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Indoor thermal energy harvesting for battery-free IoT building applications

***Abstract**. The article presents results of the introductory research related to harvesting thermal energy using the cold water pipeline supplying the building as well as scavenging thermal energy from the return path of the central heating installation. Both ambient energy sources are of low quality thus are characterized by a low temperature parameter. Yet, it has been proven that even such low quality waste heat sources can be utilized to power wireless sensors operated in large area building automation systems when the low-energy LoRa communication scheme is put in use.*

***Streszczenie.** W artykule przedstawiono wyniki wstępnych badań związanych z pozyskiwaniem energii cieplnej z wykorzystaniem rurociągu zimnej wody zasilającego budynek, a także odzyskiem energii cieplnej z drogi powrotnej instalacji centralnego ogrzewania. Oba źródła energii charakteryzują się niskim parametrem temperatury. Udowodniono jednak, że nawet takie niskoenergetyczne źródła ciepła odpadowego mogą być wykorzystane do zasilania bezprzewodowych czujników pracujących w wielkopowierzchniowych systemach automatyki budynkowej przy zastosowaniu niskoenergetycznego schematu komunikacji LoRa. (**Zbieranie energii cieplnej w pomieszczeniach do zastosowań IoT w budynkach bez baterii**)*

Keywords: IoT, energy harvesting, smart building, waste heat.
Słowa kluczowe: IoT, pozyskiwanie energii, inteligentny budynek, ciepło odpadowe.

Introduction

As early as in 1999, British visionary Kevin Ashton used the term Internet of Things (IoT) [1, 2] to point to a technological universe in which all kinds of sensors and other specialized instruments and electronic devices, as well as everyday appliances, will work not as autonomous units but as a distributed collection of cooperating devices, sharing data and providing massive amount of information on their neighboring realm. The concept of using remote IoT sensing and actuating devices in building automation systems is currently one of the leading directions in the development of such types of distributed solutions. Due to a number of difficulties and significant costs associated with the implementation of wired installations in building automation systems, wireless solutions are very attractive and increasingly used. Unfortunately, true wireless solutions also require local, wireless power supply. In common practice it is realised using primary or secondary batteries, requiring recurring replacement or recharging. Such activity generates serious service costs especially in case of complex building automation systems using thousands of wireless sensors. On the other hand, among all the components commonly employed in building automation systems, sensors are characterised by the relatively lowest level of energy consumption, which is why wireless sensor networks (WSN) display a tendency for the fastest development of battery-free power supply [3].

Indoor energy harvesting using ambient or waste energy is thus an attractive solution in this context and is becoming an increasingly common way to power IoT remote sensors. Ambient energy sources for such IoT devices should provide a permanent possibility to scavenge energy, but should also be based on the environmental or waste nature of the energy obtained (thus, they should not require providing extra energy in the remote location). Two examples of the use of non-obvious sources of thermal energy ensuring power supply for building automation system wireless sensors networked to BMS (Building Management System) are thus described in the following part of the article.

Even a small temperature difference between the p-metal-n (p-m-n) junction in a semiconductor Thermoelectric Generator (TEG) causes the flow of electrons and holes generating a potential difference. As a result, TEGs convert thermal energy directly into electricity and are currently the most commonly used devices for scavenging ambient thermal energy. In the simplest case, the relationship between the open circuit voltage V_o at the unloaded TEG output and the temperature difference ΔT between its hot and cold side is expressed by the following formula (1):

$$V_o = k\alpha\Delta T \quad (1)$$

where: α - Seeback coefficient of a single p-m-n junction, k - number of junctions connected in series in TEG.

In fact, the relationship (1) is not linear because α depends nonlinearly on the temperature of the junction(s). In addition, the Z factor (figure of merit), which determines the amount of energy generated by TEG, also non-linearly depends on the temperature and reaches its maximum value at a temperature depending on the semiconductor materials from which the junction is made. What's more, TEG has a non-zero internal resistance (usually from a fraction to a few ohms), which also nonlinearly depends on the temperature. Finally, the amount of energy that can be supplied by TEG to the load depends nonlinearly on both the temperature difference and the average temperature of the TEG junctions. Although there have been attempts to theoretically predict the real power factor and energy effectiveness of TEGs based on material properties [4] yet only real measurements can provide an insight into energy available for the load in specific engineering cases.

