Solar Energy Harvesting and Pavement Sensing

Kang-Won Wayne Lee, Michael Greenfield, Austin DeCotis, and Kevin Lapierre

Abstract An attempt was made to generate the required voltage in asphalt pavement to operate roadway sensors utilizing a temperature difference between two thermoelectric generators (TEGs). To enable output voltage by the TEGs below the asphalt surface layer, the harvester was installed with the copper plate 25 mm (1 in.) below the top surface layer. The copper plate is heated from the sun's rays penetrating the asphalt surface layer and transferring the energy into the harvester system. The power generated from the TEGs allows temperature difference readings, as well as maximum power output voltage. Optimizing the harvester for efficiency and sustainability were top priorities. Once the copper plate receives the required voltage from the heat generation, the Arduino can be turned on. To communicate with the Arduino board in the current set-up, a USB cord gets plugged into the Arduino with the other end into the computer. The software program *Arduino* should then be opened on the computer to read data from the apparatus. An SD card or Bluetooth receiver was implemented into the solar harvester unit. This allows data for retrieval to be stored without an external power source (i.e., computer), allowing the harvester to operate freely. The strain transducer was installed into the asphalt surface layer for strain monitoring of the roadway. The SD card/USB would be able to store the information from the pavement strain transducer. Data retrieval would be achieved simply by unplugging the card from the harvester unit and uploading it to a computer.

Keywords Solar energy harvesting · Thermoelectric generator · Copper plate · Arduino · Asphalt pavement sensing · Strain transducer

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1 Introduction and Background

1.1 Project Motivation

The properties of asphalt pavement allow the accumulation and dissipation of solar energy on a daily cycle. Heat is absorbed in pavements, causing many detrimental effects such as the degradation of pavement, heat island effect, and increased costs for cooling nearby structures [8]. Harvesting solar energy from pavement has the potential to provide many substantial benefits such as extending the service life of pavements, improving the air quality, lowering impacts to the climate, and producing energy [6]. The Rhode Island Transportation Research Center (RITRC) team at the University of Rhode Island (URI) investigated important aspects of energy harvesting via an embedded solar harvester system, which was created to reduce pavement distresses and to enhance evaluating pavement performance [7].

Typically, sun shining on pavement provides it with thermal energy throughout the day. Past studies have confirmed that pavement temperature rises and falls each day, and the magnitude of the daily fluctuations varies with albedo (fraction of reflected sunlight), light absorption by the pavement, and emission, all of which can vary with latitude, with season of the year, and with the pavement itself [4]. Pavement temperature falls at night as it radiates heat back into the atmosphere and as heat is conducted into underlying layers and subgrade soils.

Harvesting energy from pavement refers to injecting engineered processes into this daily thermal cycle. The goal is to capture part of the daily energy flow and to channel it to other uses. The benefits cited above for energy harvesting arise from the lower temperatures that can result from extracting energy from pavement more quickly than can be obtained in a typical daily cycle.

1.2 Objectives and Tasks

Efforts focused on building an apparatus that can harvest thermal energy from a pavement by a *thermoelectric* approach rather than relying on harvesting thermal energy directly. Opposing semiconductors in a "thermoelectric generator" create electrical voltage when they are brought to different temperatures. A ceramic barrier provides electrical insulation between the opposing surfaces and cuts down on direct heat transfer. Instead, energy flows from higher to lower electrical potential through a wire, transferring the energy electrically rather than thermally. This creates a possibility of harvesting energy by powering an external circuit with this voltage. The electrical power becomes available for use within the pavement itself.

2 Energy Harvesting and Advanced Technologies for Road Assessment

The URI research team performed experiments utilizing the Seebeck Effect [7, 13]. The Seebeck principle comprises two dissimilar electrical conductors or semiconductors that have a difference in temperature, which produces a voltage difference between the two substances [3, 10]. Recently, an experiment using the Seebeck principle was performed to develop a self-powered battery-less structural health monitoring (SHM) system for transportation infrastructure [5]. The system would be capable of processing analog voltage input from a variety of sensors, such as strain gauges, traffic counters and piezoelectric weighing strips [9]. An energy harvester driven by thermoelectric generators (TEGs) powered their system. TEGs function on the Seebeck/Peltier principle, allowing thermal differences between the upper and lower layers of asphalt concrete to be translated into electrical energy [11]. The surface heat of the pavement would be transferred from the surface to the lower layers through insulated copper plates, and the lower part of the harvester was kept cool through a heat sink [12]. Thermoelectric generators can power SHM systems when enough of a temperature differential exists to power the TEGs. This SHM system developed by the Texas A&M University (TAMU) team appeared to be successful. The system accepts analog voltage input from a variety of sensors, is readily programmable, functions without a storage battery, and can continuously retrieve wireless data. The URI research team has been conducting similar studies independently. Literature review utilizing the Seebeck/Peltier Effect (thermoelectric effect) was further researched and reviewed. An effort was made to harvest solar energy for developing a road performance assessment tool, as described below.

2.1 Methodology

The setup has two broad functions. The first setup harvests some of the thermal energy that is available by converting it into electric voltage. This provides a capability to do useful work in real time. The second setup uses the electrical power provided by the energy harvesting system to power a strain sensor. The sensor monitors pavement deformation or strains of passing traffic. This second setup involves conversion of the generated voltage into a steady flow that can operate the sensor and its electronics.

