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Energy Harvesting—Technical Analysis of Evolution, Control Strategies, and Future Aspects

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Abstract—This paper provides a technical analysis of energy harvesting (EH) in the field of power and energy sector, including different aspects of harvesting energy, individual case history, control strategies of harvesting in the field of power and energy sector together with the current trend and future aspects of it. EH is comparatively a new concept which is growing very fast since the 20th century and catching new generation research approaches. This paper not only describes the past and current scenarios of harvesting energy with radio frequency (RF) and renewables but also gives author's own anticipation of the upcoming future trends of it by comparing the case histories.

Index Terms—Energy harvesting (EH), piezoelectric, radio frequency (RF), solar, triboelectric, wind.

1. Introduction

Energy harvesting (EH) is the process to capture and use energy from ambient sources, which is also known as energy scavenging. Energy harvesters provide small power to drive low powered electronic devices. In recent years, EH research has grown in a rapid pace due to its application in self-powered small electronic devices[1]. There are different sectors where harvesting energy plays a vital role and the strategy is getting popular over the years and as a result getting further improved. This research tries to gather technical aspects of EH, giving a detailed review of the different sectors where EH is being implemented. In addition, it analyzes the control system of each individual harvesting technique in different fields, and finally the research ends with author's individual creative summary of previous history, current trend, and future possible approaches.

2. EH—Different Aspects

Different fields of energy technologies have investigated for the possibility of EH in the past few decades. They can be mainly categorized in two parts, renewable and non-renewable EH. To keep the scope of this work precise,

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this paper mainly focuses on renewable EH technologies for low powered electronic devices. But nonetheless the most prominent non-renewable EH technology, radio frequency (RF) EH, is also included in this paper to ensure the reader of an updated view of the whole field. The topics of EH discussed in this paper are shown in Fig. 1.

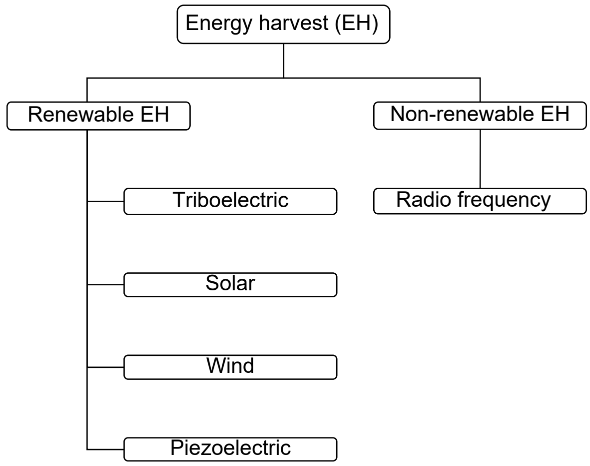

Fig. 1. Scope of the study.

3. RF EH

In a system level implementation, a sensor network consisting of three leaf nodes was demonstrated by Percy *et al*.[2]. The harvester circuitry uses an impedance-tuned rectifier circuit to convert energy from RF to usable DC voltage. It consists of the omni-directional receiving antenna, impedance matching network, power management module, energy storage, and a wireless sensor. The energy conversion efficiency of the proposed system is found to be 39.1%. Through measurement and simulation results, it is shown that the system has the ability to supply few sensors at a longer distance (>3 m) or many sensors at a short distance (<3 m).

An RF-DC converter energy harvester was proposed by Scorcioni *et al*. implemented with the 130 nm complementary metal-oxide-semiconductor transistor (CMOS) technology producing an output of 2 V at −14 dBm with a maximum efficiency of 45% measured at 868 MHz[3]. The same authors later improved the design with the RF-DC converter and a differential PCB custom antenna producing an output of 2 V at −16 dBm with a maximum efficiency of 60% (custom antenna design)[4]. A self-calibrating RF energy harvester was presented by Stoopman *et al*.[5]. Measurement at 868 MHz in an anechoic chamber showed the −26.3 dBm sensitivity with 1 V output and 25 m range for a 1.78 W RF source in an office corridor. The maximum efficiency of the harvester was 31.5%. The RF energy harvester was implemented in a 90 nm CMOS technology and comprise of a 5-stage bridge connected rectifier and a 7-bit capacitor bank. The same researchers later proposed a design based on the similar 90 nm CMOS for producing the output of 1 V at −27 dBm with the highest efficiency of 40% at −17 dBm[6].

