“A REVIEW ON ENERGY HARVESTING FROM ROADS”

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Abstract

Harvesting Energy stands alone as one of the most promising techniques for approaching the global energy problem without depleting natural resources. Energy harvesting technologies from road infrastructure is a new research territory that encompasses technologies that capture the wasted energy occurred at pavements, accumulate and store it for later use. Their most enticing characteristic is that they already offer extended paved surfaces. Paved surfaces with conductive pipes, PV sound barriers, nanomaterials or Phase Change Materials, piezosensors and thermoelectrical generators and induction heating technique are just the most updated representatives. Their outputs can be listed as production of electric energy and district heating and cooling, deicing surfaces or powering wireless networks and monitoring pavements conditions along with the enhancement of their self-healing process. The objective of this thesis is to review them and identify their strong and weak points. The three Green Roadway Concepts that shaped, proposed and implemented, theoretically are identical for the long- and short-term challenges that they meet. Their forthcoming future is here and only their in-situ implementation can prove their viability and prominence.

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1 INTRODUCTION

Energy surrounds us and is available in many different forms, such as wind and solar energy or thermal and mechanical energy. Mankind's trends are characterized by an ascending energy consumption profile that has its detrimental consequences on energy security and the environment's viability. These matters have highlighted the need for novel and cutting edge methods for energy harvesting that also includes energy conservation and its final utilization. *Energy Harvesting* or *Scavenging* is the process of capturing the wasted energy from naturally occurring energy sources, accumulating and storing it for later use.

One of these "naturally occurring" energy sources is the asphalt pavements that all day long receive vast amounts of solar energy which gets dissipated as thermal energy at their inner structure. The resulting augmented temperatures with the traffic loads affect dramatically the surrounding environment and the service life of the pavements through raveling and rutting incidents (see figure 1). What makes the concept of harvesting energy from pavements enticing is that they offer an existed infrastructure that its dimensions are countless.

Figure1: Raveling /Rutting (Park, P.,n.d)

To a large extend, energy harvesting from pavements is a new research territory and encompasses techniques that somehow use the same principals that could be used in general building engineering regarding the materials usage. The routes for storing, conditioning, conserving and finally, using the harvested energy are matters that rely on multiple scientific technologies like nanoscience, electrical, mechanical and environmental engineering.

The scope of this study is:

- To review the current research literature about harvesting energy technologies from pavements.

- To investigate and shape three prospective energy harvesting concepts or *Green Road Concepts (GRCs)* after analyzing critically the already mentioned technologies.
- To evaluate the proposed GRCs using as criterion their direct, intermediate and long-term development.

The layout of this thesis is to firstly scrutinize the available harvesting energy technologies for pavement engineering application, by separating them at the groups of: asphalt solar collectors combined with pipes; photovoltaic applications (PV); piezoelectrical and thermoelectrical generators; induction heating and; phase change materials and nanomaterials. The next chapter strives to develop three possible energy harvesting systems by incorporating together two of the above mentioned technologies. The next step is the evaluation part of the new-designed energy harvesting systems taking into consideration several important factors.

2 ENERGY HARVESTING REVIEW

2.1 Introduction

Energy harvesting or energy scavenging technologies refer to applications that capture and exploit the unused and depleted energy so as to convert it to a more usable form. For this, every kind of energy can be exploited such as solar, wind or strain and kinetic energy. Moreover, thermal energy due to temperature gradients and ambient vibrations constitute some of the major sources of energy that has a lot of potential for being harvested. Harvesting energy stands alone as one of the most promising techniques for approaching the global energy problem without depleting natural resources. The hierarchy at the energy harvesting procedure is; firstly, the capture of energy; secondly, the storage of energy that includes its condition before its final use (figure 2).

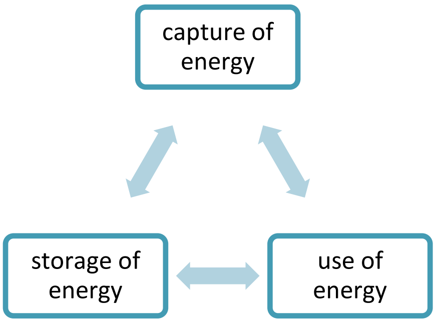

Figure 2: Energy harvesting principle

This chapter summarizes some of the major studies that have been conducted on energy harvesting in the pavement engineering sector. Extending the role of the asphalt pavements to become solar heat collectors and storage systems has emerged as a potential ground breaking technology considering how integral part of our society the infrastructure is. After choosing the appropriate application for the harvesting procedure, the extracted energy from these surfaces could for instance be utilized for domestic hot water, district heating or cooling, de-icing paved surfaces, recharging automobiles or cars and healing of the pavements.

2.1.1 Asphalt solar collector combined with piping system

Energy harvesting from surfaces that serve as solar collectors is no longer conceived as a new technology and is often discussed in combination with embedding pipes and pumps in particular arrangements to harvest the extracted solar energy and convert it to thermal or electric energy. These so called ‘asphalt collectors’ are also known as asphalt solar collector (ASC) and they circulate water through a series of pipes below the pavement surface. The principle is that the radiation from the sun and atmosphere is absorbed in the pavement through an increase in warmth which is captured by water piping system and stored in the ground or other storage reservoirs over summertime (Wu et al., 2011). The stored energy could then be used for supporting nearby facilities for district heating and cooling, electricity, recharging or de-icing the roads (e.g. via a hydronic system).

Liu et al. (2007) developed a numerical model to analyze the snow-melting process on a heated pavement surface, via an energy harvesting system. In that model they predicted the surface temperatures by studying the heat flux over the seasons as well as the weather data. Modelling the hydronic system at a bridge deck, they showed that the time for the pre-heating of the bridge along with the water pipe spacing determines directly the snow melting performance and the maximum fluid temperature. They concluded that the design of such an energy harvesting system should be based on calculation of the required heating system capacity, the fluid temperature and the density of the embedded piping system. That research showed that in order to achieve smaller pre-heating periods a dense arrangement of the pipes was required. Similarly, Dawson et al. (2011) called this structure a “Thermally Optimized Pavement” as they propose the installation of the pipes either close to the surface (serving hydronic purposes) or at the bottom of the pavement (low-grade heat source during winter and as a heat sink during summer).

Gao et al. (2010) also investigated the performance of an ice-snow melting system on the road, coupled with a Slab Solar Collection which included an array of embedded pipes and underground seasonal thermal energy storage. The experimental results indicated that the efficiency of the heat collection rises with the increment of flow rate and denser pipe configuration, always taking into consideration the ambient temperature, solar radiation and wind velocity. Particularly, by using the temperature difference (between inlet and outlet of the slab) per pipe length, Gao et al. (2010) proved that when the flow rate increased, the effective time of absorbing heat of the fluid in the pipe has been shortened. The measured heat per surface area showed that under certain conditions of flow rate and pipes spacing, the higher flow rate and smaller pipe spacing can heighten the heat collecting efficiency and he concluded that a denser configuration of pipes account for achieving 42% heat collecting efficiency.

Xu et al. (2012) investigated the role of the melting process at the thermal transition along the pavement. The effect of the melting process on the thermal properties of the hydronic system played an important role during the simulation of temperature and snow free area. They found that the wetted pavement increases significantly its thermal conductivity and in turn improves the snow melting performance.

Mallick et al. (2009; 2011b) highlighted that advanced asphalt pavements that include an energy harvesting system, in addition to reducing Urban Heating Island effect, also significantly reduce rutting in asphalt pavements. In their research, they performed a large scale experiment to investigate the interaction among mechanisms like conduction, convention and radiation with the engineering parts of the whole system like the geometry of the pipes, the temperature of the inlet water and rate of the flow fluid. Experimental data like wind speed and solar radiation were measured and solar radiation data were modelled with time. By using only one pipe and a particular range of fluid flow rate, temperature data were collected at several points into the slab. After the division of the slab into 2 domains the experimental setup was modelled in finite element method so as to determine the temperature at different levels into the pavement. In general, the experimental data from the slab and theoretical data from the simulation model gave a good correlation regarding the input temperature at the pavement system and the surrounding air. They concluded that the parameter that affects largely the distribution of the temperature at the slap and the cooling of the surface pavement is the diameter of the pipe, while the flow rate of the fluid does not affect significantly the temperature of the surrounding space and the slab. They found that the larger the pipe diameter becomes, the steeper temperature variation occurs from pipe to pavement surface as the larger diameter results in lower level of water temperatures and a higher rate of lowering the pavement surface**.**

As Wu et al. (2011) underlined *“thermal collection starts as long as the temperature of the location of the pipes reaches the balance temperature needed by specific heat transfer flow rate, wind speed, irradiation intensity and other conditions”.* The cooled pavement surface may enhance its stiffness specifically in hot climatic conditions and may reduce or prevent deformation, and hence extend the life of the pavement. But in general, when trying to scavenge the stored energy from the pavements while trying to mitigate the UHI effect requires considering important interactions among the albedo, the material type, thickness of the different pavement levels etc (Stempihar et al., 2011).

