Energy Harvesting Technology Advances and Practical Applications: State of the Art

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Abstract—**The humanity gets increasingly concerned about the environmental footprint it leaves on the Earth. Conventional methods of energy generation as fossil fuels are not alone under attention including all types of batteries. This impulses a rapid development of methods for energy extraction from alternative sources. Energy harvesting is a nonstop growing field of research which aims to provide energy for low-power applications with specific power requirements. This paper makes an overview of these technologies and provides current state of the art for each harvesting technology.**

Index Terms—**Energy Harvesting, photonic energy, photovoltaic, motion energy, piezoelectric, thermal energy, thermoelectric generator, Radio Frequency (RF) energy, power management, power electronics.**

I. Introduction

ENERGY HARVESTING raises as one of the key emerging technologies of the twenty first century. The environment can supply a certain amount of energy. The recollection of this energy and its conversion to electrical energy is generally referred to as energy harvesting. In terms of volume of produced power, energy harvesting often includes small or even tiny systems which produce power in the range from nanowatts to milliwatts [1].

The mentioned magnitude range of possible harvested energy narrows its suitability for many applications. Wireless devices, such as sensors or actuators, become the main applications category. Home and industrial automation, construction, health care are the main application fields. The amount of energy that can be recollected in a particular environment, size requirements, weight, lifetime, ecological demands are the key factors for determination if energy harvesting is appropriate for an application.

The present paper will provide a brief overview of each harvesting source available nowadays and reveal current state-of-the-art solutions within the field.

II. Energy Harvesting Technologies

Next energy sources were considered feasible for energy harvesting: light, motion, temperature variation, electromagnetic radiation and chemical energy. Motion energy harvesting uses three types of transducer: piezoelectric, electromagnetic and electrostatic. Light harvesters use photoelectric effect, electromagnetic harvesters use induction and thermal harvesters use thermoelectric effect, also called the Seebeck effect. There are also a number of chemical reactions which are capable to produce energy.

A. Photonic Energy Harvesting

Photonic energy harvesting methods can be resumed in recollection and conversion of light or solar energy into electrical power. This kind of energy has been renowned as ecologically clean and inexhaustible. The working principle is based on photovoltaic (PV) materials which absorb a large number of photons. The electrical power is obtained when a sufficient number of photons were recollected to activate the electric optical pool [2]. This recollection is only possible when a device with appropriate structure and design is employed.

The efficiency of harvesting process strongly depends on the environment. To obtain more power these devices have to be placed in conditions of good lightning, if possible where mostly exposed to the sun. Solar cells can be connected in series or in parallel to achieve the desired power levels. Trends in the market lead to the reduction of costs for solar cells what makes it a good option to be the energy harvesting source for wireless network nodes.

Current movements of research and development in solar energy harvesting take two clearly distinct development trends: PV panels building integration and batteryless self-powered IoT sensor devices.

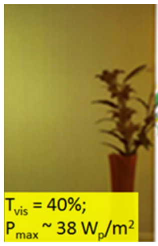
Growing every day environmental concerns intensively impulse the development of alternative energy systems to conventional fossil fuels power plants. Though, a large-scale development and deployment is not yet a near-future reality, conventional PV cells on roofs of residential buildings is a rapidly growing practice. Recent solar energy development goes toward the direction of building-integrated PV (BIPV) cells.

The recognition of being an advantageous and profitable sources of renewable energy source came to building windows and glazing systems. Recent developments in semitransparent concentrating and non-concentrating BIPV technologies shown performance improvements reaching 27.3% of conversion efficiency [3] and 20.9% of overall efficiency [4] based on perovskite PVs. Figure 1 shows performance comparisons for currently available commercialized semitransparent BIPV technologies.

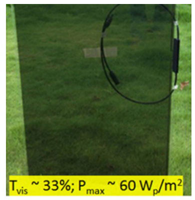
The average transparency T_{vis} percentage and peak-rated electric power P_{max} were taken directly from corresponding manufacturers' specifications. Figure 1a presents Sunjoule product from AGC (Asahi Glass Corporation, Japan) [5], Onyx Solar a-Si high-transparency BIPV [6] presented in Figure 1b and Hanergy BIPV panels using a-Si [7] in Figure 1c.

