sustainability

Review

Energy Harvesting on Airport Pavements: State-of-the-Art

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Abstract: Society is dependent on transport systems, not only to meet its daily needs with short journeys but also to meet their arising needs with longer distances. The ability to connect remote regions and the trip duration makes the aircraft a mode of transport for distant travel. However, it impacts greenhouse gas production. The survey for new ways to reduce greenhouse gas emissions emerges from the contribution of energy harvesting systems. Energy harvesting technology has been presenting prosperous solutions and applications in road pavements. Due to the similarity between road pavements, this paper addresses state-of-the-art technologies for airport pavements and road pavements, aiming to analyze which ones can be developed for application in airport pavements. An analysis is presented not only for the density, efficiency, and energy generation, but also for each energy harvesting technology's implementation and technology readiness level. The photovoltaic technology, to be incorporated into airport pavements, will allow sustainable energy generation dependent on the airport location. The hydraulic/pneumatic technology, to be incorporated into the airport pavements, will generate electrical energy based on aircraft movement.

Keywords: airport pavements; energy harvesting; renewable energy; road pavements

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1. Introduction

Civil aviation produced 2% of all human-made carbon emissions with a total value of around 859 million tons of CO_2 in 2017 [1]. According to Airport Council International (ACI) [2], the global average annual growth rate from 2017 till 2040 refers to an increase of 4.1% on passenger traffic, 2.4% on air cargo, and 2% at aircraft movements. The previous forecast suffered a setback due to the COVID-19 pandemic.

The COVID-19 pandemic has created a 64.2% reduction in passengers traffic by the year 2020 [3]. The author considers that the existing passenger traffic levels will be reached in 2023 for domestic traffic and 2024 for international traffic. Eurocontrol [4] points to air traffic recovery expectation, in 2021, to values of 51% compared to the year 2019.

Although aviation is responsible for 12% of CO_2 emissions compared to all modes of transport, it performs about 80% of its emissions on flights considered impractical to perform by another mode of transport, with an average aircraft occupancy of 82%, higher value compared to others transportations modes [5]. In an effort to combat the climate effects of the growth of this mode of transport, the CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation) program was created to set limits on CO_2 emissions based on the average between 2019 and 2020, later adjusted to the exclusive 2019 average [6]. The airports also channeled their efforts, searching for renewable energy to create conditions for energy independence and aid for resilience besides their 5% CO_2 emissions contribution to all civil aviation. Measures to reduce greenhouse gas emissions should not be underrated due to the present situation, but have increased decarbonization funding [4].

Energy harvesting has been a growing subject of research in recent years, with solutions for various areas addressing new forms of energy production solutions, even for airport pavements. It approaches aviation's needs and provides a local energy source that translates into a form of energy resilience for airports. Note that this energy source will also fit in with the sustainable development goals developed by the United Nations, which address a set of measures to improve a sustainable future for all [7].

This paper aims to review the energy harvesting technologies with the possible implementation of airport pavements, using ambient energy or traffic-based energy as primary sources. The analysis will focus not only on the energy capacity, but also on how the system is implemented, the TRL (technological readiness level), and the system's standby to consider the aircraft's robustness and movements performed by the aircraft on the airport pavement.

2. Energy Harvesting on Airport Pavements

2.1. Concepts

2.1.1. Energy Harvesting

Yildiz [8] refers that "energy harvesting is also known as energy scavenging or power harvesting, and it is the process where energy is obtained from the environment". Khaligh and Onar [9] clarify that this form of energy generation remains free from the use of fossil fuels and the generation units are decentralized [10,11]. Wardlaw et al. [12] consider using this energy harvesting to supply electrical energy to equipment, sensors, signage, and other demands in rural areas without having the limit of the electrical grid.

Several references to the various forms of energy harvesting in the literature review, distinct from macro energy harvesting when generation units allow a large power generation and micro energy harvesting when generating units are referred to as small generating units [13]. Macro energy harvesting is the energy associated with solar, wind, tidal energy, while micro energy harvesting is more associated with generation from electromagnetic effects, vibration, or human body motion [8,9].

Solar and wind are uncertain energy sources, since they vary throughout the day, season, and geographic location. This fact needs to be considered, despite the high production capacity of macro energy harvesting.

Micro energy harvesting finds in this field a differentiating feature, because primary energy is based on the movement of people, vehicles, trains, aircraft, and other forms that produce the vibration or movement of structures. Favorable situations for the possibility of energy conversion when it is most needed, that is, the kinetic energy of vehicles can be converted into electric energy for street lighting, while the movement of aircraft can provide electricity to be used at the airport. Based on an airport pavement application, micro energy harvesting only depends on aircraft movement, information known in advance by the airport management that can predict the electric energy generation.

Harb [14] identifies several micro-energy harvesting sources as motion, vibration, mechanical energy, electromagnetic, thermal, momentum, pressure gradients, micro water flow, solar, and biological. The author provides some examples of motion, vibration, or mechanical energy, such as floors, stairs, object movement, and even regenerative braking; this set of samples could also include pavements. Another set of examples is pointed out in electromagnetic or radiofrequency (RF), based on the energy harvesting of electromagnetic waves coming from cellular, radio, tv base stations, and other devices that emit wireless communication signals.

Yildiz [8] uses a graphic to exemplify the process from capturing ambient energy sources and energy harvesting systems to storage units based on battery, capacitor, or supercapacitor; this process is presented in Figure 1.