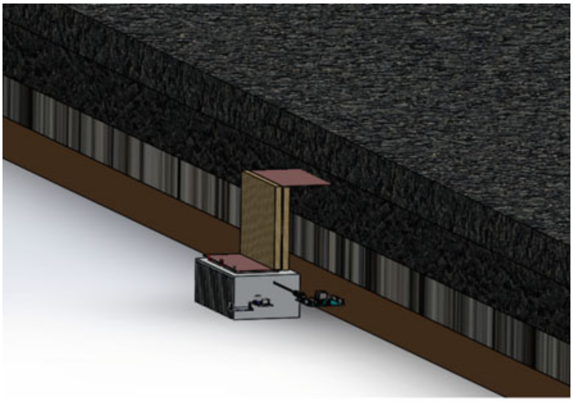
2.2 *Apparatus to Harvest Solar Energy*

2.2.1 Thermoelectric Generators

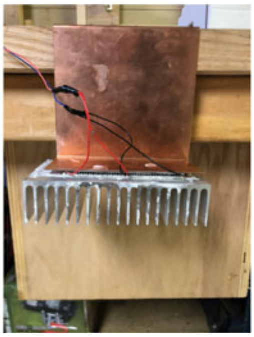
TEGs power the system by translating a thermal difference in temperature between their upper and lower layers into electrical energy. They convert the environmental energy that exists in the form of a thermal gradient into electrical energy. Normally heat would flow down a temperature gradient in the form of thermal conduction. Instead, the TEG replaces that energy flow with a form of electrical energy that flows from a higher voltage to a lower voltage. This voltage that drives that electrical current can be directed through a circuit, which provides for extracting useful electrical work from the pavement.

The layers within a TEG consist of two different semi-conductor materials (p-type and n-type elements) between two ceramic substrates to generate voltage. As one side of the TEG becomes hot due to heat transfer from the upper pavement layer, the other same remains a colder temperature, allowing a voltage to be produced. A cartoon depicts the overall structure (Fig. 1a) and a photograph depicts the system

Fig. 1 Solar energy harvesting system. **a** Cartoon of the harvesting system depicted next to an asphalt pavement. **b** Photograph of the TEGs between the copper plate and heat sink during benchtop testing. Pairs of black and red wires indicate the parallel physical and electrical geometries



(a) Computer generated model of harvesting system



(b) Copper plate, TEGs, aluminium heat sink during benchtop testing (Fig. 1b). A TXL-287–03 TEG from TXL Group Inc was used in this study. It employs a bismuth telluride thermoelectric material. Further information is available at TXL Group, Inc. Two TEGs in parallel were used to increase the available current.

2.2.2 Copper Plate Apparatus

A first step is to deliver heat from the hot pavement surface to the TEGs that extract the useful energy. Normally this heat flows from surface to interior directly through the pavement. This creates a temperature gradient within the pavement that is incapable of allowing energy to be extracted. To circumvent this typical equilibrium, an easier path was created for channeling heat flow to the embedded TEGs. This took the form of a long, thin plate. The main experimental setup consists of an "L" shape design 470 mm (18.5 in.) long × 150 mm (6 in.) wide × 1.59 mm (0.0625 in.) thick copper sheet that absorbs heat from the asphalt pavement. The size of the copper plate was determined in correspondence with the size of the TEGs. The lower end of the copper has a 63 mm (2.5 in.), 90-degree bend, where it meets the TEGs. Copper was selected because it is an excellent heat conductor and has a high thermal conductivity. Copper is also very durable and has a specific heat of 385 J/kg C at 25 °C [1]. Multiple on-line sources cite a density of 8.96 g/cm^3 and a thermal conductivity of 401 W/m–K at 0 °C. This copper sheet connects to two TEGs, which are electrically connected in parallel, by a thin layer of thermal paste (Fig. 1b).

The role of the copper plate is to deliver heat to the TEG, so the upper surface of the TEG becomes much warmer than its bottom surface. To decrease losses along the copper, Styrofoam insulation was added to the solar harvester. The R value of the insulation was approximately 2.8. The insulation was added to the 150 mm (6 in.) bent part of the copper plate on both sides. The two insulation pieces were wrapped in electrical tape to mimic a seal around the insulation. An adhesive was used to hold the insulation in place. The insulation enables heat transfer to stay within the vicinity of the copper.

2.2.3 Heat Sink

Attached to the bottom side of the TEGs was an aluminum heat sink, which is used to dissipate the heat away from the TEGs (Fig. 1). Dissipating the heat away from the TEG allows for a greater temperature difference between the two sides of the TEG, producing an electrical current for sustainable power generation. The heat sink is attached to the colder (bottom) side of the TEG. The heat sink is 180.3 mm (7.1in.) long × 99 mm (3.9in.) wide × 45.7 mm (1.8in.) tall.

2.3 Apparatus to Use Solar Energy—Strain Sensing as an Example

Electrical energy must be used in real time unless a reservoir such as a rechargeable battery is present to utilize the electrical voltage and current. As a demonstration that energy harvesting can work, and as an added benefit, the energy harvesting apparatus was used to power a strain sensor that can monitor pavement durability. The system to power and activate the sensor requires a steady voltage within a narrow range. Thus, electrical circuitry and hardware was implemented to employ the TEGs as the power source. Programming of the strain sensor controller (the “Arduino” board) was also required.