2.1.2 Photovoltaic (PV) applications in the road infrastructure

Researchers at the Korea Institute (Kang-Won et al., 2010) also investigated several approaches to harvest solar energy from asphalt pavements. In addition to the heat generated inside the pavement itself, they also intended to identify if it is feasible to utilize current solar cell or photovoltaic technologies by embedding those into the pavement infrastructure. It should be noted, however, that current thin film solar cells are difficult to use in surfaces that receive vast mechanical load cycles and environmental conditioning could cause premature corrosion and wear. For this reason the researchers are developing new thin film solar cells that can meet the requirements for using it on road surfaces.

Looking at the potential contribution of PV solar technologies for energy harvesting from highway engineering, PV sound or noise barriers (PVNBs or PVSBs) are a plausible alternative to use as infrastructure for energy harvesting techniques. Transport infrastructure has been using PV noise barriers since the late ‘90s as acoustic barriers – especially in densely populated and industrialized areas – and as producers of electricity. There exist many studies that quantified the potential of the PV sound barriers along highways and railways in Europe. In the following a summary of these studies is given.

Nordmann et al. (2004; 2005) examined the potential of the existing PVSB infrastructure for six European countries. With a generating capacity of 800 MWp and technical potential of 680GWh electricity per year, PV noise barriers could be a provoking contributor to the growing green energy market regarding that European legislation requires acoustic protection measures along railways and highways. Grasseli et al. (2007) examined 6 PVSB test-sites configurations under the typical constraints for a road application in order to assess their acoustical and energy performance. The conducted qualification tests analyzed parameters like proper plants construction, safety in normal operating conditions and in occurrence of accidental events, PV and acoustic performance, durability assessment and maintainability. The conducted tests showed that the reliability of the PV system is critically depended on its maintenance. They noted that the overheating of the PV modules along with the contamination from the vehicles should not be underestimated if a long life operation is to be assured. Shkrebtii et al. (2008) had developed a numerical model to optimize the photo-conversion efficiency of a-Si:H (amorphous-Si) solar cells with contact grid. Their purpose was to ascertain the prospective applications of a-Si:H solar cells as photovoltaic elements in sound barriers. What make amorphous Si solar cells ideal for the sound barrier infrastructure are their low production cost and their high efficiency. Additionally these cells can be deposited on a variety of substrate materials.

Over the years, PVs have been utilized in a small but considerable extend at parking lots and generally at small-scale road infrastructure. Golden et al. (2007) highlighted the implementation of PV solar panels at parking canopies to mitigate UIH effect at parking facilities. Lowering the peak temperatures of the paved surfaces results in moderating of their oxidation and volatilization. As *the researchers pointed out "these processes lead to losses in plasticity, resulting in hard and brittle pavements, susceptible to cracking under stress".* An important aspect to study is the PVs storage capacity in correlation with the thermal storage of the pavements. Strauss et al. (2009) regarded parking lots in a different way. They introduce the philosophy of a 'Vehicle Surfaces Parking Lot PV Solar Energy Power Generation System' that cover vehicles and busses with high efficiency PV cells and the produced electricity is injected into a direct current network and then into alternating current level by using inverters. They found that using small-surface solar panels at the vehicles in order to cover small-scale applications like charge of batteries and air conditioning can be expanded by exploiting their abilities when they are parked for long hours at parking lots without roofs. In that sense, automobiles and busses are more than transportation means with mechanical load carry systems. Their electrical interconnection through the use of advanced structured cabling, DC/AC voltage conversion and components of measurement and control is a new solar energy application that relates to V2G (Vehicle-to-Grid). The concept of that system would be of interest for smart electric power generation, in order to cover energy demands of lighting, heating and ventilation systems of immediate buildings, thereon producing considerable savings.

Generally speaking, any structure being upgraded or build today will be scrutinized for its green credentials. Golden's concept was identically applied at the Blackfriars Railway Bridge in London, that is expected to produce 900 MWh of green electricity every year because of the 4.400 solar panels installed as a roof above the railway tracks. From its environmental side this can be translated into 500 tons less carbon emissions (Matthiew, 2011).

In Netherlands the TNO -SolarRoad project utilizes the Dutch cycle paths to embed solar panels with the purpose to control pavement's temperature (heating/cooling). There is no doubt that with the increasing popularity of cycling, cities are going to have to incorporate the cycling paths into their infrastructure planning (TNO, 2011). TNO, along with the Province of Noord-Holland, the Ooms Avenhorn Group and Imtech plan to install, in 2012, a pilot project consisting of a modular cycle path system (TLC, 2011). The cycle path (100m) is constructed of concrete elements (1.5 - 2.5m) which are covered by a glass top layer (transparent top and optical layer together, 1cm). Underneath the thick hardened glass layer, crystal silicon solar cells are laid. The module's functionality will determine from how much energy will be harvested and stored and how smart ICT applications can enable the energy produced in peak periods (a lot of sun) to be distributed as efficiently as possible for the periods of little or no light.

2.1.3 Generators

2.1.3.1 Embedded piezoelectric sensors

This section deals with the application of piezoelectric devices or sensors in the pavement infrastructure. These systems generate an electric voltage when exposed to alterations at their dimensions caused by mechanical stresses (vibrations). Particularly, piezoelectricity provides a convenient transducer effect between electrical and mechanical oscillations. Reversibly, an applied electric field at piezoelectric materials will produce mechanical stress. Piezoelectric materials are widely available in many forms including single crystal (e.g. quartz), piezoceramic (e.g. lead zirconate titanate or PZT), thin film (e.g. sputtered zinc oxide), screen printable thick-films based upon piezoceramic powders and polymeric materials such as polyvinylidenefluoride (PVDF) (Beeby et al., 2006). By now, piezoelectric materials have been researched for the fabrication of wearable e-textiles and glove-based user interfaces (Edmison et al., 2002) or producing power from small-scale vibrations like footsteps. For these market challenges, piezomaterials offer the desired functionality that can be easily meshed into hybrid materials. The type and magnitude of the applied stimulus determines the producing power but in general piezomaterials produce a broad range of voltages. While they can respond to any type of physical stimulus (tensile force, torsion, pressure) piezoelectrics do not have a minimum requirement for producing a response. Edmison et al. (2002) pointed out that detecting the type and magnitude of the applied stimulus is somehow *“limited only from the sensitivity of the interface and any contributing environmental variables”.* Asphalt pavements throughout their lifetime endure heavy and light loads that cause stress, strain, deformation and vibration. At the same time, the pavement obtains strain and kinetic energies from the work of vehicle load and gravity (Zhao et al., 2010). Piezoelectric transducers embedded into the pavements have the potential to harvest the waste mechanical energy as well as to store it in electronic capacitor (see figure 3). This energy harvesting technique was first introduced to power wireless sensors networks and for traffic and heath monitoring of concrete surfaces. The harvested energy can be used for small scale road applications like road furniture, lighting, roadside advertising or railway and airport signage where the installation and maintenance cost are low.

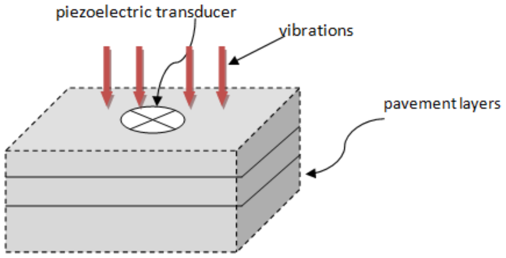

Figure 3: Schematic of piezoelectric transducers embedded in a pavement

Zhao et al. (2010) studied the performance of the Cymbal, a piezoelectric transducer that can be applied at surfaces for monitoring problems like cracks initiation (a composite of thin PZT or lead zirconate titanate disk and metal end cap at both sides of PZT) by relating the potential electric energy with its geometric parameters like the cavity of the depth, the thickness of the PZT, the thickness of the cap steel and the diameter of the end cap (see figure….).

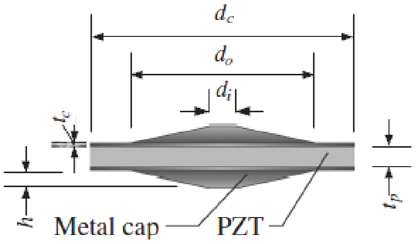

Figure 4: Schematic layout of the PZT transducer (Zhao et al., 2010)

The researchers tried to evaluate the efficiency of the sensor by using its potential electrical output and its coupling effects with the pavement (pavement's displacement). So increasing both the diameter and the thickness of the PZT and the thickness of the cap steel, the potential energy is increased along with the cost. Finite Element Modelling gave a series of design parameters which were used for designing the appropriate transducer embedded at the bottom of the first pavement layer so as to generate about 98 Volt electric potential with 0.06 J storage capacity. Its potential maximum output power is about 1.2mW at 20 Hz vehicle load frequency.

Another possibility of the piezoelectric devices is to use piezoelectric cantilevers in vehicle-excited manholes. Ye at al. (2009) investigated the optimisation of a piezoelectric cantilever system using a genetic algorithm based approach (choosing manually the system's frequencies) with numerical simulations. By using recorded data from a vehicle-excited manhole the maximum output power of the system was evaluated. The researchers concluded that the algorithm based approach has shown great potential and the possibility for energy harvesting from ambient vibrations – especially from heavy loads – is feasible. In general, the widespread use of the system would enable far greater scrutiny and hence understanding of the behavior of road vehicles. One disadvantage that is related with the life cycle of the system is its maintenance as the heavy traffic loads demands regular and constant inspections.