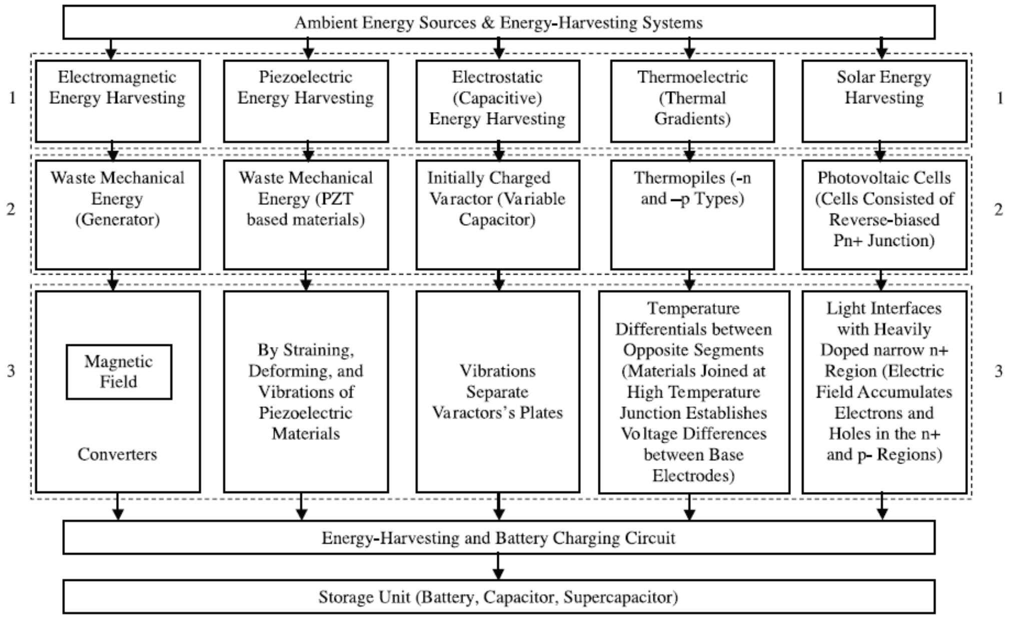


Figure 1. Ambient Energy Sources and Energy-Harvesting Systems (Reprint with permission from ref. [8]. Copyright 2009 Faruk Yildiz).

Yildiz [8] divides his analysis into 3 points, referenced in Figure 1. In steps 1 and 2, the author refers to the technology used to harvest energy. In point 3, he describes how to convert the energy previously captured into electrical energy. The resultant energy is then stored and made available for consumption.

2.1.2. Airport Pavement

The pavement is a sturdy structure or surface layer placed over existing materials to improve traffic passing performance. When thinking about pavements, the most common to imagine and recognize are the roads, as these are the pavements that citizens widely use. Nevertheless, there are also car parks, sidewalks, port facilities, runways, taxiways, etc.

The pavement commonly comprises several layers of processed materials with physical properties capable of strengthening the materials covered by them. The most processed material is usually located near the pavement's surface, which is most subject to the stress imposed by the transport systems.

AAA [15] refers that "pavements for airports are not fundamentally different from road pavements or other applications". The author points out that the differences are based on the type of transportation system, as the aircraft creates technical requirements for the airport pavement that are different than the road pavement. Moreover, the author stands out that an airport pavement is submitted to fewer load repetitions, but higher traffic wanders than a road pavement; moreover, in the airport pavement, the combination of wheel load and tire pressure is much higher than in a road pavement.

The aircraft is more substantial, less stable, and less tolerable to friction reduction or pavement defects. Aircrafts are devices designed to fly, and it is necessary to consider that the aircraft, unlike a road vehicle, cannot reduce its landing speed based on weather conditions, making this process at a typical speed of 260 to 280 km/h with no significant margin for a speed reduction, since the aircraft can stall [16].

Another aspect of the aircraft construction is that the landing gear, or undercarriages, the primary set of tires on the aircraft, are placed in the center of gravity, while in the road vehicle, the interrelated element, the wheels, are placed in the four corners, and due to that, the aircraft is less stable. Lack of friction can arise by various means; it can naturally be caused by hydroplaning, which, while in road vehicles, can be overcome by slowing down, however, this is not a possible feature, as mentioned above, in the aircraft. It is further hampered by the maximum allowance of 2% for the transverse slope on a pavement with a pavement width, generally between 30 and 75 m. An additional requirement arises from the fact that the aircraft's tires do not have a transverse tread pattern, making it difficult to drive out water when the aircraft's ground circulation at high speed. The last consideration is due to defects in the pavement that can create a loss of stones that could be ingested by aircraft engines, damaging them [15].

2.2. Pavement Energy Harvesting

2.2.1. Introduction

Into energy harvesting systems, some technologies are only applied to the road; others also refer to airports' applicability; in some references, the investigation analysis is applied to the general pavement without mentioning any specific application.

The search and classification will be made relating to the technology; inside each one will be considered for general pavement purposes and implementation on road environment or airport environment.

The pavements are exposed to two sources of energy: ambient energy and mechanical energy. Ambient energy is the result of natural elements such as the incidence of solar radiation, wind, and rain. Mechanical energy is the result of the passing transport that travels on the pavements. In both cases, this energy should be exploited as a promising technique for generating useful energy without depleting natural resources [17].

Gholikhani et al. [11] describes a classification of existing energy harvesting technologies divided by mechanical energy, pavement heat, and solar radiation. Furthermore, the author presents the harvesting technologies. Figure 2 illustrates the classification of the technologies under analysis in this literary review.

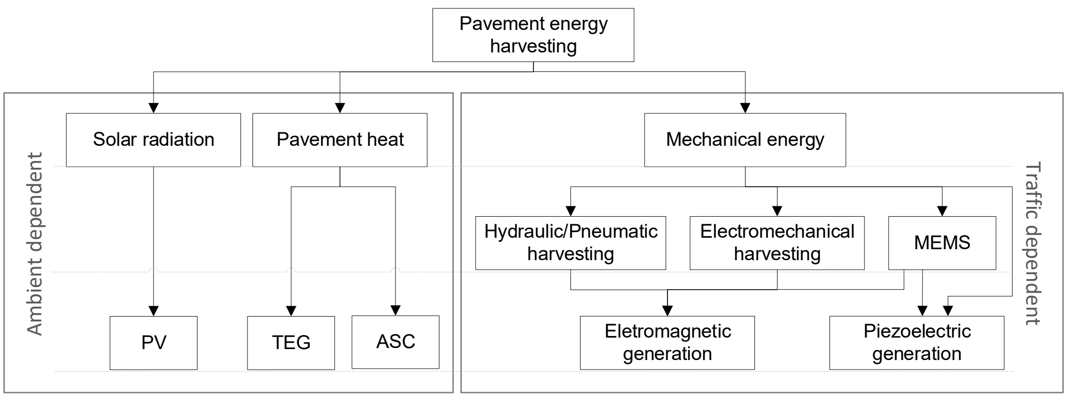


Figure 2. Pavement energy harvesting technologies.