2.3.1 Boost Converter

A boost converter is used to amplify the voltage of the solar apparatus and to keep the available voltage around 7 V. It can take an input voltage of 2–24 V and make an output of 5–28 V. Without the boost converter, the TEGs would only be able to produce a certain temperature-dependent voltage that is not a constant power to supply the Arduino. The TEGs are then connected to a boost converter to amplify the voltage produced by the TEGs. A boost converter allows a low voltage to be converted to a higher voltage easily while stepping down the current. The TEGs must maintain an output voltage of at least 2 V to power the boost converter. This boost converter is connected directly to an Arduino Uno board to allow programming of a road performance monitoring sensor.

2.3.2 Analog Digital Converter

An HX711 analog digital converter is used to power the Wheatstone bridge connection sensor, whose characteristics and specifications are listed in Table 1. The converter easily converts the analog signal of the strain sensor into a digital signal, to allow electrical signals for data processing purposes. Without the digital converter, the signal from the sensor would not be easily readable.

2.3.3 Arduino Uno Board

The Arduino Uno is the control behind the solar apparatus. It is a microcontroller-based board that can be easily programmed to control sensors via an Arduino code written in a form of Java. The Arduino requires an input voltage of 7 to 12 V, so the boost converter is required to maintain the minimum voltage of 7 V. The Arduino Uno is then connected to an HX711 Analog Digital Converter to power the roadway sensor.

Table 1 Characteristics of dynatest PAST sensor

Specifications				
Type	PAST II (For AC or PCC)		PCCST (for PCC only)	
Range	Up to 1500 μstrain		Do.	
Configuration	Single strain gage (1/4 bridge)		Do.	
Cell material	Epoxy—Fiberglass		Do.	
Coatings	Epoxy—Silicon—PFT—Titanium		Epoxy—Silicon—PFT	
Resistance	120 Ω ±1.0%; GF=2.0		Do.	
Voltage	Up to 12 V (full bridge)		Do.	
Temperature	−30° to 150 °C	−22° to 300 °F	−30° to 150 °C	−22° to 300 °F
ΣE-modulus	≈2200 MPa	≈320 ksi	≈14,000 MPa	≈2000 ksi
Cross section	≈0.5 sq. cm	≈0.078 sq. in	≈0.25 sq. cm	≈0.04 sq. in
Cell force	0.110 N/μstrain	≈0.024 Ibf/μstrain	0.35 N/μstrain	≈0.08 Ibf/μstrain
Fatigue life	Theoretically up to 10^8 cycles		Do.	
Service life	Typically >36 months		Do.	

2.3.4 Wheatstone Bridge Sensor—5 kg Load Cell (Strain Sensor)

The Wheatstone bridge circuit is attached to the Arduino board. This sensor chosen was a 5 kg load cell (Fig. 2). It contains a Wheatstone bridge connection, which is accurate in measuring very low resistances without requiring a lot of power (Table 1).

Fig. 2 Dynatest wheatstone bridge connection sensor

2.4 Procedure to Build Solar Harvester

The two TEGs were connected in parallel by connecting the positive and negative wires with solder. Thermal epoxy was applied to the bottom end of the copper plate to act as an adhesive for the TEGs. The 2-bond epoxy was mixed with a stirring stick to ensure a proper homogenous mixture. The epoxy was then placed onto the hot side of the TEGs and attached onto the lip of the copper plate. After drying of the epoxy, shrink tubes were added to the negative and positive leads of the TEGs to secure the connection. The heat gun was applied to the shrink tubing which allowed the tubing to connect to the wiring. The shrink tubing replaced the black electrical tape and would ensure proper a moisture barrier from temperature changes. The epoxy was set for 24 h to allow proper drying time [9, 11].

Next, the thermal heat sink was attached to the cold side of the TEG. Another 24 h was required to allow the heat sink to dry completely. Styrofoam insulation with an R value of 2.8 was then cut out and attached to both sides of the 150 mm (6 in.) tall section copper plate. Electrical tape bonded the copper between the two pieces of insulation. Another section of Styrofoam was also attached to the bottom side of the 470 mm (18.5 in.) section. The insulation allows the heat loss from the sides and bottom the copper plate to be minimized, transferring the heat to the TEGs rather than to the surrounding pavement. An adhesive was used to hold the insulation in place.

The positive and negative ends of the TEGs were then soldered to the input side of the DC-DC boost converter. The boost converters set screw was turned to maintain a correct input voltage of 10 V for the Arduino board. The Arduino board can be powered from 7 to 12 V of power supply. The boost converters output pins are then soldered to a DC power cable (18 AWG), connecting into the DC barrel jack, allowing power to the Arduino Uno. The Arduino then connects to HX711 analog digital converter and the output connects to the 5 kg load cell sensor [5]. Code for the load cell was written in Java using the Arduino software. This code can be changed and altered depending on the type of sensor used.

2.5 Procedure to Install Solar Harvester and Sensor in the Field

To install the solar harvester and strain sensor, a cross section of asphalt pavement structure was developed as shown in Fig. 3. There was a preliminary survey with URI Facility officers at the Plains Road Extension on May 8, 2020. When a contractor cut out pavement sections, solar harvester and strain sensor were installed on June 29, 2020.