Energy demand of wireless sensor IoT devices

Remote sensors used in building automation applications use various standards for low-power radio communication. While Bluetooth Low Energy (BLE), Z-Wave and ZigBee in practice can only be used in small buildings due to their strongly limited range (especially in buildings using concrete-reinforced frames in their construction), LoRa radio link and LoRaWAN network protocol has proved to be applicable in much more demanding large-area locations including multi storey office buildings or large shopping malls [5, 6].

The energy demand of the wireless sensor designed to work inside such types of large-area buildings was therefore estimated for a prototype sensor platform based on the

CMWX1ZZABZ-078 radio module (Murata) and the LoRaWAN long-range wireless communication protocol [7]. The platform was also fitted with an ultra low power multiparametric sensor (BME280, Bosch Sensortechnik) providing basic environmental data (temperature, humidity and pressure). Such platforms have been successfully applied as endpoint sensor devices in large building automation systems and the acquired remote measurement data was used directly by the control algorithms of the respective BMS [5, 6].

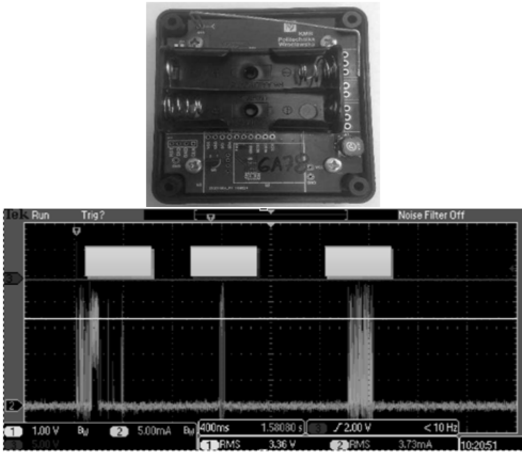


Fig. 1. Battery-powered autonomous sensor platform with environmental multiparametric sensor and LoRaWAN communication: a) prototype interior view, b) changes in battery voltage (purple curve), supply voltage (yellow curve) and supply current (green curve) during one measurement and data transmission cycle (7.2 V battery voltage).

The power supply parameters recorded during a typical measurement and transmitting cycle of the discussed sensor platform (battery-powered by two 3.6V lithium batteries) operating in Class A LoRa communication protocol are illustrated in Fig. 1b. The platform full operation cycle consists of 3 phases. Phase 1 consists of the microcontroller and the radio system awakening and measurement of environmental parameters and is associated with the consumption of approx. 11.1 mJ of energy. Phase 2, during which data is sent to the LoRa server, requires approx. 2.4 mJ of energy, while phase 3, associated with receiving a return telegram from the LoRa server, requires approx. 8.4 mJ. Thus, the entire measurement and transmission cycle consumes approximately 21.9 mJ of energy. Based on the above, it has been estimated that in order to effectively use the energy harvesting to battery-free supply of such a type of the sensor platform, at least 22 mJ of energy should be made available by the energy harvester to complete each measurement and data transmission cycle.

Indoor thermal energy harvesting using building cold water supply

As (1) indicates, temperature difference forcing heat flow is an indispensable prerequisite for thermal energy harvesting using TEG. Usually, solutions of this type are based on an energy source with a temperature higher than the ambient used as a ‘cooler’ forcing the heat flow towards the ambient (the ambient is thus gaining energy). In this case however, it is rather a recovery of energy lost by an object (source) than the actual harvesting of energy from the ambient. However, if we have a cold object with a temperature lower than the ambient temperature, then we are dealing with a real ambient energy harvesting because the flow of energy takes place from the ambient to the object (the ambient is thus losing energy). In a building, such an easily accessible but nonobvious ‘source’ of cold can be a drinking water supply connection. And such a type of energy harvester can provide battery-free power to the remote IoT and BMS system sensors, enabling, for example, remote operation of electronic water consumption metering devices in buildings.

In order to estimate the amount of electrical energy made available by such an unusual, inverted system of heat and cold sources, 2 experiments were performed. In the first of them, a commercially available thermopile (type TEC1-12710, dimensions 40x40x3 mm [8]) was fixed (using thermally conducting glue) to the lower base of a commercially-available single-stream water meter (type SMART+ JS1,6-02; commonly installed at the building water supply). The thermopile was equipped with a heatsink (type ICK PDA 21x21, Fisher Elektronik) with dimensions 53.5x53.5x16.5mm and thermal resistance 7 K/W (when natural convection cooling is considered). The water meter was additionally thermally insulated using a purpose-build XPS casing so that the heat exchange with the ambient took place practically only through the thermopile. During the measurements, the water meter was positioned so as to maximize the natural convection around the heatsink. The water meter was supplied with water at flow rate 7,5 l/min using a chiller. The water meter prepared in this way and its location during the measurements were illustrated in figure 2. Temperature of water (T_w), water meter housing (T_m) and ambient air (T_a) as well as the open circuit output voltage of the thermopile (V_T) were recorded using WAGO 750-8202 PLC [9] fitted with additional expansion modules.