Lu *et al*.[7] proposed an ultra-high frequency (UHF) RF energy harvester with the efficient dual path structure including a low power path, a high power path, and a control mechanism to maintain a high power conversion efficiency (PCE) for a wide range of inputs by switching paths. Implemented in 65 nm CMOS technology and measured at 900 MHz, this design showed a sensitivity of −17.7 dBm for 1 V. The peak efficiency was 36.5%, and above 20% PCE could be maintained from −16 dBm to −5 dBm with a range of 11 dBm, while the single path rectifiers could only maintain the high PCE with a range of 8 dBm.

Kamalinejad *et al*.[8] have given an overview of enabling technologies for wireless energy harvesting (WEH) to Internet of things (IoT) systems. A power management unit (PMU) architecture was proposed for battery operated systems using WEH. For the proposed system in the ring topology, using WEH increased the lifetime of the battery assisted low power sensor devices by 30%, and additionally using the wake-up radio scheme (WUR) enhanced the lifetime by further 110%; and in the randomly distributed multihop topology, the lifetime enhancement through WEH for a node at a similar distance compared with that of the ring topology was 510%. Therefore, it was shown using WEH in the multihop topology increases the lifetime of the devices more. The scenarios and their respective interpretation in this paper assumed the transmission channel to be static and time invariant, but practically channel characteristics vary with environment and time, further studies considering the above can complement the findings of this study.

For wireless communications systems, Kang *et al*.[9] proposed a full duplex communications scheme for simultaneous downlink wireless power transfer (WPT) for EH and uplink information transmission with the hybrid access point (HAP). Time division multiple access (TDMA) was enabled to allow multiuser uplink transmission, users could continuously harvest wireless power from the HAP until its transmission slot. The simulations in the paper considered two scheduling orders as increasing and decreasing. However, joint optimization of time allocation and the scheduling order may further improve the system performance. Moreover, the antenna pattern for transmit-receive was assumed to be fixed, but [10] and [11] showed that a higher sum rate could be achieved by dynamically selecting the transmit-receive antenna pair for the full duplex system. References [12] and [13] comprehensively reviewed the topic of harvesting energy from RF. While the first paper focused on different EH techniques in terms of circuits and applications, the second paper mainly focused on scheduling policies, resource allocation, medium access, and networking issues.

4. Renewable EH

4.1. Triboelectric EH

Chen *et al*. presented a triboelectric nanogenerator network (TENG NW) for large scale implementation[14]; the working principle of TENG is based on electrostatic induction and coupling between contact electrification. A unit of the proposed nanogenerator has the arch shaped top and bottom plates with a multilayer core. Both top and bottom of the triboelectric nanogenerator are made of polyethylene terephthalate (PET), and both top and bottom layers of the functional core are a polytetrafluoroethylene (PTFE) film with copper as back electrodes. The aluminum thin film is sandwiched between the top and bottom layers of the functional core, playing dual roles as an electrode and a contact surface, and acrylic is used as the structural supporting material, as shown in Fig. 2. The network is created by connecting many nanogenerators together in mesh. The kinetic energy from wave energy can be converted into electricity with the proposed TENG. The advantage of the proposed TENG NW is the scalability; it can be used in a large scale with estimated power output of 1.15 MW from a 1 km^2 water surface. The major concern for implementing such system is the integration aspects with the existing electricity network which will require further research[15].