Figure 4 shows connections among the TEGs, boost converter, Arduino Uno, amplifier, and load cell sensor. Together, these units constitute the electronics of the

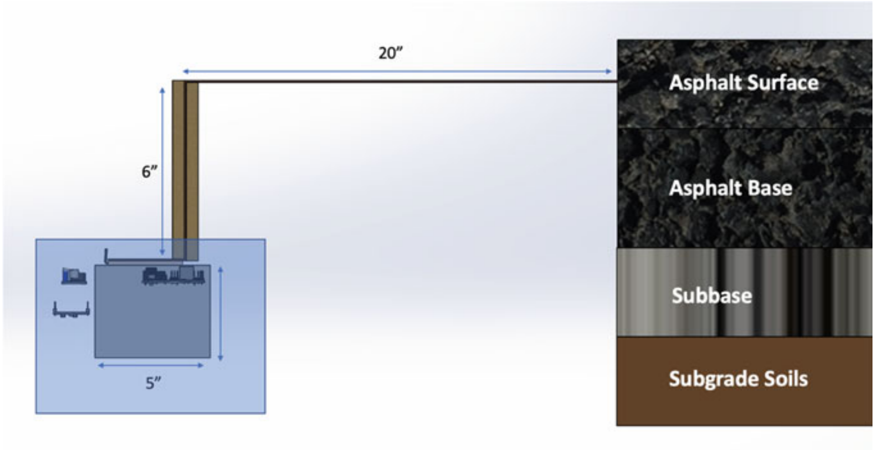


Fig. 3 Cross section of Solar Harvester, embedded in shoulder of road 25 mm (1in) below asphalt surface

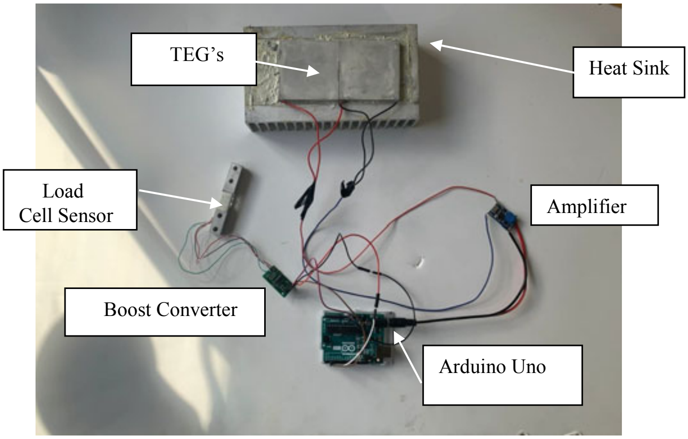


Fig. 4 Connections between TEGs, Boost converter, Arduino Uno, Amplifier, and load cell sensor

energy harvesting system. They were encased within an irrigation protection box for use in the field to protect them from moisture, rain, snow, and groundwater.

2.6 Verification Before Field Installation

In a laboratory-scale test of the electronics for powering the sensor, two AA batteries were connected in series as an initial test for a power supply to the Arduino Uno. The

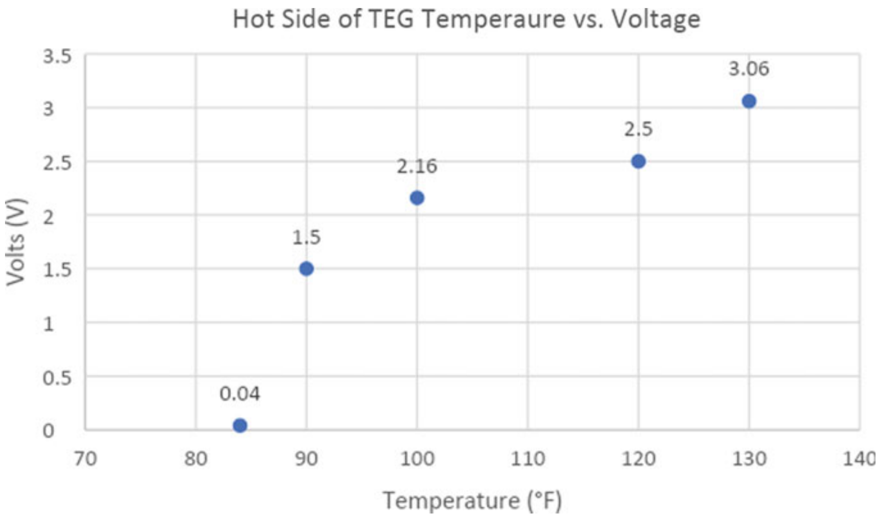


Fig. 5 Temperature of the hot side of TEG with its corresponding voltage; ambient air temperature 23 °C (74°F)

batteries were soldered to the boost converter and then the DC cable jack produced a current of approximately 200 mA, which successfully powered the Arduino.

The solar energy harvester was tested in the laboratory by applying a heat gun to the top layer of the copper. The copper was heated to approximately 54 °C (130º F). The copper was able to effectively transfer heat to the top layer of the TEG, resulting in a power generation of 3 V. This voltage exceeds the minimum two volts required for the boost converter, resulting in a powered Arduino. Varying the heating rate altered the temperature on the upper surface of the TEGs, which subsequently altered the voltage generated (Fig. 5). Even a hot-side temperature of 32.2 °C (90°F) was enough to generate some voltage when the cold-side temperature was 23.3 °C (74°F).

