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Electric energy harvesting solutions review from roads pavements

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Abstract

This paper is concerned with an overview of novel experimental green technologies roadway energy harvesting that could guarantee, in a not so distant future, a significant source of electric power and lead a decrease of greenhouse gases (CO_2) emission.
Two different most promising free emission technologies for energy harvesting from road pavements are considered and analyzed as: the piezoelectric system for generating electric power from vehicular traffic stresses and the photovoltaic panels for converting solar energy into electricity.
Finally, as case study, a preliminary application analysis of these two technologies on an A24 motorway section located in central Italy has been carried out and the results are discussed and compared in terms of energy production.
KEY WORDS: *roads energy harvesting, piezoelectric roadways, solar roadways, renewable energy*

1. Introduction

Even if compared to the past decade vehicles have become more energy efficient, current EU transport still depends on oil and oil products for 96% of its energy needs. EU strategy implies the drastic reduction of world greenhouse gas emissions by 80-95% below 1990 levels by 2050. It is clear that the actual transport system is not sustainable and it cannot develop on the next years along the same criteria [1].

In this scenario, innovation in technology of "zero" emission vehicles [2, 3] and sustainable infrastructures can play a key role for emissions reduction. These considerations point out the necessity of investing in the innovation of transport systems (vehicles, infrastructures and their interactions) considering alternative solutions.

Current highway network is the result of a design and development model conceived in the sixties. This implies that we are actually dealing with the technologies and the road conception developed more than 55 years ago. Nowadays, on the contrary, the highway when properly designed and requalified through the integration of specific systems, it can become a valuable energetic source [4].

It is well known that EU transportation (both commercial and non-commercial) mainly take place by road and has been noticeably increasing year by year. In particular, the middle-long-range transport is mostly practiced on the highway network.

Since the energetic and emission problems have a global impact, it is necessary to explore and test novel technologies for all road infrastructures sustainability [5].

2. Technologies for electric energy production from the road pavements

Internationally different technologies are developed and tested in order to generate electrical or thermal energies from the road pavements. It should be noted that these technologies are still under development and the experimental applications are limited to very few cases and they have been provided in often very wide range. Moreover, limited scientific publications are available in technical literature.

In this paper the piezoelectric and photovoltaic technologies for electricity production from road pavement are reviewed and analyzed.

2.1 Piezoelectric technology

Piezoelectric materials (Barium Titanate, Lead Titanate, Lead Zirconate Titanate, etc. [6] are crystals that have the property to generate current when compressed or vibrated and vice versa they generate a stress when voltage is applied to them.

So the piezoelectric devices, if appropriately integrated into an electromechanical system, can be suitable for road applications in order to convert vehicles motion into electrical power.

The working principle is based on the piezoelectricity effect, for which piezoelectric crystals generate electric voltage from elastic deformations (Fig. 1).

Different products (Innowattech, Cook Chennnault, Virginia Tech, Oregon DOT, Berkeley tech. [7]), to be installed under the asphalt pavement (or inside of the railway sleepers) have been designed in order to generate direct current (DC) from the transit of vehicles/trains [8].

As illustrated in Fig. 2, the DC output of the piezoelectric units electrically connected in series can be:

i) converted by DC-to-AC converter in alternate current (AC) for directly feeding electrical devices or the electrical grid;
ii) accumulated in a storage (i.e. battery) system. The accumulated energy can be used for local power needs or transferred into grid.