Another distinctive development trend of solar energy harvesting relates to the Internet of Things (IoT) field. Conventional IoT node comprises a small embedded system usually

(a) Onyx a-Si



(b) Hanergy a-Si



(c) CdTe

Fig. 1: Semitransparent commercially available BIPV technologies

powered with a Lipo battery. Current developments follow toward power-autonomous batteryless design sensor nodes technologies. Embedded systems optimized power consumption has to be achieved by designers yet and strongly depends on concrete application-related environment. In such applications supercapacitors are used instead of batteries to provide uninterrupted service during nighttime. At the same time, manufacturers offer solutions to leverage and optimize power management for such designs. Texas Instruments's BQ25502 [8] and AEM10941 from e-peas [9] are highly optimized chips developed exclusively for applications where a battery presence is optional.

Ultrahigh frequency (UHF) radiofrequency identification (RFID) technology is widely used nowadays for inventory tracking purposes. The RFID technology is suitable for a range of application with close-distance range. The major distance-limiting factor which impedes the RFID from enlarging its application suitability is power consumption. Typical RFID IC is powered through a passive interface that harvesters power from the reader device, and data transfer is carried using the same channel. Communication range is limited by the input power. Incorporating previously mentioned perovskite PV panels into minimalistic RFID sensor design allows to achieve longer communication ranges. Researchers from [10] and [11] proposed this approach and increased the range up to 20 m. Also new tracking systems were developed based on these advances.

B. Motion Energy Harvesting

Motion energy harvesting principally uses mechanisms capable to take advantage from the piezoelectric effect. The motion energy is converted into the electrical power by means of the piezoelectric effect. The effect consists in a generation of electrical charge through mechanical strains on a piezoelectric material layer. This charge, when transmitted on wires, produces AC power output which is captured by the transducer and transformed to desired characteristics. Natural and synthetic materials, also crystals on compression can be considered piezoelectric.

The nature of the piezoelectric effect is closely related to the occurrence of electric dipole moments in solids [12]. The change of polarization when mechanical stress has been applied to a material is of great importance. Two factors can change the polarization. First, the external stress can reorient molecular dipole moments. Second, by reconfiguration of dipole-inducing surroundings. Piezoelectric energy is then produced through a variation of polarization. This process depends of three factors: orientation of crystal polarization, crystal geometrical structure, and applied stress.

The developments in this field can truly be called revolutionizing. There are a plenty of directions in which energy harvesting using piezoelectric materials is under development or already applied nowadays. Wearable medical sensors become more miniature and sophisticated incorporating power supply based on harvested kinetic energy generated by motion of human body [13]. The Piezoelectric Energy Harvesting Research Group at Cranfield University presented a knee-joint wearable energy harvester offering outstanding results. Voltage over 20 V has been harvested and the instantaneous power reached 15 mW [14]. In [15], piezoelectric harvesting unit was introduced into a heel of a shoe harvesting energy generated by walking. Considerable amounts of power were reached, up to 378 μW. In Figure 2 presented the prototype used in the study.

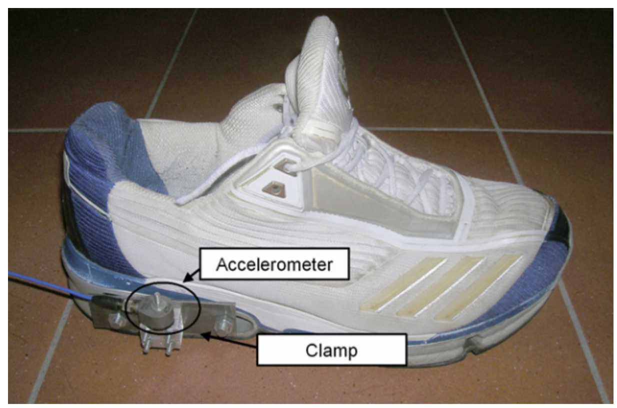


Fig. 2: Energy harvesting system mounted in a shoe

Automotive industry stands as a wide field for energy harvesting exploration. A new concept of intelligent vehicle wheels is explored and proposed in [16]. The system uses wheels rotation for energy generation and is capable to supply power up to 6.28 mW.