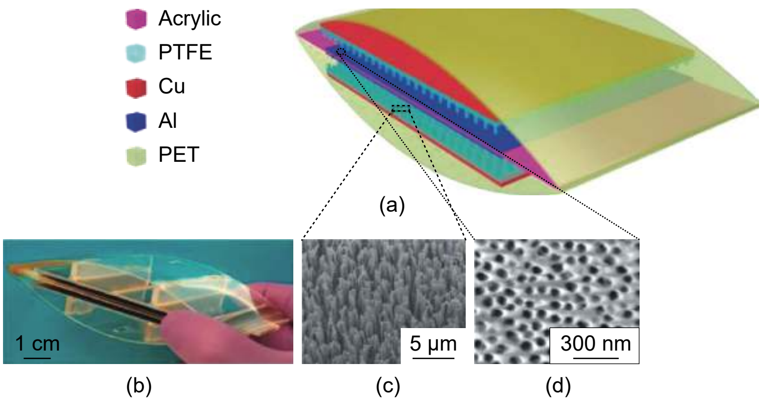

Fig. 2. Single unit in a TENG: (a) schematic illustration, (b) photograph of an as-fabricated minimum functional unit, (c) SEM image of PTFE nanowires, and (d) SEM image of nanopores on aluminum electrode[14].

Wang *et al*. constructed a fully enclosed rolling structured and freestanding triboelectric layer based nanogenerator (RF-TENG), which can harvest low-frequency water wave energy[16]. The device was sphere shaped with two electrodes and a freestanding rolling ball. Different materials were tested for the choice of the rolling ball and electrode. Finally nylon was selected as the material for the ball, and kapton was used as the triboelectric layer on aluminum electrodes. The optimized RF-TENG construction can deliver a current of 1 A and the peak power output of 10 mW. Moreover, the setup was tested to successfully power a light emitting diode (LED) and electronic thermometer. The possibility to use this proposed device in a large scale can be considered for future research to harvest wave energy.

Cheng *et al*. reported a wearable electrode free triboelectric generator (e-free TEG) to harvest human walking energy[17]. Shoe sole was used as a friction surface, and a thin film of porous ethylene-vinyl acetate copolymer (EVA) was employed under the shoe sole to increase contact electrification. The design presented in this paper did not require a vertical gap in the shoe and power could be obtained from any part of the human body. Different types of reference electrode were tested and it was found larger conductors produce better outputs. In normal walking on a marble floor, an output voltage of 810 V was achieved and the charge of over 550 nC was transferred in one step. Moreover, an array of 76 LEDs was driven by the walk of one person. This technique has great potential for the wearable and implanted technology. However, the findings in this paper only considered the marble floor, but more investigations are required for the output of the design on other surfaces, such as pavements, concrete, and asphalt. Fan *et al*. proposed an ultrathin, roll able, and paper-based TENG for acoustic EH and self-powered sound recording[18]. TENG was 125 m in thickness and the maximum power output density is 121 mW/m^2 under 117 dB SPL. Paper was used as the backbone of the proposed TENG, copper and the polytetrafluoroethylene (PTFE) membrane were used to produce electricity based on the triboelectric and induction principles. To enhance the acoustic response, holes on 400 m are punched in the paper and polymer nanowires were created on PTFE for increasing the triboelectric effect. The flexibility of paper allows for a wide range of applications of this design, it was demonstrated by harvesting electricity from cellphone conversation to charge a capacitor of 2 F at the rate of 0.144 V/s. The concept presented in this work can be extensively implemented in a broad range of applications including acoustic EH and sensing.

Yang *et al*. proposed a triboelectric generator with flexible plastic metal (PM) films as the conductive layers with two polymers PET and polydimethylsiloxane (PDMS) as the triboelectric layers[19]. This design allows the device to be flexible. The PDMS array was fabricated with microstructure to increase friction and PM was prepared with the mixture of gallium, indium, and a glaze powder. The average output of this triboelectric generator was 80 V with a current of 37.20 A. In the paper the device was shown to light LED lamps. And EH (currents & voltages) in different modes of driving the generator was also demonstrated.

Chen *et al*. reported a bio-inspired triboelectric nano-generator design which resembled the motion of a jellyfish and worked under water[20]. The bionic-jellyfish triboelectric nano-generator (bjTENG) was made of the polymeric thin film that works as a triboelectric material with a unique elastic structure. The working procedure of the device was based on the liquid pressure induced contact separation of the triboelectric layers. In the experiments shown in [20], a sustainable output of 143 V, 11.8 mA/m^2, and 22.1 μC/m^2 in a low frequency of 0.75 Hz at a water depth of 60 cm was produced. The bjTENG was tested both in air-water interface and under water. One interesting aspect of the research work was to demonstrate the applications of bjTENG in different practical situations, such as LED lighting, the self-powered temperature sensor system, and wireless self-powered fluctuation warning system. Among other literatures, [21] gave a concise overview of applications and possibility of bjTENG. And [22] provided a review of different triboelectric technological development.

