Soil-Based Thermoelectric Energy Harvesting System for IoT Devices

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Abstract. This paper describes an approach to harvesting electrical energy from a thermal excited Peltier cell. To this day, Peltier cells have been used for cooling purposes as the most popular use among other projects. The present research dives into the possible use of these cells to generate enough energy to power sensors that can be used and introduced into the concept of IoT and, more specifically, Smart Cities. Taking advantage of the Seebeck effect and using a cylindrical shape to be easily installed into the soil, the developed solution was to generate enough energy to power a small IoT device, while charging a backup battery using the thermal difference for the proposed device. Throughout several tests and analysis, it was possible to, not only affirm that it is possible to generate energy but also achieve a design that works obtaining energy in an average day of up to 35 or 40% of the time. This approach can be used for different low power applications.

Keywords: Energy Harvesting · Low Power · Peltier Cells · Seebeck effect · Smart Cities

1 Introduction

The concept of Smart Cities lies in the idea of connectivity; "the wireless sensors, IoT (internet of things), networked and sharing technologies can offer a substantial service solution for smart cities". As technology keeps developing, more energy-efficient systems appear. To take advantage of the environment, currently, some IoT devices that help to bring the concept of Smart Cities to the present are outdoor sensors, providing data wirelessly throughout the city. These systems are designed to be as efficient and low-powered as possible, but until now their main source of power was batteries, so when the energy wears out, there is the need to change the battery. However, some of these devices have a battery life of up to five years or more. The innovation presented in the research of the paper is a system that will work for more than five years as the system is able to function properly without any external participation for an unlimited amount of time [3,6,9].

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Energy Harvesting (EH) is a technology that allows a different approach to this type of application and others; their implementation exists with different energy sources, such as photovoltaic (PV) cell, piezoelectric transducer (PZT), and thermoelectric generator (TEG). These are the energy harvesters that can generate power from the environment, converting one natural way of energy into electricity [8,12].

TEG (based on the Seebeck effect) is the one energy harvest that will be subject to study due to the ever-present temperature differences in everyday conditions. This type of behavior, if looked at closely, can be a power source that provides an advantage to many applications, not only in the frame of Smart Cities, but in any environment, from industry to nature. This project explores its implementation as a surface ground harvester with an easy installation, taking advantage of the thermal difference between levels of soil. This allows the system to generate electricity and be self-sufficient to power different applications.

As the intention is to design an energy harvesting device, it must be able to generate and extract energy for as long as possible, to work properly every time. For the system to achieve a high level of efficiency, it must be able to generate a minimum power throughout the entire year, which, depending on the geolocation of the application, may present significant implications. An approach that can work in most environments will be researched for both tropical higher temperatures and northern ecosystems; that way the system will be able to generate energy in both winter and summer, as well as in the transitive seasons.

Several tests and studies are presented, as well as the investigation with external information about the soil behavior. The support in other research was necessary and specific for the study to assure the optimal conditions.

There are several projects and research in the energy harvesting area, as the technology evolves towards self-sufficient systems and takes advantage of the available resources. Those projects go from automotive exhaust systems (Zang et al., [12]) to solar-based parking sensors (Solic, Leoni, et al., [11]) and hybrid energy harvesting systems (Yoon et al., [5]), such as solar thermoelectric hybrid power system (Babu & Ponnambalam, [2]).

Nonetheless, the purpose of this research is to explore a different perspective to the frame of energy harvesting, by proposing a system that is not only self-sufficient and simple, but also stimulates the transition to the concept of Smart Cities. This happens by providing a fast and flexible shift in some of the various Smart City sectors, such as smart environment, smart living and smart mobility, by using in situ sources of energy. These sources do not require external alterations in the surrounding's infrastructure and do not express any direct impacts on the located environment.

2 Soil Analysis Setup

To understand and extract relevant data of the proposed environments (different soil locations), a thermal acquisition probe was designed and built.

2.1 Probe Design and Characteristics

The probe was created to collect data on soil temperature and determine the proper length of the thermal conduction system. It consisted of a small box containing all the electronic equipment necessary for peripheral data, energy management circuits and storage for the collecting of the different temperatures.