Ambient energy harvesting plays an important role for applications within smart and environment metering. Fluid movements energy harvesting is experiencing significant development. Fluid flow harvesting systems discussed in [17] start to find practical application as river water quality monitoring [18].

C. Thermal Energy Harvesting

The thermoelectric energy harvesting is founded on the Seebeck effect. It was discovered by T.J. Seebeck in 1821 researching metal thermocouples [19]. It consists in conversion of a heat flow into electricity. Figure 3 illustrates the working principle of the Seebeck effect.

Two materials, A and B, are placed in a way that both have two common sides. One side should be maintained at high temperature T2 and the other at low temperature T1. The

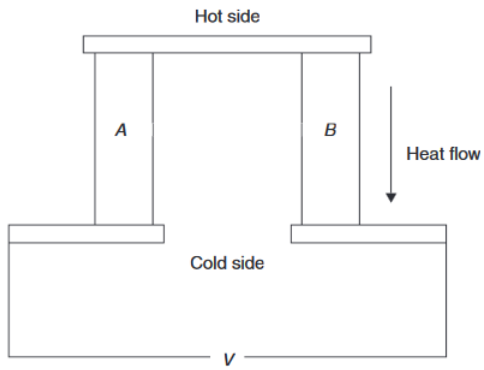


Fig. 3: Thermoelectric generator working principle

electrical connection of the materials are performed on high temperature side while the voltage is monitored across the cold side terminals. Free particles (electrons and holes) in a material spread according to a heat flow created by the temperature difference. Another elements moved by the heat flow are phonons or lattice vibrations. The motion of charged particles will concentrate space charges at both material terminals. These charges, in turn, create an opposing electric field. The opposing field exists while the complete equilibrium condition has not been reached.

If the materials A and B from the Figure 3 were identical, the resulting potential differences would cancel each other generating no voltage. However, if A and B are different, the output voltage will be a positive value. The load connected to the output terminals will receive the generated power. This way the electrical power is generated by the heat flow. The resulting structure was called a thermocouple.

A common industry trend is to shrink size of components and under this tendency new geometry and designs appear. Recently, innovative planar thermoelectric nanogenerators (nanoTEGs) were introduced by [20]. Thousands of nanoTEG cells with dimensions magnitude of μm are connected in parallel or in series depending on the desirable power output. Figure 4 shows cell's structure and functional scheme which produces power density level of 0.06 μW for 0.5 cm^2 of surface area for a temperature difference of 6.8 K.

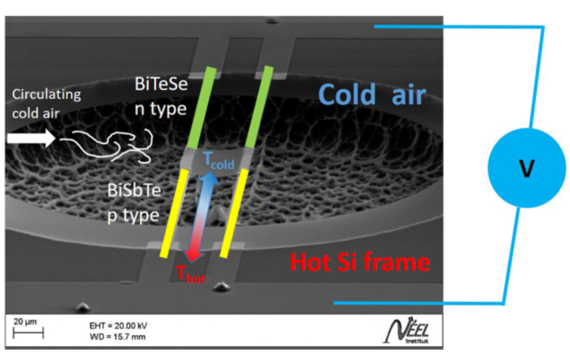


Fig. 4: NanoTEG cell under electron microscope view [20]

Interesting use case shown by [21] demonstrates how this conventional thermoelectric generators can be used in energy harvesting based on gradients in the earth surface. The study demonstrates that using this method is feasible to supply enough energy for a generic wireless sensor node. Possible extracted power level reaches 27.2 mW. Similar approach were performed in [22] where the source of thermal gradient was street asphalt.