Wischke et al. (2011) tried to study the application of piezoceramic sensors at tunnels. They showed that the vehicle vibrations at any location across the tunnel (pavement and walls) were too small for useful scavenging energy because of the vehicle suspensions and their pneumatic tires. They noted that the potential of harvesting the railway (tracks) vibrations is much higher. Their field measurements showed that *"at least 135 μJ were delivered to the electrical load from 85 % of all trains".* Nevertheless, it should be mentioned that modern designs of trains and vehicles incorporate novel dampers so as to improve travelling comfort by eliminating the vibrations. This undersupply can be overcome by applying vibration harvesters with more cantilevers.

Israeli engineers and Innowattech have developed a technology, focusing on harvesting and converting mechanical strain into electrical current through Piezoelectric Generators (IPEG). The mechanical energy is derived from the compression stress created during the vehicles' travel on road that eventually causes to the asphalt vertical deformation. This deformation is transformed into electrical energy instead of being wasted as heat. The accumulated electric energy is transferred and stored via harvesting module while can be used later for local power needs or routed into the grid. IPEG is conceived as a pioneering invention in the field of Parasitic Energy (Hanlon, 2008). IPEGs' implementation into the road layers can be done via electronic cards so to store traffic-generated energy and they are covered with a layer of asphalt either concrete or composite concrete.

2.1.3.2 Thermoelectrical Generators

Thermoelectrical generators (TEGs) represent a technique that harvests energy from the thermal gradient of the pavement infrastructure. TEGs have been called environmentally benign, contain no moving parts and can be used to capture “free" waste heat for electricity generation (Wu et al., 2011). The produced electricity can power advanced sensors for monitoring the spatial and temporal distribution of distresses that deteriorates the pavement infrastructure**.** Analytically, these devices exploit the temperature difference between the pavement subgrade and the pavement surface that provides a potential source for electricity generation using the thermoelectrical principles. Unfortunately their low efficiency is their major drawback, something that could be improved by using novel materials for their fabrication. Wu et al. (2011) studied the implementation of these thermoelectric modules on the surface of the pavements and by conducting simulations they tried to optimize their design. The important aspect behind the efficiency is a guaranteed high temperature difference between the upper and lower surface of the thermoelectrical (TE) module. They propose the connection of the lower part of the module with the subgrade soil via high thermal conductive materials in order to facilitate the heat conduction and thus increase electricity production.

Hasebe et al. (2006) developed a pavement-cooling system using a thermoelectric generator. Solar heat is collected by a water piping system underneath the pavement and this water is cooled by river water on the thermoelectric generator installed besides the road. They found that the generated power by the temperature difference between heated transfer medium and cold water was sufficient for the pump. The laboratory experiments showed that under particular electrical resistance (determined by the electrical load) increasing the flow rate increases the power efficiency of the system. The simulation of the experimental apparatus by using a Finite Element Analysis showed that the power output decreases during the day with its minimum at the time that the temperature of the river has its maximum. The inlet temperature at the heat collection tube was shown to increase slower than the temperature of the river water and the difference has its minimum when the river water has its maximum. Both studies revealed low efficiency to power any electrical component and only by connecting parallel many TE modules this can be increased.

2.1.4 Induction Heating

The idea of introducing conductive particles in the asphalt mixture, with the objective of heating it via induction, offers an alternative way of energy harvesting through pavements. The harvested energy through magnetic induction systems can range up to 1 kW (Apparna, 2007) and has been mentioned in connection with improved healing of damages in asphalt surfaces. In this sense the idea of induction healing is to activate the self-healing capacity of porous asphalt concrete at high temperatures.

Liu et al. (2012) studied the optimization of the mechanical properties of an asphalt concrete sample by adding steel fibers so as to make it electrically conductive and suitable for induction heating. Numerous of tests were conducted about how the steel wool mixture affects the electrical conductivity, the induction heating speed, the particle loss, the indirect tensile fatigue resistance and the indirect tensile strength. In general, steel wool reinforces largely the mechanical properties of the asphalt (delaying raveling) and enhances its self-healing. It should be mentioned that for the same quantity of steel wool the bitumen sample exhibits the optimal maximum induction speed and the maximum electrical conductivity while for the other factors (already mentioned) steel wool have to be decreased. Additionally, the induction-conductive sample revealed a fatigue life extension (strength of the material under cyclic stresses) ratio about 190% more than the original fatigue life. This ratio correlates with its ability to resist higher fatigue loading without developing damage due to fatigue failure. In the same vein, Heymsfield et al. (2011) examined this conductive configuration after applying to an airfield runway because it prevents snow/ice accumulation by maintaining the (runway) slab surface at minimum freezing temperature. Moreover, this anti-icing system is grid energy independent as it uses electrical energy (DC) from a PV array and a number of batteries.

In another research Liu et al. (2011) revealed that induction heating of mastic asphalt and porous asphalt concrete can recover faster the stiffness of the surfaces. Analytically, during the induction heating, cracks in asphalt mastic beams disappeared because of the flow of bitumen. Also here the fatigue life extension was used so as to evaluate the efficiency of the healing rate and is proved to be depended on the steel wool presence into the mixture that offers to the system the reinforcement to stand heavy loads.

2.1.5 Materials

2.1.5.1 Embedded phase change materials

PCMs are novel materials that can store and release heat energy in a latent form during the transition of the melting to the freezing phase. During the freezing period the material releases large amounts of energy in the form of latent heat of fusion. When the material is melted, an equal amount of energy is absorbed from the immediate environment as it changes from solid to liquid (PCM, 2009) As Bo et al. (2011) point out that *"PCM has the virtue of a high density of heat accumulation, small in size and a thermostatic process when absorb and release heat".* These materials have already been used as building materials. In that sense, regarding pavement infrastructure the heat released by a PCM during solidification may delay the decrease in surface temperature or the heat absorbed and stored during the melting process can moderate the ambient temperature.

Energy harvesting from pavements by using phase change materials (PCM) relates, also with the self-healing process. Self-healing of asphalt pavements is temperature dependent and high temperature levels have positive effect on the recovery period. Asphalt pavements with PCM can be temperature-control pavements as they can adjust their temperature - in a relatively small range - through storing and releasing thermal energy during phase change process (solid to solid or solid to liquid) (Chen et al. 2011). Chen et al. (2011) examined the feasibility of temperature self-control asphalt pavement using PCM in order to prevent rutting. The theoretical analysis revealed that the phase change temperature of PCM - pavement should be 3-5℃ less than the softening point (starting point of dynamic stability decrease) of the plain asphalt-sample. The validation of their theoretical results was conducted by using as PCM-pavement a paraffin/expanded graphite composite. As the temperature starts to increase, the increasing rate at the PCM-pavement is lower than that of the plain asphalt, while during the cooling process the temperature decrease rate of asphalt concrete with PCM is higher than that of control sample.

PCMs embedded into pavements can, also, mitigate dramatically the UHI effect something that had been tested continuously throughout the use of PCMs at the building sector. Bo et al. (2011) studied the potential of the PCMs into asphalt mixture (by a ratio of 20%) by testing its thermal conductivity and effective heat. Both these parameters showed an ascending profile under different exposure temperatures. By using the latent thermal characteristics and temperature control function of PCM, the temperature change rate of the asphalt mixture after the heating/cooling process is decreased. In other words, at the PCM-asphalt the emergence of extreme peak temperatures are delayed meanwhile shorten the duration of the extreme high/low temperature (Bo et al., 2011; Ma et al., 2010).

What is more, Ma et al. (2011) tried to solve the leaking problem of the PCM from the asphalt mixture by applying the carrier-adsorbed packing method. The thermophysical properties of different carriers and packaging materials were analyzed by scanning electron microscope and differential scanning calorimetry. The compound shape stabilized PCM with silica and ethyl cellulose were ended up to represent the most efficient carriers as they enhance better the phase transition temperature and latent heat of the material.

2.1.5.2 Nanomaterials

Several preliminary studies have been devoted to advance the structure of the asphalt (both durability and stiffness) by using special nanomaterials. Nanotechnology encompasses the techniques of manipulation of the structure at the nanometer scale to develop a new generation of tailored, multifunctional, cementitious composites with superior mechanical performance and durability (Sanchez et al., 2010). The application of nanotechnology at road engineering is somehow an uncharted territory and intends to improve the performance of the surfaces (resist ageing and reinstate cracks) by the development of novel materials and the use of characterization methods to improve the understanding of these materials. Polymers modifiers such as styrene–butadiene rubber

(SBR), styrene–butadiene–styrene (SBS), ethylene vinyl acetate (EVA), polyethylene (Goh et al., 2011), montomorillonite (You et al., 2011; Goh et al.; 2011) and microfiber and other layered silicates (nanoclay) are widely used in the modification of polymer structures to advance their mechanical and thermal properties. Concerning energy harvesting from roads, nanotechnology offers better materials that prolong the service life of the pavements by moderating thermal and vehicular stresses and so prohibiting rutting and raveling incidents.