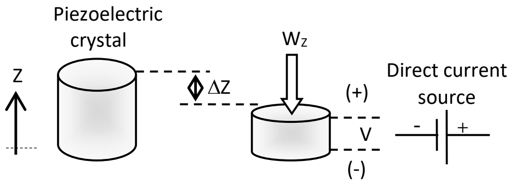


Fig. 1 Work principle of piezoelectric crystal effect

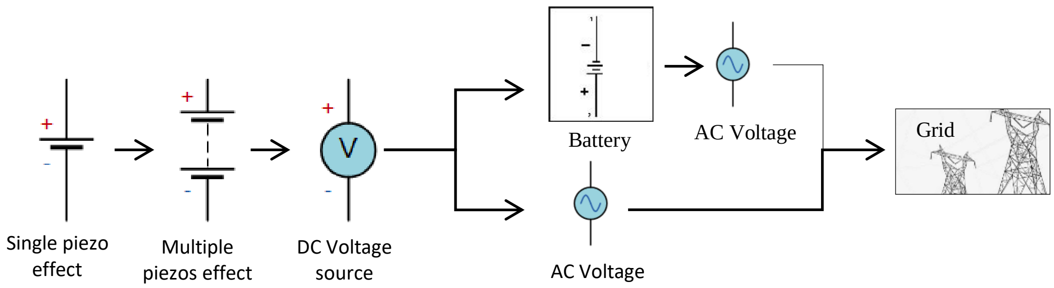


Fig. 2 Flow chart scheme

The main parameters that determine the electricity outcomes of piezoelectricity are: crystalline structure (biomorph or unimorph), geometry (shape) that influence vibration mode, thickness, fixation (fixing constraints between the piezoelectric and the road structure), magnitude of load vertical component (W_Z) [9].

As the piezoelectric device efficiency is strictly related to stress frequency (Hz) and to load (F_Z) magnitude, the road practical system energy power output increases with the rise of vehicles weight and transit frequency (vehicle/h).

The efficiency of piezoelectric devices is also 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 [10].

An interesting application for the production of piezoelectric energy from roadways comes directly from an Israeli company (Innowatech) with its research offices located in the Institution of Technion, Haifa (Israel). This company has developed a piezoelectric device suitable for producing electricity from the traffic-related movement of the road platform [11].

In particular, the vertical load component (W_Z) by vehicle tires produces a compressive stress that proportionally decreases with depth [12]. For this reason, generators designed by Innowattech are placed in the road pavement to a depth of 5 centimeters, where stresses produced by vehicles are more intense (Fig. 3).

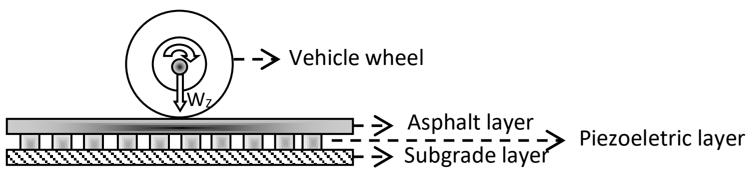


Fig. 3 Piezoelectric roadway cross-section

This solution, when applied to a highway, produces electricity as a function of the number of vehicles, of their weight and speed. Consequently, the greater is the traffic and the more convenient will be this solution.

The operational steps for the piezoelectric generators installation on the road pavement are the following [13]:

- Cutting of the pavement surface
- Laydown of a quick-setting concrete
- Positioning of the piezoelectric generators (30×30 cm) and drowning in quick-setting concrete
- Connecting the cables
- Overlaying the generators with an asphalt layer (to provide better adhesion between concrete and asphalt layer)
- Laydown of final asphalt wearing layer

Once completed the installation, generators collect the mechanical energy produced by vehicles and convert it into electricity, which is then transferred in storage systems (i.e. batteries) installed along the roadway.

This system provides the following advantages: no occupation of areas adjacent to the roadway, operates in any weather conditions and reduced maintenance operations.

First tests by Innowattech dealt with the installation of piezoelectric nano-generators along a stretch of 10 meters in a road asphalt pavement. In this case the generators could potentially produce about 2 kWh. This trial allowed to experimentally verify that the system works better when traffic is at least 600 vehicles/hour with an average speed of about 72 km/h. Currently the system is under testing and it is characterized by high implementation costs that could be reduced if a production in mass will be promoted [13].

2.2 Photovoltaic panels as a road surface

Nowadays, PV systems are commonly known; they can be distinguished in rooftop or ground-mounted systems and are able to convert solar energy into electricity. Among the multiple uses, there are very interesting photovoltaic panel applications on roadways. In particular, these solar panels can be integrated on noise barriers, shelters of parking service stations or even on the road surface. In this paper we treated about the last type.

The photovoltaic panel placed on the road surface is a pioneering idea by the American engineer Scott Brusaw who, supported by his working team, realized the "Solar Panel Road". This device is a photovoltaic panel able to convert solar energy into electricity and concurrently bear loads and stresses caused by road traffic [14].

