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# Waste heat energy harvesting system for winter monitoring of honeybee colonies

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**Abstract**

As the most commonly managed bee in the world, the European honeybee significantly impacts agriculture via crop pollination. The increasing occurrence of weather extremes caused by climate change, together with diseases and human activity, provoke the winter loss of numerous colonies of managed bees in Europe and around the world. This work proposes an autonomous system aimed at monitoring managed honeybee colonies to estimate the size and strength of the winter cluster. The system comprises temperature sensors strategically placed within the hive, as well as a communication module allowing data transfer, and it is powered by using the energy harvesting approach, i.e., a thermoelectric generator (TEG) able to utilize the temperature gradient between the hive interior and the environment. All the system components in direct contact with the colony are to be designed in such a way that their impact on the colony is minimised, as well as by respecting the so called "bee space". Initial measurements in a conventional Langstroth hive, combined with a validated finite element TEG model, have clearly shown the possibility of generating a sufficient amount of electrical energy to power the foreseen design setup.

Energy harvesting, thermoelectric generator, hive monitoring, autonomous sensors

## 1. Introduction

The European honeybee (*Apis mellifera*) represents the most commonly managed bee in the world, with a significant impact on agriculture (crop pollination). With growing effects of climate change, new pests and diseases as well as human activity, about 10 % of managed bee colonies in Europe succumb to winter losses each year [1–3]. In fact, in a cold winter environment the colony has to maintain the individual bee's body temperature of at least 16 °C, while the temperature of the brood needs to be around 35 °C [4, 5]. To achieve such conditions, a considerable metabolic production of energy is needed, with honey reserves being utilized by the bees as the primary energy source. The cluster should be warm enough to enable the colony enough mobility to defend itself, as well as to reach the honey stores.

**Figure 1.** A honeybee colony in a winter cluster [5]

The colony forms therefore a tight cluster within the hive, as shown in Figure 1, typically ranging from ~ 100 up to ~ 240 mm in diameter, corresponding to approximately 3 - 7 standard Langstroth frames. The colony also has to manage its food stores in order for them to last until spring [3, 4].

Generally, if a colony declines or dies out during winter, a considerable amount of time may pass before it is noticed by the beekeeper (typically upon the first spring inspection), and by that time clues to the causes of such events are lost [1]. To determine the causes, the timely sampling and analysis of honeybee colonies is, therefore, required.

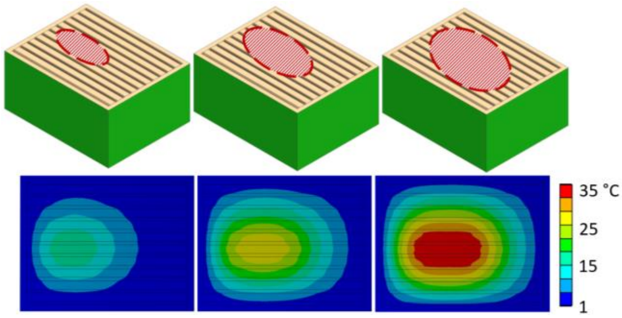
## 2. Hive monitoring

In the last decade there was a significant increase in the use of electronic systems aimed at monitoring the state of honeybee colonies. These systems, both commercially available as those under development, most commonly measure temperature and humidity in a single point within and outside the hive. To perceive soon enough the nectar flow in spring, in some specific cases additional parameters are also monitored, e.g. the presence of the queen, brood temperature or the mass of the hive [6–8]. Such systems are almost exclusively powered by conventional batteries, which necessitate periodical human intervention inside the hive, disturbing thus the microclimate within it, particularly during the winter. What is more, batteries have a significant impact on the environment due to their production process as well as their disposal [9, 10].

An autonomous system aimed at colony strength monitoring is thus suggested in this work, comprising several temperature sensors placed in the hives, enabling the estimation of the winter cluster size and strength, as well as a suitable communication module. The overall sensor node is designed to utilize the waste heat produced by the colony, transducing it into electricity via a thermoelectric generator (TEG).