The section inserted in the soil was an array of five DS18B20 sensors at different depths, which, to simplify the design, must remain below 20 cm of length and 2.5 cm in diameter, and have a cylindrical shape for practical reasons, since it only required a simple drill to perform the installation. The overall system architecture is shown in Fig. 1 as follows:

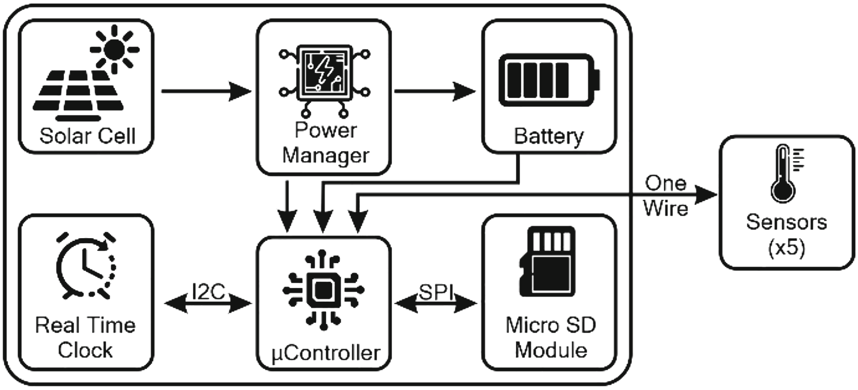


Fig. 1. Block scheme of the Soil Measurement System.

To achieve better autonomy, there were defined and implemented the following requirements:

- Use of low-power configuration to reduce power consumption by the microcontroller and peripherals.
- Implementation of a solar cell system to take advantage of the environment and increment system durability.
- Power management to avoid consumption of energy when sensors and modules are not being used.

The sensors got tested in a controlled environment to ensure that the measurements were accurate and verified with an error of the readings lower than $\pm 0.5\,^{\circ}\mathrm{C}$.

The microcontroller is in a low-power mode for five minutes until it "wakes up" and gets the sensors' readings and respective timing; then the data is stored into the micro-SD card, and the microcontroller goes back to "sleep" mode.

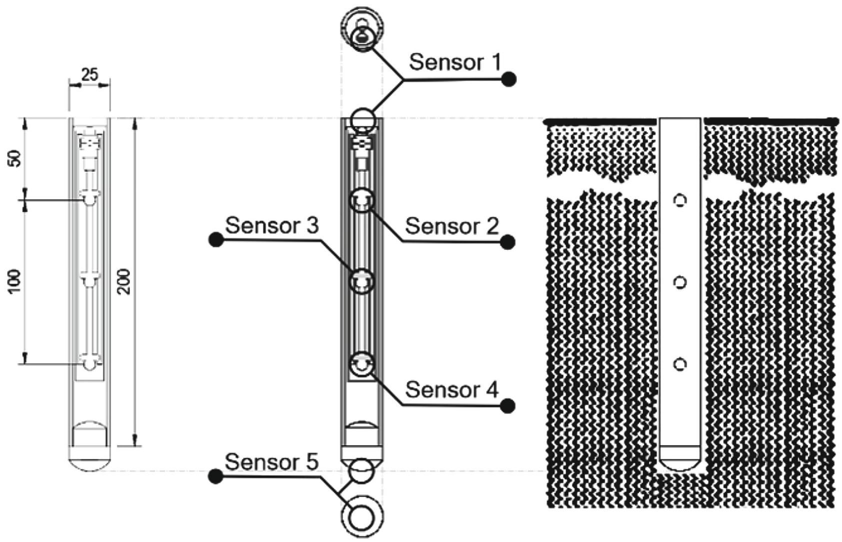


Fig. 2. Probe details and depth illustration on soil.

2.2 Probe Usage and Test Implementation

The probe was used to collect data from different scenarios, representing locations where the system might be implemented, all within the Braga District in Portugal. The surroundings, such as trees and buildings, have a direct impact on the soil's temperature.

Figure 2 presents the probe, built with five sensors located at different depths with the objective of acquiring different temperature readings to define the best approach for the device.

The left side of the illustration shows how the probe was introduced into the soil, leaving Sensor 1 exposed. The materials used to build the probe were made from PVC and PLA to avoid conducting temperature from one point to another.

One of the most relevant aspects of the data collecting operation was the methodology used to place the sensors. That is because the way to extract the dirt of the hole has a significant impact on the readings. As we might change the ground composition and structure while digging the hole, the approach involved designing a drill that was the exact diameter of the probe; with this tool, we not only preserve the order and composition of the environment, but we also test the concept of an installation for the system.

2.3 Location Characteristics

After every three consecutive days of readings, the probe was relocated to a new place to keep the environment analysis process.