The load cell and Arduino were tested by using the five-volt USB jack on the Arduino and connecting it to a computer. The load cell was calibrated using Arduino software. The Arduino code allowed the Arduino to property read any loads (in grams) the sensor experiences; with collecting data continuously. Examples of these data are in Fig. 5.

2.7 *Installation*

The solar harvester was installed along Plains Road near the URI campus on July 29, 2020. The site was chosen to satisfy requests from the URI facilities office, who kindly incorporated the construction work into the scope of work of an existing project elsewhere at the university. Plans for the installation are shown in Fig. 6. A

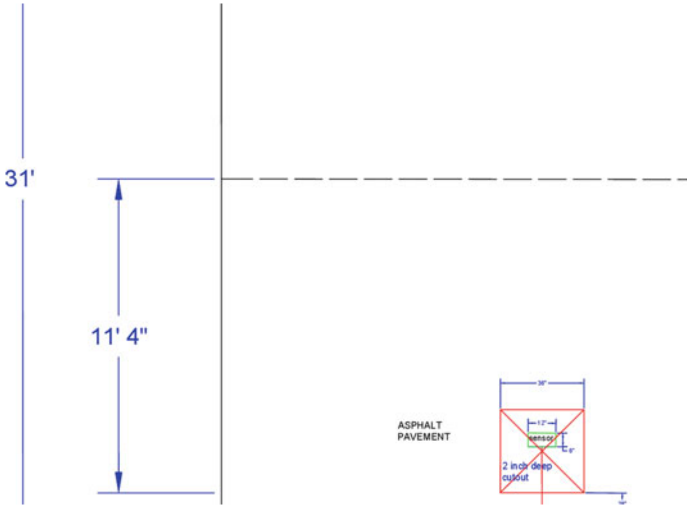


Fig. 6 Plans for the location, layout, and geometry of the installed energy harvester and strain sensor on Plains Road in Kingston, RI

realization of the plans on the road and shoulder, prior to construction, is shown in Fig. 7.

The first step was to dig a hole (Fig. 8) for the irrigation protection box to be inserted, which holds the electronics of the harvester. The hole was dug to the height of the irrigation box to make it flush with grade. The dirt was then back filled and compacted to hold the irrigation box securely. A 900 × 900 × 106 mm (36 × 36 × 4 ¼ in.) section of pavement was saw cut and removed from the road for the strain sensor. Next, the copper plate was inserted into the box with temperature gauges along the top, middle, and end section of the top surface. This allows for data collection of the varying temperatures along the copper heat plate.

The Dynatest strain sensor was placed into the base of the pavement cutout with the middle section of its H bar parallel with the roadway. The sensor was placed within the average passenger-side wheel path. The wiring of the sensor was placed in a 6¼ mm (¼ in.) sawcut line and sealed with silicon epoxy. Asphalt pavement was carefully placed over the sensor and hand tamped due to the sensitivity of the sensor. The remainder of the asphalt cutout was filled and compacted with a compacting machine, keeping away from the sensor. The asphalt temperature reading just before placement was recorded to be 110 °C (230°F). A 50 mm (2 in.) thickness of asphalt was then placed over the copper apparatus. It was compacted with the hand tamp and then properly dried. The next day, a hole was cut into the irrigation box to allow the end of the sensor wiring to be accessible in the irrigation box. The irrigation box has two bolts and two caps to make the top cover air/watertight.

Fig. 7 Markings for the saw cuts for strain sensor (in the road) and energy harvester (in the shoulder) on Plains Road

Fig. 8 Digging a hole for the irrigation box in the shoulder

2.8 Strain Measurement

The installed energy harvester and load cell strain sensor are now ready for in-field experiments. As a start, the sensor can be tested by using a P-3500 Strain indicator provided for the project by Kevin Broccolo of URI Civil Engineering. The wires connect into the wire jacks and the strain can be monitored.

2.9 Summary and Future Works

Further testing is needed to evaluate this implementation of the energy harvesting device into the roadway. Now that the solar harvester has been installed into the shoulder of a roadway, the ability of heat transfer to generate electrical energy needs to be tested in this real-world application. The temperature difference between the two TEGs will generate the required voltage to operate the roadway sensors. To enable output voltage by the TEGs below the asphalt surface layer, the harvester was installed with the copper plate 25 mm (1 in.) below the top layer. This allows temperature difference readings as well as maximum power output voltage. This copper plate will be heated from the sun heating the asphalt surface layer and transferring the energy into the harvester system.

During installation of the solar harvester apparatus, multiple K type thermocouples were placed among the solar harvester in the following areas:

1. Top part of road surface
2. Top of copper plate along two ends and middle
3. Hot temperature side of TEG junction
4. Cold temperature side of TEG junction
5. Cold temperature sink portion
6. Intermediate points along copper that transfers heat to/from the semiconductor, but not near it
7. Any sort of measurement in duplicate or triplicate for reliability.

These thermocouples will allow data to be collected. Subsequent analysis will enable estimating where thermal losses occur. Optimizing the harvester for efficiency and sustainability are top priorities.

