Energy Autonomous LPWAN Node for Walls and Bridges: 4 Seasons Results

Prof. Dr. Marcel Meli
University of Applied Sciences, School of Engineering
Institute of Embedded Systems
Winterthur, Switzerland
marcel.meli@zhaw.ch

Benjamin Maij
University of Applied Sciences, School of Engineering
Institute of Embedded Systems
Winterthur, Switzerland

***Abstract*—Measuring and monitoring the state of infrastructure built with concrete, such as buildings or bridges, is important to prevent damages or other serious issues. Some requirements for monitoring devices are long operation lifetime, robustness against adverse temperatures or weather conditions, low maintenance costs. Providing access over long distances to the measurement data is a welcome feature. Due to harsh temperature conditions and maintenance costs, batteries might not always be a recommended energy source. One approach is to harvest energy in the operating environment using Thermoelectric Generators (TEG). This energy harvesting method takes advantage of the temperature differences between ambient air and concrete to convert thermal energy into electrical energy. This work presents the results of a yearlong investigation of an energy autonomous long range wireless node installed on a bridge and powered by harvesting energy from temperature differences. The work concentrates on the reliability of the energy source and shows that, apart from a few days in November and December, sufficient energy can be harvested to transmit several LoRaWAN compatible messages per day with sensor data as payload.**

Keywords—TEG; concrete infrastructure; energy harvesting; infrastructure maintenance; LPWAN; supercapacitor; low-power; temperature differences; long range; LoRa; LoRaWAN

I. Introduction and Aim of this Work

Measurements that determine the condition of concrete infrastructure such as bridges, dams, residential buildings, retaining walls, subways, and similar infrastructures are important to monitor their state or even avoid disasters in extreme cases. With appropriate sensors, one could reduce costs by preventing unnecessary maintenance work. Condition measurements are carried out over several decades and usually require electrical energy. This energy could be obtained from batteries. However, batteries are often not recommended for use in low or high temperature environments. They also have the disadvantage that they are expensive to replace. An alternative is to use solar cells, which convert light directly into electrical energy. They can only be operated when there is sufficient light intensity. Dirt or contamination of the photocell can reduce their efficiency and make them unusable. Thermoelectric generators (TEG) in combination with appropriate DCDC converters and electrical energy storage devices make it possible to gather sufficient electrical energy on concrete infrastructures even with small temperature differences. Temperature gradients of a few degrees Celsius between air and concrete infrastructure are usually given by the day and night cycle and the change in weather. TEGs are also robust in harsh environment. The aim of this work is to investigate the applicability and reliability of TEGs as electrical energy sources for energy autonomous IoT sensors. For that purpose, an IoT sensor node was mounted on a concrete bridge for the duration of one year [1,2]. The bridge used is in Switzerland, in the canton of Thurgau. A similar work has been presented in [3], where the TEG is fixed to a tree instead of a concrete wall.

II. Temperature Difference as Energy Source

Thermoelectric generators (TEG) serve as harvesters, which directly convert the temperature differences between the concrete infrastructure and the ambient air into electrical energy. The main components of such a system are shown in Fig. 1. The Temperature between heat sink and TEG, and concrete infrastructure and TEG were measured to determine the temperature difference. For further explanation the measured temperatures at both sides of the TEG are plotted in Fig. 2. In addition, the ambient air temperature recorded from a local weather station is plotted [4]. The temperature curves clearly indicate the thermodynamic behavior of ambient air, heat sink and concrete infrastructure for one day and night cycle. Ambient air is most dynamic, followed by the heat sink and the concrete infrastructure, which has the lowest dynamic. The cyclic temperature differences applied to the TEG is the result of the differences in dynamics. In a better optimized energy harvesting setup, the heat sink temperature should be as

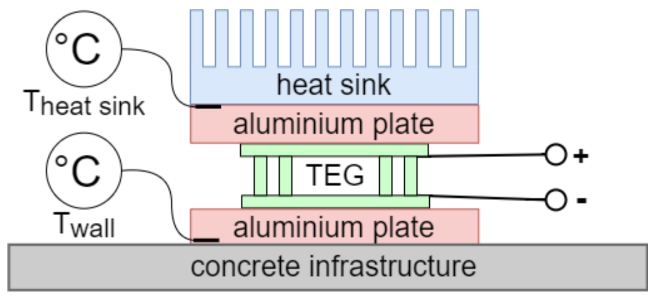

Fig. 1. Overview over the main components of TEG as energy harvester. A temperature sensor is placed in each of the thermoconductive aluminium plates.