In particular, Goh et al. (2011) studied the performance of two fabricated asphalt materials modified with nanoclay and carbon microfiber in terms of tensile strength after conditioning to various deicer solutions including water. Deicers solutions have got deleterious effects on asphalt structure as they decrease their chemical resistance affecting with that way their elasticity and strength. Laboratory tests revealed that both nanoclay- and carbon-microfiber asphalt samples increase their tensile strength after exposure to water rather than under dry conditions. Subjecting the nanomodified asphalt mixtures to deicers had shown that the presence of at least 1.5% nanoclay offers higher tensile strength, improve their viscoelasticity and decreases the moisture damage potential. You et al. (2011) reviewed the potential of nanomaterials at improving the asphalt pavement performance in comparison with the polymer – modified asphalt mixtures. In the same vein, they fabricated numerous of nanoclay modified asphalt samples and compare them with original asphalt binder after examine their viscosity, elasticity and tensile strength. They proved that the nanoclay-modified asphalt holds promise for improving viscosity and elastic behavior which means better performance of rutting-resistance and fatigue cracking.

2.2 Advantages and challenges

Sources of energy at pavements surfaces can primarily be identified as solar radiation and mechanical energy from the stresses caused by traffic. The storage of the harvested energy is desirable to occur at the inner structure of the pavement minimizing with that way the use of batteries and the transition of the new form of energy and its prospective use is determined from the system that was chosen to be applied.

Primarily, special care should be taken simultaneously for optimizing the thermophysical properties of the pavement materials if they are designed to enable heat transfer and storage as well as helping to reduce the risk of damage due to freeze-thaw cycling in colder regions. Regarding PCMs, the main difficulties for their utility are the need to ensure the reversibility of the phase change, the precise identification of the adequate material – it must be operative in the range of temperatures required by the application, the limitations regarding the transfer of energy to and from PCMs, their incorporation and implementation and finally, the preservation of their performance in time (Cocu et al n.d). Thermally optimized pavements with piping system that serve also as hydronic systems had been studied extensively and already applied at areas that accept low-traffic load like parking lots or squares. What has to be done in order to optimize thoughtfully that harvesting configuration is to study the effect of the pipe(s) depth at the thermal conductivity of the pavement along with the strains that the pipes accept from the traffic load. Additionally, deicing the road pavements can be succeeded through induction heating.

Harvesting energy from pavements by piezoelectricity is a new research field of pavement engineering as by now it has been used for harvesting small – scale energy from pedestrians or bikes in order to supply batteries, road lighting and furniture etc. It is challenging enough the idea of mining the energy occurred from heavy traffic loads by using only small piezoelectric devices/sensors applied at particular layouts across the pavement infrastructure. What is more, pyroelectric materials similarly to piezoelectric crystals generate alternate current (AC) but from temperature gradient. These are regarded to be "the bridge between ferroelectrics and piezoelectrics" and they exhibit electric polarization when they are subjected to a uniform temperature change. This pyroelectric effect occurs only in crystals which lack a center of symmetry and also have a polar axis (Lang, 2005). Batra et al. (2011) strived to examine the ability of high quality single- and poly-crystalline pyroelectric materials embedded at pavements to produce electricity. The whole procedure was conducted by employing during the simulation real temperature data obtained from climatic database for the area of Huntsville-Alabama, USA.

Utilizing the solar panel technology in connection to road infrastructure has been researched on a limited basis and only PV sound barriers had been researched and applied in a larger extend. Published studies had already shown that they represent today one of the most economic applications of grid-connected PVs for harvesting energy with the additional benefits of large scale plants. The configuration of PVSBs along a strip of land near road or rail infrastructure, while the asphalt structure had been modified with piezoelectric sensors or conductive materials have the potential to be applicable as a harvesting energy system for the pavement engineering.

Table 1 summarizes the advantages and disadvantages for the above mentioned harvesting energy technologies that had been applied or have the potential to be applied at the pavement infrastructure. Studying their pros and cons is one of the tools for figuring out their combined implementation so as to design and create efficient harvesting systems.

Among harvesting technologies one that struggles for its potential is the Solar Roadways® concept. According to its investigator, Solar Roadways® strives to substitute thousands of miles of American highways and by-ways with solar panels so as to harvest the absorbed solar energy and after its storage to distribute it either for heating and cooling or to electrify the immediate buildings and facilities. Despite its initially "science fiction" concept, the founders have already deployed a 45-mile prototype roadway between Coeur D'Alene and Sandpoint, Idaho. Furthermore, the Federal Highway Administration was so impressed by the prototype that it proposed to the company to apply for a $750,000 grant to continue his work (Yvkoff, 2011). These solar road panels contain LEDs for illuminating the road lines, a heating element to prevent snow/ice accumulation and a microprocessor board for real time control and communications (Renewable Energy World, 2011).

Table 1: Comparing the energy harvesting technologies

	ADVANTAGES	DISADVANTAGES
PV-Noise Barriers	• No limitations at land use (LU) • High technical potential • Large scale (grid connected) • EU legislation-promotion	• Film quality determines the efficiency
PV canopies	• No limitations at LU • Mitigation of UHI effects (micro/macro scale) • Lower the oxidation and volatilization of the surfaces	• Microclimate variability: need for more intensive studies • Need for quantification of diurnal micro scale impacts to human comfort
PV bridge roofs	Same conceptual design with the PV canopies at parking lots. But here the bridge carries rigorous traffic load everyday because it represents the only way for between 2 locations	
PV-V2G	• No limitations at LU • Smart electric power generation: lighting and ventilation • Boosting the current power electrical generation • Cooperation with side-smaller cars applications	• Elevated initial costs • Estimated total costs are country's electricity power generation depended
PiezoElectric sesnsors	• Exploitation of waste mechanical energy • Cooperation with side-smaller cars applications (batteries, powering traffic lights, sings) • New hybrid vehicle-technology can be enhanced by its applicability	• Regular and constant inspections for moderate the effects of the heavy traffic loads • Not appropriate for large scale energy harvesting
Asphalt Solar Collector/Hydronic	• No LU constraints • Existence of many demonstration plants • Faces directly the UIH effect at urban areas • Decrease the electricity demand for heating and cooling purposes • Improve life cycle of the roads' surfaces • Decrease the chemicals for de-icing the roads/squares	• Returned year of the initial investment • Climate referenced • Real conditions are much more complicated • Any modelling tool has to deal with variable precipitation, temperature, humidity, wind speed or solar radiation
TNO	• No limitations at LU—incorporation of existing sideways and cycle paths • Short period of return investment. 4-5yrs for South EU and 5-8 yrs for Netherlands • The generated electricity can be used for street lighting, traffic systems and for immediate households	• Questionable return year investment • Need for advanced PV materials
Induction charging	• Enhances particle-loss resistance, tensile strength and fatigue resistance • Probably implemented at existing surfaces	• Need for demonstration plants (no information about in situ development)
Nanomaterials	• Reinforce the pavement structure • Ongoing and forthcoming research	• Cost • Need for demonstration plants
Phase Change materials	• Reinforce the pavement structure • Moderate UHI effect	• Need for solving their leaking problem from asphalt mixture

3 “GREEN ROAD CONCEPT”: A SUSTAINABLE ROADWAY SYSTEM

3.1 Introduction

The “Green Road Concept” should serve a dual purpose; mining the energy that is otherwise wasted by vehicles, incident solar radiation and pedestrians and; secure the service life of the pavement by improving their thermal and mechanical properties. This configuration is a sustainable road that uses limited natural resources for its use, reduces energy consumption and greenhouse gases emissions, prohibits the pollution of the air, water and noise and ensures traffic safety and health. The questions that need to be answered so as to analyze efficiently the implementation of more than one technology at a prospective roadway system like the “Green Road Concept” are:

- How is the flow of energy and how the interface(s) affect it?
- How the integration of those technologies will enable the thermal and mechanical performance of the pavement structure?
- Which factors determine the energy efficiency?
- Are the technologies overlapped efficiently or there are gaps at their performance and function?
- Which are the prospective costs and payback period?

Whatever is the purpose of an applied technology at a future sustainable roadway system, special attention should be focused on optimizing the thermophysical properties of the pavement materials. This can be done by two ways; either by using light- or heavy-weight and normal aggregates to produce concrete like limestone, quartzite, natural sand, sintered pulverised fuel ash lightweight aggregate (Lytag®), cooled iron shot (Ferag®), copper fibers, etc or; by replacing particular asphalt mixture with phase change materials (PCMs). Both these two groups can enhance the absorptance of incident solar energy and its storage across the pavement’s layers and mitigating the UHI effect by regulating the surface of the temperature. As a result they can prologue the service life of the pavement by reducing incidents of raveling/rutting. Last but not least, nanomaterials are possible to be incorporated at the pavement infrastructure instead of PCMs or simpler asphalt modifications but in that case their ascending costs arise many concerns because of their fabrication.

3.2 Green road concept- 1

Considering their location and readiness for application, PV sound barriers (PVSBs) and induction charging techniques can be implemented at the same configuration. Analytically, PVSBs alone combine the needs of clean energy production with traffic noise mitigation (Remmer at al., 2005). Especially when they are to be applied at highways that are near to urban and industrialized cities, where the sound abatement needs and energy demand are high, they can be grid-connected systems and the use of batteries is not necessary.

On the other hand, induction charging technique enables, theoretically, the self-healing process of the pavement structure by adding into the asphalt mixture conductive additives like steel wool or cooper fibers so as to make it electrically conductive. In general, asphalt mixtures that contain cooper fiber or steel wool had showed better resistance against fatigue (Dawson et al., 2011) while the interconnection behavior of copper fibres could further enhance the thermal conductivity. However, this increase is unlikely to deliver a significant economic benefit regarding the typical cost associated with the purchase of copper fibres (Dawson et al., 2011).