RITRC recommends that a SD card or Bluetooth receiver be implemented into the solar harvester unit. This will allow data for retrieval to be stored without an external power source (i.e., computer), allowing the harvester to operate freely. The SD card/USB will be able to store the information from the pavement strain transducer or other structural health monitoring sensors. Data retrieval would be achieved simply by unplugging the card from the harvester unit and uploading it to a computer.

RITRC also recommends that the Dynatest Pavement Strain Transducer gets installed into the asphalt surface layer for strain monitoring of the roadway. This sensor is capable of 100,000,000 cycles and has a service life that exceeds 36 months.

Another recommendation is a box for the Arduino itself so it can be mounted inside the irrigation box without any movement of the electronic components. A box can be easily printed using the 3D printers if an appropriate size is not found in a commercial source.

This solar apparatus will allow any type of roadway sensor/road monitoring device to be installed. Any sensor can be programmed and configured into the Arduino board.

The solar apparatus can be further developed by creating a "manhole" for the electrical configuration of the harvester. A manhole will enable access to the electrical connection to allow different sensors to be tested from the Arduino board. It also prevents outside parameters from damaging the electrical connections. The recommended box configuration should be like an irrigation system box because it forms a watertight seal. Water cannot be allowed to enter the box because the electrical components would be compromised from the environment. The box will have to be approximately 300 mm by 300 mm (one foot wide by one foot) deep to allow proper room for the configuration. A small hole will have to be drilled through the box for the sensor wires going into the roadway. This hole can then be watertight by corking the remaining gaps in the hole.

It is also recommended adding an energy storage device such as a capacitor to the TEG's output wires to store voltage that is produced. The TEGs send current to the boost converter, but if there is not a continuous supply of two volts, the boost converter will not amplify the voltage to power on the Arduino Uno.

The Arduino can be turned on by a powered button that gets pressed/reset. Once the copper plate receives the required voltage from the heat generation, the Arduino can be turned on. To communicate with the Arduino board in the current set-up, a USB cord gets plugged into the Arduino with the other end into the computer. The software program *Arduino* should then be opened on the computer to read data from the apparatus. Code must be written in the software to run the sensor properly.

3 Thermodynamic Analysis of Solar Energy Harvesting Processes

The goals of thermodynamic modeling work are to assess the viability of the energy harvesting strategies that were considered. Most calculations were done for the thermoelectric energy generation approach.

3.1 Example of Heat Flow Condition During Thermoelectric Energy Harvesting

The energy harvesting system that uses a thermoelectric generator (TEG) was described earlier. It relies on bringing heat from a hot pavement surface down to the top surface of a TEG. Simultaneously the opposite side of the TEG is in thermal contact with cooler temperatures below the road. The temperature difference causes a voltage across a semiconductor. Connecting the opposite ends through a circuit allows for electrical work to be performed.

The heat is brought to the TEG through a copper plate. A wide upper surface warms the copper with an intent of it reaching the pavement temperature. Insulation along its sides is intended to allow heat to transfer *through* the copper and thus down from the surface while simultaneously blocking heat flow from the copper *into* the surrounding asphalt that is less hot.

A first calculation illustrates the rate that thermal energy can be carried through the copper to the TEG. Applying the First Law of thermodynamics within a thin section of the copper (the "system") indicates that heat flow changes the internal energy of the copper,

$$\mathrm{dQ} = \mathrm{Md}\,\hat{\mathrm{U}} \approx \mathrm{MC}_p\mathrm{dT} \quad (1)$$

The driving force for heat flow through an insulated portion of the copper is that there is a temperature difference between the asphalt near the surface and the buried location of the TEG. Fourier's Law of heat conduction expresses this driving force by using the thermal conductivity of copper,

$$\frac{\dot{Q}}{A} = k\nabla T = k\frac{\mathrm{dT}}{\mathrm{dx}} \quad (2)$$

Multiple sources cite a thermal conductivity k = 401 W/mK near room temperature for copper. Its heat capacity is Cp = 0.385 J/g°C at 25 °C [1, 2].

An estimate of the heat transfer rate can be made by replacing the derivative in Eq. (2) with finite differences in temperature and position. Here we assume a linear temperature gradient between 140°F (60 °C) and 68°F (20 °C) for simplicity along the 6″ length of copper. Inputting the dimensions of the copper plate and employing unit conversions as needed indicates

$$\dot{Q} = \mathrm{kA}\frac{\mathrm{dT}}{\mathrm{dx}} = (6.5 \times 0.0625\,\mathrm{in}^2)(401\ \mathrm{W/mK})\left(\frac{40\,\mathrm{K}}{6\,\mathrm{in}}\right)\left(\frac{0.0254\,\mathrm{m}}{\mathrm{in}}\right) = 27.6\,\mathrm{W} \quad (3)$$

We note that the temperature change of (60–20 °C) = 40 °C is identical in degrees Kelvin. The first factor on the right side provides the cross-sectional area of copper normal to the flow direction.

This calculation indicates that heat flow can proceed as quickly as 27.6 W between hot pavement and a cool TEG. The experiments of Chap. 3 involve work production rates that are closer to a range of 1–3 W. It can be concluded that sufficient energy is potentially available through heat transfer through the copper.

