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Thermoelectric and Hybrid Generators in Wearable Devices and Clothes

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Abstract—**This paper discusses the necessity and ways of replacing batteries in BSNs and other wearable devices with energy scavengers. The stresses are made on thermoelectric energy converters of human body heat into electrical power and on rules of their designing. The reasons for and possible ways of hybridizing wearable thermoelectric converters with photovoltaic cells are discussed, too. The examples of energy scavengers, both wearable and in clothing, for self-powered wireless sensors are described.**

Keywords: thermoelectric, photovoltaic, autonomous device, energy scavenging, wearable electronics, self-powered device

I. INTRODUCTION

BSNs as well as the majority of other wearable sensors and medical devices designed for a mass production cannot rely only on batteries. Indeed, certain autonomy offered by the batteries is quite limited, on one hand, by the weight of primary batteries and their service life. On the other hand, it is limited by the minimum power required for both signal processing and wireless communications. Therefore, the service life of batteries is not long enough unless their size grows or their recharging must be performed. In case of devices integrated in garments, the situation is furthermore complicated by necessity of their laundry, so that a primary or a secondary battery must be easily accessible for changing or recharging, but waterproof. Environmental aspects while starting mass production of millions BSNs must be taken into consideration, too. The energy scavengers are therefore the only feasible solution for wearable low-power electronics, like BSNs, on the market. They can extend the service life of the power supply to the end-of-life of a device or a piece of clothing in which such power supply is used. Thereby, BSNs and other wearable devices become service-free for their entire lifetime enabling wide spread of such devices on the market.

Wearable photovoltaic (PV) cells work quite well in the office and outdoors, however, the necessity of changing a clothing ensemble and periodic wearing man's suit jackets or outdoor pieces of clothing on top of the indoor clothing ensemble decreases effectiveness or even applicability of photovoltaic power supplies in wearable devices. The illumination conditions at home are worse than in the office. Therefore, especially in case of a person spending most of his/her daytime at home, e.g., in case of an aged, disabled or sick person, photovoltaic cells offer insufficient power per unit area.

Thermoelectric converters of human body heat into electricity for powering wearable electronics are very strong competitors to photovoltaic cells. The authors believe that a wearable thermoelectric generator (TEG) is the best power supply in moderate climate for the target applications and this paper explains why. Furthermore, the TEGs preferably should be combined with PV cells and the reasons for that are discussed, too.

II. A TEG ON THE HUMAN BODY

Unlike in most of today's applications of TEGs, the thermal resistance of heat source must be taken into account in wearable systems. This is explained by the fact that during evolution, the warm-blooded animals have arrived to a very effective thermal management. This includes a very high thermal resistance of the body at ambient temperatures below 20-25°C if the skin temperature decreases below thermal comfort [1, 2]. As a result, not much heat is dissipated from the skin and the only about 5 mW/cm^2 is available through convection and radiation indoors, on average.

The heat generation is related to metabolic activity that, in its turn, depends on a person's physical activity. Let us compare two sportsmen. The first man is running at 10 km/hr while the other one is racing on a bicycle at 25 km/hr. This activity requires a metabolic rate of about 10.3 MET in both men. They are 1.9 m-tall and weigh 84 kg. Accounting for Du Bois equation, a heat of almost 1.1 kW is produced in their bodies. It can be dissipated through convection and radiation with no heavy sweating (i) only on a cloudy day at temperatures not exceeding 18 – 20°C, and (ii) only from a bicyclist. The heat transfer coefficient on runner will not allow dissipating this heat through convection and radiation. The runner will sweat even at 18 – 20°C to cool himself. If the same physical load takes place at, e.g., stationary bicycling (at about 190 W, vigorous effort), most of the heat is dissipated through sweating.

Let us imagine that someone has made a wearable device having a power consumption of 100 μW with a TEG as a power supply for one of above sportsmen. We assume that a heat flow of at least 25 mW/cm^2 flows through the skin. At 20°C, this would result in a thermoelectric efficiency of 0.56% on the thermally matched TEG [3] and a power of

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140 μW/cm^2 on electrically matched load. Logically, the TEG must occupy not more than 1 cm^2 area on the skin.