At this GRC the role of PVSBs is manifold; they are grid-connected; they moderate noise levels and; offer the needed electricity for the induction healing process. When micro cracks occur in porous asphalt, induction heating can be applied to the material to increase the temperature. That is to say, the interface concerning the flow of energy between these technologies is the propagation of the PV electricity to the pavement's inner structure in order to increase the temperature. The flow of the energy for that configuration is shown in figure 5. The incident solar radiation produces electricity according to photovoltaic phenomenon and with the appropriate mechanical links (regulators, inverters, batteries) part of the produced electricity is leaked to the pavement while the rest inserted to the grid. The closure of the micro cracks prevents finally raveling through prohibiting the formation of macro cracks (Liu et al., 2012). With the appropriate power management of the system the temperature increase could perhaps also help in the deicing of the pavement's surface.

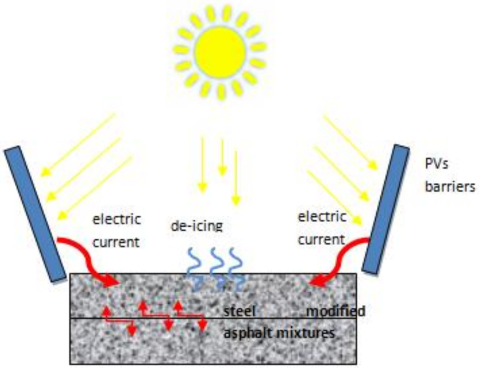

Figure 5: Flow of energy at the CRC-1

Integrating PVs at existing noise barriers (see figure 6) allow, primarily, cost reduction as they consist of sound insulating materials (Plexiglas or glass sheets) and they enable the self healing of the road surface as they offer the needed electricity for the induction process. In a large extend these added value cost savings improve the overall PV feasibility.

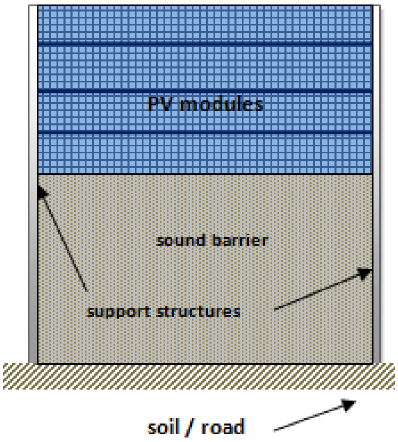

Figure 6: Layout of a PVSB.

Literature review had analyzed only induction heating for mastic and porous asphalt samples after adding into their skeleton a variety of portions steel wool (type 00). The modified “steel” asphalt can be paved on existing pavement surfaces by adding one more layer in which particular portion of steel fibers had been added into the mixing procedure. Liu et al. (2012) showed that “the optimal conductivity corresponds with the optimal heating speed while the indirect tensile strength, at low temperatures, corresponds with the particle loss” so in that sense the proportion of the steel wool into the asphalt mixture should have been compensate – somehow – with the system’s capacity and the traffic load.

Parameters that determine the PVSB efficiency are the orientation of the PVs, their tilt angle (in order to exploit the maximum incident solar radiation) and their ventilation (not constrained in closed structures). As for their orientation, it may differ from the optimum angle because the sound barriers position depends on road direction and receivers configuration. For that reason, multi-oriented or flexible mounting systems like top-mounted (upgrading existing sound barriers) or cassette, allowing PV surfaces to be correctly oriented independently of the road direction (Schirone et al., 2003). The former configuration compensates somehow the excellent noise abatement with the limited PV efficiency while the latter can succeed both in important noise moderation and PV efficiency. As for their tilt angle, it should be chosen high enough to hinder soil accumulation.

PVSBs are accompanied with the appropriate inverters so as to change direct current (DC) to alternate current (AC) just before entering to the grid network. A good matching between the inverter input operating range and the fluctuations of the PV array output due to temperature and irradiance modifications, has to be guaranteed otherwise significant energy losses can happen either in the form of cut-off during extreme temperatures or as premature switch-off of the inverter because for low irradiance (Schirone et al., 2003).

High solar intensity along with the appropriate PV mounting systems ensure a seamlessly energy harvesting efficiency with respect to PVSBs infrastructure. Regarding the induction heating part here the potential efficiency is more complicated as it is vastly determined from the traffic load, the heating and resting periods (till 85°C and around 20h, respectively) and their repeated cycles. The more heating and resting episodes, the better improvement at the self-healing capacity and fatigue resistance of the pavement. Additionally, heating should not be applied too early or too late because if it is too early porous asphalt concrete can heal the damage by itself but if it is too late, the healing efficiency will be very poor, because structural deformation will have happened that is beyond the healing capability of asphalt concrete (Liu et al., 2011).

By now PVSBs had proved their performance as they represent an already established technology especially at low latitude locations. As for the induction charging technology, excessive percentages of cooper or steel fibers can deteriorate the mechanical performance of the asphalt pavement resulting in raveling. Liu et al. (2012) pointed out that *"…beyond the percolation threshold, the conductive network* (determined from the adding steel) *develops and spreads gradually in three dimensions with the increase of the content of steel wool. So, adding more steel wool causes a sharp decrease of the electrical resistivity".*

3.3 Green road concept-2

Equipping the pavement infrastructure with fluid pipes along with prerequisite materials' adjustments is a popular studied configuration. The core of that system is the fluid-working pipes that provide a path to harness the stored thermal energy. Asphalt pavements absorb a large amount of heat and consequently experience an increase in temperature under hot climatic conditions because of their low conductivity (1.8kW/mK) and large heat capacity (1200J/kgK) (Mallick et al., 2011a). The thermal energy is then transferred to the fluid through convection, increasing the temperature of the fluid and lowering the temperature of the surrounding pavement.

Alone, this harvesting system can be used for deicing and heating/cooling purposes by having a double function which is determined from climate conditions:

- In summer, cold water is pumped up from an underground storage tank/medium and transported through pipes in the upper asphalt layer of the pavement. Because of the sun, the water gets warm and the thermal energy via heat exchanger is transported into another underground reservoir and held at this location until required.
- In winter, the system reverses its operation. The stored previously heated water flows from the hot storage reservoir to nearby facilities for heating purposes and or utilized through the asphalt pavement for deicing purposes (Sullivan et al., 2007).

Dehdezi et al. (2011) and Dawson et al. (2011) proposed not only installing pipes closer to asphalt surface but also at shallower depths. Incorporating the pipes into the surface layer by applying simultaneously high diffusive materials (like cooper fibers or quartzite) while applying below high thermal resistance materials limits the time for the fluid to absorb the high temperature heat. High diffusivity materials allow heat to penetrate rapidly into the pavement that significantly increase the temperature at pipes locations while those applied at lower layers "seal" the absorbed heat**.** Additionally, they moderate the thermal stresses resulting in minimizing the likelihood of deformation because of expansion and contraction. This configuration can be used both as hydronic system for deicing the pavement surface (during winter, hot water obtained from summer and stored in insulated chambers, can be flowed for deicing purposes) and for mitigating the UHI effect by regulating better the surface temperature at countries that face extremely summer temperatures.

Moreover, applying that system at locations with high solar intensity with the help of a solar powered-pump or ground source heat pumps, the heated water can be used directly at nearby facilities or as feedwater for industrial applications, for powering absorption chillers for cooling, as well for providing supplementary heat for electricity generation with the use of ORC turbines (Mallick et al., 2009). Additionally, water circulating in the pipe network could also be used directly as a heating system for swimming pools which are usually operated at between 20˚C and 27˚C (Dehdezi et al., 2011).

On the other hand, installing the pipes at shallower depths while applying at layers closer to the surface materials with low diffusivity (lower thermal conductivity) and high volumetric heat capacity, reducing temperature fluctuations that are responsible for the thermal stresses. Moderating temperature fluctuations imposes a stabilized temperature profile for the pavement always higher than the ambient temperature. So during winter the inner layers will remain at higher temperature than the temperature of the ambient environment and during summer the inverse. Additionally, the materials that surround the pipes should have high thermal conductivity so as to permit rapid heat transfer to the above layers. That configuration is ideal for airports that face problems related with snowfall because airports' infrastructure has got high demands for heating and cooling as they are adjacent to vast airfield pavement surfaces. In general applied that configuration at cold regions can minimize the risk of damage due to freeze-thaw cycling because of moderation at extreme temperature fluctuations.

Nevertheless, applying PCMs at the same framework with fluid-piping system instead of the already mentioned simpler materials modification has not been studied, yet. They have already proved their functionality and efficiency for ice storage, conservation and transport of temperature sensitive materials and building applications (Zalba et al., 2003). Only recently, PCMs are regarded as ideal thermal energy storage systems for the pavement engineering after their impregnation at asphalt mixtures and that for boosting the self-healing capacity of the pavement.

