# PAVENERGY RESEARCH PROJECT – RESULTS ALREADY ACHIEVED AND NEW DEVELOPMENTS PLANNED FOR THE YEARS TO COME

**Adelino Ferreira**

Research Centre for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Portugal
Email: adelino@dec.uc.pt

**Abstract*:*** This paper presents the PAVENERGY research project, which has carried out at the University of Coimbra, in Portugal, since June 1st, 2016 and will end on April 30th, 2020. The following results have been achieved so far: one startup has been created (PAVNEXT); one prototype has been constructed; one pilot plant has been installed; one patent has been submitted, and which is in the final stage of approval; eleven innovation and entrepreneurship prizes have been won, five at national level and six at international level; one PhD thesis has been finished; ten articles have been published in Web of Science journals; seventeen articles have been presented in international conferences; one article has been presented in a national conference. This paper describes what was planned, what has already been done, what will be done in the next few months and what is planned for the years to come.

**Keywords:** *Clean energy, Energy harvesting, Road pavement, Vehicle road interaction.*

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## 1. Introduction

Nowadays, most electrical energy production uses fossil fuel combustion, which makes economies dependent on fuel costs. This is also leading to irreversible environmental damage, with growing levels of $CO_2$ emissions. According to the International Energy Agency [1], in 2014, globally, more than 80% of energy production came from fossil fuels. Urgent action is required to change the paradigm of electrical energy generation as, presently, energy is mostly produced outside cities, consumes non-renewable resources and induces energy loss between the point of production and the point of consumption. Energy production must be based on renewable resources, decentralized, happen near to the point of consumption and, preferably, when it is needed.

Besides the major sources of energy (hydro, solar, wind and waves), energy harvesting has recently been adopted on a micro-scale, in which it is possible to generate electrical energy from small energy variations, such as thermal gradients, pressure, vibrations, radiofrequency or electromagnetic radiation, among others [2]. 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 [3].

Cities are full of roads and streets where vehicles circulate and their engines consume energy 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 a vehicle's wheels

[4, 5]. As vehicles abound in all cities in developed countries, this means that a considerable amount of energy is transferred to road pavements and is never 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, which would also reduce the need to "import" energy from distant places.

The growing energy demand in cities and the knowledge that road pavements are permanently exposed to great amounts of energy, providing an opportunity to investigate and develop technology that would allow a significant part of that wasted energy to be converted into electrical energy. This is defined as a Road Pavement Energy Harvesting (RPEH) system.

The main objective of the PAVENERGY project at the University of Coimbra, in Portugal, is the development of an efficient solution to harvest the energy released from vehicles to the road pavement and convert it into electrical energy. To accomplish this, the project was designed to have seven work packages (WPs): 1) Evaluation of the state-of-the-art in terms of pavement energy harvest solutions; 2) Development of a software tool for simulating the interaction between vehicles and energy harvest systems; 3) Development of a pavement electrical energy harvest system; 4) Implementation of a full-scale pavement section with the electrical energy harvest system; 5) Execution of monitored tests using real traffic or a traffic simulator; 6) Application of the pavement electrical energy harvest system in a speed control hump on a municipal road; 7) Dissemination of the results of the research Project. This paper describes what was planned, what has already been done, what will be done in the next few months and what is planned for the years ahead.

## 2. Methodology

The research project started with an extensive literature review and state-of-the-art analysis related to energy harvesting technologies, with special emphasis on ones which can be applied to the road pavement and that are able to convert vehicle released energy into electrical energy (WP 1). This allowed us to identify the positive aspects of each solution and also the main failures and disadvantages of the existing technologies.

Preceding the development of the energy harvesting unit, a study of the Vehicle-Road Interaction (VRI) was undertaken (WP 2), including the main vehicle dynamics models and the road pavement parameters, so that this interaction could be properly evaluated depending on the vehicle characteristics and actions (acceleration, braking, free rolling) and taking into consideration the road pavement characteristics (materials, slope, shape, among others), in order to quantify the energy released from vehicles to the road pavement precisely, the energy absorbed by the road pavement material and the energy delivered to the conversion system. None of the existing research projects within the field of RPEH had a complete model for the energy released from vehicles with vehicle and road pavement characteristics as inputs of the RPEH system [6]. This research programme aimed to develop and validate such a model.