In the evening, our champion celebrates his victory in a restaurant while wearing the same device. His metabolic rate has returned to a basal rate of 123 W. There is no wind in the restaurant, too. The heat flow through the skin is the only 6 mW/cm^2, but over 2 mW/cm^2 are due to sweating and inhalation, so that the heat flow through the TEG is 3.6 mW/cm^2. In addition, the thermal resistance of his body has increased by a coefficient of six, up to 500 cm^{2}K/W. This causes additional significant thermal mismatch of the TEG with a thermal generator [4] resulting in (i) a temperature drop on the thermopile of 0.9°C and (ii) a poor thermoelectric efficiency of 0.068%, which is 8 times less than during the exercise. Therefore, the same TEG produces 2.4 μW/cm^2 in the restaurant, i.e., 60 times less than at the time of exercise despite the fact that the ambient temperature is almost the same, i.e., 22°C. As a result, there is a shortage of power during the dinner and the device worn by our sportsman stops.

This simple example shows that a wearable TEG cannot be designed for exercise conditions, but for typical both the metabolic rate and heat flow. At the system level, a short- or long-term power reserve must be provided in the form of rechargeable battery or a capacitor to avoid power shortages. The power gained by a TEG on occasional basis can be then uniformly redistributed and consumed over a period of time.

Basing on both theoretical analyses [3, 5] and the measured device characteristics [6], we conclude that the correctly designed TEG in right location on the human body can produce approximately 10 – 30 μW/cm^2 in moderate climate, on 24-hour average. The produced power depends on the thickness of a TEG and its size: the thicker the TEG, the better its power generation while the larger the TEG, the less power per unit area must be expected.

III. WEARABLE THERMOPILES AND TEGS

There are specific requirements to both the thermopile and TEG in energy scavengers including wearable devices. First of all, the thermal resistance of a thermopile R_{tp} for maximum power generation must be equal to

$$R_{tp} = \frac{R_{pp}\, R_{TEG}}{R_{pp} - R_{TEG}}\,, \tag{1}$$

where R_{pp} is the thermal resistance of air and holding elements (if any) located between the cold and hot plates of a TEG, i.e., thermally in parallel to the thermopile, and R_{TEG} is the optimal thermal resistance of a TEG (at which power generation maximizes). The latter can be obtained as

$$R_{TEG} = \frac{\left(R_{body} + R_{si}\right)R_{et}}{2\left(R_{body} + R_{si}\right) + R_{et}}\,. \tag{2}$$

where R_{body} is the thermal resistance of human body in location of a TEG (it is the thermal resistance between the body core and the chosen location on the skin), R_{si} is the thermal resistance of a heat sink, i.e., the thermal resistance due to convection and radiation on the outer side of TEG, and R_{et} is the thermal resistance of TEG temporarily assuming that thermoelectric materials have a thermal conductivity equal to the one of air (i.e., the TEG is empty, with no thermoelectric material in it). Eq. (2) is called equation of thermal matching of a TEG with the environment [3]. The last requirement is that the factor N, defined as

$$N = R_{et}\,/(R_{body} + R_{si}), \tag{3}$$

must be at least equal to one, but preferably N must be more than one. This factor depends on the size of hot and cold plates and the distance between them, i.e., on the thickness of a TEG. Therefore, the thinner TEG, the less power it produces.

