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Energy Harvesting on Road Pavements

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***Abstract*—With the growing need for alternative energy sources, research into energy harvesting technologies has increased considerably in recent years. The particular case of energy harvesting on road pavements is a very recent area of research. This paper deals with the development of energy harvesting technologies for road pavements, identifies the technologies that have being studied and developed, examines how such technologies can be divided in different classes and gives a technical analysis and comparison of those technologies, using the results achieved with prototypes.**

***Keywords*—road pavements; energy harvesting; renewable energy.**

I. Introduction

In the area of renewable energies, besides the major energy sources (hydro, solar, wind, waves), energy harvesting has recently been adopted on a micro-scale concept, where it is possible to generate electrical energy from small energy variations, such as thermal gradients, pressure, vibrations, radiofrequency or electromagnetic radiation, among others [1]. Road surfaces are continuously exposed to two phenomena: solar radiation and vehicle loads. From both of these it is possible to extract energy, which, using specific technologies, can be transformed into electrical energy [2]. Within cities, there are roads that carry vehicles, the main option for mobility. Vehicles consume energy to work their engines and release energy in different ways, by way of different components. Part of the energy released by vehicles goes into the road pavement. 15% to 21% of the energy is transferred to the vehicle's wheels [3,4]. As vehicles abound in all cities in developed countries, this means that a considerable amount of energy is transferred to road pavements without being used. Roads are also exposed to solar radiation, which induces thermal gradients between its layers. This solar radiation and the resulting thermal gradients can also be transformed into useful energy. So road pavements represent a considerable source of energy ready to be harvested and converted into useful forms of energy, such as electrical energy, at the same time reducing the need to "import" energy from distant places.

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The present paper aims to review the energy harvesting technologies with possible implementation on road pavements, using both solar energy and vehicle released energy as an energy source.

II. Road Pavement Energy Harvesting Technologies

Energy Harvesting is described as a concept by which energy is captured, converted, stored, and utilized using various sources, by employing interfaces, storage devices, and other units [5,6]. Simplified, energy harvesting is the conversion of ambient energy present in the environment into other useful means of energy, as for example, in electrical energy [7]. Energy harvesting is divided in two main groups: macro energy harvesting sources, associated with solar, wind, hydro and ocean energy; and micro energy harvesting, associated with electromagnetic, electrostatic, heat, thermal variations, mechanical vibrations, acoustic, and human body motion, as energy sources [5,8,9]. Macro energy harvesting is related to large scale energy harvesting, usually in the order of kJ or more. Micro energy harvesting is related to small scale energy harvesting, usually in the order of a J or less.

From the energy harvesting technologies identified by Harb [8], two groups of technologies have a great potential for implementation on pavements: one uses solar radiation as an energy source; and the other uses the mechanical energy from vehicle loads. Considering these energy sources, different technologies and systems have been developed and tested in recent years. The main energy harvesting technologies applicable on road pavement can be divided into two main groups, as presented in Fig. 1. The first group is related to technologies that make use of the solar exposure on the road pavement. Solar radiation can be directly harvested by photovoltaic cells and transformed into electrical energy; it can induce thermal gradients between the road pavement layers, which can be used to power thermoelectric generators (TEGs), which produce electrical energy, or be harvested by Asphalt Solar Collectors (ASC), which extract the temperature accumulated on the road pavement. Induction heating is a concept in which introducing conductive particles in the asphalt mixture provides self-healing capacities autonomously at high temperatures by harvesting solar radiation. The second group is related to technologies that make use of the mechanical energy transferred from vehicles to the road surface. This can be harvested directly by piezoelectric harvesters, which generate electrical energy; or it can be harvested by Hydraulic, pneumatic, electromechanical or micro-electromechanical (MEMS) systems, that transfer the harvested energy to electromagnetic generators, which produce electrical energy. In the case of MEMS, they can also transfer the harvested energy to piezoelectric generators.