A typical energy harvesting system usually has three different units: harvesting, conversion and storage. The harvesting component is always the first, as this is responsible for capturing energy from the external sources. In most cases, the conversion unit is the second and storage is the third.

However, in some specific cases, storage is included between the harvesting and the conversion units, working as a buffer for the harvested energy and allowing the global efficiency of the system to be maximized. For energy harvested from a vehicle's mechanical energy, this approach has never been reported and one of the goals of this research is to evaluate the best combination of these different components of the global system, by studying the efficiency of different combinations.

Following the development of the computational model, the energy conversion unit was developed (WP 3), and included four main components: energy harvesting; energy conversion; energy storage; and the energy storage controller units. Each unit represents a different component of the system, but the model combines them so that they can all work as a single unit. Each component was physically and computationally modelled, using different systems for the conversion and storage units. The performance of each component was evaluated by considering the energy received and delivered or converted, allowing the efficiency of each component and of the complete system to be determined. Using this approach, it has been possible to identify the inefficiencies of each component of the system and, consequently, the parts that need to be optimized to increase the global efficiency of the complete system.

After concluding the physical and computational models and performing the computational simulations and identifying the most efficient solution, a prototype was developed (WP 5) to validate the models and the computational simulations using experimental data (WP 6). This step was useful for calibrating the models and optimizing the results. Finally, a real scale model was implemented in a real environment (a municipal road), so that it can be tested using real traffic, in a real scenario, to evaluate its efficiency and effectiveness.

## 3. Developments

### 3.1 Evaluation of the State-of-the-Art in Terms of Pavement Energy Harvest Solutions

Energy harvesting is divided into 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, acoustics and human body motion as energy sources [2, 7, 8]. 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 [7], 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 to road pavements can be divided into two main groups, as presented in Figure 1.

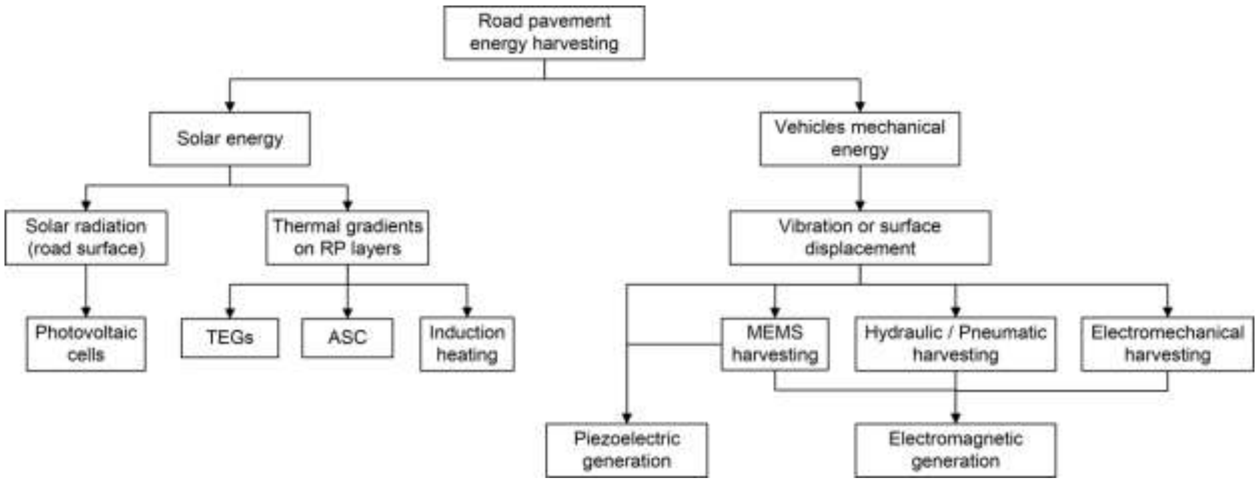


Figure 1: Road pavement energy harvesting technologies.

The first group is related to technologies that make use of the solar exposure of 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 in 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, which 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.