3.2 Example of Heat Flow Dynamics During Energy Harvesting

A more detailed example of the heat flow dynamics within the vertical section of the copper plate during energy harvesting can be obtained by combining Eqs. (1) and (2) into Fourier's second law of heat conduction,

$$\frac{\partial T}{\partial t} = \frac{k}{\rho C_p} \nabla^2 T \tag{4}$$

which can then be solved for the time- and position-dependence of temperature in the copper between positions $x = 0$ at the upper part with a hotter temperature (such as 140 °F or 60 °C) and $x = L$ at the lower part with a cooler temperature, such as 68°F or 20 °C. Solving this differential equation requires two boundary conditions in position and one initial condition in time. A possible initial condition specifies this lower temperature throughout the copper at $t = 0$. At $x = 0$, assume the hot temperature is maintained. To track the rate that the copper can heat up, neglect heat transfers out of the copper at $x = L$. From Eq. (2), this sets the temperature position derivative to zero.

When the thermal conductivity, mass density, and heat capacity are sufficiently independent of temperature, Eq. (4) can be solved analytically by using the separation of variables method. Briefly, it first is rewritten in terms of a dimensionless change in temperature compared to the warm and cool extremes,

$$\theta = \frac{T(x,t) - T_0}{T_1 - T_0} \tag{5}$$

Equation (4) remains the same with this substitution, other than T being replaced by θ. The boundary conditions become $\theta = 0$ at $x = 0$ at all times, θ ' $= 0$ at $x = L$ at all times; the initial condition is $\theta = 1$ everywhere at $t = 0$.

Next, the function $\theta(x,t)$ is written as a product of a time-dependent function $f(t)$ and a position-dependent function $g(x)$. Substituting these into Eq. (4), applying the derivatives, and rearranging leads to the differential equations

$$\frac{\rho C_p}{k} \frac{1}{f} \frac{\partial f}{\partial t} = \frac{1}{g} \frac{d^2 g}{dx^2} = -(\text{constant}) \tag{6}$$

The two equations for f and g must equal a constant because they are equal for various times and positions, with time affecting only the f equation and position affecting only the g equation. The negative sign in front of the constant is chosen for convenience later. Solving each side, applying the initial condition, and applying the boundary conditions leads to the following equation for the temperature change,

$$\theta = \frac{T(x,t) - T_0}{T_1 - T_0} = \sum_n \frac{2}{\pi} \frac{1}{(n-1/2)} \exp\left(-\frac{k}{\rho C_p} \frac{\pi^2}{L^2} (n-1/2)^2 t\right)$$
$$\sin\left(\pi(n-1/2)\frac{x}{L}\right) \tag{7}$$

Theoretically, the integer n spans from 1 to infinity. In practice, the exponential term ensures that contributions become negligible for large enough n at long enough times. Here, a maximum of 200 terms was chosen. The ratio $(k/\rho C_p)$ is called thermal diffusivity. It is often notated as α and has units of (length squared per time).

As an example of using Eq. (7), the temperature profile along the length $L = 6$ in of the copper plate going into the ground can be calculated. Temperatures of $T_0 = 140$°F $= 60$ °C and $T_1 = 68$°F $= 20$ °C are specified. Thermal conductivity k and heat capacity C_p are listed near Eq. (2) above and in Sect. 2. The density $\rho = 8.96$ g/cm^3.

Figure 9 shows results from the model over times from 0 to 300 s. As a consequence of the high thermal diffusivity of copper, which is largely attributed to its high thermal conductivity, the temperature rises rapidly along the copper plate. The temperature is predicted to exceed 110 °F over the first inch after only 10 s. The entire plate is predicted to reach 100 °F after about 1 min and 120°F after just over 2 min. After 5 min, nearly the entire plate has reached its upper surface temperature of 140 °F. This suggests that the copper plate setup will be effectively at bringing heat from near the hot asphalt surface down to the TEG.

While this model calculation is encouraging, it is not expected to correspond precisely with experimental measurements. It assumes that the temperature near the asphalt surface instantaneously reaches 140°F (60 °C) at time zero, as does the horizontal copper plate. In reality, the asphalt will heat up over time due to incoming

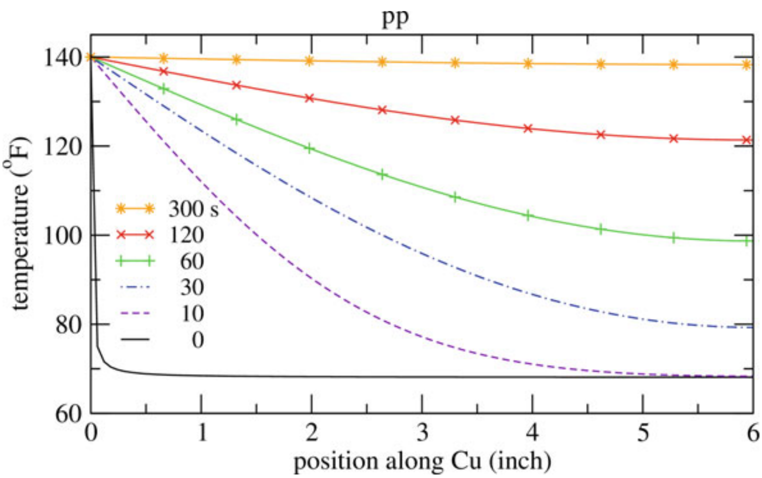


Fig. 9 Model results for temperature within the vertical copper plate, assuming perfect insulation along the sides and an instantaneous rise to 140°F at the top

solar radiation, and some time will be required to transfer that heat into the adjoining copper. This would provide a less sudden driving force for bringing heat to the TEG.