Figure 2 outset references the main sources of primary energy sources, ambient dependent, and traffic dependent. In ambient dependent, the classification resides into two groups; solar energy can be captured directly where the placement of photovoltaic (PV) panels will generate an immediate production of electricity. The energy can also be made indirectly by the pavement heat produced when the sun induces radiation in the pavement. This thermal energy is transformed into electric energy through thermoelectric generators (TEGs) that use the temperature difference between layers of the pavement or asphalt solar collector (ASC), which is based on the transport of thermal energy from the pavement's outside unit to be consumed as thermal energy.

In the other group, the mechanical energy, the energy is harvesting by the transport movement. This energy has two distinct forms of electric power generation, the first in a straightforward process using piezoelectric. The compression of the material will generate electricity. The energy generation is done by piezoelectric devices directly, or it can be done indirectly using different harvesting equipment. For indirect mechanical harvesting devices, it can be done by hydraulic, pneumatic, electromechanical, or microelectromechanical

(MEMS) that harvest and condition the mechanical energy for generation purposes, the conversion to electric energy, on the set of devices, is mainly done by an electromechanical generator. In the case of MEMS, it can also be converted to electric energy via a piezoelectric generator.

2.2.2. Photovoltaic Pavement Generation

In 1954, Bell Labs produced the world's first practical solar cell with a 6% efficiency; nowadays, Sunpower [18] is presented as the world's most efficient cell technology, with an efficiency of up to 22.8%. Increasing efficiency values and a decrease in price over the last few decades are excellent reasons to innovate and develop photovoltaic cells.

PV pavement generation has been in the press in recent years about its deployment of panels in a pedestrian and road area to prove the concept and final products.

The solar road is based on a concept where solar cells are embedded in materials that replace or stand on pavements. This application's attribute is addressed to researchers from the Korea Institute [19] who had to develop new thin-film solar cells, since existing ones did not meet the technical requirements. The authors' problems were mechanical load support and weather conditions, causing premature solar cell damage.

From a product standpoint, in 2010, Scott and Julie Brusaw created a device to replace the upper layer that they named Solar Roadways [20]. According to the creators, the device displays on its top layer tempered glass cut in a hexagonal shape, and the choice of this material lies in the capabilities of hardness, strength, durability, and transmittance. The device has been subjected to impact tests in university civil engineering labs, with a carrying capacity of up to 250,000 lbs (113,890 kg) and traction and load tests meeting the requirements to be applied to road pavements. Technical data announced by the creators constitute an installed power of 36 W on an individual device with an area of 0.37 m^2 that can be added accordingly, an efficiency of 11.2%, 30 years lifetime with PV panel degradation, and T3 temperature range (−40 °C to +125 °C). The device is also equipped with embedded LED lights, which, according to Roadways [20], may replace the road surface marking. The product's creators also refer to the placement of sensors that allow the detection of obstacles such as rocks or animals for safety and additional heating elements for pavement defrost.

The first solar road to be implemented in the real-world was SolaRoad [21] (Figure 3), which carried out a 70 m solar bicycle path in the Netherlands in 2014. Subsequently, it carried out other implementations, not only in the Netherlands but also in France. The company had evolved the application from bicycle path to road pavement with heavy traffic, as well as a 150 m long bus lane in 2019.

Figure 3. PV pavement product from SolaRoad (Reprint with permission from ref. [21]. Copyright 2019 SolaRoad).

SolaRoad [21] claims "a robust solar panel with a skid-resistant, translucent coating mounted on a concrete slab" and refers that the concrete slab provides support and loading capacity, while the solar panel generates electricity when solar radiation occurs. The device is coated with a product that protects the solar panel and offers skid resistance for traffic. The combination is a road surface that provides safety and comfort to bikes or vehicles while harvesting electricity from the sun.

The first solar road for vehicles was inaugurated at the end of 2016 in Normandy, France. The system was based on a one-lane way, 1 km, 2800 m^2 of the area covered by photovoltaic panels with the name of WattWay [22]. WattWay by Colas [22] claims that the "product is composed by cells inserted in superposed layers that ensure resistance and tire grip" and the device with just a few millimeters thick can be applied to the existing pavement without the need to rip out the current pavement layer, i.e., without the additional need for any civil engineering work. However, the news from 22 July of 2019 in the newspaper Le Monde exposes that the product improvement was needed because the system did not reach the expected production values. The journalist found that some panels came loose, others broke up, and the worst case being the premature removal of 10% of devices from the total lane. It was also found that the system design did not consider thunderstorms, leaf mold, and farm tractors. An additional problem was the noise produced by the vehicles passing by, which had required the reduction of the speed limit to be 70 km/h [23].

Smart Road by Qilu Transportation Development Group Co. [24] is a 1080 m long solar road for vehicles in Jinan, Shandong Province at the end of 2018. The system has 5875 m^2 of solar panels [25]. Sun et al. [26] refers that underneath the panels are sensors that can monitor temperature, traffic flow, and axle load, and in the future will have technology to charge electric vehicles (EVs) on the go, extending their range. No energy generation was found.

Some added values presented by inventors may be a little out of range with reality or not so well explained. Taking Solar Roadways [20] has an example, which refers to the ability to unfreeze the road pavement but does not tell how it will do once cells are covered by snow and so with no energy harvesting capability. An additional question is wear and tear in solutions that use glass. Glass can break, causing dirt on the pavement and even flat tires. This material's constitution is resistant to UV radiation and intensive use, making it opaque, thus reducing the PV cells' energy production efficiency.

The analysis of this technology makes it possible to verify that although there are several inventors, some attempts need to be improved, but it is encouraging to find that there is the case of SolaRoad [21], which has seen installations increased and fulfilling estimated energy predictions.