Resistance temperature sensors Pt1000 class B with a measurement accuracy of (0.3 + 0.005*|T|)°C (where T is the measured temperature) coupled to a multichannel 14-bit analog to digital converter module with a total measurement error of 0.01%/K were used in the presented tests.

Voltage and current were measured by means of a UNIT UT890C digital multimeter using +/-600 mV and +/-60 mA range with a measurement error of ±(0.5%*reading+0.5) mV and ±(0.8%*reading+0,08) mA respectively. The power was numerically calculated using the corresponding measured voltage and current values.

Fig. 2. Laboratory set-up for testing heat energy harvester based on cold tap water meter

Measurements were carried out for the temperature of water flowing through the discussed modified water meter varying in the range 4.7 - 13ºC and the ambient air temperature in the room oscillating between 16.6 and 17.0°C. Such conditions correspond to the actual temperatures of cold water supplying buildings in Poland in the annual cycle while the air temperature was similar to the temperature inside technical rooms in buildings, in which media connections are installed. It should be however noted, that depending on the geographical location and the type of building and water connection, changes in the temperature of cold water supply in the annual cycle may be greater and reach even the range of 2 - 27 ºC [10].

A similar thermoelectric harvester solution has been recently presented by Gould [11]. However, it was using a geometrically smaller TEG (30mmx30mmx3.8mm) as compared to the TEG used in the current study as well as it was not exploiting thermally uninsulated water meter housing. Gould's design produced thermoelectric voltage in the range 70-80 mV at 11-13ºC temperature difference. Contrary to this, the harvester presented in the current paper for a similar temperature difference can supply output voltage exceeding 90mV i.e. at least 12% higher. Moreover, the thermal insulation of water meter housing, used in the current design allows to obtain higher instantaneous power values resulting from a flow of fresh cold water feeding the building after a long period of network inactivity, in which the temperature of the water meter housing approaches the ambient temperature value. The thermal insulation also significantly extends the time in which the thermoelectric generator operates in thermally transient conditions resulting in extended temperature difference and thus increased power output. The insulation is significantly reducing the flow of thermal energy from the environment to the water meter casing, thereby constraining the temperature of the water meter casing to quickly align with the ambient temperature. The direct effect of this action is to improve the total energy output of the energy harvester over longer time periods.

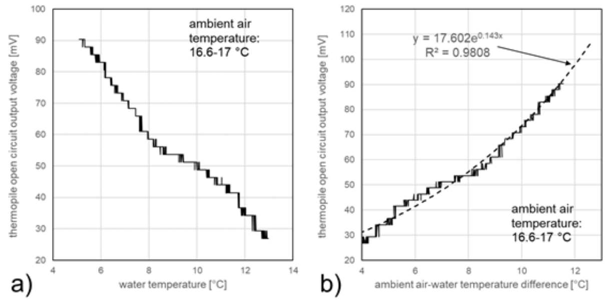


Fig. 3. Experimental record of the thermopile open circuit output voltage as a function of: a) supply water temperature, b) ambient air and supply water temperature difference.

The measurements have proved that the difference between the supply water temperature and the temperature of the water meter housing is negligible thus both values may be used concurrently. Figure 3a shows an experimental record of the thermopile open circuit output voltage as a function of the supply water temperature while figure 3b illustrates its dependence on ambient air and supply water temperature difference. The nonlinearities of the dependencies shown in Fig. 3 result mainly from temperature-related changes in the Seebeck coefficient of the thermopile. On the other hand, the relationship illustrated in figure 3b can be well approximated using an exponential dependency (as indicated with a dashed line) with an absolute error not exceeding 5,4 mV.