These requirements result in a semi-empty TEG, where the thermopile occupies only a minor part of the TEG volume; the rest must be air. If a small-size thermopile, e.g., a micromachined one, replaces in such TEG, e.g., a watch-size TEG, the thermopile purchased on the market, it must be really empty, with micrograms of thermoelectric material in it. The parasitic thermal resistance connected in parallel to the thermopile, plays so important role that application of a high-Z thermoelectric materials, e.g., nanostructured ones, would not offer the advantages that one might expect. Such materials are being constructed to have low thermal conductivity that is anyway shunted thermally by the parasitic thermal conductance at low thermocouple dimensions. Therefore, the advantages of nanomaterials in energy scavengers approximately halve as compared with earlier expectations based on phonon scattering, so that only minor improvements to existing devices would be feasible if any of such materials could be available. We can conclude that nanostructured thermoelectrics might be much more better only in high temperature applications.

All the variables in (2 – 3) can be easily calculated, except the thermal resistance of human body. A limited amount of experimental data can be found in literature, see, e.g., [1, 2]. In this work, the measurement of thermal resistance of a clothed person is performed in his trunk and proximal upper arm. The measurements were conducted using a TEG with a thermal resistance of 580 cm^{2}K/W. The TEG had a round hot plate of 3 cm in diameter. Such measurement technique would give inaccurate results for human body properties themselves. Instead, it provides precise measurement of the thermal resistance of human body under the attached TEG (matched thermally), which is more useful in context of this paper.

The experiments have been carried out in the office, at a temperature of 23°C, with some weak airflow generated by air conditioning system. The TEG has been integrated into the front side of a short-sleeve shirt, Fig. 1. The human body properties have been measured in nine locations marked with white stickers. The skin temperature in measured locations was different. The thermal resistance, Fig. 2, depended on skin temperature and varied within a factor of 4.

Variations in thermal resistance of the body accompanied by variations of both the heat flow and temperature of a boundary layer of convection induced by the body, resulted in varying power generation by the TEG from one location to another. In the used test device, the power production varied between 2.9 and 8.8 μW/cm^2, i.e., within a factor of three.

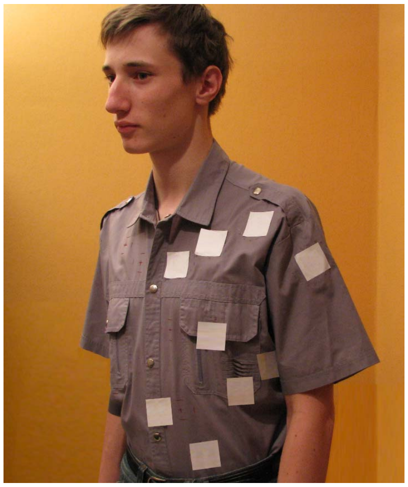

Figure 1. The shirt used for measurements of the thermal resistance of human body.

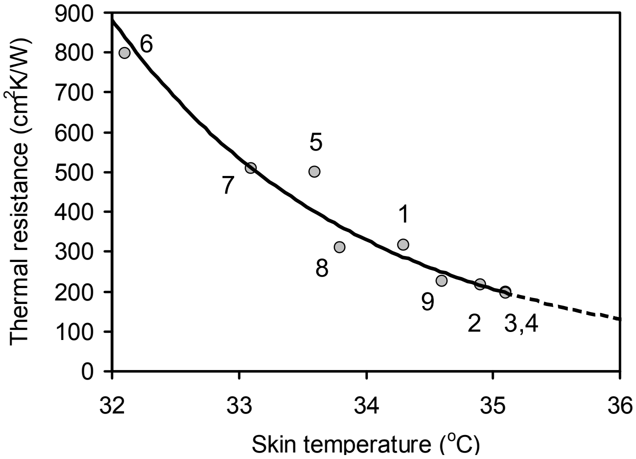

Figure 2. Dependence of the thermal resistance in human trunk at 23°C under attached TEG on skin temperature in nine locations (see Fig. 1).

To demonstrate importance of accounting for the thermal resistance of the body, its comparative measurements have been performed in three locations: on a forehead, in a left wrist (on the radial artery) and in a chest, left side around lowest ribs. The heat flow at 22.8°C has been found to be exactly the same, however, the skin temperature was different: from 33.8°C in the wrist (on the radial artery) to 35.8°C in the forehead. The corresponding thermal resistance of the body varied from one location to another by a factor of three. Analyzing (1 – 3), one can conclude that wearable TEG cannot be optimized unless the thermal resistance of human body is known.