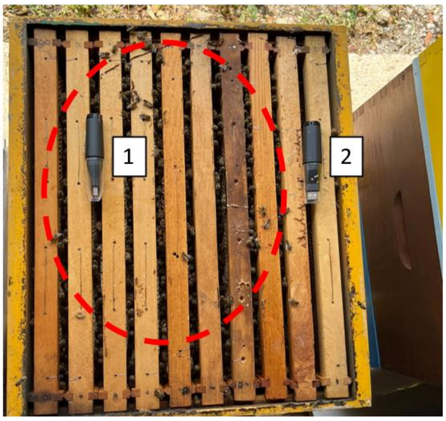
In fact, as a honeybee colony overwinters within a tight cluster, the size of which corresponds to the strength of the colony [11], a measurable temperature difference occurs between the zone of the hive occupied by the cluster and the remaining zones without bees [12, 13]. Due to hot air rising to the top of the hive, a temperature map can then be obtained by strategically placing temperature sensors above the frames. Such a map would reflect the size of the cluster, and thus the strength of the colony itself.

To assess the viability of such an approach, a finite element (FE) heat transfer simulation is carried out using ANSYS® Workbench 18.0 [14, 15], where three different cluster sizes are considered, i.e., clusters occupying 3, 5 and 7 hive frames. The maximal temperatures occurring within the cluster are set according to available literature [3, 14], while the ambient temperature is set at 1°C, thus emulating average winter conditions in the considered environment in the inland of the Istrian peninsula in Croatia. The resulting temperature maps above the clusters for each of the studied case are displayed in Figure 2, where a clear difference in the distribution of temperature can be observed for different cluster sizes.

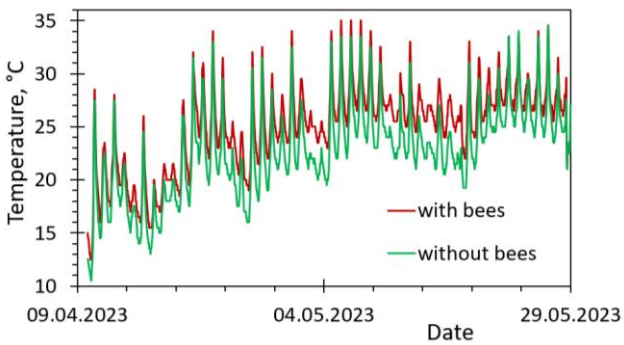



(a) (b) (c)

**Figure 2.** FE simulations of heat transfer within a beehive containing a winter cluster occupying 3 (a), 5 (b) and 7 frames (c)




(a)




(b)

**Figure 3.** Honeybee colony inner temperature measurements [9]

What is more, to initially assess the temperature differences between areas with and without bees, measurements are performed on a colony in a period from early to late spring by placing 2 sensors above (1) and away (2) from the bee cluster (Figure 3a), resulting in an average 2 °C temperature difference (Figure 3b) [9]. Both studies indicate, therefore, the feasibility of the above-described monitoring approach based on temperature difference to estimate the size and strength of the colony.

**3. Hive waste heat energy harvesting**

For the ideated system, there are several potential power supply options that can be considered, e.g. batteries or solar power. In this case, when an autonomous system aimed at winter monitoring is being studied, an energy harvesting (EH) approach based on thermoelectric waste heat is proposed instead, with the goal of utilizing the metabolic heat generated by the honeybee colony and typically lost through the hive walls [3, 16]. The EH approach [17, 18] is selected here to minimise the mentioned drawbacks related to battery usage [9, 10]. The possibility to use photovoltaics is, in turn, limited due to short and typically cloudy or foggy days in the considered region, though it could be considered as an addition to the TEG energy production, forming thus a hybrid EH system [18].

To assess the possibility of using thermoelectric EH as a power source, temperatures within and outside a standard wooden Langstroth beehive are measured next during the winter period in the studied environment. The measurements are performed by placing one data logger inside the hive, above the cluster of bees, while the other is placed on top of the hive roof. The thus obtained data shown in Figure 4 provide the input parameters, i.e., the thermal gradient between the maximum and minimum temperature, required for analysing the potential power generation. A fairly consistent thermal gradient, with an average temperature difference of about 21.3 °C, is hence obtained.