4.2. Solar EH

Yu *et al*. designed a circuit to store power generated by photovoltaic cells in super capacitors and delivered to drive sensor nodes[23]. The proposed design was proposed for indoor light harvesting in the μW power levels. The system consisted of the light transducers, energy storage circuit, maximum power point tracking (MPPT) circuit, a DC-DC boost converter, and discharging circuit. In experiments the setup was shown to successfully drive a wireless temperature and humidity sensor node. Circuit diagram of the proposed system is given in Fig. 3.

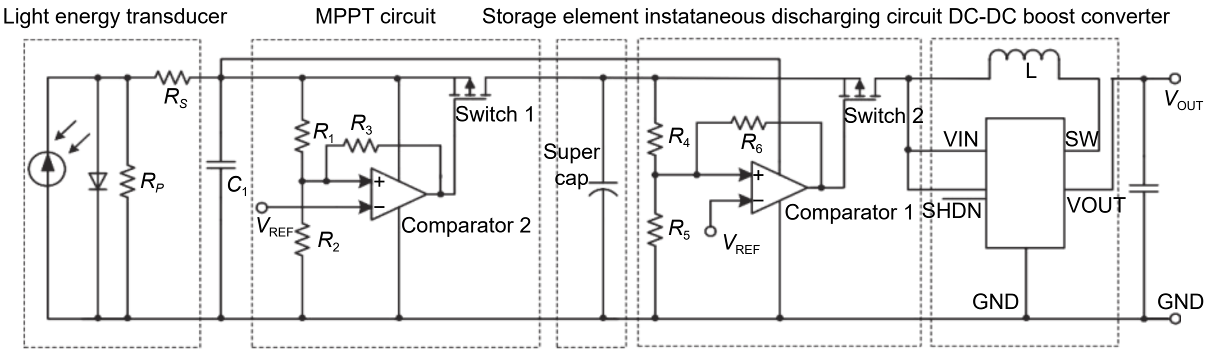

Fig. 3. Circuit diagram for indoor light harvesting[23].

Chuang *et al*. presented a self-sustained solar powered sensor module (SPSM)[24]. The module contained a solar panel, DC-DC converter, MPPT circuit, capacitor based energy buffer, and sensor node. The control system was based on BASIC script. The module was cheaper compared with other alternative designs due to using ordinary capacitors. Experiment results showed that the module could operate under indoor, streetlight, and outdoor conditions. With MPPT, the charging time was reduced to 100 ms and a conversion efficiency of 71% was achieved. Li and Shi proposed an MPPT based hardware controlled charge management circuit for solar EH in the wireless sensor network[25]. The circuit used a lithium battery. To prolong the battery life, an RS trigger circuit was implemented to charge the battery only when the voltage was lower than a specified value. The system could produce a stable supply with 5 V output through a USB interface.

Fröhlich *et al*. in their paper compared the performance of two modes of solar EH, namely directly coupled system and MPPT integrated circuit (IC) based system[26]. The directly coupled system was based on the design in [27] with some modifications to make the circuit efficient. SPV1040 from STMicroelectronics was chosen among different available ICs in the MPPT system, and both systems were used to change a NiMH battery. The experiments in different environmental conditions showed that the directly coupled circuit performed better than the MPPT IC based circuit.

Shrivastava *et al*. presented a 130 nm CMOS based boost converter with the capable of harvesting energy from thermoelectric/solar cell inputs as low as 10 mV[28]. This work was an improvement of the previous works by the same authors[29]. The proposed converter works at a high efficiency in a broad range, achieving 53% and 83% at 20 mV and 300 mV, respectively. Furthermore, the device could startup from RF signals, which makes it more versatile. Chiou *et al*. demonstrated a wide range input solar EH circuit with a reconfigurable capacitor array to cope up with the input voltage instability due to the variation of solar energy input[30]. The design used a switched-capacitor (SC) converter; the startup voltage of the device was 75 mV with a peak efficiency of 77% and over 40% for the input voltages from 300 mV to 1.2 V. For conducting experiments on the design, a test chip was fabricated in the Taiwan Semiconductor Manufacturing Company (TSMC) 90 nm process technology. Simulations were conducted and verified with experimental results.