After identifying the different road pavement energy harvesting technologies, an intensive study was conducted to evaluate the state-of-the-art related to each of those technologies. This study was presented by Duarte and Ferreira [6], and allowed us to conclude that, unlike other renewable energy sources, there is a wide variety of pavement energy harvesting systems, which are all at different stages of development and which are competing against each other to get an opportunity in the market. In the last fifteen years or so, there has been more research and development (R&D) into road pavement energy harvesting carried out by companies than by Universities, which has led to a lack of scientific evidence being available on the developed technologies. The tests performed were not fully characterized in the literature, meaning very limited information is 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 does not generate electrical energy). In the field of road pavement energy harvesting, most of the technologies are at a laboratorial and prototype validation stage.

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

Of the technologies that use solar energy, photovoltaic systems are the most efficient and mature. However, the implementation on road pavements is still a challenge as glass is used in photovoltaic cells, causing difficulties with 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, although efficiency is considerably reduced.

Of the technologies that use vehicle mechanical energy as an energy source, piezoelectric technology was the first to get the attention of researchers. However, due to its low 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 into 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. They are also simpler to install than piezoelectric devices and they currently offer a higher likelihood of success as an effective solution for effectively transforming vehicle mechanical energy into electrical energy.

Micro Electromechanical Systems (MEMS) also promise much 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. However, pavement vibrations provide only 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.

### 3.2 Development of a Software Tool for Simulating the Interaction Between Vehicles and Energy Harvesting Systems

Road vehicles move in different ways (acceleration, braking, etc.), each movement behaviour having different distributions of forces at different moments, which will lead to different values of released energy. To perform a credible energy transfer analysis, it is important to have a quantification of both the static forces and dynamic forces that a vehicle induces on the road pavement. This last component will depend on the vehicle’s oscillations. The factor which most contributes to these oscillations is the road surface, which can have different profiles and can be made of different materials. This is more relevant in the case of pavement energy harvesting devices, which induce higher oscillations in the vehicle.

Prior to the development of a new RPEH system, a software tool for simulating the interaction between vehicles and energy harvest systems was developed, which allows the user to introduce the vehicle’s parameters, including its mechanical properties and geometry, motion parameters and driving conditions, as well as the road parameters and the desired device characteristics and parameters. The software tool was named RoadVISS and was presented by Duarte *et al*. [9]. This software tool allows the user to simulate the vehicle-road interaction from an energetic perspective, by calculating the energy lost by the vehicle during the interaction with the obstacle, as well as acceleration and velocity, and the energy received by the obstacle, considering its mechanical characteristics and properties. It also allows users to select the vehicle model (quarter car or bicycle car model), interaction model (single force or contact patch analysis), to enable us to compare both models and come to a conclusion on their precision.

The next steps of the research consisted in carrying out a study intended to overcome an existing gap in our knowledge, by precisely quantifying the energy delivered by a road vehicle in motion onto a speed reducer or an energy harvesting device, both in terms of the vehicle's characteristics and the characteristics of the device, thus evaluating the efficiency of the energy exchanging process. With this, it was possible to determine the importance of each parameter in the extraction of the vehicle's energy and optimize the efficiency of the device. This part of the research aimed to simulate the vehicle-road interaction, using the software tool RoadVISS, in order to determine which is the best vehicle model and interaction model, as well as to study the effects of road pavement devices (speed reducers and energy harvest devices), on the energy released by the vehicle. The energy captured by the speed reducer or energy harvesting equipment is also quantified and the energy conversion efficiency is evaluated, depending on the evaluated parameters. This study was presented by Duarte et al. [10], and has allowed us to conclude that the new models for characterizing the vehicle-road interaction were 67% more accurate than existing models, which did not consider the contact patch of the vehicle nor the surface displacement of a device in the pavement. Regarding variations in the surface parameters (shape and displacement), it was concluded that these variables have a great influence in the energy released by the vehicle, as well as in the energy harvested by the surface of the device. The surface shape and its maximum displacement are the variables which contribute most to the interaction results, both in terms of the vehicle's released energy and the surface harvested energy. Other variables can be changed during the simulations, such as the vehicle or harvester geometry, which will impact the amount of energy released and harvested. The selection of the surface parameters should be done according to the goals of each application and an ideal solution for all scenarios was identified. It also allowed us to conclude that, to design a pavement energy harvesting device, a huge amount of simulations should be performed, comparing the different key variables and optimizing its design for the place of application, design speeds, average traffic weights and available space for the device, among other features. RoadVISS software allows the user to perform these simulations and it is an appropriate tool to support the design of new pavement energy harvesting devices.