IV. TEGs in Wearable Wireless Devices

The electrical power generated by a TEG varies proportionally to the square of heat flow. This allows dramatically improving the power by using a small-size radiator in a wearable TEG (meaning that it is still comfortable while being worn: not too big, not yet heavy, and not that cold). Using a radiator in a watch-size TEG allows tripling the generated power [7]. In this way, a power of 25 μW/cm^2 is obtained at 22°C on a sitting person in the office [7]. This value coincides with theoretical predictions for the upper limit of power generation at such conditions, and at a state-of-the-art Z of 3×10^{-3}, on 24-hour average [3, 5] for a 1.5 cm-thick device.

Several versions of wrist TEGs have been fabricated in 2004 – 2006, Fig. 3, offering a power of 150 – 250 μW, on average (indoors). The voltage on the matched load was typically within the 0.8 – 1.2 V range, depending on the design version. Their power generation has been measured at different both ambient temperature and physical activities. Some of the results are shown in Fig. 4. The TEGs work well at ambient temperatures by few degrees either lower or higher than the skin temperature. [The colors in lower curve mark: the subject feels cold (gray), feels normal (lime), feels hot (coral); the blue color corresponds to heat flow from air into the wrist accompanied by the changed polarity of generated voltage.] As a rule of thumb, at 23°C, the thermoelectric generator shown in Fig. 3 (b) typically produces about 20 μW/cm^2 on a sitting person, a half of it on immobilized person, but doubled power while walking.

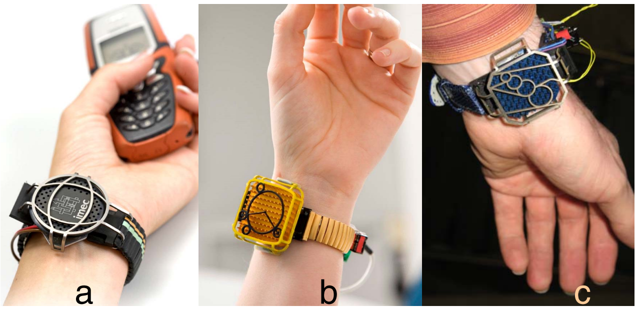

Figure 3. Wrist thermoelectric generators: (a) a waterproof device for outdoor use, (b) a TEG for indoor use, and (c) a wireless sensor node for tracking the power generation on people in real life.

The TEGs have been used for powering different battery-free wireless sensor nodes. In Fig. 3 (b), the first battery-free medical device (a wireless pulse oximeter) is shown, which is operated at a power consumption of 62 μW at the output update rate every 15 s [8].

The sensor node shown in Fig. 3 (c) has been designed for tracking (i) the temperature in the wrist under the TEG, (ii) the ambient temperature and (iii) the produced power [7]. The TEG has been designed for high ambient temperatures; it provides enough voltage and power for the application at a temperature difference of 2 – 3°C between the skin and ambient air. In order to always keep the voltage on the supercapacitor within the 0.8 – 1.1 V, the sensor node has been provided with variable duty cycle for the data transmission pulses. The duty cycle has a dynamic range of 10^3 enabling the interval between transmissions from 0.1 s to 100 s, Fig. 5. Therefore, the supercapacitor neither reaches the charge saturation nor its complete discharge, thereby enabling measurement of the true power production. This sensor node allowed collecting precious statistic data in the real life of a citizen within the most critical application temperature range, i.e., when the skin temperature approached air temperature. The power transferred into the supercapacitor vs. temperature difference is shown in Fig. 6.