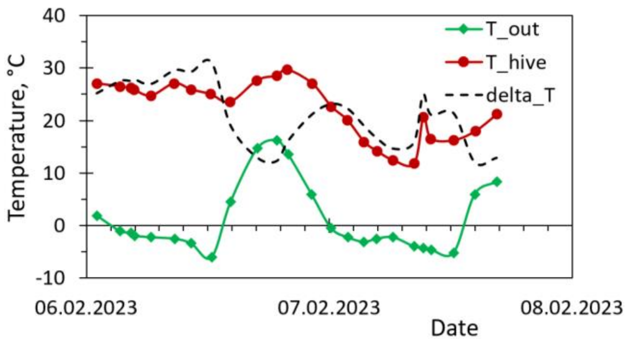
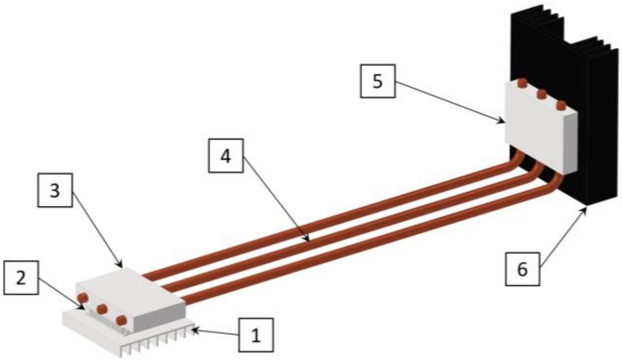


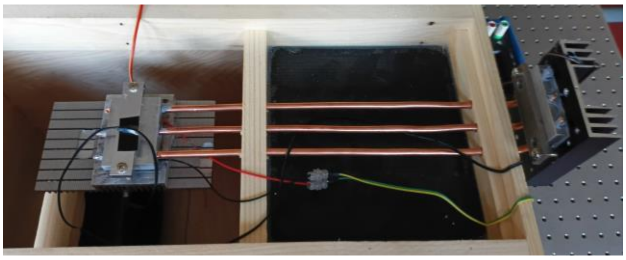

**Figure 4.** Honeybee temperature measurements at the actual beehive placement location during the winter - inner vs. ambient temperature

To utilize the available temperature gradient, a Tecteg® TEG2-126LDT thermoelectric generator [19] is considered in this frame. Firstly, an experimentally validated FE model of the considered TEG is developed by using ANSYS® Mechanical 18.0 [20], with the respective boundary conditions simulating the real working conditions with the average inner and outer measured temperatures of $T_{out\_av}$ = 0.9 °C and $T_{in\_av}$ = 22.3 °C. The maximum determined voltage and power outputs, at a load resistance of 4 Ω, are, thus, $P_{max}$ = 38.6 mW and $U_{max}$ = 0.39 V.

A prototype energy harvesting device, able to utilize the determined temperature gradient, is designed next. The harvester, depicted in Figure 5a, comprises an inner heatsink (1), heated by the hot air above the bee cluster, the chosen TEG2-126LDT thermoelectric generator (2), two QG-IF-A6-1X3 aluminium heat pipe interface blocks (3 and 5), three QY-SHP-D6-400SA sintered copper heat pipes with ultrapure water, enabling an efficient heat transfer from the hive interior (4) and the outer heatsink (6), able to dissipate the heat into the environment. This harvester assembly in then integrated into a standard 5 frame Langstroth (LR) nucleus hive (Figure 5b) and tested in laboratory conditions by imposing different temperature gradients comparable to those occurring in a real hive housing of a honeybee colony.




(a)



(b)

**Figure 5.** CAD model of the waste heat harvester prototype (a) and the harvester integrated into a nucleus hive (b)

As shown in Figure 6, the performance of the harvester is assessed by heating the air within the hive (1) comprising the integrated harvester (2) by using a digitally controlled conventional KLW-007E1-EU400 ceramic (PTC) heater (3) placed within the hive. The voltage generated by the TEG is routed via a TE 1051 [21] variable resistance box (4) to the National Instruments MyRIO® device (5) [22] serving as a DAQ system, connected to a LabVIEW® control virtual instrument (VI) [23] running on a PC (6). Along with the generated voltage, the temperatures on both the inner and outer heatsink are also monitored by using sensors connected to the DAQ device.