The calculation also neglects heat losses into the neighboring asphalt through the insulation. Such heat losses would cause a temperature gradient across the copper plate in its thin dimension at each time. The better the insulation, the smaller this effect. The rate of heat conduction into the insulation from the copper and into the asphalt from the insulation would each mediate these effects. Indeed, the intent of the Styrofoam insulation is to minimize the extent of this heat flow.

Calculations were not performed for the extraction of heat from the TEG via the heat sink. Fewer details about the geometry and the physical relationship between the heat sink and the road subbase were available for the calculations.

3.3 Summary from Modeling

A heat flow analysis of the TEG setup indicates that enough thermal energy flow is possible through the vertical copper plate to allow the TEG to generate electrical work at the desired voltages, though at low currents. A dynamic analysis shows that if the insulation works sufficiently well such that heat flow is channeled along the copper plate rather than through its sides, the temperature at the upper surface of the TEG can become very close to the upper pavement temperature. Thus, it is reasonable to consider a hot-side temperature driving force that is near the hot temperature of an asphalt pavement surface that receives solar heating.

4 Conclusions and Recommendations

An effort was made to create an efficient asphalt pavement solar collector using thermoelectric generators. Thorough testing was needed to evaluate the implementation of the energy harvesting device into the roadway. The temperature difference between the two TEGs will generate the required voltage to operate the roadway sensors. Now that the solar harvester has been installed into the shoulder of a roadway, the ability of heat transfer to generate electrical energy needs to be tested in this real-world application. To enable output voltage by the TEGs below the asphalt surface layer, the harvester was installed with the copper plate 25 mm (1 in.) below the top layer. This allows temperature difference readings as well as maximum power output voltage. This copper plate will be heated from the sun heating the asphalt surface layer and transfer the energy into the harvester system. Calculations show that this heat transfer is reasonable if heat flow along the plate into deeper asphalt layers can be neglected.

During installation of the solar harvester apparatus, multiple K-type thermocouples were placed among the solar harvester in the following areas: Top part of road surface, Top of copper plate along two ends and middle, Hot temperature side of TEG junction, Cold temperature side of TEG junction, Cold temperature sink portion, Intermediate points along copper that transfers heat to/from the semiconductor, but not near it, and any sort of measurement in duplicate or triplicate for reliability. These thermocouples will allow time and temperature data to be collected. Subsequent analysis will enable estimating where thermal losses occur. Optimizing the harvester for efficiency and sustainability are top priorities. An SD card or Bluetooth receiver was implemented into the solar harvester unit. This will allow data for retrieval to be stored without an external power source (i.e., computer), allowing the harvester to operate freely. The SD card/USB will be able to store the information from the pavement strain transducer or other structural health monitoring sensors. Data retrieval would be achieved simply by unplugging the card from the harvester unit and uploading it to a computer.

Another recommendation is a box for the Arduino itself so it can be mounted inside the irrigation box without any movement of the electronic components. A box can be easily printed using the 3D printers if an appropriate size is not found in a commercial source. This solar apparatus will allow any type of roadway sensor/road monitoring device to be installed. Any sensor can be programmed and configured into the Arduino board.

The solar apparatus can be further developed by creating a "manhole" for the electrical configuration of the harvester. A manhole will enable access to the electrical connection to allow different sensors to be tested from the Arduino board. It also prevents outside parameters from damaging the electrical connections. The recommended box configuration should be like an irrigation system box because it forms a watertight seal. Water cannot be allowed to enter the box because the electrical components would be compromised from the environment. The box will have to be approximately 300 mm by 300 mm (one foot wide by one foot) deep to allow proper room for the configuration. A small hole will have to be drilled through the box for the sensor wires going into the roadway. This hole can then be watertight by corking the remaining gaps in the hole. It is also recommended adding an energy storage device such as a capacitor to the TEG's output wires to store voltage that is produced. The TEGs send current to the boost converter, but if there is not a continuous supply of two volts, the boost converter will not amplify the voltage to power on the Arduino Uno. The Arduino can be turned on by a powered button that gets pressed/reset. Once the copper plate receives the required voltage from the heat generation, the Arduino can be turned on. To communicate with the Arduino board in the current set-up, a USB cord gets plugged into the Arduino with the other end into the computer. The software program *Arduino* should then be opened on the computer to read data from the apparatus. Code must be written in the software to run the sensor properly.

The Dynatest Pavement Strain Transducer was installed into the asphalt surface layer for strain monitoring of the roadway. This sensor is capable of 100,000,000 cycles and has a service life that exceeds 36 months.

A combination of dynamic heat transfer and thermodynamics modeling indicates that the use of a copper plate should enable heat from near a pavement surface to reach a TEG that is further below the surface to enable a voltage-generating temperature difference to be obtained.

If the advanced technology approaches begun in this research are successful, they will enable pavement lifetime through extracting energy from asphalt pavement, enabling it to persist at a lower temperature. Sensing equipment that is powered through thermally generated electrical energy will enable for ongoing monitoring of road quality and stress–strain conditions without ongoing external power requirements. This in situ power generation enables technologies that are being pursued within other projects of the RITRC [7].

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