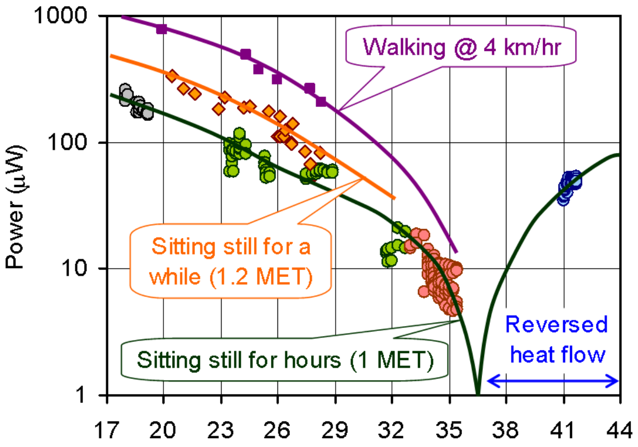

Figure 4. Power generation in the office by a wrist thermoelectric generator similar to the one shown in Fig. 3 (b).

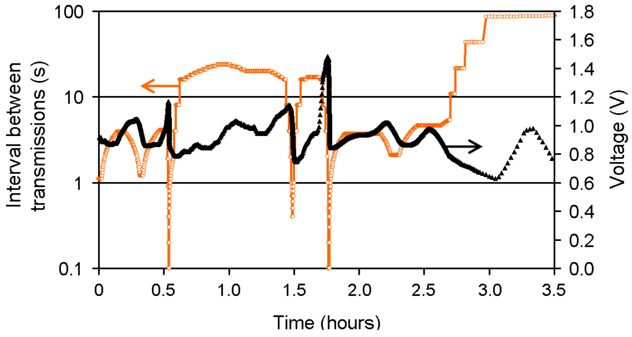

Figure 5. A fragment of recorded variable interval between transmissions and corresponding variations in the voltage of supercapacitor.

An interesting observation is that when the skin temperature approaches the air temperature, the power generation minimizes, but, on average, it is not zero. The difference of temperatures from place to place (e.g., in a shadow/in the sun), unstable wind, different person's activity, accompanied by varying skin temperature provide partial power generation at all the ambient conditions. The power minimum observed at air temperatures around 36°C is comparatively low, so that PV cells become competitive with TEGs even indoors (on 24-hour average). High ambient temperatures however happen when there is a plenty of sunlight. Therefore, combining PV cell with a TEG allows compensating the minimum power production by the latter if a secondary battery is used in the system instead of a supercapacitor.

At typical indoor temperatures of 20 – 25°C, the variations of power generation within the 50 – 350 µW range have been observed, Fig. 6. In order to avoid saturation of a supercapacitor in wearable systems, it must be comparatively large, or should be replaced with a secondary battery. (If the charge storage element is fully charged, there is no energy transfer into it from the TEG, so the energy produced at this moment is wasted.) Another advantage of using a battery as a long-term charge storage element is that the power produced on average exceeds the minima of power at typical temperatures of 20 – 25°C by a coefficient of two. Therefore, ideally, a wearable device with a battery can have an energy scavenger two times smaller than the same device equipped with a supercapacitor. Furthermore, taking into account variable ambient temperature, both indoor-to-outdoor and winter-to-summer, a battery could allow uniform power redistribution over very long periods of time thereby would enable further miniaturizing energy scavengers.

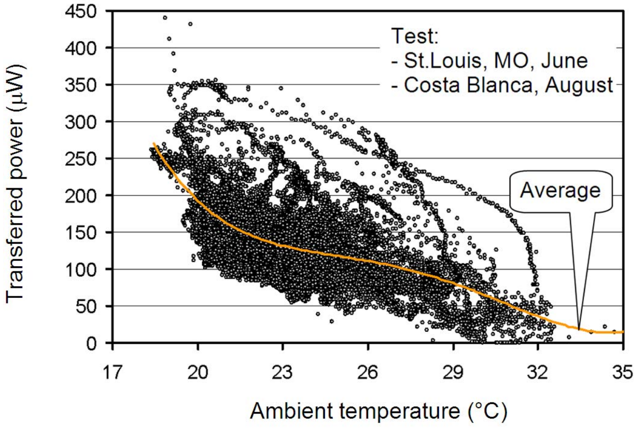

Figure 6. Over 32,000 measurement points of the power generation in real life. Weak dependence of power on temperature within a temperature range of 22 – 27°C is caused by the vasomotor response.