2.2.3. Thermoelectricity

The effect that allows energy harvesting using thermoelectricity is called Seebeck, a fact discovered in 1821 by T. J. Seeback which allows, through the thermoelectric generator (TEG), to convert the temperature gradient into electrical energy; therefore, it is only necessary to provide a temperature gradient at the two ends of the thermoelectric generator [27]. The temperature gradient can be found in the ambient, such as on the pavement where solar radiation occurs. The conversion to electricity is done directly, making it a promising technology [28].

The thermoelectric module resides in a solid device consisting of two semiconductors (N-type and P-type) arranged so that one side is subjected to a heat source, and the other one to heat emission. In Seeback technology, it is necessary to combine low thermal conductivity and low electrical resistivity to achieve high conversion efficiency. The thermoelectric semiconductors are regularly used to overcome the constraint of isotropic metals, whose enhancement is confined by the Wiedemann-Franz law [28]. The biggest challenge for improving the efficiency of this technology lies in the use of new materials.

Hasebe et al. [29] propose a solution based on capturing the pavement's thermal energy and then transforming it into electrical energy by a thermoelectric generator. The temperature difference in the thermoelectric generator happens through the circulation of water, through pipes inserted in the pavement to absorb its thermal energy. The other part of the generator is exposed to water from the inlet (Figure 4).

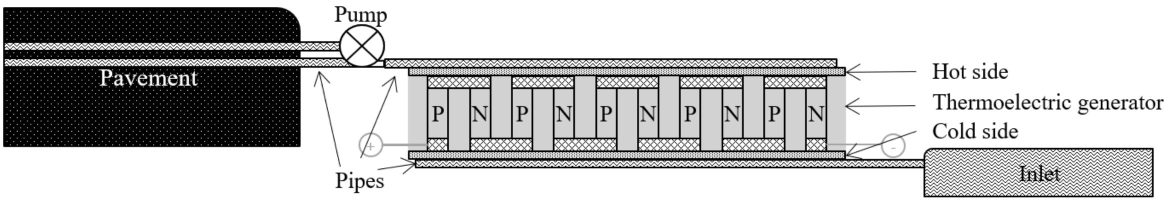


Figure 4. Concept of pipe-pavement-thermoelectric generator system (PP-TEG).

Laboratory tests using 19 Bi-Te cells (1.23 cm^3 each), with a maximum installed power of 5.0 W at ΔT of 40.5 °C, yielded generation values of 2.9 W when the ΔT of 25.9 °C and 0.9 W to ΔT of 11.5 °C.

Wu and Yu [30] have developed a product to power pavement monitoring sensors. Hasebe's system's differences lie in a compact device rather than the need to create a pipeline network. The system designed by Wu and Yu [31] consists of applying aluminum plates and rods to transfer the thermal energy between the pavement surface and the ground.

Laboratory testing of the system yielded 0.05 mW output with a 2.05% efficiency. The authors used computer simulation to optimize the system application, concluding that they would be able to achieve 0.02 W and 1000 J per day to power a pavement monitoring device [30]. The study conducted with Quantum Well material and the resulting prototype achieved an efficiency of 1.6% on a 7.7 cm^3 device able to produce 0.02 W under a 6.44 K thermal gradient [32].

Park et al. [33] carried out an investigation using different TEGs for comparison, but similar to that of Wu and Yu [31]. After selecting the best thermoelectric generator, the authors focused their work on improving the heat exchanger, which allowed them to reach 40 mW. Park et al. [33] thus claimed a generation about 800 times higher than the current technology applied to pavement energy harvesting.

Liang and Li [34] performed experiments on asphalt pavements created by the temperature gradients from infrared lamps; the results showed that the thermoelectric generator's optimum depth of placement resides at a depth between 2 cm to 3 cm below the surface. Outdoor tests showed, using four TEGs, production values of 2592 J. The authors stated that these devices presented excellent durability when placed at a depth of 2 cm.

Datta et al. [35] use finite element analysis for prototype construction, obtaining a thermal gradient of 16 °C with a TEG placement depth of 18 cm using copper plates. The laboratory tests showed a production capacity of 1.67 mW/°C, and the real environment tests were able to provide between 4.0 mW and 6.5 mW. The authors used funds and awards to leverage technology to be applied to freeways and airport runways to generate electricity for powering signage and data collection systems.

Wang et al. [36] noted that this technology is theoretically feasible, but it is necessary to improve system efficiency by improving the structural design and material properties of TEG. Another reason for concern presented by the author is its location and durability when exposed to traffic.

Despite the direct electric power production by TEG, the technology needs to be substantially improved. Moreover, the present technology addresses the electric power supply of electrical equipment with low power consumption.

2.2.4. Asphalt Solar Collector

The asphalt solar collector is a system consisting of a network of pipes placed during pavement construction. A fluid circulates to capture the thermal energy generated indirectly by solar radiation on the pipeline network's pavement. The asphalt pavement has a predominantly black color, absorbing solar radiation, thus causing thermal energy.

Asphalt solar collector is based on three processes: conduction, convection, and radiation, as shown in Figure 5.

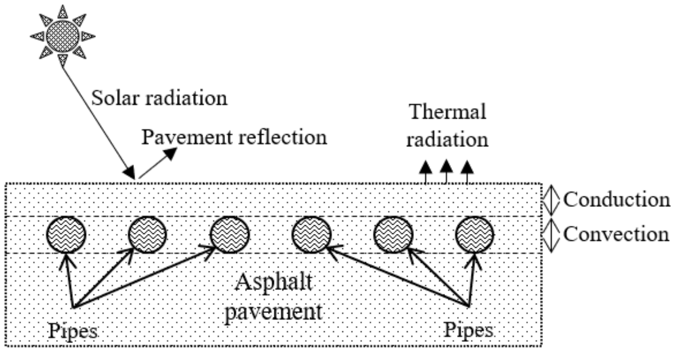


Figure 5. Heat transfer mechanisms in asphalt solar collectors.