The places where the probe was located varied in terms of surroundings with the goal of observing the different behaviors of the soil's temperature in different conditions. In terms of environment, the system was exposed to three main types of conditions:

– Open space with clear direct sunlight.
– Partially open space with some direct sunlight.
– Closed space with little to no sunlight.

Open space with clear and direct sunlight refers to open grassland without sources of shadow or cover from the sun; partially open space with some direct sunlight refers to spaces with trees and buildings where in some part of the day, the sun shines directly into the ground; and finally closed space with little to no sunlight where the sun was little or mostly not incident due to buildings, or trees nearby that make difficult for the sunlight to warm the soil. Besides the ideal environment, the data collected went through some weather changes, such as sunny days, partially rainy and cloudy days.

3 System and Hardware Evaluation

3.1 Thermal Simulation

Once the data was collected and some analysis on the results was done, the second part of the study was an approach on the thermal conductive simulation. The system, to function as best as possible, needs a way to conduct two different temperatures to one specific point. That could be done using materials such as iron and steel, which are excellent thermal conductors. Another great thermal conductor can be aluminum, which was selected due to its characteristics and non-corrosive properties.

This evaluation was designed to determine in which depth the Peltier cells should be used to assure more efficiency. To execute this, virtually simulation using a finite element method (FEM) in Fusion360 software was used and evaluated with several thermal characteristics and different materials for temperature conductivity. In total, three materials were evaluated, including aluminum, and four temperature differences.

The simulation software uses 5179 nodes and 2799 elements for the test. A proposed design of the system was introduced in the simulation, and the referential temperatures were added to the extremities of the device in order to simulate the conditions that would be obtained in the real test. Then, an estimation of the thermal behavior of the material is shown as a result, exposing the thermal conductivity losses and effectiveness. The conditions of the test are shown in Table 1.

3.2 Peltier Cells Characteristics

One of the most relevant aspects to determine in the development of the energy system is the Peltier cells used. For the test to try to identify the most effective ones, the following cells got tested:

Table 1. Material Characteristics used in the Simulation

	Aluminium	Porcelain	PET Plastic		Aluminium	Porcelain	PET Plastic
Density (kg/mm^3)	2.7E-06	3.4E-06	1.541E-06	Poisson's Ratio	0.33	0	0.417
Young's Modulus (MPa)	68900	0	2758	Yield Strength (MPa)	275	0	54.4
Ultimate Tensile Strength (MPa)	310	0	55.1	Thermal Conductivity W/(mm C)	0.23	0.002092	3E-04
Thermal Expansion Coefficient (C)	2.36E-05	0	7.02E-07	Specific Heat J/(kg C)	897	753	2287

- TES1-03102 (15 mm × 15 mm × 2.3 mm)
- TES1-03103 (20 mm × 20 mm × 5 mm)
- TES1-03104 (20 mm × 20 mm × 4 mm)

These cells differ in size and efficiency, where the smaller ones were TES1-03102 and the bigger ones were TES1-03104. These cells were selected to be compared in terms of size and efficiency, since the goal of the project is to create an EH device capable to fit specific limited dimensions to keep it portable and easy to install.

3.3 Peltier Cells Testing Setup

The Peltier cells testing setup consisted in simulating a controlled environment with conditions that will exist in the real outdoor solution that is being studied with the probe and simulation tools. Therefore, the Peltier cell will be exposed to different temperatures in both extremities, to see how it responds and how many volts can be generated from the difference of temperature that it is exposed to.

Two sensors DS18B20 are installed, one on each side of the Peltier cell; and for better thermal conductivity a thermal paste with a density of 2.0 g/cm^3 and thermal conductivity of 1.93w/mk was used to assure that temperatures were both accurately read by the sensors and properly transmitted to the Peltier cell.

The scheme presented in Fig. 3 shows that the data is recorded by serial port. The experience environment was controlled by a cooler which was configured to set the ambient temperature at 20 °C; the Peltier cells were submitted on one end to a controlled heat plate and the other end to a fan cooler to generate a differential of temperature. Each side had a sensor with the intention to keep a close track of the temperature.

The heat plate operates manually by setting the desired temperature in Celsius.