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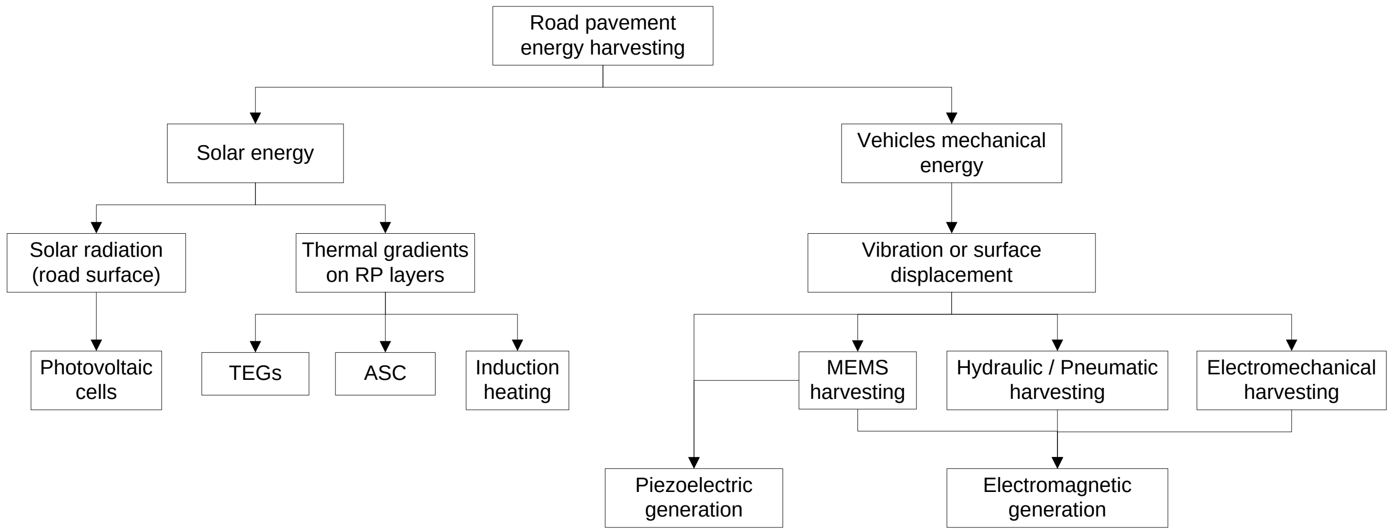

Figure 1. Road pavement energy harvesting technologies

III. Technical Analysis

To perform a technical analysis and evaluate an energy generation technology, the most commonly used parameters are the installed power (per area or volume), the conversion efficiency, the power density, and the energy generation of the technology in normal operating conditions (Table I). In the specific case of road pavement energy harvesting, it also is important to classify the technologies according to the installation method, as this is an important issue regarding the final cost of the solution, the driving and safety conditions and the maintenance operations of the equipment. Finally, as these are mostly new technologies, it is important to classify them regarding their development status.

Following the analysis of the different technologies presented in this study, the main characteristics of each one are presented in Table II. For this analysis, the technologies that convert both solar and vehicle mechanical energy into useful electrical energy and which have been tested on road pavements were considered. So, ASC, induction healing and MEMS technologies were excluded from the analysis.

From Table II, it may be seen that most of the studies do not meet all the parameters required to perform a complete technical analysis, hindering a more detailed and direct comparison of all the technologies. Most researchers or companies present only the energy generation capacity and installation method of the developed devices and only a few studies present the installed power and the conversion efficiency of the technologies. From this analysis, one can conclude that the systems that make use of vehicle mechanical energy have a higher conversion efficiency and energy generation capacity than the systems that make use of solar radiation. In terms of energy generation, hydraulic and electromechanical systems present higher capacities.

TABLE I. PARAMETERS FOR PERFORMING A TECHNICAL ANALYSIS

Parameter	Description
Installed Power	The installed power of an electric energy generation device is its energy generation capacity in nominal conditions, i.e. the maximum theoretical power it can generate. It is related to the output power and is expressed in watts (W). In many cases, it is expressed by comparing the installed power with the occupied area of the device (W/m^2), or with the occupied volume of the device (W/m^3). In micro energy harvesting devices the analysis is usually done in regard to volume.
Conversion Efficiency	Energy conversion efficiency (η) is the ratio between the useful output of an energy conversion device and the energy input. In the case of electrical machines, the output is electrical energy measured in Joules (J), or electrical power measured in watts (W). The energy conversion efficiency is a dimensionless parameter, usually expressed in percentage.
Energy Generation	Energy generation is used to quantify the amount of electrical energy generated under the operating conditions. It gives the energy input of the system, its efficiency, and the installed power. Usually it is expressed in Joules, but in some micro energy harvesting devices, it can also be related to the volume (J/m^3). In the analysis of energy harvesting devices, sometimes power generation is also presented, related to the volume of the device (W/m^3).
Installation Method (IM)	The different energy harvesting devices can be installed in the road pavement using different techniques, and in different layers of the road pavement. Four main installation methods were identified.
Technology readiness level (TRL)	Technology readiness levels (TRLs) are measures used to evaluate the maturity of a technology during its developmental stages.

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TABLE II. TECHNICAL ANALYSIS OF DIFFERENT ROAD PAVEMENT ENERGY HARVESTING TECHNOLOGIES

Technology	Company or R&D Inst.	Installed Power W/m^2	Conversion Efficiency	Energy Generation	Installation Method (IM)[1]	TRL[2]
Photovoltaic	Solar Roadways [10,11]	97.3	11.2%	N.A.	1	4
	TNO [12,13]	N.A.	N.A.	N.A.	2	7[3]
TEG	[15]	N.A.	N.A.	38.0 mW/cm^3	3	3
	[16]	N.A.	1.6%	2.6 mW/cm^3	3	3
Piezoelectric	Innowattech [17]	N.A.	N.A.	5.8 J/Veh.m	3	4
	Genziko [18]	1942.0	N.A.	40.0 J/Veh.m	3	4
Hydraulic	Kinergy Power [19]	N.A.	N.A.	188.0 J/Veh.m	1/2	4
	New Energy Technologies [20]	N.A.	N.A.	N.A.	1/2	4
Electro-mechanical	Waydip [21,22,23]	833.0	50.0%	680.0 $\mu W/cm^4$ 180.0 J/Veh.m	2	4
	Underground Power [24]	N.A.	85.0%[3]	N.A.	1/2	4
	Highway Energy Services [25]	N.A.	N.A.	N.A.	2	3
	Energy Intelligence [26]	N.A.	N.A.	N.A.	2	3