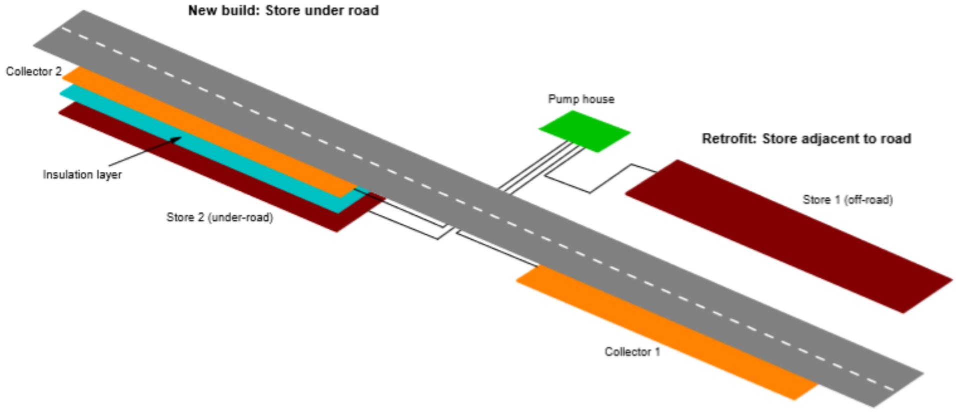
Conduction is the process responsible for thermal energy transporting between the surface and the pipes; convection occurs when there is a thermal difference between the different environments; in this case, between the fluid flows through the pipes, the pipes themselves, the pavement, and the environment. The last process is radiation that reaches the pavement, including solar radiation that will cause thermal energy, the latter naturally dissipating into the environment.

The asphalt solar collector's heat harvested can be turned into electricity or used to, for example, heat buildings. Since the system has a network of pavement pipes, it allows the pavement to be heated and cooled; pavement heating is useful in winter for snow melting. It is beneficial to cool the pavement in summer and thus reduce the Urban Heat Island (UHI) [37].

SERSO was a pioneer project using solar collectors for a snow-melting system [38]. The positive results of the project triggered interest in other researchers to improve the system. The system's improvement was made by applying other materials such as carbon fiber or graphite powders to improve asphalt thermal conductivity [39,40]. Another improvement was based on the increase in the flow rate [31]. Additionally, piping geometry was compared by Matrawy and Farkas [41] and spacing by Chen, Bhowmick and Mallick [42].

Despite all the efforts, the system has some limitations, namely, the possibility of causing damage to the pavement due to the placement of pipes inside; another critical point is the difficulty of pavement maintenance and rehabilitation.

Airport solutions are offered, for example, by a company named ICAX [43], which, mindful of weather conditions, had developed a product that could have prevented the shutdown of Heathrow airport in December 2010 after an extreme weather event that froze the infrastructure. The company successfully tested in Hiroshima (Figure 6) by keeping the road ice-free for over two years [44].



(**a**)

(**b**)

Figure 6. ICAX prototype (**a**) 3D schematic, and (**b**) pipework (Reprint with permission from ref. [44]. Copyright 2007 TRL Ltd.).

The studies are mainly based on using thermal energy, mostly for snow melting, with an energy capacity between 150 and 250 W/m^2 in summer [45].

Mirzanamadi et al. [46] present research where it stores the solar incidence energy on the pavement during the summer, releasing it during the winter to avoid freezing the roads. An investigation where the storage capacity in primary energy in thermal energy is explored through borehole thermal energy storage (BTES). The author mentioned that BTES is widely used in this system and consists of vertical holes with a depth between 30 m and 200 m [47].

However, this technology is only being studied for energy self-consumption on the pavement, never considered for electrical energy extraction. Another highlighter consideration of this technology in the form of accumulation is the use of no conversion of energy; that is, energy is captured, stored, and always used as thermal energy.

2.2.5. Piezoelectric Technologies

Pierre and Jacques Curie, in 1880, were the first individuals to develop an energy harvesting method from pressure.

The piezoelectric material can produce electricity when subjected to mechanical stress capable of deforming its geometry. Its constitution can be by different materials classified in the following categories: single crystalline material, piezoceramics, piezoelectric semiconductors, polymer, piezoelectric composites, and glass ceramics; the most common being polymers and ceramics.

Regarding their design, these assume some differences as the cymbal [48], multilayer [49,50], bridge [51], moonie [48], thin layer unimorph driver and sensor (THUNDER) [52], reduced and internally biased oxide wafer (RAINBOW) [53], macro-fiber composite (MFC) and bimorph [54]. The most commonly used designs for energy harvesting are cymbal and bridge.

Zhao et al. [51,55] studied the cymbal piezoelectric application on roadways with a potential energy of 0.06 J per vehicle passage with less than 15% conversion efficiency.

Roshani et al. [56,57] performed laboratory tests with simulation based on finite element analysis, concluding that the output voltage was significantly increased with increasing load, contact duration, and amount of traffic.

Moure et al. [58] developed optimizations on asphalt pavement, claiming that a 100 m road would produce over 65 MWh per year using 30,000 cymbals. Papagiannakis et al. [59] developed the highway sensing and energy conversion (HiSEC) system with a production capacity of between 10 and 241 Wh per year for each module applied. Other authors contributed to this technology by developing other methods of application and materials for piezoelectric devices, as well as areas for application [60–67].

Hill et al. [68] compared products developed by Innowattech and Genziko, where they found that Innowattech had a production capacity of 5.76 J, while Genziko had a value of 40.00 J. The authors were not elucidated by the method used, highlighting the real environment's lack of tests.

Patent applications WO 2013/014631A2 [69] and WO 2013/038415A1 [70] are related to systems that make use of piezoelectric transducers in pavement surfaces, including airport's runway. However, no references to aircraft energy harvesting real applications were found.