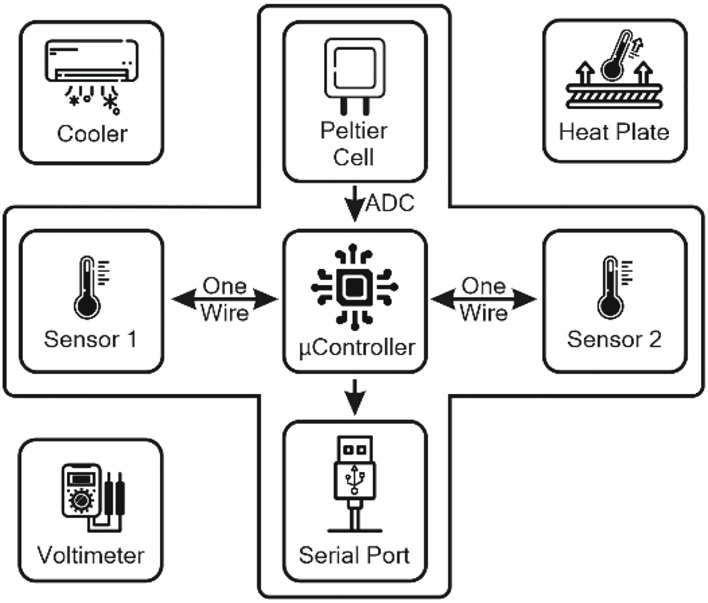


Fig. 3. Block scheme Peltier measurement system.

3.4 Peltier Cell Test and Procedure Implementation

The Peltier cell was exposed to different temperatures on each side and generated an electric voltage in the terminals of the cell, measured with a microcontroller as shown in Fig. 3 with an ADC input. The microcontroller worked with a reference value of 1.1V and a resolution of 10 bits. To confirm the readings a voltmeter was used.

In the experience, the start point is when both the heat plate and the other extreme of the cell are at the same temperature, which means $\Delta 0$ (20 °C in each side). At that point the temperature of the heat plate will be increased in steps of 5 °C until it reaches a maximum of a $\Delta 20$ °C. Then a cooldown process will be initiated in which there is no data being collected. This process ends when the initial conditions are met.

To do effective analysis and avoid errors, each test was repeated five times to ensure that the data was accurate and has a solid base. Not only single cells were tested but also groups of the same cells in different configurations, to determine if there is a possibility to obtain more energy without compromising the initial goals of the project.

These tests were:

– Using two cells one on the top of the other, creating a "sandwich" formation, where one extreme of one cell will be directly exposed to one side and the other cell to the other.

– Using both cells side by side where both cells are exposed to the same temperatures in both sides.

In both tests, a serial electrical connection was used to get a higher output in voltage. Lastly, the polarity effect was tested, which means exposing the other side of the cell to the inverse temperature to understand if it is possible to generate the same energy in the inverse polarity of the cell.

4 Results

4.1 Soil Behavior and Probe Results

The data in the tests was collected between April and May of 2021, and the location where those tests took place was Braga District in Portugal. By that time the season was Spring, therefore the data obtained is only a portion of an entire year.

Once the data was ordered, it was possible to observe the temperature's behavior in an optimal sunny day, in graphic terms, as follows:

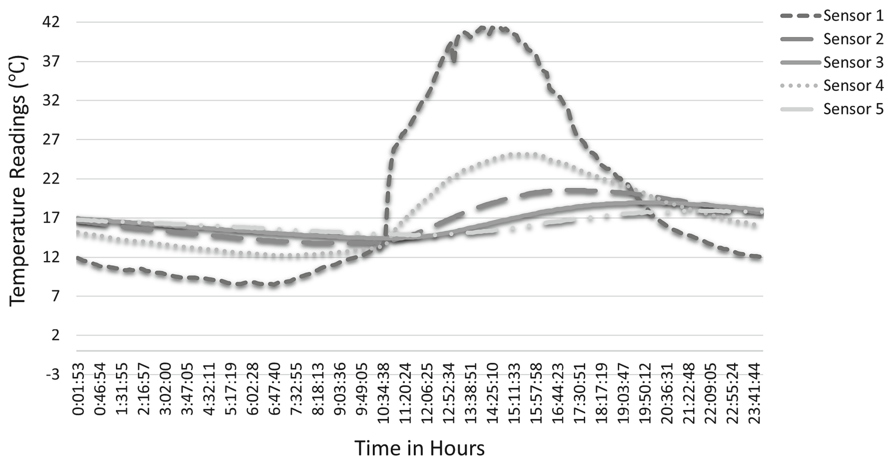


Fig. 4. Graphic behavior of the soil temperature variation for one days.

As shown in Fig. 4 it is possible to understand that the temperature difference has a larger delta between Sensor 1 and Sensor 5. This profile occurs due to a higher temperature stability that is directly correlated with the depth of the soil. This presents as opportunity for EH and will be object of analysis through this chapter. Therefore, for the data analysis, all data shown forward will focus on the data obtained by Sensors 1 and 5 since the others do not represent any particular interest to the project and the implementation that follows the development.