Using the measurement set-up described above its energy effectiveness was also tested in the summertime (mid-June). The value of voltage and current at the output of the thermopile loaded with a 1 ohm resistor (reproducing the optimal load resistance, which is discussed in the following part of the manuscript) were studied together with the temperature difference between the room temperature (27.2ºC) and the temperature of the heatsink of the water meter housing. The measurements illustrated in figure 4a were carried out from the moment the harvester was supplied with cold water until the temperature of the water meter housing stabilized at the temperature of water supplying the meter (14.9 ºC). Under the measurement conditions, the temperature stabilized after about 250 s at the temperature difference 12.3 ºC (in relation to the surrounding air). It resulted in a steady state thermopile output voltage of 61.04 mV at 24,4 mA output current, corresponding to 1.49 mW load-matched output power. On the other hand, the peak output power of the thermopile was achieved in the transient state after approx. 40 s of the harvester operation at 146.5 mV and 58.1 mA of current, corresponding to an instantaneous power of 8.51 mW. Thus, the total energy supplied by the thermopile to the matched load during the 250 s transient period was equal to 846.46 mJ. Thus, energy harvested in such a short period of time in theory would allow for 38 cycles of measurement and data transmission cycles performed by the LoRa remote measurement platform discussed in chapter 2. However, such calculation does not take into account the energy losses in the ULV (Ultra Low Voltage) DC-DC converter, necessary to power such a platform from the heat energy harvester in question due to its low output voltage. Using a ULV DC-DC converter with an approximate 40 % total efficiency [12], the actual instantaneous power available for the IoT remote sensor system would peak at approximately 3.4 mW decreasing to approx. 0.68 mW in longer time periods. Further, assuming about 30 % combined efficiency of the ULV DC-DC converter and the energy storage system, the discussed thermal energy harvester would allow more than 12 measurement and transmission cycles to be carried out by the LoRa remote sensor platform using energy harvested during the 250 s transient period. In addition, the 146.5 mV transient maximum output voltage of the harvester allows the use of a DC-DC converter with a relatively high cold start voltage.

The catalogue value of the internal resistance of the TEC 12710 thermopile used in the experiments is 1,08 Ω at 25 ºC [8]. In the above-described stable operating conditions of the harvester (i.e. after 250 s when the water meter housing stabilized at 14.9ºC) a test of the optimal load of the thermopile was also carried out. It consisted in the measurement of the output voltage and current for the thermopile loaded with a variable resistance in the range of 1-1000 ohms, which is illustrated in Figure 4b. In the discussed stable thermal conditions, the highest power of 1.49 mW was recorded for 1 ohm load at the thermopile output voltage 61.04 mV, which translates to 59,5 % of the open circuit voltage of the unloaded thermopile (102,54 mV). Thus, the MPP (Maximal Power Point) of the thermopile in the discussed design may be supposed to be close to 60 %.

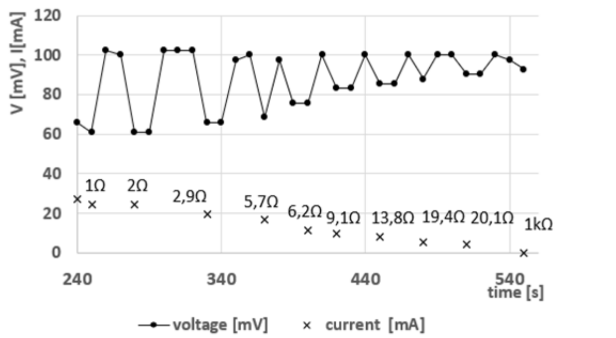


Fig. 4. a) Experimental record of the measured voltage and current values for a cell loaded with a resistance of 1 ohm up to the stabilized temperature conditions of the water meter housing (heat sink),

The actual temperature of the water meter housing installed on the pipeline supplying a single-family house in a daily cycle was also recorded. Figure 7 illustrates exemplary daily changes in this temperature along with the temperature of the ambient air. On the basis of these studies, it was observed that the temperature of the water meter housing decreases sharply with each water intake from the installation. However, during the day there are about 6 - 8 cycles of long-term water intake stopping, which cause the water meter to attain the temperature close to the ambient. Thus, each time water flows again through a water meter that has previously reached a temperature close to the ambient temperature, its temperature decreases strongly and rapidly. This allows to obtain in these conditions an energy peak close to the maximum energy effectiveness of the harvester discussed earlier.