1:
IM 1 - On the road pavement surface, fixed to the upper layer (the device surface becomes the new road surface);
IM 2 - Embedded in the road pavement, upper layer, surface exposed (the device surface becomes the new road surface);
IM 3 - Embedded in the road pavement, upper layer, surface covered by road pavement material;
IM 4 - Embedded in the road pavement, lower layer, surface covered by road pavement material.
2:
TRL 1 - Basic principles observed and reported;
TRL 2 - Technology concept and/or application formulated;
TRL 3 - Analytical and experimental critical function and/or characteristic proof-of-concept;
TRL 4 - Component validation in laboratory environment;
TRL 5 - Component validation in relevant environment;
TRL 6 - System/subsystem model or prototype demonstration in a relevant environment;
TRL 7 - System prototype demonstration in an operational environment;
TRL 8 - Actual system completed and qualified through tests and demonstration;
TRL 9 - Actual system proven in operational environment.
3:
For cycle lanes. For road pavements, it has only been conceptualized, not prototyped (TRL 1/2).
4:
Efficiency on a 1:10 scale, and not considering the losses of control, storage and deliver energy to an electrical load.

In terms of installation methods, photovoltaic systems are mainly applied using installation method 1, while TEG systems are applied under the road surface, using installation methods 3 and 4. Piezoelectric systems are also applied using installation method 3, while the hydraulic and electromechanical systems can both be installed using methods 1 or 2, with their surface in direct contact with vehicle wheels, to maximize the energy input to the system.

In terms of development status, one can conclude that none of these devices are fully validated and available on the market; they are generally at TRL 3 or 4. The TNO system is on TRL 7, but this is for cycle path application and does not present any evidence of application on roads.

In order to fully determine if any technology is viable, an economic analysis should also be performed. In such an analysis, the most important factor is the levelized cost of electricity, which determines the cost per watt produced, relating the total economic investment in a technology to the energy generated [27]. However, no technology is fully developed and available on the market. So, no economic data of any product is yet available and such analysis cannot be performed at this stage.

IV. Conclusions

The concept of road pavement energy harvesting has become increasingly popular over the last few years. Unlike the case of wind energy, the present situation shows a wide variety of energy harvesting systems, at several stages of development, competing against each other to get an opportunity in the market. In the last fifteen years or so, the R&D activity in road pavement energy harvesting has been developed more by companies than by Universities, leading to a lack of scientific evidence being available on the developed technologies. The tests performed were not fully characterized in the literature, making very limited information available about the experimental tests and results obtained. It is clear than none of the developed technologies has been fully developed and validated, as none of them have entered the market with a finished and certified product (with the exception of ASC, which is an energy harvesting system, but not to generate electrical energy). In the road pavement energy harvesting field, most of the technologies are at a laboratorial and prototyping validation stage.

Comparing the technologies that make use of solar energy as their energy source, with the technologies that make use of vehicle mechanical energy, the former is at a more advanced developmental stage, as it makes use of more mature systems and technologies. However, presently, most R&D is being performed on the latter, mainly due to the higher potential that these systems present, in terms of energy conversion efficiency, energy generation and adaptability to road pavement conditions.

Comparing the technologies that make use of solar energy as an energy source, photovoltaic systems are the most efficient and mature. However, the implementation on road pavements is still a challenge, as glass has been used on the photovoltaic cells, causing difficulties for vehicle adherence, which is essential to guarantee rolling capacity and safety conditions. Systems that make use of TEGs are easier to install on the road pavement, however efficiency is considerably reduced.

Comparing the technologies that make use of vehicle mechanical energy as an energy source, piezoelectric technology was the first to get the attention of researchers. However, due to its lower energy conversion efficiency, the developments with this technology have decreased in the last two or three years. On the other hand, there has been an increase in research and development of electromechanical systems that harvest vehicle mechanical energy and, using electromagnetic generators, generate electrical energy. These, together with hydraulic systems, have registered the highest energy generation values in experimental tests. Their installation is also simpler than the installation of piezoelectric devices and they currently present a higher likelihood of success as an effective solution to transform vehicle mechanical energy into electrical energy effectively.

MEMS also present potential in this field since they have been successful in other applications. However, in the case of road pavement energy harvesting, they have been applied to harvesting pavement vibrations instead of directly harvesting vehicle mechanical energy. Pavement vibrations represent a small amount of the available energy, leading to a low level of energy generation. In the future, these systems should also be developed to harvest vehicle mechanical energy in order to maximize energy generation.

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