2.2.6. MEMS Harvesting Systems

Electromagnetic generators operate based on Faraday's law based on electric current induction when the electrical conductor is moving across a magnetic field. The MEMS harvesting system is usually composed of a coil attached to a movable mass that traverses one magnetic field. The coil's movement inside the magnetic field will produce an electrical current proportional to the existing movement [71]. The movable part can be the magnetic field with the coil is fixed [72]. As the electrical connection is made with the coil, this last configuration is preferable. The amount of electric energy generated depends on the magnetic field's strength, the relative movement's velocity, and the coil's number of turns.

Small electromagnetic generators have been developed to convert ambient and traffic energy sources (mostly mechanical vibrations) into electrical energy [73–78]. Research has been prototyping microelectromechanical systems at scale [79–81] and on macro-scale [82,83] to improve the performance of electromagnetic energy harvesting.

Since the electromagnetic generator is a movement transducer, its application is preferred when vibration occurs in the structure, such as bridges [84,85]. Bridges are particularly susceptible to vibrations caused by intermittent dynamic loading and, in that point, MEMS are profitable for the structural health monitoring of bridges. Studies have been focused on energy harvesting MEMS for low-frequency oscillations in concrete and cable-stayed bridges.

Sazonov et al. [84] reported a field trial of an energy harvesting designed with the key criterion: the typical working frequency of the energy harvesting device should equal one of the bridge's normal vibrational modes. This reported device generated up to 12.5 mW of power from traffic-induced oscillations.

Harb [14] had researched different MEMS systems in the laboratory and concluded that those devices presented a maximum energy conversion efficiency of 18%, with ten cells and a buck converter.

Jung et al. [86–88] studied the feasibility of EM energy harvesting devices to power a wireless sensor network (WSN) affixed to the bridge cable. The concept was subjected to mathematical analysis, laboratory testing, and on-site trial. The prototype generated up to 15.46 mW of power when affixed to the bridge's stay cable. However, the device suffered from the limited power output, because the surface friction combined with the spring component's sizable deflection limited the mass's motion. To effectively overcome this constraint, the researchers further suggested an alternative design of a rotational vibrating system instead of a translational system.

Kim et al. [89] incorporated a movable mass and a rotational generator in place of the EM induction elements, making it possible to tune the device to the bridge's stay cable frequency. A normalized power of 35.67 mW (or more than double that of the original design) was achieved. This would be enough to maintain a wireless sensor hub for one or two readings daily, subject to fair to moderate wind speeds.

Zorlu and Külah [90] developed a MEMS-based system for generating electrical power. The system developed by the authors relied on the device vibration, so pavement implementation was a possibility. Although laboratory tests indicated a maximum power of 3.2 mW/cm^3, the developed prototype could only produce 6.0 μW/cm^3.

By taking advantage of electromagnetic induction, continuous AC will be induced. Nevertheless, electromagnetic energy harvesting efficiency is low, and the harvested energy is not high enough to power electronic systems. Despite the research carried out, the implementations on road pavement are specific and used in areas where substantial vibration levels occur, like bridges. As the airport pavement does not contemplate these conditions, this technology is left for future consideration if MEMS evolution has considerable progress, as it currently allows one to solve problems specific to road structures, such as structural health monitoring.

2.2.7. Hydraulic and Pneumatic Technologies

Fluids have an undeniable ability to produce work. Hydraulics, the branch of science that studies the mechanical properties of fluids, has provided essential tools for developing hydraulic equipment present in a wide range of machines, such as road vehicles, aircraft, lifts, and compactors.

Blaise Pascal established the power transmission capacity in a closed system in 1647. According to this law, it is possible to multiply forces, which is a phenomenon that surrounds us daily since the braking system of vehicles uses hydraulic technology. When the driver depresses the brake pedal, fluid circulating in the hydraulic lines is pushed to the brake pad to reduce vehicle speed. Heavy-duty road vehicles use pneumatic braking systems, and when the driver depresses the brake pedal, it relieves air pressure causing the brake to act.

Hydraulic systems are also used on aircraft to slow down on runways. Hydraulic power systems manage the flaps, landing gear, and flight control. Once more, hydraulic liquids do this by carrying forces applied at one location to another point on the aircraft. Space shuttles contain hydraulic systems that could work even in a harsh environment.

Regarding energy harvesting using this technology, car shock absorbers were first addressed. The shock absorbers are designed to provide stability to the vehicle's suspension. However, the impacts to which they are subjected, kinetic energy, are wasted by the shock absorber. The regenerative suspension, which incorporates energy harvesting systems, tends to harness the kinetic energy that was previously wasted to convert it into electrical energy [91].

Zuo and Zhang [92] demonstrated that the power production potential, a typical passenger car, could range from 100 W to 400 W. Fairbanks [93] analyzed that a 300 W output would correspond to a 3% reduction in fuel. An additional aspect shows that improved vehicle stability can be achieved when using regenerative suspension due to its ability to tune [94–96].

The hydraulic regenerative shock absorbers, which harvest the motion energy from hydraulic absorbers to drive the electric generator, studied by some researchers that have implemented the hydraulic energy harvesters in vehicle suspensions studied their performances theoretically and experimentally [97,98].

Horianopoulos and Horianopoulos [99] developed a hydraulic device to harvest energy on road pavements [100]. The authors describe the ability to generate hundreds of kW to more than 10 MW without any concrete evidence despite showing prototype testing. There are several products for road pavements are KinergyCarpet™ (Figure 7) and KinerBump™.