The solar roadway panel, designed to substitute the asphalt wearing course, is composed of the following three layers (Fig. 4a)

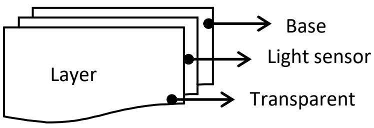
- Surface layer made of a rough glass, anti-abrasive, self-cleaning and highly resistant, which contains photovoltaic cells and led diodes; this layer has the main function to resist weathering and protect the electronic apparatus located underneath;
- Intermediate electronic layer, which contains a microprocessor for controlling and monitoring loadings and lighting;
- Bottom layer, which carries the energy collected by the intermediate layer to various storage systems connected to the roadway and transmit the pavement load to subgrade layer.

Each of the solar roadway hexagonal panels covers an area of about 13.38 m^2 [15]. The DC produced energy is carried to storage systems located near the road surface and can be directed to a primary network for satisfying various energy requirements (e.g. homes, street lighting and road signs, service stations. The DC is converted to AC energy by a DC-to-AC converter or solar micro inverter and then is fed to the electrical grid.

The proceeds would be significant in terms of energy amount: it has been estimated that, for an average daily solar irradiation of 4 hours, each photovoltaic panel should be able to produce around 7.6 kWh per day [16]. However, maintenance procedures for dust accumulation, the duration of photovoltaic cells and the high costs still make the photovoltaic panel for road surfaces in need of improvements.

The Solar Roadways is currently being tested in a section of a highway (70 km long) located between Coeur D'Alene and Sandpoint in Idaho.

4(a)



4(b)

Fig. 4 (a) Main layers of panel road 4 (b) Wattway solar panel road [source: http://www.wattwaybycolas.com/en/]

Also in France, a photovoltaic pavement has been realized and named with the explicit term Wattway (Fig. 4b). This system has been developed by the National Institute of Solar Energy (INES) in cooperation with Colas (company specialized in transport infrastructure). This construction represents an example of a unified concept of photovoltaic road surface: Wattway slabs include photovoltaic cells made of polycrystalline silicon incorporated in a substrate few millimeters thick. At the side, the system is connected to a case that contains electronic security components. The slabs are antiskid, resistant, adaptable to every surface and have been designed to bear the traffic of all types of vehicles, including heavy trucks. The installation of these slabs is very easy: they can be directly glued on the existing pavement surface without any further constructions [17,18].

3. Case study

The Italian Motorway A24 (166 km long with 14 sections) that connects on West-East directions the cities of Roma, L'Aquila and Teramo has been selected for carrying out a case study by applying the two road energy harvesting technology systems described in the previous sections

More in detail, two A24 motorway sections (Fig. 5) have been taken into consideration in order to evaluate the potential electric output of the two different kind of energy harvesting technologies:

- Stretch A: Roma East - Castel Madama toll booths with piezoelectric system;
- Stretch B: L'Aquila East - West toll booths with PV system.

Fig. 5 A24 Motorway

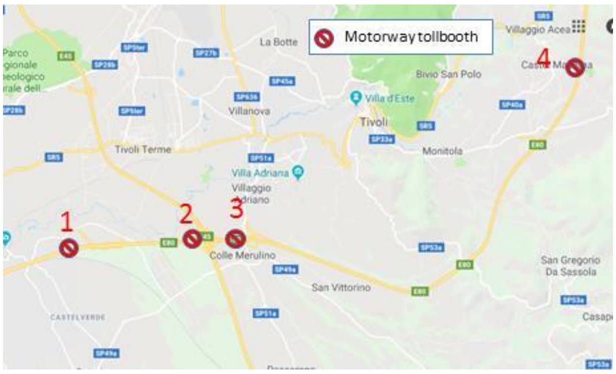


Fig. 6 A24 motorway sections: piezoelectric application

3.1 Piezoelectric system for road pavements

A vehicular traffic analysis on all the fourteen A24 motorway sections has been performed by using the data (reference year 2014) provided by the company “Strada dei Parchi SpA” that manage this motorway.