### 3.3 Development of a Pavement Electrical Energy Harvesting System

To develop a new and more efficient solution for pavement energy harvesting, different road pavement energy harvesting devices using electromechanical systems were studied, modelled and simulated, in order to determine the efficiency of their different components. Then, a new electromechanical system was proposed, to transmit the energy received by the surface of the RPEH device into an electromagnetic generator, which was also modelled and simulated, in order to determine its efficiency.

This development was presented by Duarte *et al*. [11], where two typical electromechanical systems were modelled and, using the software tool previously developed, computational simulations were performed to obtain the values of the energy harvested, transmitted, delivered, converted and consumed by the RPEH device. In addition, the proposed new electromechanical system was modelled and the models were added to the software tool.

From the analysis of the results, it was concluded that the proposed electromechanical system, under the same conditions as the other two systems, was twice as efficient as the rack and pinion and four times more efficient than the lever system for the same simulation scenario. Its main advantage is an increase in the transmitted force, leading to a higher mechanical energy transmission, meaning there is a greater acceleration of the pinion and, consequently, of the inertia wheel and the generator shaft, leading to a higher rotation speed and a higher amount of energy transmission, delivery and conversion.

During this stage, another solution was also modelled, based on a hydraulic device, presented by Duarte *et al*. [12], which followed the same methodology: to model an existing hydraulic system, as well as a propose a new solution, which would be integrated into the software tool, to perform computational simulations and to obtain the values of the energy harvested, transmitted, delivered, converted and consumed by each solution, as well as the efficiency of each process.

From the analysis of the results, it was concluded that the proposed new system, under the same conditions as a standard hydraulic system, is far more efficient in the same simulation scenarios. Its main advantage is in the greater force transmitted from the surface to the hydraulic circuit, leading to a higher mechanical energy transmission. This particular characteristic means that higher accelerations can be induced on the cylinder piston and, consequently, higher acceleration and rotational speed can be achieved in the inertia wheel and the generator shaft, leading to higher delivery and conversion efficiency.

### 3.4 Implementation of a Full-Scale Pavement Section with the Electrical Energy Harvesting System

After the development of these new and more efficient solutions, the goal was to evaluate both solutions experimentally by designing and producing prototypes, which could be tested in a pavement section. For the new proposed solution based on an electromechanical device, Duarte [13] presented the prototype of the new solution, which was not only designed, but also constructed and prepared for monitored tests (Figures 2 and 3). The prototype of the new solution based on a hydraulic device has been designed and is currently under construction.

Figure 2: Prototype of the road pavement energy harvesting system.

Figure 3: Prototype installed in a road pavement.

### 3.5 Execution of Monitored Tests Using Real Traffic or a Traffic Simulator

For the device based on an electromechanical system, the prototype that was developed in WP 4, the monitored tests were conducted and the results presented by Duarte [13]. The experimental results obtained with a prototype based on the proposed system allowed most of the computational simulation results to be validated, with the exception of the electrical energy generated. The differences were understood and justified due to several parts that needed to be added to the mechanical system so that it could become operational in a prototype. These changes added inertia and friction to the system, leading to lower energy generation values and lower energy conversion efficiencies, especially for lower vehicle speeds, where the forces were lower. When comparing the experimental results with other devices based on electromechanical systems, these results can be considered positive, since they are better than the results obtained with all the existing systems, both in terms of conversion efficiency and electrical energy generated per area, with an average conversion efficiency of 52.6% for a vehicle speed of 50 km/h, a maximum energy conversion efficiency of 60.5%, and a maximum energy generation of 72.4 J, for light vehicle actuation, using a surface area of only 0.33 $m^2$. The prototype proved that this solution is the most efficient solution that exists in the literature.