Since there are several variables attached to the conditions, the data presented will be arranged first as an overall view and then the further specific

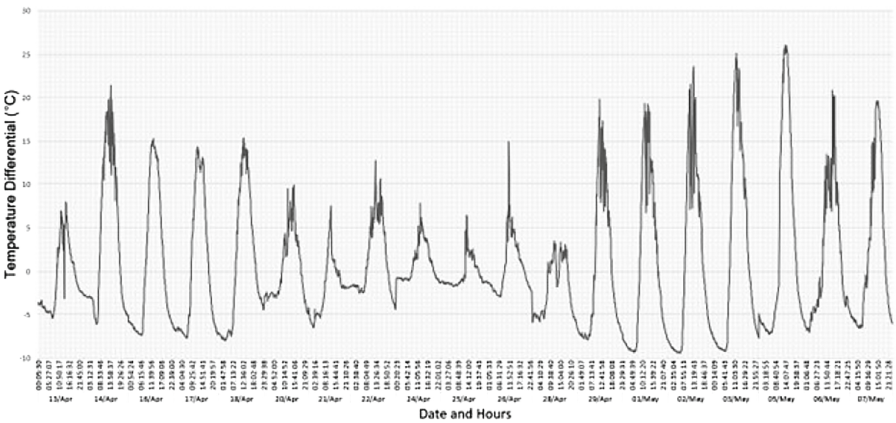


Fig. 5. Graphic of the temperature differentials in the data collected.

analysis will be presented to generate a solid base of the information in this section.

Figure 5 presents all data from different data points with different ambient conditions, creating a direct impact on the temperature presented in the probe. When the differential goes below zero that means that the surface of the soil is cooler than the bottom of the probe. Normally during the Spring season these conditions occur during nighttime.

With the information we have in the picture we can affirm that at least once a day and in every scenario the probe must be able to detect at least a difference of 5 °C.

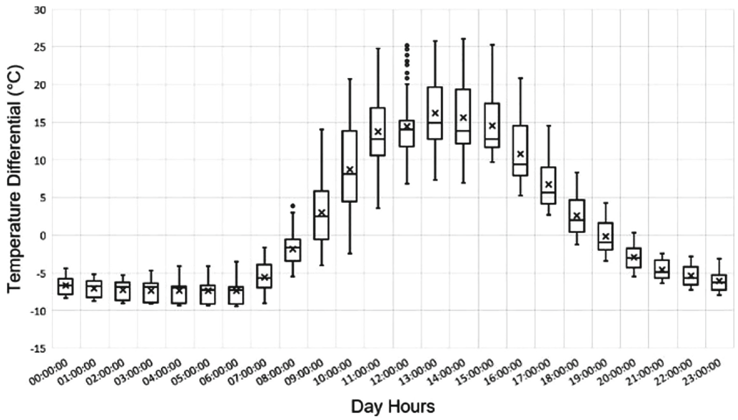
As the data was collected in different data points, the behavior of the data in the three specific conditions will be shown in the following figures:

In Fig. 6a it is possible to see the behavior of thermal difference between the surface of the ground and 20cm deep. The conditions of this data are an open space with direct sunlight most of the day, considered optimal conditions for the project.

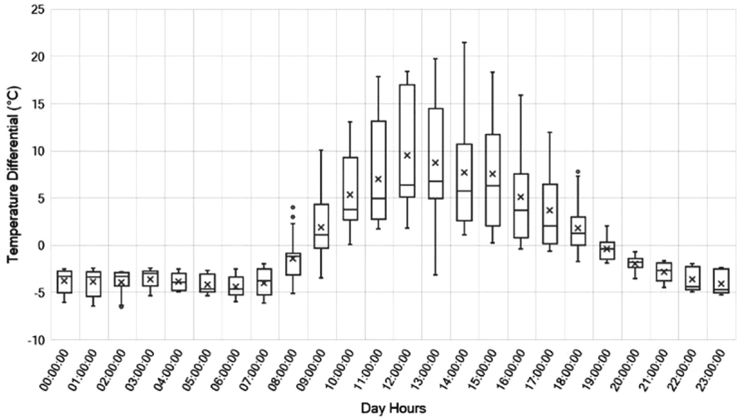
Figures 6a, 6b and 6c show the three conditions where the analysis was located. The location is an important factor to consider in order to have a real understanding of the environments' behavior. The weather conditions also represent an important variable since it has a direct impact on the temperature in the ambient and the rain might have some thermal effects on the deep soil.