Maybe it is sufficient to be equipping the upper part of the pavement with pipes while introducing at the intermediate layers PCMs of high diffusivity in order to enable the flow of energy and eliminate the thermal stresses. If the piping configuration is to be applied at shallower depths then the low diffusivity PCMs at the intermediate layers can facilitate the absorptance of the thermal energy, regulate its diffusivity and finally, prohibit the losses at the surrounding environment. Another concept is to use PCM as building material for the storage reservoirs. In that sense, PCMs will have a double role at this energy harvesting system; they are to serve not only for materials modifications so as to enhance the thermal performance of the pavement along with its self-healing but also as thermal energy storage (TES) medium.

Studying this concept demands for understanding its two sections; piping configuration and; PCMs (figure 7). Regarding the first one, three parameters determine the amount of the harvested energy; the location (latitude); fluid temperature and; arrangement of the pipes (spacing, depth, material and diameter). The concept of scavenging the energy from pavements seems to be feasible for areas with relatively higher solar radiation. As for the pipes, literature review had revealed that the installation of a denser piping configuration (preferably serpentine) so as to enlarge the flow length of the working fluid and the high flow rate of the fluid are indispensable for the optimization of the system's efficiency. These details will minimize the time frame of the working fluid to absorb heat and with the appropriate choice of materials adjustments (regardless installing the pipes closer to the surface or at shallower depths) they will boost the effectiveness of the harvesting procedure.

Installing the piping system closer to surface so as to work as collection - hydronic - system, the appropriate depth can be around 40mm from the surface so as not to increase the time that the working fluid needs to absorb the heat. Particularly, when the thermal conductivity of the layers approaches the value of 3 the melting snow time can be controlled within 0.5h (Chen at al., 2011). Regarding pipes' material, choosing moderate-to-high thermal conductive materials enhance the absorptance of the thermal energy from the working fluid, increasing its temperature and thus lowering the temperature of the surrounding pavement (Mallick et al., 2011b). Additionally, plastic pipes are more efficient in heat extraction while they are considerably cheaper than the cooper ones (Siebert et al., 2010). Dawson et al. (2011) modelled the installation of 2 pipes (the one above of the other) at the first surface layer, each of them at 40mm and 120mm from the surface. As for the installation of the pipes at shallower depths, 1500mm distance from the surface is identical for the harvesting and storage procedure.

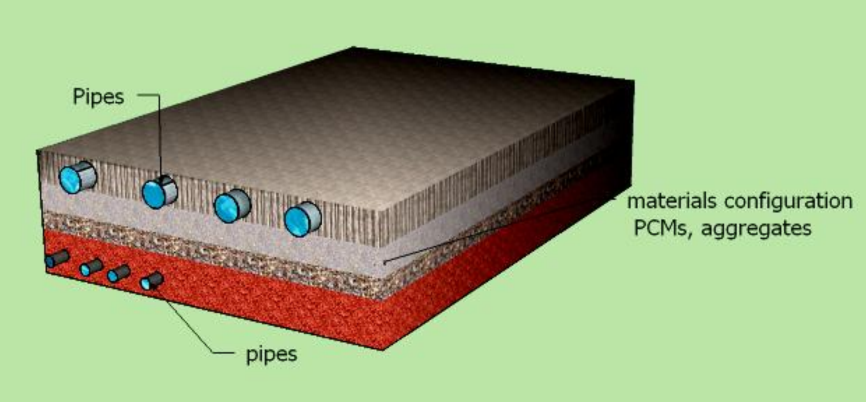

Figure 7: Schematic of GRC-2

As for the diameter, only Mallick et al. (2011b) studied this factor (for one pipe configuration), by proving that when the pipe diameter increases a steeper temperature variation occurs between pipe and surface and the determinant factor for the harvesting efficiency is the flow rate. This means that the larger the diameter, the lower water temperature and a higher rate of cooling of the pavement surface (ideal for locations that face the UHI effects during summer). The temperature distribution is uniform only for small diameter while in general it varies gradually along the pipe diameter something that could lead to irregular deformations (the high temperatures side will be susceptible to permanent deformation under repeated traffic loading, while the low temperatures side will be susceptible to thermal cracking) (Chen at al.,2011).

As for the PCMs, they do not have so many technical characteristics apart from the precise identification of the melting and solid state's temperature point so as to ensure their reversibility in other words, choosing the most adequate material. What have to be analyzed before designing and integrating together these two harvesting technologies is how the pipes will response to the transition phases of the PCMs and the traffic stresses and probably this factor represent the only “weakness” of this prospective combination. The PCMs should not contribute in raveling and rutting incidents as they must attenuate, at least, the thermal distributions of distresses.

Another factor that needs to be considered is the thermal conductivity of the created asphalt mixture after the incorporation of the PCMs or the aggregates. By now the literature review has revealed that the “external materials” are mixed in proportions of 20% - 50% of dry components and the final measured thermal conductivity lies between 0.22 and 10.71 (W/mK) with the simpler aggregates having the larger scale and the higher values (Dawson et al., 2011, Cocu et al n.d). Additionally, the thermal conductivity of asphalt mixtures with the simpler aggregates under wet condition reveals an ascending profile (Dawson et al., 2011).

The prospective heat collecting capacity is location dependent (solar radiation intensity, wind velocity and ambient temperature). Mallick et al. (2011a) calculated through a spreadsheet that the prospective harvested energy that is available at 2 different depths (25 and 50mm) for Boston (42.4o) is no more than 200 kWh while for Miami (25.8o) approaches 550kWh (with increasing pipe flow rate). In general, they stated that this configuration can be feasible only for areas with relatively high solar radiation (no high latitude locations). For example, for Swedish locations like Luleå, Lund and Stockholm with latitudes from 55.7^{o} – 65.5^{o} the annually solar radiation (south projection angle) is not more than 150 kWh/m^2 (Rönnelid et al., 1998) which reveals that these amounts of solar energy cannot be harvested efficiently. But in general, there is a lack on research about the evaluation of installing the pipes at shallower depths and for its implementation at colder regions.

3.4 Green road concept-3

Piezoelectric materials or piezoceramics have been proved to harvest kinetic energy in the form of vibrations so as to power the wireless connectivity of portable devices and computer peripherals and can be used, also as sensors for health monitoring and deduction of cracks (Wang et al., 2009). Additionally, piezoelectric materials can be used as actuators because they can strained or displaced when an electric voltage is applied across their pole axis (like PZTs). PZTs can be used for passive vibration suppression where the force from the vibration strains them generating a voltage difference (electrical energy) that can then be dissipated through a resistive circuit. Another technique to deduct real vibrations is to implement a piezo-sensor into a manhole cover.

This technology can be used in combination with asphalt solar collector system (ASC) after materials adjustments (PCMs or modified asphalt mixtures) at full-time occupied areas like parking lots or at low traffic roads nearby malls and residential areas. This configuration can be ideal, also for airways since the traffic load there is heavier and more intensive and the large scale vibrations with the appropriate smart power management are feasible to power wireless sensor nodes for air-traffic signage and for de-icing purposes. While the ASC system can serve for hydronic, district heating/cooling purposes or as feedwater for other applications, the implemented piezoelectric sensors can monitor full time the pavement conditions as they are affected by the coupled thermal-mechanical stresses from the temperature gradient and vehicular loads (Chen at al., 2011) and the stresses owing to the placement of pipes. Implementing simultaneously the ASC technique (close to the surface or at shallower depths) with piezoelectric cantilevers can be also an ideal combination for noise abatement. On a second thought the presence of PV panels can cover the undersupply at the electricity production. So the purpose of powering traffic lights and signals, road advertising, portable devices or improving the sensors network performance can be covered seamlessly.

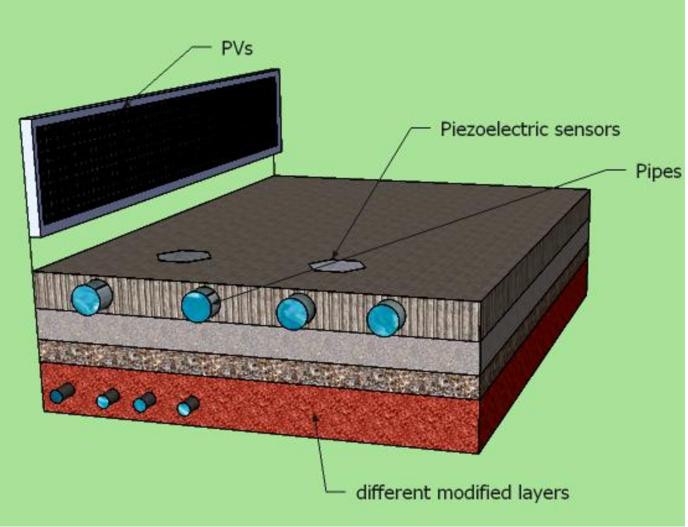

Figure 8: Schematic of GRC-3

Thermoelectrical generators (TEGs) can be used similarly with the piezoelectric sensors without neglecting the materials modifications that can offer the improvement of the pavement service life. But maybe it is not feasible implementing together ASC system with TEGs because the latter need to be incorporated deeply in the pavement structure.