### 3.6 Application of the pavement electrical energy harvest system in a speed control hump of a municipal road

This work package consists of the implementation of a full scale pavement energy harvesting system in a municipal road, to test the proposed solution in a real environment and with real traffic. An initial implementation was performed [14], which allowed us to collect important data about the efficiency of the system in a real environment, as well as to understand the challenges of a real-environment application. In this paper, the application of a ten-module pilot plant in a real environment was presented (Figure 4), which was implemented on a road in Covilhã, Portugal. In 1 day, the ten-module pilot plant was able to generate a maximum of 547,230 J of electric energy, or 152 Wh, with an average energy generation of 145 J/m$^2$ per vehicle passage. A 12 m$^2$ solution is now being designed and will be implemented and tested during the first semester of 2020, allowing a full validation of the new proposed system based on the electromechanical system.

Figure 4: Ten-module pilot plant of the system.

### 3.7 Dissemination of the Results of the Research Project

During the course of this research project, ten papers have been published in top ranked journals, as mentioned during this paper, and seventeen papers have been presented in international conferences. The prototypes and demonstration models of the PAVENERGY research project have received several innovation and entrepreneurship prizes: Innovation in Road Safety 2016 (1st); BIG Smart Cities Coimbra 2017 (1st); BIG Smart Cities Portugal 2017 (1st); Climate LaunchPad Urban Transitions 2017 (1st); World Smart Cities Innovative Ideas 2017 (3rd); Horizon 2020 SME Instrument 2017; Valorpneu Innovation 2018 (1st); Prio Jump Start Accelerator 2018 (1st); Cleantech Camp 2019 (3rd); Portugal Air Summit 2019 (2nd); Portugal Mobi Summit 2019 (2nd).

## 4. New Developments Between Now and the End of the Research Project

After all the developments and validations mentioned in the previous section, further developments will be made before the end of this research project. Firstly, the new pavement energy harvesting system based on a hydraulic device [12], which was modelled and developed based on computational simulations, will be prototyped (WP 4), which will allow us to get experimental data based on monitored tests (WP 5). With these developments, both WP 4 and WP 5 will be completed, and this will allow for a full validation of this system. Experimental results will be compared with the computational simulations results, as well as with results from similar systems presented in the literature. Secondly, a 12 $m^2$ energy harvesting system will be implemented in a road pavement of a municipal road, which will allow for a full validation of this new proposed solution in a real environment, thus finishing WP 6. Based on these new developments, two papers are expected to be published in journals of the Web of Science.

## 5. New Developments for the Years to Come

After the end of this research project, and based on all the new knowledge obtained from this research, a new research project will be proposed based on the new technologies developed during this period. One application for these technologies is the development of a pavement energy harvesting system that works with people motion, harvesting kinetic energy from people and converting it into electrical energy. Some research has already been done [15, 16] and some opportunities to explore this topic have already been identified. Another application is the development of a new energy harvesting solution for railways, converting the kinetic energy from trains into electrical energy. A state-of-the-art assessment has already been carried out [17], and some opportunities to explore this area have already been identified. Finally, further developments to the hydraulic system can be made, with a full-scale implementation in a real environment, with more research on the optimization of the system, including adding energy storage solutions. The research team has already started to explore this line of study [18, 19] with promising results, and experimental research should follow to confirm these results.

## 6. Conclusions

Pavement energy harvesting systems have become progressively better over the last few years. The PAVENERGY research project has already produced new knowledge and new developments in this field of research. In this article, the research plan is presented, including all the work packages, the objectives, key activities and achieved results. Most of the work has already been concluded, and the key results have been presented in this article, among which we highlighted the experimental validation of one of the proposed solutions, based on an electromechanical system, and the development of another solution, based on a hydraulic device, for which the prototype is still under development. The achieved results of the experimental validation of the pavement energy harvesting system based on an electromechanical system are above the values existing in the literature from competitive technologies, making the proposed system the most efficient one presented in the literature and the system with the highest energy generation values. Finally, further development of this research project and some possibilities for new research projects are also presented, showing that there is potential for new developments in this technology.

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