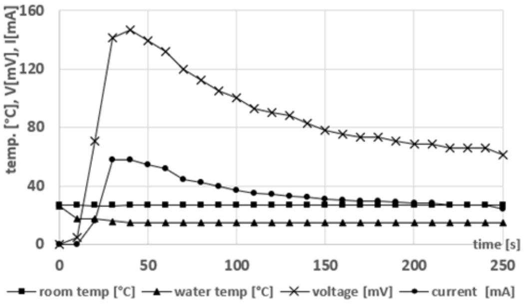


Fig. 4. b) The value of the measured voltage and current for a cell loaded with a resistance in the range 1 Ω- 1 kΩ.

Taking into account the data presented in Figure 5 and assuming the relationship between the output voltage of the unloaded thermopile and the temperature difference T_A-T_M as in Figure 3b as well as the 1 Ω optimal load of the thermopile causing its output voltage to drop to 60 % of its open circuit voltage, it is possible to estimate the average amount of energy supplied by the discussed harvester during 1 day. Such an estimate gives 20,4 J. Again, assuming 30 % combined efficiency of the ULV DC-DC converter and the energy storage system, it allows to perform 278 measurement and transmission cycles of the remote LoRa platform daily, i.e. over 11 cycles per hour. This is a period of time sufficient from the point of view of the requirements of control algorithms implemented in typical BMS systems. Moreover, such a harvester would probably be able to provide battery-free power to the radio transmitting system, which is increasingly integrated with the water meter, as such a module can work approximetely 10 years when battery-powered [13].

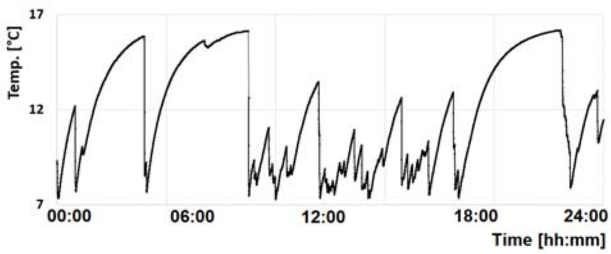


Fig 5. Exemplary daily record of water temperature in the building supply pipe

The presented calculations, although based on real data, are only estimates. The actual energy effectiveness of the described thermal energy harvester will be closely related to the intensity of real water uptake. However, taking into account the estimated amount of energy possible to obtain in the daily period, this is a very attractive solution.

Harvesting energy from heating system return

The second attempt to harvest thermal energy indoor discussed in this paper relies on regenerating low quality heat from the domestic heating system return network. The return temperature strongly depends on the type of the heating system installed and may vary from as high as 65°C for coal-fired boilers [14] to as low as 30-35°C for heat pumps [15]. The return temperature depends also on the radiator type (convector radiator, underfloor heating) and the thermal state of the building and in practice are lower than the standard-depicted and may even become as low as 20-23°C if COP of the heat pump is optimized through the return temperature tweaking [16]. The tests described in the following part of the text were carried out using a domestic underfloor heating system fitted with a condensing gas boiler operating at a constant 50°C supply temperature (providing the best energy effectiveness of the boiler). The main system return distributor located close to the boiler was fitted with a flat duralumin base support to which a thermopile and its radiator were attached using a thermally conducting paste and a thermal insulation pad between the base and the radiator. TEC1-12710 thermopile and ICK PDA 21x21 radiator were used as in the previously described water meter experiments. A magnetic detachable radiator fitting minimizing its thermal coupling to other parts was the main difference as detailed in fig. 6a.

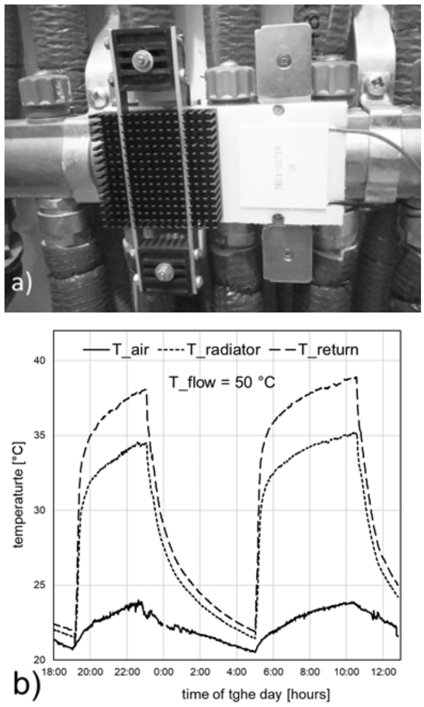
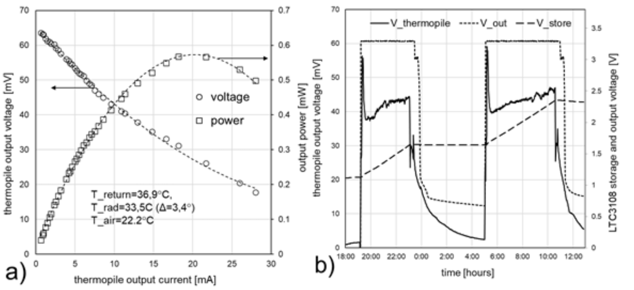