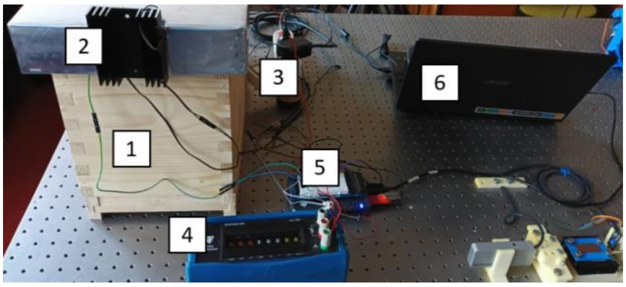
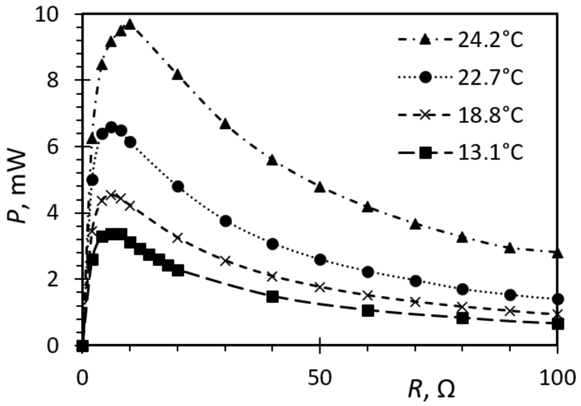


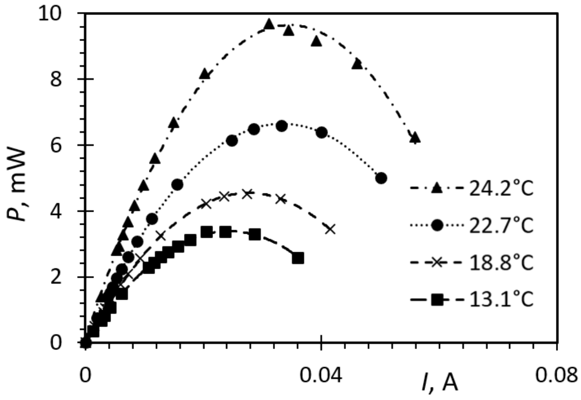

**Figure 6.** Experimental setup for testing the waste heat energy harvester

### *3.1. Results*

The voltage generated by the harvester for different temperature differences is used to calculate the power output, both in relation to the load resistance values *R* (Figure 7a), as well as the current *I* (Figure 7b). Maximum power outputs ranging from *P* = 3.5 to 9.7 mW can be observed at the optimal resistances of $R_{load}$ = 8 – 10 Ω. The respective voltages generally range from *U* = 0.25 to 0.32 V. During the measurements it was determined that a more efficient outer heatsink is required at the cold end, enhancing thus heat dissipation, and, finally, increasing the thermal gradient, i.e., the temperature difference at the TEG itself. This would, in turn, result in an increased power output of the overall system. What is more, the inner heatsink also needs to be carefully designed in terms of the so called "bee space", i.e., by respecting the requirement that all gap sizes are to be held between 6 and 9 mm to keep the colony from filling them up with propolis resin or wax comb, thus minimizing the intrusion into the colony itself.




(a)




(b)

**Figure 7.** Experimentally assessed power outputs *P* of the waste heat energy harvester at different temperature gradients vs. load resistance *R* (a) and current *I* (b)

What is more, possibilities to develop design configurations comprising a larger number of TEG transducers and/or heatsinks, such as that of Figure 8, are also being explored [24].