Table 2 illustrates the average hours during which the temperature difference falls within the specified ranges.

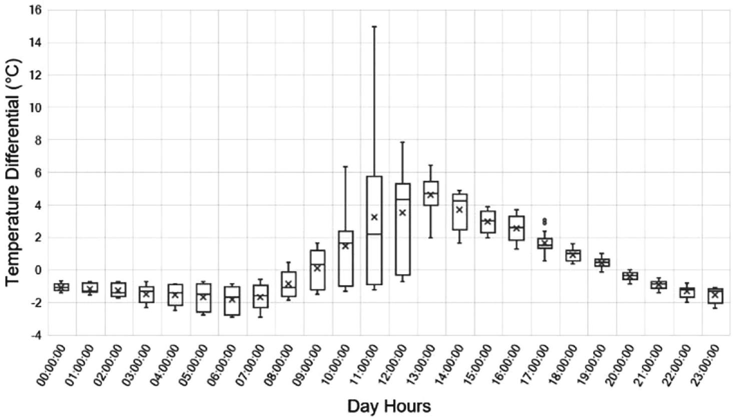
As part of the relevant information regarding the weather conditions, the dates from 24/Apr to 26/Apr, which are from group 3, were rainy days.



(a) Data from nine days in an open space clear direct sunlight.



(b) Data from seven days in a partially open space with some direct light.



(c) Close space with little to no sunlight data from three days.

Fig. 6. Variation in different scenarios

Table 2. Duration of a temperature difference by location

Delta Interpretation (ºC)			
Temperature parameter	Group 1[a]	Group 2[b]	Group 3[c]
$-10\,^\circ\mathrm{C} < \Delta T < -5\,^\circ\mathrm{C}$	8:23:30	3:36:14	0:00:00
$10\,^\circ\mathrm{C} > \Delta T > 5\,^\circ\mathrm{C}$	1:57:14	2:10:20	0:47:24
$-15\,^\circ\mathrm{C} < \Delta T < -10\,^\circ\mathrm{C}$	0:00:00	0:00:00	0:00:00
$15\,^\circ\mathrm{C} > \Delta T > 10\,^\circ\mathrm{C}$	2:45:47	0:47:40	0:03:47
$\Delta T < -15\,^\circ\mathrm{C}$	0:00:00	0:00:00	0:00:00
$\Delta T > 15\,^\circ\mathrm{C}$	2:02:36	0:32:47	0:00:00

[a] Open Space and Clear direct sunlight
[b] Partially open space some direct sunlight
[c] Close space with little to no sunlight

Table 3. Hours of Thermal difference higher than five degrees.

Data Groups			
	Group 1	Group 2	Group 3
Total Positive Hours ($\Delta T > 5\,^\circ\mathrm{C}$)	6:45:36	3:30:47	0:51:11
Total Negative Hours ($\Delta T < -5\,^\circ\mathrm{C}$)	8:23:30	3:36:14	0:00:00
Total Hours	15:09:06	7:07:01	0:51:11

4.2 Thermal Simulation Results

The data obtained by the simulation of thermal conductivity for the creation of the system shows the following results:

Figure 7 presents the different configurations that might become the solution for the system, as the position of the cell might have a direct impact on the performance of the energy harvesting solution. The three arrangements show the different possibilities, and below the delta difference achieved in each attempt.

4.3 Peltier Energy Generation and Study Results

The present test was performed in a controlled environment which enables better control of the test conditions and variables.

In Fig. 9 we can see energy generated for two cells arranged in different ways; the two configurations were defined as "Sandwich" and "Parallel".

5 Analysis and Discussion

5.1 Energy Generated by Peltier Cell

Figure 8 shows the energy generated by the different cells used; the results have shown that even when there is a difference in the size of the cells, it did not represent a significant change in the energy generated by the cells.