Fig. 6. Thermal energy harvester fitted to the return distributor of a domestic heating system: a) detailed view, b) exemplary temperature record on a winter day (detailed description in the text).

The thermopile output voltage was routed to ULV dc-dc converter based on LTC3108 chip (Linear Technology) and 1:100 (Coilcraft) miniature step-up transformer while 2.5F/5V supercapacitor connected to LTC3108 VSTOR pin was used as an energy storage device. Temperatures of the return base support (T_return), the radiator (T_rad) and ambient air (T_amb) in the vicinity of the radiator together with the thermopile (V_thermopile), storage capacitor (V_stor) and the LTC3108 main output (V_out) voltages were recorded using Arduino-based measurement system. While the system temperature measurement error was identical to the one already stated for the water meter experiments the relative voltage measurement error was in this case not higher than 0.01%. Fig. 6b displays temperature changes recorded for the harvester on an exemplary winter day when the heating system was activated 2 times. The real temperature difference experienced by the thermopile was exceeding 3°C during most of the heating period rising up to 3.8 °C at its end. The thermopile current-voltage and power curves recorded at the mid-temperature difference (3.4°C) were shown in fig. 7a. The maximal output power of the thermopile in such thermal conditions reached 0.57 mW at the MPP point equal to approx. 50 % of the open circuit voltage.



Figs. 7. Performance of the thermoelectric energy harvester operated on the return path of the domestic heating system: a) current-voltage and current-power characteristic at the mid-temperature difference (3.4°C), b) daily record of system voltages.

Fig. 7b illustrates the harvester voltages recorded during the discussed exemplary 1-day long period. As it may be observed, the thermopile was operated below its MPP because the 1:100 step-up transformer used in the design did not provide the thermopile load matching and the LTC3108 chip was not fitted with MPP tracking. However, if we suppose that the power curve shown in fig. 7a was not seriously changed during both heating periods (due to change in the thermopile mean temperature) thus the thermopile operated most of the time at 37-46 mV output voltage was delivering approx. 0.37-0.49 mW of power. During both heating periods the supercapacitor storage voltage V_STOR was steadily rising at a mean rate of 127 mV/h. Thus, taking into account the storage capacitance (2,5 F) the mean charging current was equal to 88.4 µA while the mean charging power was equal to 0.176 mW. It translates to 36-48 % DC-DC converter efficiency which agrees well with the LTC3108 datasheet [10]. The total energy generated by the harvester and stored in the supercapacitor during both heating periods was equal to 5.27 J. Taking again into account the energy consumption of the remote LoRa measuring platform discussed previously it would translate to almost 240 measurement and transmission cycles performed during 15 hours (i.e. more than 15 cycles per hour). Thus, it fully satisfies the requirements of BMS systems.

Summary

The paper presents the results of research related to an unconventional way of obtaining electricity in buildings to power low-energy IoT remote sensing devices interfaced to building automation systems. Two proprietary thermal energy harvesters were designed and tested. The first one was intended to be installed on the cold water meter housing while the second one was prepared for fitting to the return path of the central heating system. On the basis of the conducted research, an average energy production of the water meter harvester was estimated to be 6,12 J per average summer day while the heating system harvester was making over 5 J of electrical energy available for an external load on an averaged winter day. In both cases it was also estimated that it is possible to power low-energy IoT devices in this way. The estimates were performed based on the supply energy demand of the proprietary wireless LoRa sensor platform which has been successfully used in large-size buildings for remote measurement and data transmission to the BMS system. The presented research proves the possibility of using the entirely battery-free power supply for real IoT measuring devices used in the building automation solutions. With the current market and business trends, solutions allowing for battery-free power supply of wireless IoT devices will provide serious benefits due to the significant increase in the service-free working time of such vital building automation components.

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