4 EVALUATION OF THE POTENTIAL OF HARVESTING ENERGY FROM PAVEMENTS

4.1 Introduction

Asphalt pavements experience many fluctuations in their temperature profile because they absorb vast amounts of heat especially under hot climatic conditions. Their low thermal conductivity and large heating capacity make them an ideal means for harvesting the wasted thermal energy and with supporting energy harvesting technologies, they have the ability to mitigate some energy and environmental problems. The three proposed systems or Green Road Concepts (GRCs) that are to be evaluated consist of:

- GRC-1: Asphalt conductive pavement with photovoltaic sound barriers
- GRC-2: Asphalt Solar Collector (ASC) with embedded working fluid pipes and phase change materials (PCM)
- GRC-3: Asphalt Solar Collector with embedded pipes and piezoelectric sensors

Separately, the potential of harvesting heat energy from a specific site depends on a number of factors that can be grouped as location-dependent (solar intensity, ambient temperature, wind velocity, maximum temperature reached for the working fluid, etc), materials-dependent (PCMs, simpler materials modifications, materials for the PV cells and materials for the pipes) and mechanic-dependent (traffic loads, frequency etc). There are several structural analyses and design issues that need to be handled to make sure that such a system can survive the fluctuations of stresses due to loading and changing environmental conditions (Mallick et al., 2011).

Evaluating the proposed energy harvesting systems demands for comparing their operation and performance along seven vital key-sections; the already gained expertise from previous technologies; flow of energy; potential efficiency; needed technology/space with respect to normal pavements; cost and payback period (time to reach positive cash flow); timeframe and recyclability and; environmental friendliness. For some technologies like the induction charging and the piezo-sensors the information about their timeframe, cost or their potential efficiency are limited because they do not have tested in situ road implementation. Trying to solve this weakness the evaluation part analyzes which of the prospective energy harvesting systems can be implemented and developed in short-, intermediate- and long-term in respect to the above mentioned factors.

Before starting the evaluation no one can doubt about their environmental friendliness –not at their whole extend - as they are designed to reduce energy consumption, pollution’s levels and GHG emissions. Nevertheless they must ensure that they do not jeopardize the sustainability of the pavement which can have detrimental effects at driving conditions. Assessing their environmental profile demands for investigating their effects during construction, implementation, and operation and decommission. That means that their sustainability should be reassured from a lifecycle perspective that it is not the actual purpose of this thesis, Hence a more detailed evaluation of their environmentally friendliness from a lifecycle perspective should be recommended!

4.2 Direct implementation: PVSBs & Induction charging

PVSBs are developed along roads or a general strip of land and their role is versatile; they produce electricity (grid-connected) and; they offer traffic noise mitigation. By now the installed PVSBs have used multi-crystalline and amorphous silicon modules but the multi junction solar cells – being currently the most promising PV technology with efficiency near to 40% - can boost the efficiency of the system while, in contradiction they blow off the overall costs.

Induction heating technology is designed to activate the self-healing capacity of asphalt pavements by increasing their temperature so as to prohibit, in a final stage, raveling and rutting. This can be done by incorporate at the asphalt mixtures particular proportions of steel wool or cooper fibres. Those are determined by the system's capacity and the traffic load.

What makes this energy harvesting concept ideal for immediate installation is that it uses existing sound barriers (with insulating materials) for mounting the PV cells and the conductive asphalt layer can be applied at existing road with the appropriate surface modifications. Furthermore, **the flow of energy** has "clean boundaries" which facilitates firstly, the theoretical analysis and finally the structural and mechanical design of the system**.** PV electric energy (Direct Current) can be supplied directly to the conductive asphalt pavement negating the need for inversion. "Isolating" the electricity propagation to the pavement from the grid means that no energy and grid line extension costs are incurred as the PV electric current will be supplied directly for the induction heating process (Heymsfield et al., 2011). But in that case the need of regulators and batteries is imminent as they supply energy to the pavement and store excess energy in case of periods that sunlight is unavailable (Kirkgaard, 1999). In contrast, regarding that the cost of batteries is not negligible and because the induction heating process is not to be used continuously, maybe the idea of connecting the asphalt system with the grid can be more advantageous than using batteries.

The efficiency of the system is determined in a large extend, by the PV cells, the batteries bank and the inverters (matching point between inverter range and fluctuations of PV array). In addition, choosing the appropriate mounting system with the right tilt angle are factors that can boost system's efficiency.

As for the added conductive additives at the asphalt mixture, the clustering must be avoided because it can deteriorate the strength of the pavement because through corrosion of steel wool results in raveling and rutting. This effects on the sustainability of the pavement, let alone not has any induction charging potential. Also, more research is needed to examine if the inclusion of such fibers does not cause any premature damage due to increased local stress intensities.

The **overall costs** of this system are determined primarily from the PVSBs infrastructure; PV cell materials; the supporting electrical equipment (batteries, inverters, regulators, cables etc), and; the PV mounting systems on the noise barriers. As for the induction heating infrastructure the percentage of the steel/cooper fibers at the asphalt has a defaulted high cost. Nevertheless the cost is reduced when the conductive asphalt layer is to be installed initially, during pavement construction. It might incur only a marginal cost as the cost of the pavement construction would probably be already funded from a separate budget (i.e. a budget for transportation rather than energy purposes) (Dehdezi et al., 2011). **The payback period and profitability** of this harvesting concept is largely depended on the profits from covering local supply electrical loads after PVs connection to the grid. In that point, the location plays the most important role. Additionally, extending the service life of the pavement by mitigating rutting/raveling incidents adds at the general "payback period".

The **operation life** of the PVs is between 20 and 30 years while for the inverters is no more than 20 years. The replacement of the noise barriers is depended at their material (concrete, steel, wood or vinyl) and lays between 10 and 20 years. Thus their replacement before the end of life of the system is not unlikely. As for the pavement surface, its operational life is a matter of multiple time heating/resting episodes which, in theory, increases its self-healing performance.

4.3 Intermediate implementation: ASC & Piezo-sensors

The concept of the Asphalt Solar Collector with an embedded network of working-fluid pipes is used for district heating/cooling purposes as well as for deicing water or ice. By now many projects that use the principals of the above mentioned system have been developed and implemented around Europe; SERSO project (in Switzerland, 1989); TRL Report (UK, 2007) and; RES (Netherlands, 2007) and they are related with airways, bridges or low traffic roads and sideways (Siebert et al., 2010). The heart of that system is the piping configuration implemented into the asphalt pavement. Its importance justifies somehow the special materials modifications that must be arranged so as to secure pipes' service life regarding the thermal and mechanical stresses that they accept. Combining together with the piezoelectricity sensors can be an ideal technique applied at full-time occupied areas like parking lots or taxi and bus-lanes as well as at airways where the traffic is more intense and heavy. They can serve for district heating/cooling purposes, deicing paved surfaces, monitoring the pavement's conditions and with the appropriate bank of electric capacitors, they can store the produced electrical energy for its prospective use. Moreover these compact miniaturized sensor nodes can serve for the safety of citizens and with the progress in electronics and wireless communication, can be used to form highly efficient networks so as to invigilate regular operations and in case of traffic accidents or terrorist attacks to minimize human losses (Li et al., 2008 cited in Wischke et al., 2011).

The prospective combined system has two energy harvesting sections; the asphalt solar collector and; the piezoelectric sensors. Regarding the **flow of energy**, the combined systems do not interact. Their only interface is the pavement surface where the piezo-sensors are to be implemented. For that reason the building materials for the asphalt mixtures should ensure not only the unruffled function of the piping configuration but also the service life of the sensors. On the other hand, embedding the sensors either close to the surface or at the border between the 1st and the 2nd layer should secure the thermal and the mechanical performance of the asphalt solar collector especially when the surface displacement tend to affect negatively the function of the pipes.

Assessing the application and performance of piezoelectric sensors needs for optimization of their coupling effect with the pavement surface. This will ensure not only their mechanical stability but also pipes' service life and operation. Their efficiency is determined by the electromagnetic coupling factor k and the energy transmission coefficient λ_{max}. Unfortunately these factors have not yet been calculated on situ road-experiments and for that reason the literature review evaluate the energy harvesting performance of PZTs by using the stored electric energy at open circuit (related with the stored electric energy and the output efficiency) (Zhao et al., 2010). At the same time, minimizing the surface displacement after embedding the sensors at the pavement surface is indispensable for not deteriorating pavement's performance and pipes' service life or increase vehicles' oil consumption. In that vein, special care should be focus on the contact stresses between the vehicles' tires and the layer that includes the sensors and the pipes, the shape characteristics of the asphalt layers and the load, size and material of the sensors (diameter of the PZT, material and diameter of the cavity base etc) (Zhao et al.2010). Choosing the right parameters should guarantee that the surface displacement difference with the sensor is less than that without the sensor ($p_d \geq 0$). By now only Finite Element Analysis has been used for choosing the appropriate design parameters and studying their effects at the output electrical potential. Additionally, minimizing the wires' length so as to avoid interference and noise that probably will end up in output power losses is another factor that needs to be considered (Edmison et al., 2002).

On the other hand, embedding a piezoelectric sensor into a manhole (that was modelled as a spring-mass-damper) demands for optimizing the output voltage by studying parameters like the displacement of the sensor (mass), the cantilever stiffness, the capacitance of the piezomaterials, the electrically induced damper, the resistive load etc. By now only genetic algorithms have been used so as to optimize the above mentioned parameters and calculating the potential harvested energy (Ye at al., 2009).