D. Radio Frequency Energy Harvesting

The Radio Frequency (RF) waves is another possible source of energy which has been under continuous development last decade. Briefly, it is a capability to receive and convert RF signals to electrical power. There are three wireless energy transfer techniques and RF energy transfer and one of them is applied for harvesting. Another two techniques are magnetic resonance coupling and inductive coupling. Magnetic resonance coupling employs evanescent-wave coupling for generating and transferring electrical energy between two resonators [23]. The resonator is created by adding a capacitance to an induction coil [24]. The inductive coupling is based on magnetic coupling through which the electrical energy is delivered [25]. Both coils, on transmitter and receiver have to be tuned to the same frequency. Generated magnetic field serves as the medium for energy transmission.

In contrast to RF energy harvesting the magnetic resonance and the inductive coupling are close-field wireless transmission techniques with high conversion efficiency and power density. According to the features associated to the magnetic resonance and the inductive coupling they do not suit for mobile and remote charging. However, RF electromagnetic waves cannot affect the antenna which created them if distance exceeds $\lambda/(2\pi)$ [26], therefore RF energy transfer is considered as far-field energy transfer technique [24]. The far-field energy transfer makes possible to supply energy for powering numerous electronic devices dispersed through a wide area.

Wearable medical sensor devices open a niche for different energy harvesting sources. As mentioned earlier, piezoelectric motion harvesters started exploiting this area. RF energy harvesters are good candidates for providing similar power levels to medical sensor devices. Practical applications exist in form of wearable rectenna which harvesters low-power RF energy aimed at WiFi frequency band, 2.45 GHz [27]. The combination of a full-wave Greinacher rectifier and radio frequency choke make possible output voltage up to 2.2 V what is suitable for the majority of low-power ICs. The device used in the research is shown in Figure 5.

New approaches appear with superior efficiency levels as presented the authors of [28]. Aimed to the same WiFi frequency band they achieved up to 47% more efficiency employing dc CMOS converter and specially designed internal threshold voltage cancelation technique.

E. Other Energy Harvesting Technologies

Sound is another possible niche for energy harvesting which is slowly getting attention from the research society. The harvesting process can be divided in steps starting from sound waves recollection and amplification by means of acoustic metamaterial or special resonators. The amplified sound waves may create vibrations which are directed to one of the energy

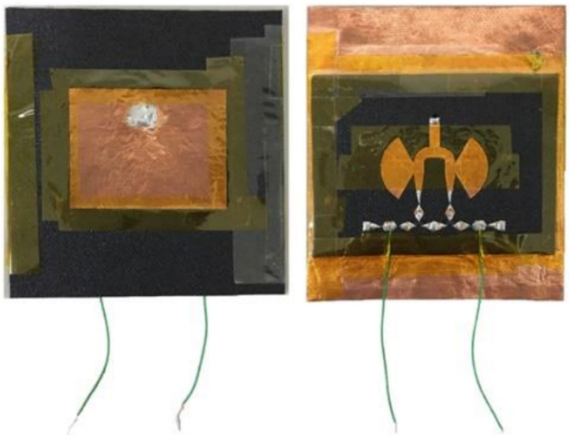


Fig. 5: Front and back views of designed in [27] energy harvesting 2.45 GHz rectenna

conversion mechanisms as piezoelectric, electromagnetic, or triboelectric transducers where it is converted to electrical AC power [29]. Finally, the electric power is rectified, regulated and stored. The experiments show that the magnitude of output power ranges in μW and mV.

The uniform and omnipresent availability of magnetic field can be considered as alternative source of energy. However, the current applications as wind turbine generators or electrical generators bound to general uses of this source.

III. Conclusion

Energy harvesting is continuously developing field of local power generation. Numerous current harvesting methods and effective applications have been presented in the document. Future expectations draw that the field will receive more attention due to environmental concerns. It is difficult to determine standard procedures and techniques for harvesting of some energy sources while other sources methods are well-established and will continue leading future trends. Research society will focus on increasing power outcome levels in each energy source.

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