entirely passive and independent of mechanical energy. Conversely, their environmental dependency restricts their productivity to the inconsistency of weather. Like piezoelectric systems, their installation is uncomplicated. Though they have a low LCOE range of 0.89 $/kWh to 2.31 $/kWh, they also have notoriously low efficiencies and outputs [1-3]. Given their modest performance, their manufacturing cost is currently too high to support a mass implementation.

Electromagnetic technology's considerable energy generation greatly supports its viability for implementation. With a TRL average of 5 and a LCOE of 37.36 $/kWh, the harvesting method is feasible for future practical applications [1]. An important consideration with respect to the electromagnetic harvesters' superior power generation is that such production is a result of vehicle impedance [9]. The speed bumps used to “harvest” mechanical energy are effectively stealing that energy from the intended motion of the passing vehicles [9]. Large scale implementations would be accompanied by an increase in speed bumps, and consequently, more abruptions in traffic flow [9]. Maintenance on electromagnetic systems would be another obstacle of implementation, as mechanical repairs would require longer road closures than those needed for piezoelectric or thermoelectric harvesters [1].

Compared to mainstream renewable energy systems, road energy harvesting is still in its infancy. Its relatively low outputs and efficiencies restrict the current applications to powering digital roadside technology. Considering the challenges presented by the incompatibility between fragile harvesters and the road itself, the development of construction-based harvesters and storage units promises a potential for greater viability. With ongoing research and improvements, it is certainly feasible that road energy harvesters will eventually harvest enough energy to partially satisfy consumer demands and significantly contribute to the sustainability of energy infrastructure.

REFERENCES

[1] Zabihi, N. and Saafi, M. Recent developments in the energy harvesting systems from road infrastructures. Sustainability, 2020, 12, 6738; https://doi.org/10.3390/su12176738

[2] Gholikhani, M., Roshani, H., Dessouky, S. and Papagiannakis, A. T. A critical review of Roadway Energy Harvesting Technologies. Applied Energy, 2020, 261, 114388; https://doi.org/10.1016/j.apenergy.2019.114388

[3] Pei, J. et al. Review and analysis of energy harvesting technologies in roadway transportation. Journal of Cleaner Production, 2021, 288, 125338. https://doi.org/10.1016/j.jclepro.2020.125338

[4] Sherren, A., Fink, K., Eshelman, J., Taha, L.Y., Anwar, S. and Brennecke, C. (2022) Design and modelling of piezoelectric road energy harvesting. Open Journal of Energy Efficiency, 11, 24-36. https://doi.org/10.4236/ojee.2022.112003

[5] Duarte, F. and Ferreira, A. Energy harvesting on road pavements: State of the art. Proceedings of the Institution of Civil Engineers – Energy, 2016, 169, 79–90. https://doi.org/10.1680/jener.15.00005.

[6] Sezer, N. and Koç, M. A comprehensive review on the state-of-the-art of Piezoelectric Energy Harvesting. Nano Energy 80, 105567 (2021). https://doi.org/10.1016/j.nanoen.2020.105567

[7] Papagiannakis, A. T., Dessouky, S., Montoya, A. and Roshani, H. Energy harvesting from roadways. Procedia Computer Science 83, 758–765 (2016). https://doi.org/10.1016/j.procs.2016.04.164

[8] Symeoni, A. A review on energy harvesting from roads. Environmental Engineering and Sustainable Infrastructure 017, 1–39 (2012).

[9] Orfei, F. Disadvantages and advantages of energy harvesting - technical articles. All About Circuits (2019). Available at: https://www.allaboutcircuits.com/technicalarticles/benefits-of-energy-harvesting-disadvantages. (Accessed: 14th June 2022)

Thomas, A. Generating power every time you hit the road. Rutgers CAIT (2019). Available at: https://cait.rutgers.edu/generating-power-every-time-you-hit-the-road/ . (Accessed: 14th June 2022)