So far, the most powerful (2.5 mW) thermoelectric energy scavenger has been fabricated in 2007 for a battery-free wireless electroencephalography (EEG) system-in-a-headband, Fig. 7 [4]. The TEG with a total area of hot plates of 64 cm^2 has been designed as 10 sections of 1.6 ×4 cm^2 area each, which are rotatable to each other in order to follow the forehead shape, Fig. 7 (b). The radiators provide effective heat dissipation into the ambient air and satisfactory thermal matching of thermopiles having an aspect ratio of 8.2. The TEG is designed for using it indoors at temperatures of 21 – 26°C, i.e., at typical temperatures maintained in hospital wards. At 22 – 23°C, the TEG produces about 30 $\mu W/cm^2$. The head does not have thermal regulation therefore at lower ambient temperatures the increased heat flow would induce a sensation of cold and discomfort. Therefore, wearing a cap or closing the radiator openings would be needed to decrease the convection heat transfer and thereby limit the heat flow through the thermopiles. Experiment proves that if, on mistake, it is not done at, e.g., 19°C the TEG produces 3.7 mW accompanied by the sensation of cold, and the patient does not accept it.

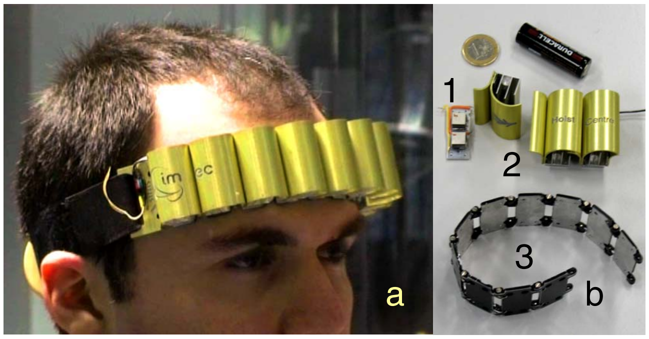

Figure 7. (a) A 2.5-mW TEG on a person and (b) its components: a thermopile unit (1), fin radiators (2), and a hot plate chain (3) compared to 1 Euro coin and AA-battery.

V. HYBRID ENERGY SCAVENGERS

The hybrid energy scavengers fabricated in 2008 have been designed primarily to avoid sensation of cold induced by thermoelectric generators in cold weather. They consist of two parallel electrical circuits, one is with a TEG, and the other is with PV cells. Additional power gained from PV cells enables decreasing heat flow through the TEG (and the produced power, too) making it comfortable in harsh weather conditions. One of the scavengers is shown in Fig. 8. In this device, PV cells serve simultaneously as the outer surface of the radiator to dissipate body heat into the ambient.

Figure 8. Two-channel wireless EEG system with hybrid energy scavenger.

The hybrid power supply provides more than 1 mW on average in most of situations, which is more than enough for the targeted application consuming 0.8 mW. The absolute and relative input power gained from the thermoelectric and PV power supplies constantly varies, reflecting variations in illumination and in heat transfer from the head. E.g., the power generated by PV cells in direct sunlight near noon was 45 mW while a power of 0.2 mW was measured in the office, far from the window on a cloudy day. The TEG provides much more uniform power output than PV cells because it depends mainly on air temperature. At 22°C, indoors, the TEG generates 1.5 mW, while outdoors, at 9.5°C with no wind, the power increases to 5.5 mW. The EEG system is battery-free, so all the power exceeding 1 mW is typically wasted which is a drawback. However, using a supercapacitor instead of secondary battery allowed demonstration of the nice system feature: in less than 1 min (typically, in 10 – 30 s) after putting it on, the supercapacitor is fully charged and the system performs self-start from the body heat.