The evaluation of the average annual traffic per hour in each motorway stretches allowed the identification of the segments with more than 600 vehicles/h per direction. Only the first three (near Rome area) out of fourteen segments resulted suitable for the installation in the pavement structure of the piezoelectric device, as follows: segment 1-2 between Roma East toll booths - Connection A1/A24; segment 2-3 between connection A1/A24 – Tivoli toll booths; segment 3-4 between Tivoli– Castel Madama toll booths (Fig. 6).

The system energy output calculation was performed by taking into account the performance data of the Innowattech system [13].

Table 1 lists for each segment the traffic volume and the electric energy per Km. As can be noted, the electric energy production value is between 208 -355 kWh/km for direction. The potential amount of piezoelectric energy that can be potentially produced in this A24 motorway stretch (sections 1-4) is around 7.7 MWh.

Calculation results show an average hourly specific energy output of 0.06457 kW/m^2 equals to about 565 kW/m^2 per year at an average traffic volume of 830 vehicles/h.

Table 1. Energy produced by the piezoelectric device in the A24 Motorway.

Segment	Traffic volume [vehicles/h]		Energy per Km [kWh]		Length [Km]	Total Energy [MWh]	
	Right lane	Left lane	Right lane	Left lane		Right lane	Left lane
1-2	1066	944	355	315	3.2	1.1	1.0
2-3	881	850	294	283	1.5	0.5	0.4
3-4	630	624	210	208	11.2	2.4	2.3
					Sum	4.0	3.7
					Total	7.7	

3.2 Photovoltaic panel for road pavements

In this sub-section, the installation of PV panel for road pavements in the motorway segment between L'Aquila West and East toll booths was taken into consideration (Fig. 7). The selected motorway section is characterized by an average flow of 220 vehicle/h per lane.

The electric energy (E) produced by a standard photovoltaic (PV) array integrated in a road pavement is calculated as

$$E = \eta_m \cdot \eta_b \cdot \eta_s \cdot S \cdot G \qquad (1)$$

where η_m is the module efficiency, η_b is the system efficiency taking into account the losses due to temperature and low irradiance (using local ambient temperature), loss due to angular reflectance effects and other losses (cables, inverter etc.), η_s is the losses related to vehicular traffic effect, S is the PV area, G is the average sum of global irradiation per square meter received by the PV modules of the given system.

The PV performance was calculated at L'Aquila location (42°22'0" North, 13°23'22" East, Elevation: 693 m a.s.l.) by using PVGIS-CMSAF tool [19] with the following environmental and technological assumptions:

- Yearly in-plane solar irradiation of 1560 kWh/m^2
- Cadmiun telluride (CdTe) PV technology
- Total system losses: $\eta_T = \eta_m \cdot \eta_b \cdot \eta_s = 0.7$

Fig. 8 illustrates the specific monthly energy output. Calculation results show a specific yearly energy output of 913 kWh/kWpeak which equals to about 130 kWh/m^2 per year.

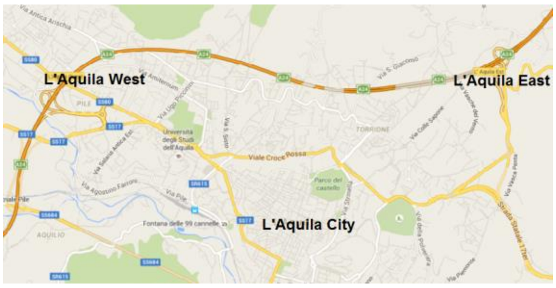


Fig. 7 L'Aquila West - East toll booths motorway section

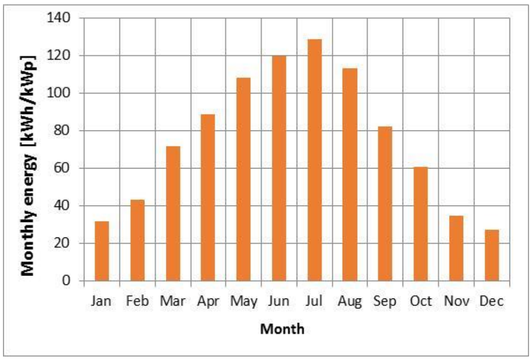


Fig. 8 Monthly energy output

4. Conclusions

In the current paper piezoelectric and PV technologies for energy harvesting from road pavements were reviewed and examined. As case study, the application of the technologies were preliminary simulated on a two different A24 motorway sections in central Italy.