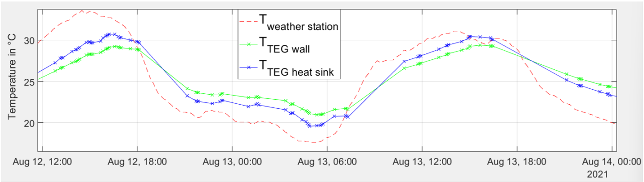

Fig. 2. Temperature curves of ambient air (red), TEG heat sink side (blue) and TEG wall side (green)

close to the ambient air temperature as possible. The sign of the voltage at the TEG output can be positive or negative, depending on the temperature difference. It means that the power management electronics should take that variation into account.

III. Requirements for the Energy-Autonomous IoT Sensor Node

The TEG output voltage is normally in tens of millivolts, which is too small to be used directly to power most electronic components. A bipolar DCDC converter boosts that output, independent of its sign. By means of a power management unit and an energy storage device (supercapacitor), sufficient energy is accumulated to operate an IoT sensor node. Once there is enough power, the embedded system is started for measurement and communication. The MCU of the sensor node has the task of reading out external sensors. The measured data is transmitted over the air, using LoRaWAN with maximal range configuration (SF12 with +14 dBm in Europe), via the Swisscom network (LoRaWAN gateways) to a back-end server. The server and corresponding software receive and store the measurement data for later use. Fig. 3 gives an overview of the main hardware components of an energy autonomous IoT sensor application using LoRaWAN.

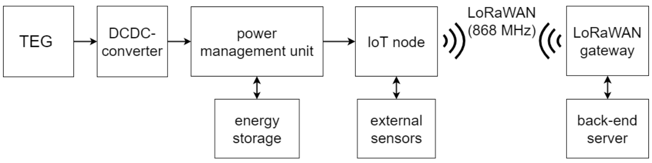

Fig. 3. Overview of the main hardware components of an energy-autonomous IoT sensor application

IV. Method to Estimate the Harvested Energy

The harvested energy of the energy autonomous IoT sensor application is estimated by counting the number of frames transmitted by the sensor node and multiplying it with the reference energy consumption. That reference was determined by measuring the mean energy consumption of one single measurement and transmission sequence. The reference energy consumption is 190.86 mJ. Since the standard deviation of the reference is 0.45 mJ (0.2 %), the mean energy consumption is considered to be constant. As an example, for 20 transmissions 20 x 190.86 mJ = 3.82 Joules are considered to be harvested.

V. Findings

A. Discussion of a day with "good" harvesting outcome

Fig. 4 shows three temperature curves of 24th April 2021. The red curve shows data from a local weather station close to the place where the sensor node is installed. The green and blue

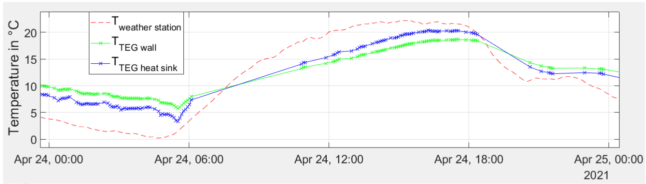

Fig. 4. Temperature curves of ambient air (red), TEG heat sink side (blue) and TEG wall side (green)

curves show temperatures measured and transmitted by the sensor node. On that day, the sensor node harvested enough energy to operate 126 times in 24 hours. This is equivalent to at least 126 x 190.86 mJ = 24.0 Joules of harvested electrical energy. During that day, the temperature of ambient air ranged from about 0.1 °C to 22.6 °C.

B. Discussion of a days with worst harvesting outcome

Fig. 5 shows the temperature curves of multiple days in November 2021, where the harvested energy was not always sufficient to operate the sensor node. On the 11th November three measurements were transmitted. On the 14th November one single measurement was transmitted. During that day the temperature range of ambient air was from about 6.9 °C to 9.6 °C.