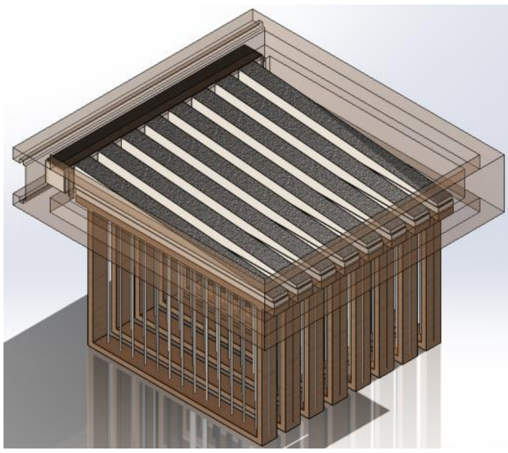


**Figure 8.** Design configuration with several heatsinks in the hive [24]

### *3.2. Hive monitoring system*

As it is schematically depicted in Figure 9, the final integrated autonomous hive monitoring system, intended to be used during winter conditions, comprises then an array of ultra-low power temperature sensors, e.g. the MCP9700 low-power linear active thermistor [25] (a possibility of using other sensor principles, such as ultra-low power IR cameras, could also be considered), combined with AD converters as well as ultra-low power CPU and communication modules. These components are to be powered by the energy stored in a supercapacitor, which is in turn charged via the TEG, exploiting the thermal gradient present between the colony and the environment. To utilize the power generated by the harvester for powering this system and successfully charge the supercapacitor, the low generated voltages would need to be increased via a step-up DC-DC converter. To manage the power distribution within the system, a suitable power management module is also needed. Additionally, by employing smart duty cycles, i.e., by limiting the operational time of components with large power requirements (especially the communication module), the overall power consumption of the system could be significantly reduced.

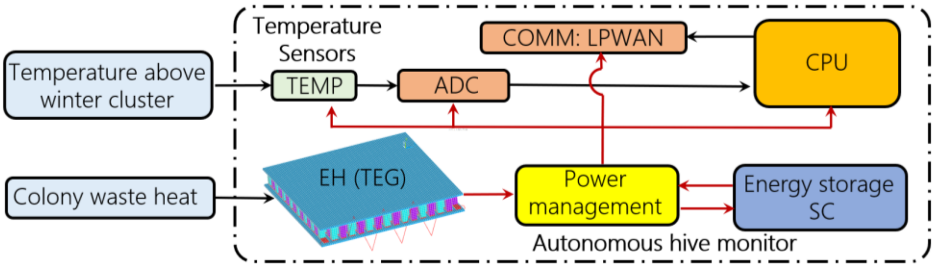



**Figure 9.** Schematic representation of the suggested autonomous hive monitoring system [14]

## 4. Conclusions and outlook

After a short introduction into managed honeybee colonies, with an emphasis on the issues of overwintering and the potential benefits of hive monitoring, an innovative autonomous hive monitoring system is proposed in this work. The system is to be powered by a novel approach based on thermoelectric EH principles able to utilize the thermal gradient between the honeybee colony and the surrounding environment.

An original method of assessing the size and strength of the colony by obtaining the temperature map above the cluster is suggested next, along with heat transfer simulations and temperature measurements supporting its viability. The possibility of practically utilizing the thermal gradient is discussed next, supported by data collected from a honeybee colony itself. Based on the data collected in the hive, a suitable TEG is numerically modelled by using ANSYS®, allowing to estimate a power generation of 38 mW.

A prototype energy harvester assembly is then designed and constructed, based on the same TEG, and comprising two heatsinks and heat pipes used to dissipate the heat generated by the colony into the environment. The harvester is integrated into a hive nucleus and tested in laboratory conditions by producing a thermal gradient comparable to that found in the actual colony. It is established that at different thermal gradients and with connected electrical load resistances of 8 - 10 Ω, the harvester is able to generate voltages ranging from 0.25 - 0.32 V and power outputs ranging from 3.5 to 9.7 mW. This is lower than the values calculated via FE simulations; the difference could be attributed to the fact that in the FE model the thermal gradient is applied directly at the hot and cold ends of the TEG, simulating an ideal case, while the temperatures during the experiment (ambient temperatures inside and outside the hive) are measured at the heatsinks, resulting in a thermal gradient at the TEG that is significantly lower than that in the FE model.

The essential components of the suggested hive monitoring system are finally described, considering also, to keep power consumption as low as possible and thus extend the autonomy of the proposed system, power management and duty cycles.

Further studies are required to develop a fully functional device. The development of suitable heatsinks, both inner and outer, is herein of crucial importance in terms of heat dissipation efficiency as well as of minimizing the intrusion into the honeybee colony while considering bee space. Moreover, a suitable step-up DC-DC converter needs to be paired with the harvester and the supercapacitor. What is more, the sensor array also needs to be designed and tested in combination with the CPU and the communication system, enabling thus a more exact assessment of the overall power requirements. Finally, the harvester needs to be tested on a factual hive containing a honeybee colony during winter conditions. The integration of additional EH principles, e.g. photovoltaics, will also be considered, constituting thus a novel hybrid EH approach to hive monitoring.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