According to the vehicular traffic and environmental conditions taken into account in the study, the results show:

- The piezoelectric system generates an average hourly specific energy output of 0.06457 kW/m^2 equals to about 565 kW/m^2 per year at an average traffic volume of 830 vehicles/h.
- The photovoltaic system generates a specific yearly energy output of 913 kWh/kWp which equals to about 130 kWh/m^2 per year with yearly in-plane solar irradiation of 1560 kWh/m^2

The results of the preliminary analysis show that the highway when properly designed and requalified through the integration of specific systems, it can become a valuable energetic source.

Future research efforts should seek to better understand the costs of electric energy harvesting solutions from road pavement in order to calculate the energy production cost.

References

1. **European Commission** 2011. White paper, 144 Final, Brusssels.
2. **D'Ovidio, G.; Masciovecchio, C.; Rotondale A.** 2016. Hydrogen fuel cell and kinetic energy recover system technologies for powering urban bus with zero emission energy cycle, Journal of IET Intelligent Transport Systems 10(9): 573-578.
3. **D'Ovidio, G.; Carpenito, A.; Masciovecchio, C.; Ometto A.** 2017. Preliminary Analysis on Advanced Technologies for Hydrogen Light-Rail Train Application in Sub-urban non Electrified Routes, Ingegneria Ferroviaria 72(11): 865-878.
4. **Hickson, K.** 2013. Race for Sustainability: Energy, Economy, Environment and Ethics. Singapore.
5. **Xiong, et al.** 2012. New technologies for development of renewable energy in the public right-of-way. DTFH61-10-C-00016. FHWA 9th Quarterly Report, Virginia Tech. October.
6. **Hill D, Agarwal A, Tong** N. 2014. Assessment of Piezoelectric Materials for Roadway Energy Harvesting. DNV Kema.
7. **Dikshit, T.; Shrivastava, D.; Gorey, A.; Gupta, A.; Parandkar P.** 2010. Energy Harvesting via Piezoelectricity. International Journal of Information Technology (2): 265-270.
8. **Kour, R. Charif, A.** 2016. Piezoelectric roads: energy harvesting method using piezoelectric technology, Innovative Energy & Research 5(1): 1000132.
9. **Ibrahim, S.; Ali W**. 2012. Power enhancement for piezoelectric energy harvester. Proceedings of the World Congress on Engineering, London Vol. 2: 1018-1023.
10. **Nelson, W.** 2010. Piezoelectric materials: structure, properties and applications, New York: Nova Science Publishers.

11. **Edery-Azulay, L.** 2010. Innowattech: Harvesting energy and data; a standalone technology. First International Symposium. The Highway to Innovation, Israel national roads company Ltd, Tel Aviv**.**
12. **Songsukthawan, P.; Jettanasen C.** 2015. Performance Analysis of Maximum Power Transfer in Piezoelectric Energy Harvesting. Proceedings of the International Multi Conference of Engineers and Computer Scientists Vol. 2: 670-673.
13. **Kurzweilai, R.** 2011. Innowattech attach harvests mechanical energy from roadways. [online cit.: 2018-04-10]. Available from: http://www.kurzweilai.net/innowattech-harvests-mechanical-energy-from-roadways.
14. **Stephy, J.; Keerthi S.J.** 2017. A review on solar roadways: the future of roads, International journal of recent innovation in engineering and research 2(3): 104-108.
15. **Alark, A.; Kulkarni** 2013. Solar roadways – Rebuilding our infrastructure and economy, International journal of engineering and applications 3(3): 1429-1436.
16. **PhysOrg.com** 2009. Solar roadways awarded DOT contract to pave roads with solar cells. [online cit.: 2009-09-07] Available from: https://phys.org/news/2009-09-solar-roadways-awarded-dot-pave.html.
17. **Wattway in France** 2016. [online cit.: 2016-12-22] Available from: https://www.theverge.com/solar-panel-road-electricity-france-normandy.
18. **Wattway by colas** 2018. [online cit.: 2018-5-3]: Available from: http://www.wattwaybycolas.com/en/
19. **PVGIS-CMSAF tool** 2018. [online citation: 2018-06-08] Available from: http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html.