As tested outdoors down to a temperature of 7 °C, the device is very comfortable for the user. As a rule of thumb, at 10°C outdoors, PV cells generate 8 times more power than the TEG while indoors the latter offers 8 times more power than PV cells in the office.

By using a two-way power supply that exploits both the heat dissipated from person's temples and ambient light as energy sources, the dimensions and weight of the TEG are reduced. Furthermore, the location on the hair is much more convenient, according to user's responses. This further increases the patient's quality of life. In addition, the EEG system works much more reliably at high ambient temperature like 28°C (with available light).

VI. SYSTEMS IN CLOTHING

The system for integrating into a piece of clothing must be smaller than the EEG systems described above. The only way to make them really small is to decrease the power consumption, because the energy scavengers already work near the theoretical limits. However, as discussed above, using a secondary battery enables scaling down the scavengers (by a factor of 2 – 5). The first example of a body-powered system-in-a-shirt is fabricated in 2009, Fig. 9. The thermoelectric modules have a size of 3 cm × 4 cm × 0.65 cm, Fig. 10. When the shirt is put on, the system is powered by 14 thermoelectric modules producing about 0.9 mW during sedentary activity in the office. However, if the person walks indoors, the power production increases in a few minutes up to 2 – 3 mW due to forced convection. The TEG is neither cold nor obtrusive for the user. In winter, the outdoor clothing is worn on top of shirts. However, as measured outdoors at about 10 °C on a person wearing a thick jacket, the power generation is by about 10 – 20% better than indoors with no jacket. Energy storage in the battery also has a drawback, i.e., the self-discharge of battery. Therefore, when the shirt is taken off, it should be stored in the place where light could periodically reach small PV cells located on shoulders. The cells provide both the standby power and compensation for the battery self-discharge until next using of the shirt. The shirt has waterproof encapsulation of its components: an electronic module on double-sided flex, wiring, PV cells and thermopiles. It sustains its laundry, a hard drying cycle (tested at 1000 rpm) and pressing. An example of transmitted electrocardiogram is shown in Fig. 11.

Figure 9. Body-powered wireless electrocardiography shirt.

Figure 10. Thermoelectric module of the shirt compared with 1 Euro coin.

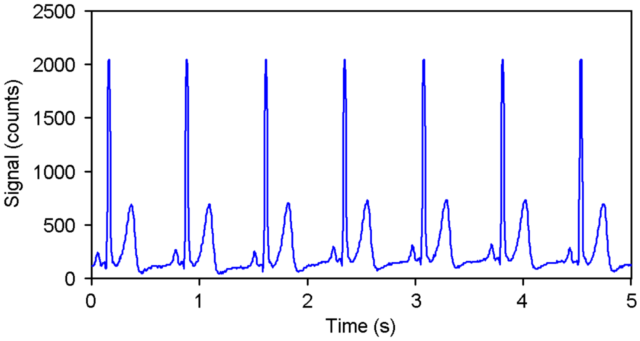

Figure 11. Raw electrocardiography data transmitted by the shirt (no noise reduction technique applied).

VII. CONCLUSION

The main conclusion of this work is that PV cells cannot compete with thermoelectric generators in wearable devices, and especially in clothes. First of all, an optimized TEG produces more power per unit area of the human body. Furthermore, the piece of clothing with integrated energy scavenger worn today may then stay in a wardrobe for weeks or months. In this scenario, the self-discharge of a battery, in particular, in small-size devices (that are certainly the target) prohibits its use in such devices. The only feasible solution is a supercapacitor for both short-term charge storage and buffering peak loads. However, PV cells cannot work with such short-term energy storage element, but require a rechargeable battery.

As shown in the paper, hybridization of TEGs with PV cells is one of the best design choices. In certain applications, this solution allows secondary battery and therefore the scavenger of smaller size. As the example of such device, the first electrocardiography shirt is demonstrated which is powered by scavengers for its entire service life and does not require any service except periodic laundry.

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