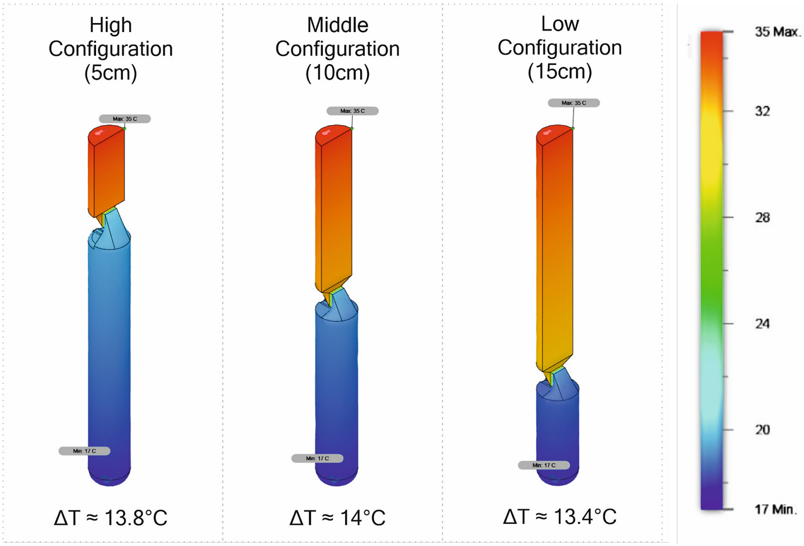


Fig. 7. Temperature transmission from material conduction.

The voltage generated by the cells with a differential of 5 °C is near 30 mV, which is the minimum voltage needed by the LTC3109, the energy harvesting IC responsible to harvest the energy from the Peltier cells.

5.2 Thermal Simulation

Figure 7 shows how, according to the spot in the system where the Peltier cell is located, the performance might be affected. The data points towards a middle solution as being the most effective in terms of thermal efficiency, even when the difference is not significant in terms of temperature. However, when it comes to energy harvesting the goal is to assure the best possible conditions to obtain the ideal outcome.

5.3 Soil Behavior

As shown in Figs. 6a, 6b and 6c, the behavior could be significantly different given the type of location and the surroundings where the system is located. Data shown in Table 3 suggests that the first two groups show significant temperature differences in comparison with group 3. Group 3 has two conditions that need to be considered, which are the poor sunlight and the fact that the data collected was on rainy days. Nevertheless, the information serves to identify the poor conditions for the system to be installed.

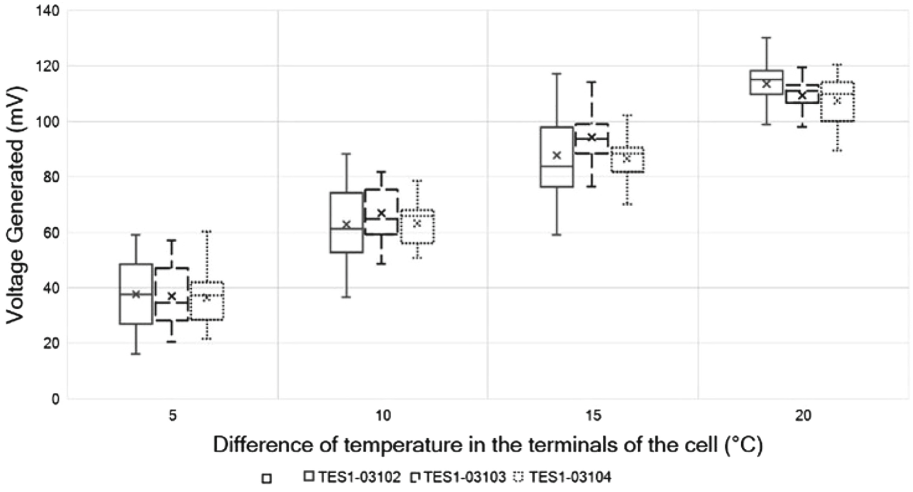


Fig. 8. Peltier cells output generation comparison.

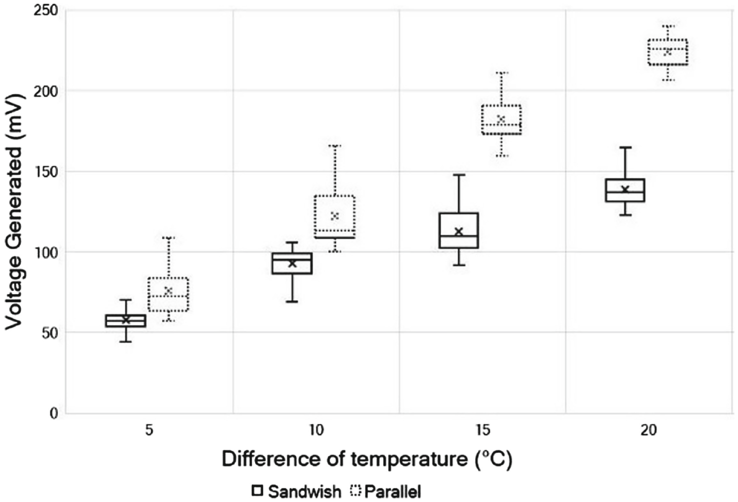


Fig. 9. Peltier cells coupling analysis.