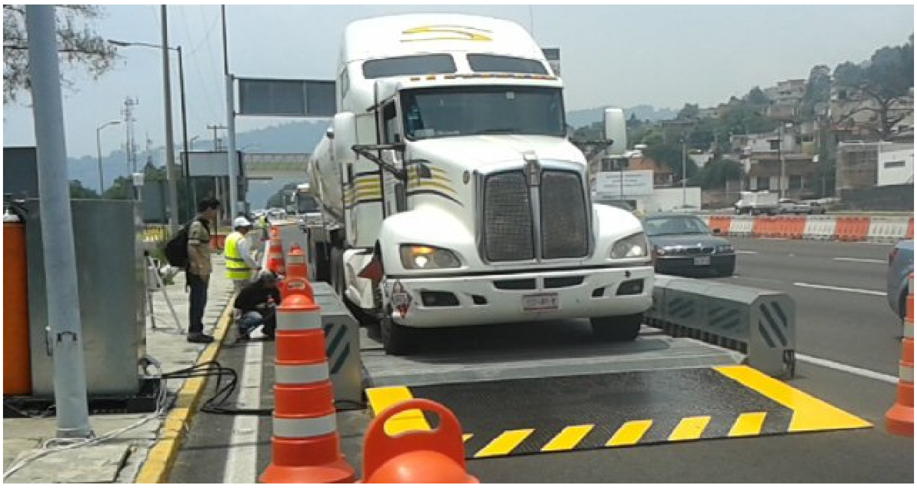


Figure 7. KinergyCarpet™ prototype application (Reprint with permission from ref. [100]. Copyright 2015 KinergyPower).

Ting et al. [101] developed a mechanical system with hydraulic transmission consisting of piston plates to reduce the vehicles' speed on roadways downhill. The author presents a theoretical analysis followed by experimental measurements with a prototype's construction, giving an overall result of 41%. The result includes the efficiency of 90% of the piston plate, potential energy storage of 95%, hydraulic transmission of 58%, and the electric generator of 83%. The efficiency obtained has made it possible to consider the product's marketing. However, it is necessary to improve the system's safety by changing the piston plates because they consist of metal [101].

Duarte et al. [102] made a simulation based on hydraulic system proposing a new hydraulic system that reaches mechanical energy transmission and delivery efficiency of more than 95% and global efficiency from the mechanical energy harvested by the surface to the electrical energy consumed by the electric load of 74% without experimental measurements.

2.2.8. Electromagnetic Technologies

Michael Faraday was the inventor of the first electromagnetic generator in 1831. Today, electromechanical generators provide a significant portion of all the electricity that is consumed worldwide. These generators are usually associated with the final conversion of mechanical energy to electrical energy in the most varied environments, such as thermoelectric power plants and dams.

The electromechanical energy harvesting device is based on mechanical equipment able to maximize mechanical energy harvesting simultaneously as its conversion to electrical energy. One of the parameters that influence this technology's efficiency is the speed of the vehicle [72,102].

The electrical energy which can be usefully extracted from a generator depends on the electromagnetic damping, which depends on the flux linkage gradient, the number of coil turns, coil impedance, and load impedance. These factors also depend on scale, so typically, as dimension decreases, the magnitude of the magnetic fields decreases, and the quality of the coils decreases, and hence the ability to extract electrical energy may be reduced [72].

Pirisi et al. [103] produced a generator described as a tubular permanent magnet linear generator. This electromechanical device converted linear motion into electrical energy. The authors created a 1:10 scale prototype and conduct experimental tests in the laboratory.

They claim a conversion efficiency of 85% between the mechanical energy applied to the slider of the generator and the electrical output efficiency.

Duarte and Casimiro [104] introduced an electromechanical system that allows the conversion of the energy released from vehicles to the pavement into electricity. However, the full-scale prototype made in Portugal (Figure 8) showed a conversion efficiency of less than 20%, contrary to the expectation of reaching 60% planned [105]. Duarte et al. [106] further presents a new prototype in a simulation environment that can produce electric energy with an efficiency of 60.5% and a maximum energy generation of 72.4 J.

Figure 8. Waydip real-scale prototype (Reprint with permission from ref. [105]. Copyright 2014 Waydip).

Wang et al. [107] designed, developed, and tested a speed bump energy harvester to harvest large-scale energy in a short period. The prototype developed, which produced up to 1270 W peak electrical power, produced 1120 W when submitted to in-field tests. The author refers that the system can convert both upward and downward impulses created by the vehicle. The research only presents peak power, and so it is needed the electric energy produced by the system in each car passage, or system efficiency, for comparison and understanding purposes.

Qi et al. [108] propose a system based on a chessboard sliding plate for energy harvesting on the road. The author obtained 62% efficiency on simulation and 57% on experiments, concluding that it could produce 33 J when submitted to 62 J of energy. Energy efficiency intends to be considered in future research as well as reliability and economics [108].

Gholikhani et al. [109] developed an electromagnetic speed bump that was simultaneously able to harvest the vehicle's kinetic energy and control its speed. The author conducted laboratory tests that result in an average power of 3.0 mW recognizing the low energy production due to the development stage. Further research intends to improve the prototype and test it into real traffic loads [110].

3. Analysis

The analysis of the existing technologies in this work varies from whether their application is subject to environmental factors or traffic factors. When the energy harvesting system is subject to environmental factors, the system will depend on the system's location and orientation, which may have different inclinations and even shadings despite being implemented on the pavement. For traffic-dependent energy harvesting systems, energy production is associated with vehicle dynamics, whether road vehicle or aircraft.

The analysis is carried out to quantify the energy produced per square meter in energy harvesting due to ambient factors at the site where the author performed the tests or simulations. The quantification of the energy produced by the traffic-based energy harvesting system was based on the authors' values with different vehicles' speed and weight.

Another aspect of analysis arises from the fact that the aircraft use the same pavement for speed reduction and acceleration, and the access of this pavement is used in both directions, unlike the research carried out on road pavements. In the road pavements, the energy harvesting system is placed in areas where the vehicle intends to slow down. This allows the energy harvesting equipment to be always in the active operating mode. There are no similar areas on the airport pavement comparing to the road pavement, so it is necessary to verify that the system is or can be inactive to capture kinetic energy. The system inactivation will ensure that the aircraft does not have any additional thrust effort and consequent fuel consumption. In energy harvesting systems that depend on ambient factors, this situation does not occur, since they do not capture kinetic energy. This analysis is described in the OM (operation mode) field and presented in Table 1. The OM classifies the technology in 3 points, from 1 to 3, which corresponds to:

- OM 1—The energy harvesting system does not remove significant kinetic energy from the vehicle, or the amount of energy is equivalent from the pavement that it replaces or are inserted;
- OM 2—The energy harvesting system currently captures kinetic energy from the vehicle, but it is possible to adjust it to have a standby mode that makes it equivalent to the pavement that it replaces or is inserted;
- OM 3—The energy harvesting system always captures kinetic energy from the vehicle and no affordable solution is foreseen to set it in standby mode.