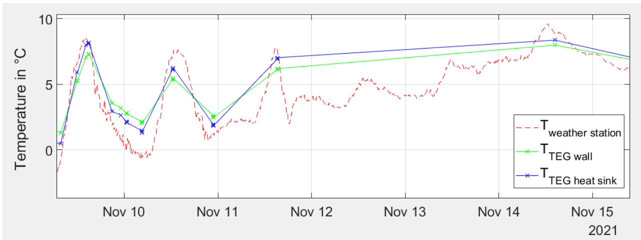

Fig. 5. Temperature curves of ambient air (red), TEG heat sink side (blue) and TEG wall side (green)

An examination of the detailed results shows that the longest period without transmission was 4 days in December. Some applications can tolerate days without measurements, others not. In many cases, energy can be stored to bridge some outage periods. The measurements considered here are in units of 190 mJ. If less than 190 mJ is harvested, it is not considered. With the appropriate type of memory, one may use less energy to measure and store the data, but not transmit. It means that measurement will still be possible, but transmission would have to wait until there is enough energy.

C. Range of sufficient temperature difference to operate

The temperature differences at mark 1 and mark 2 in Fig. 6 define an upper bound of the minimal sufficient temperature difference needed to operate the sensor node. The absolute temperature difference at mark 1 is 0.7 °C and 0.8 °C at mark 2. The accuracy of the temperature sensor is ± 0.1 °C. Since the temperature measurements at mark 1 and 2 were done by the sensor node itself, we can estimate the minimal sufficient temperature difference to operate between 0.5 °C and 1.0 °C.

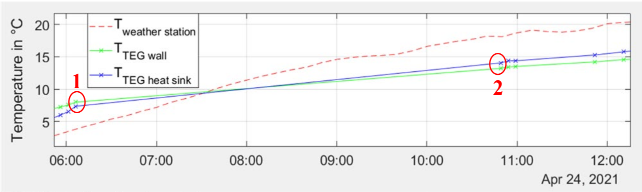

Fig. 6. Temperature curves of ambient air (red), TEG heat sink side (blue) and TEG wall side (green). Mark 1: |ΔT| = 0.7 °C, Mark 2: |ΔT| = 0.8 °C

D. *Monthly harvested energy*

Fig. 7 shows the average of the daily harvested energy on a monthly base. During the winter months, drastically less energy was harvested compared to the spring months. The overall average energy per day was 5.5 Joules.

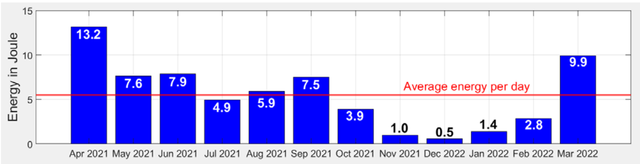

Fig. 7. Visualisation of mean harvested energy per day on a monthly base

CONCLUSIONS AND FUTURE WORK

Operating an energy autonomous IoT sensor node mounted to a concrete bridge for one year gave information about applicability and reliability of TEGs as electrical energy sources. The energy harvested varies from day to day. On one winter day, an ambient temperature changed about 2.7 °C, sufficient energy was harvested to operate the sensor node exactly once, which corresponds to approximately 0.19 Joule. On some days not enough energy was harvested. On one spring day, when the ambient temperature changed about 22.5 °C, sufficient energy was harvested to operate the sensor node 126 times. This leads to a range of daily harvested energy from zero to 24.0 Joules. The mean harvested energy per day was 5.5 Joules. On a monthly base, the mean harvested energy per day was between 13.2 Joules in April 2021 and 0.5 Joule in December 2021.

Based on the research of this work the use of TEGs as energy harvester for IoT nodes in various environments and applications might be considered to replace conventional batteries and to enhance lifetime and reduce maintenance costs.

REFERENCES

[1] B. Maij, “Bachelor Thesis: Energy Autonomous Sensors for Bridges”, December 2020

[2] Unpublished work. LPWAN nodes powered with TEGs mounted to concrete infrastructure

[3] M. Meli. L. Hegetschweiler
Harvesting energy from trees in order to power LPWAN IoT nodes
Wireless Congress 2018, Munich, 21-22 March 2018
https://doi.org/10.21256/zhaw-18842

[4] Measurement data of ambient temperature of local weather station, 1st April 2021 – 31th March 2022, Bundesamt für Meteorologie und Klimatologie, MeteoSchweiz