6 Final Proposal

The final version of the system should use two TES1-03102 Peltier cells since they are the smaller ones and, as shown in Fig. 8 and discussed previously, there is not a significant difference between them in terms of power generated.

The combination used will be Parallel of two cells to ensure more energy output since Table 3 points towards a difference of ±5 °C as being the most common condition, meaning that for the system to have a solid base of working

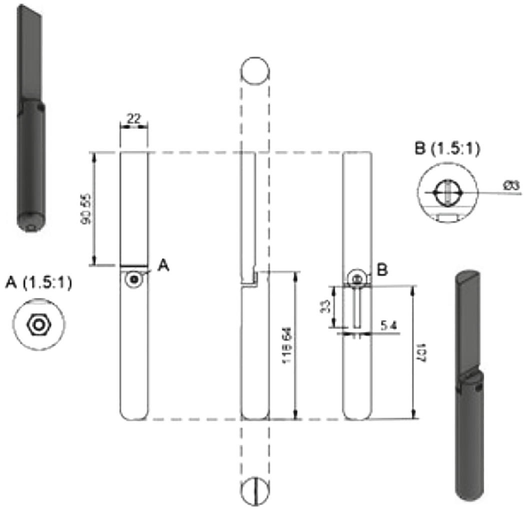


Fig. 10. Device aluminium frame for thermal conduction to the Peltier cells.

it should start working properly at a minimum of that temperature. Data shown In Fig. 8 seems to point that one cell should perform correctly because it can generate nearly 40 mV with a difference of 5 °C, but as the thermal simulation suggests there is some thermal loss in the conduction of the temperature to the cells. This means that the goal should be higher to ensure that the minimal conditions are obtained.

The test, as shown in Fig. 9, reveals that with a delta of 5 °C there is a voltage higher than 50 mV with the Parallel configuration and is significantly superior to the Sandwich configuration. That is the reason for deciding to use the two cells in a Parallel configuration to deliver the best possible conditions with all the data supporting this decision.

In Fig. 10 it is possible to see a final proposition of the solution with the Peltier cells side by side in the middle of the cylinder.

As for the electronics involved in the solution as mentioned before, the LTC3109 for the energy harvesting management device, and the LTC4070 for the battery charger manager, should be pursued as the best combination of those IC's as seen in the respective documentation (LTC3109 Typical Applications) [1,10].

The configuration used for the energy harvesting system, is to have the Peltier cells plug into delivering power to the application connected on the tension output and the Li-Ion battery connected to the LTC4070.

The kind of battery used might differ from project to project and in this matter, further alterations to the system might be needed. The device shown in Fig. 10 serves for any auto-polarity thermoelectric application.

7 Conclusions

Data presented shows that the system could be very promising as an energy harvesting solution. Although the tests have shown some conditions in which the device might not have optimal performance, the information obtained points toward an interesting system that might be functional and self-sufficient. More tests and analysis should be performed to ensure that the system will work as intended.

The behavior seen by the tests performed in this investigation matches other soil studies that confirm that the soil temperature has oscillations and this behavior is an excellent opportunity to take advantage of and be used to generate energy from it [4,13].

Test and analysis of the Peltier cells were made by laboratory analysis and then compared with external research to validate the results obtained by the test [7].

With all the analysis of the data acquired during this research and the resources and references obtained in this paper, the viability of the creation of the system is not only high but with further test and information, it is completely possible to develop this system for different kinds of applications. Nonetheless low-power applications are the most interesting field for this first generation of systems because the chances of good performance are ensured.

The study encounters some limitations as the data used for the validation of the sensor is from one single season of the year. One should go throughout checking an entire year of different conditions and extensively validate the data to observe the behavior of the soil along the year. Some important studies in difficult conditions need to be also done to see where the limits are for the proper function of the system.

As this solution passes forward to be implemented in specific IoT projects and low-power applications, more information about the energy harvesting performance and limitations will be available to transform this proposition into a more stable solution for implementation.

Regarding the initial goals, not only the solution presented shows excellent potential, but also identifies the liabilities, with the help of the validation of the system, allowing these liabilities to be spotted even before the main solution was presented. This analysis serves as milestone for further investigation in the TEG technology as a source for IoT applications with simple and useful easy-to-install solutions.

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