Table 1. Technical analysis of different energy harvesting for vehicles' pavement.

Ambient Dependent				
Technology	**Reference**	**Energy (Wh/m^2)**	**OM**	**TRL**
Photovoltaic	Solar Roadways [20]	1.13 [111]	1	8
	SolaRoad [21]	8.90 [112]	1	9
	Wattway [22]	9.98 [113]	1	9
	Smart Road [24]	-	1	8
	Solmove [114]	11.41 [114]	1	8
TEG	Hasebe et al. [29]	(7.50 W_p/m^2) [1] [29]	1	3
	Wu and Yu [33]	7.23 [1] [33]	1	3
	Datta et al. [36]	221.78 [1] [36]	1	3
Traffic Dependent				
Technology	**Reference**	**Energy (Wh/veh/m)**	**OM**	**TRL**
Piezoelectric	Innowattech (airport pavement) [115]	-	1	2
	Innowattech (road pavement) [68]	0.16–0.30 [68]	1	6
	Genziko [68]	21.60–22.60 [68]	1	4
Hydraulic	KynergyBump [116]	0.08 (vehicles) [116]	2	6
	KynergyCarpet [116]	1.75 (trucks) [116]	2	6
	Duarte et al. [102]	0.08 [102]	2	2
Electromagnetic	LYBRA [117]	0.08 [117]	3	6
	NEXT-Road [118]	0.19 [106]	3	6

[1] Value determined by extrapolation, may not be able to be obtained.

Aircraft are vehicles optimized to fly and therefore do not present the same stability and tolerance conditions as road vehicles. Thus, it is essential to understand at what stage of development the current devices are not to cause damage to the aircraft, its components, and, in an extreme case, questioning passengers and cargo's safety. The state of maturity of these new technologies is addressed as TRL (technology readiness level) and presented in

Table 1. The TRL is divided into an analysis between the value 1 and 9, where the value 2 corresponds to the formulation of the technology application, the value 3 to the proof of concept, 4 to the laboratory validation, the value 6 to the prototype demonstration, 8 for complete devices assigned to tests and qualification, and finally the value 9, the highest value, to finalized and proven systems [110].

Although presenting products and applications, some authors do not present the energy quantification and their inputs to obtain referred values. This analysis attempts to normalize the energy quantification of all researchers and products. TEG technology, which has square centimeter implementations for sensor power supply, in this analysis has been extrapolated to square meters, so this may not be feasible.

Given the airport pavement conditions, particularly concerning aircraft movement, not all technologies are eligible to be applied to the pavement. Due to its mode of operation, electromechanical technology is not amenable to an application on airport pavements because, based on current solutions, it is not possible to deactivate its operation.

From the analysis, the two main areas, ambient dependent and traffic-dependent can provide technologies capable of being applied on airport pavements for electrical energy generation. In the traffic-dependent solutions, the piezoelectric and hydraulic technologies are then considered. The piezoelectric solution has already been conceived for airport pavement implementation [114]. However, it was not possible to find this system's implementations. Although no device that allows the standby to capture kinetic energy by the system was found, energy harvesting using that technology may rely on an additional control to achieve the desired.

The survey of ambient dependent technologies verified that PV technology offers a solution that reached TRL 9 when applied to the road pavement. Maple Consulting Ltd and associates [119] conducted a study for the World Road Association (PIARC) to survey the potential for renewable energy generation to be used in the road environment, reducing the infrastructure's economic energy cost. The study was based on interviews with companies to determine their technologies' generation capacity and infrastructure consumption. SolaRoad [21] and Wattway by Colas [22] are solutions included in this analysis.

4. Conclusions

Aircraft is an essential means of transporting passengers and urgent cargo. However, they are responsible for 2% of all human-made emissions before the current pandemic. Although the current moment, caused by the COVID-19 pandemic, is susceptible to the civil aviation sector, reducing and offsetting greenhouse gas emissions should not be overlooked because they will have to be responded under the CORSIA program.

Despite contributing only 5% of the total emissions produced in the civil aviation industry, airports have been making efforts to reduce their emissions. The search for sustainable development solutions to address the United Nations goals and the facts described above create favorable conditions for researching new sources of sustainable energy generation for airport pavements.

This work surveys the existing energy harvesting technologies. Due to these technological systems' meager existence for use on airport pavement, this state-of-the-art survey the state of development on the similar pavement, road pavement. The existing technologies' classification followed the generic model used by other researchers. However, two main areas are established in this work: energy harvesting technological systems that are ambient factors dependent or vehicle traffic factors dependent. The two areas defined in this work are intended to provide a homogeneity of the values described by researchers and companies and provide a direct comparison energy-based between technologies.

The analysis performed made it possible to verify products with high maturity and their existence in the road pavement energy harvesting selling solutions. The analysis added a point based on the differences between road vehicles and aircraft. The difference between road vehicles and aircraft aid for emerging technologies for road pavements, such as electromagnetic energy, cannot be applied to airport pavement. This analysis concludes that the technologies that can be implemented on airport pavements are photovoltaic and hydraulic/pneumatic energy harvesting technologies.

The photovoltaic and hydraulic/pneumatic energy harvesting technologies, which in this survey meet the conditions to be taken into consideration for research, come about within the two main areas of energy harvesting classification. The photovoltaic technology, to be incorporated into the airport pavement, will allow sustainable energy generation dependent on the airport location. The hydraulic/pneumatic technology, to be incorporated, will generate electrical energy based on aircraft movement.

5. Future Works

Aircraft on-ground dynamics model to quantify the aircraft's forces on the airport pavement and the aircraft kinetic energy. The quantification of the aircraft's force on the pavement will refer to the robustness required to be supported by the selected ambient and traffic-dependent energy harvesting equipment. The aircraft's kinetic energy value will be used for designing the traffic-dependant energy harvesting system.

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