The **cost** for the design and integration of such a system is largely depended on its installation (labour and mechanical), the chosen material for the pipes and asphalt modifications, the multiple end use application, the electronic capacitors for the stored energy from the sensors and the maintenance of the system (Mallick et al., 2009). Literature review had revealed that the service life of the pipes is not more that 30 years determined by the applied depth. By now the plastic and metallic or coil pipes are much cheaper than the cooper ones but having lower thermal conductivity. In general choosing low cost but good performance pipe material, cost effective piping installation (heating capacity, piping layout, control system) with the appropriate asphalt mixtures modifications can reduce the initial costs dominating from the installation costs of the piping and heating equipment (Chen et al., 2011). In addition, the fabrication of the piezomaterials for the transducers adds at the overall costs along with the regular and constant inspections so as to moderate the effects of the heavy traffic load. Nevertheless, literature review has revealed that in comparison with other types of motion-sensors, piezomaterials are more functional and cost effective not only because they can easy sense the motions but also need little power requirements and are simple to interface with additional devices (Edmison at al., 2002).

The **dimensions** of the harvesting system are determined by its planned purposes of the ASC; hydronic and; district heating/cooling. Additionally, the produced electric energy from the transducers is transferred and stored into modules while can be used later for covering local power needs or routed into the grid. In general integrating the piezo-sensors at the pavement surface, it is not only a matter of “supplementing the infrastructure”. In general it is difficult enough to standardize the piezo-sensors because they are still under research regarding their use at in situ road applications. The **payback period** is defined by the prospective scavenged energy in relation with the latitude, the operational and service life of the piping network and the power management network that is needed as supplementary equipment for the piezo-sensors.

Lastly but not least, **the timeframe and recyclability** of the system is a matter of its exposure to traffic loads, maintenance inspections, potential displacement of the sensors with the pavement surface and their interaction with the piping configuration. At this point it should be highlighted the need for extensive research concerning the structural effects of the conductive pipes on pavement performance that, in a long term, affect its recyclability and service life. Literature review regarding ASC has revealed that the presence of the piping configuration in asphalt enhances complex distribution of stresses and strains with peak stresses around the pipes (Bijsterveld et al., 2002). Ooms Avenhorn Holding had developed the already mentioned Road Energy Systems® (RES) that uses a specially developed 3-D polypropylene grid with polyethylene pipes. After laboratory tests and interpretation of the results by using Fine Element method, analyses showed that where the experimental specimens bulge the FE model remains straight. In general the effect of the reinforcement grid is more than apparent as it *“enhances confinement of the asphalt and reduces excessive strains due to horizontal movements in underlying joint pavement layers due to temperature variations*” (Bijsterveld et al., 2002).

4.4 Long-term implementation: ASC & PCMs

We have already analyzed the utility of ASC and how that configuration can be implemented with PCMs at the same energy harvesting concept. The latter sub-paragraph analyses how important mechanical characteristics of the ASC influence negatively or positively the efficiency of the harvesting system along its timeframe and recyclability. So it does not add something more to repeat again the same information.

The **flow of energy** between the pipes and PCMs and the imposed mechanical stresses is a factor that determines extensively the **efficiency** of the harvesting system. The advantages of applying the pipes closer to the surface (increase temperature for the working pipe fluid) can be outweighed by the possibility of subsiding because the pipes alone accept enormous vehicular stresses. Road Energy System (RES) uses relatively soft asphaltic mix and an interlocking grid for the pipes that give the asphalt higher resistance against the crack growth (Siebert et al., 2010). Implementing, simultaneously PCMs at underneath layers should attenuate the mechanical stresses something that seems difficult enough regarding their transition phases. PCMs should be chosen at particular temperatures and pressures for their melting and solidifying phases corresponding positively with the operation of the pipes. In other words, making this system working demands for; enhancing the thermal performance of the pavement and its self-healing capacity; attenuating the mechanical stresses imposed at the pipes and; facilitating the storage of the thermal energy and its prospective release concerning the purposes of the system.

The **cost** for the design and integration of such a system is largely defined by the ASC that have already analyzed, while choosing to modify the asphalt mixture with PCMs that are relatively more expensive than simpler materials modifications will increment the overall costs, because of their fabrication. The **dimensions** of the combined system are determined by its prospective purposes; hydronic and; district heating/cooling. The standardization of the dimensions is related with the area that needs to be deiced or heated/cooled, the pumping capacity, the needed piping flow rate and the storage reservoirs. And all of these factors are needed to be considered simultaneously with the chosen PCMs or materials modification. For example, Road Energy System states that an office building with a space of 10,000m^2 requires an asphalt collector of 4,000 m^2, energy storage with a pumping capacity of 110m^3/h and a heat pump capacity of 340kW considering Dutch climatic conditions (Siebert et al., 2010). As for **the payback period** (time to reach positive cash flow), it is directly related to the amount of heat energy that is extractable (or available) in correspondence with the location, the operational performance of the piping configuration and the volume of the storage tanks. In general, the higher the latitude, the higher is the payback period (Mallick et al., 2011a). The timeframe of the systems regarding ASC has already been analyzed. Considering, now PCMs our arguments are based on theory because of the limited information about the interaction between piping configuration and PCMs.

So, the questions here to answer are related with the efficiency and costs of the PCMs in comparison with simpler asphalt aggregates (limestone, quartzite etc) and the imposed effects at the pipes because of their melting/solidifying stages. By now, the researched PCMs for enhancing the self-healing of the pavements (that already have been used for building applications) are paraffin waxes with the appropriate composite shape-stabilized materials for avoiding leakage possibility (Chen at al., 2011; Cocu et al n.d; Ma et al., 2011). What make this concept feasible only for long-term implementation are its volume and the limited information that exists concerning the interaction of the pipes with the transition phases of the PCMs.

Under severe (winter) conditions – like the Swedish ones – the optimal configuration is embedding the piping system at shallower depths while incorporating on the top layers low diffusivity materials (for PCMs: low solidification temperature point, around 2^{o}C) (Cocu et al n.d). The substantial amount of heat released by a PCM during solidification may, indeed, delay the decrease in surface temperature offering with that way an alternative deicing tool. The underneath pipes will play a secondary role as they will guarantee the storage of the thermal energy by stabilizing the temperature of the pavement at higher temperatures than those of the ambient environment.

The table below summarizes the factors that lead us for the GRCs evaluation. It is worth noting that the existence of already expertise that has been gained from other technologies plays an important role at their analysis.

Table 2: Evaluation of the GRCs

	EC1 (PVSB_IND)	EC2 (ASC_PCM)	EC3 (ASC_PIEZO)
Expertise from…	PVSBs	ASC	ASC
Flow	Easily understanding / Clear boundaries	Easily understanding but difficult in analyzing their mechanical interface	Not interactive flow of energy
Efficiency	• PV cells & cooper fibres • Location	• Pipes • Transition T-point for the PCMs • Location	• Pipes • Piezo materials • Location
Needed technology	SBs already used for the PVs while the conductive layer can be implemented on already used road	• Depends on the end-use purposes • Large scale system	• Large scale system • Piezo surfaces are determined from end-use purposes
Costs / payback period	Infos only for the PVs and SBs	Infos only for pipes and their accompanied equipment	Infos only for pipes and their accompanied equipment
Timeframe/recyclability	PVs & SBs	Pipes: no more than 30 years related with the depth	Pipes: no more than 30 years related with the depth
Environmental friendliness	Testified and justified by their actual primarily purpose of design and integration through lifecycle perspective.		

5 CONCLUSION

Energy harvesting technologies can guarantee energy security as they moderate energy consumptions problems. Primarily the term was used for describing micro harvesting autonomous devices while it is an ideal substituting for batteries. Now there is a trend towards exploiting the wasted energy from large scale plants like roads or paved surfaces which receive every day enormous amounts of solar energy and vibrations.

The 3 sustainable roadway systems developed in this thesis are designed to scavenge the energy that is gained and wasted from road infrastructure. The prospective uses are either electricity's production, district heating or cooling for nearby facilities, deicing pavement's surface or powering wireless networks and monitoring pavements conditions along with the enhancement of their self-healing process. Studying their prospective implementation is a matter of answering to questions that related with their efficiency, the needed technology, payback period and timeframe and the seamless flow of energy. While the actual purpose from the beginning was to evaluate the Green Road Concepts one-by-one with the same criteria, unfortunately for many of the proposed harvesting technologies, literature review is limited regarding experience from their in-situ implementation. For that reason the evaluation part conducted by rating them regarding their direct implementation, intermediate implementation and long-term implementation.

The GRC-3 is the most complicated and "bulkiest" system as it demands for extensive research concerning the structural negative responses between piping configuration and at the PCMs' melting and freezing phases. The GRC-1 is the most promising system for immediate implementation concerning the already availability of sound barriers or existing PVSBs. But again here the risks about corrosion problems as a result from clustering among steel fibers make that harvesting system questionable. Lastly, but not least the GRC-2 can be regarded as the "mildest" and cleverest system as the piezo-sensors alone despite that stand out for low power efficiency with the appropriate management power network can supplement in an efficient way the harvesting procedure.

No one can deny that combining altogether energy harvesting technologies and implementing at large scale plants like roads and paved surfaces is intriguing, challenging and promising. If prospective roadway concepts can be designed to harvest energy in an economic manner, then this would have long-term benefit for developing sustainable pavements by preventing rutting, UHI effects while simultaneously moderating energy consumption problems and why not ensure safe driving conditions.

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