Jokic and Magno presented a self-sustainable smart bracelet with a flexible solar harvester, sensors, and communications ability[31]. Flexible solar cells were used along with the CC2650 chip from Texas Instruments containing an ARM Cortex M3 core for processing, acquisition, and Bluetooth communications. Under typical indoor environment at a light intensity of 500 lm, the device generated 0.155 mW; in outdoor at the brightness of

10000 lm, up to 16.5 mW was generated. In the target application, the device was self-sufficient only with 1000 lm of light. The experiments conducted demonstrated that the harvested power was sufficient for the system to run independently with the usage of a pulse oximeter and an accelerometer for data acquisition and transfer in every minute. More on solar EH is available in [32] to [34]. References [32] and [33] focus on solar EH in wireless sensor networks, and [34] focuses on the development of microelectronics for solar EH.

4.3. Wind EH

Khan *et al*. developed a supercapacitor based hybrid control system which is able to store energy from low voltage wind turbines[35]-[39]. The control system, including the metal-oxide-semiconductor field effect transistors (MOSFETs) based switching technology, permitted the supercapacitor bank to be charged up from the turbine separately, and then discharged through the battery. This off-grid technique could charge a 6 V or 12 V DC battery in low wind speed areas even if the output from the turbine is as low as 4 V. Myers *et al*. designed several vertical small scale windmills integrated with piezoelectric transducers (PTs) to power up sensor networks in remote locations where the electric grid is not available[40]. The team chose PT because it was capable of producing a lot of charges under the full load condition. In addition, it was cost efficiently. The first design utilized 12 PTs which were placed between the slots around the body of the windmill. Each PT had a capacitance of 170 nF. However, the design had several drawbacks, for example, it used to reduce the lifespan of PT because of the high number of impacts. Moreover, the outputs were not in phase.

4.4. Piezoelectric EH

Roundy conducted a study in 2003 based on piezoelectric materials, lead zirconate titanate (PZT), and polyvinylidene fluorideand (PVDF), to generate power in order to replace the batteries, thus powering up the wireless electronic devices[41]. Several modifications had been made and Roundy came up with 2 designs of different lengths for the experiment. Design 1 had a total length of 1.5 cm whereas design 2 had a total length of 3 cm. Both the designs were exposed to the resistive load test and capacitive load test. Based on the output of the resistive load, the maximum power generated for designs 1 and 2 were 207 μW and 335 μW, respectively. On the other hand, for the capacitive load, the maximum output power for designs 1 and 2 were 90 μW and 180 μW, respectively. Overall, it could be observed that design 2 with a double length of design 1 was more sensitive to vibrations. One practical reason could be that design 2 had a lower damping coefficient. Therefore, it had a higher quality factor, as a result, producing higher output power.

Oh *et al*.[42] developed a tree-shaped EH system using PT that were attached to the leaves and trunk of the tree. The laminated PVDF beam of model LDT4-028K/L was used, as it produced a higher output voltage compared with the non-laminated beam. Due to the low output power, a rechargeable battery was used to store the generated power prior connecting to electronic loads. However, a control circuit was implemented to enhance the overall performance for it and make it to be a standalone system. One of the famous inventions of piezoelectric was from the Massachusetts Institute of Technology Media Lab, where energy was harvested during heel strike and toe-off[43]. PT was installed in the insole of a shoe and the materials of PVDF and PZT were used for comparing the results. The maximum voltage produced from the PVDF material was 60 V with 20 mW of power, whereas PZT was able to produce up to 150 V with 80 mW of power.

5. Summary and Future Trends

Development trends for different EH technologies have been demonstrated in this paper. The summary of the scientific progress in EH can be summarized in a trend analysis in Fig. 4. EH for small scale self-powered devices is a relatively new field, and the development of the technologies has been accelerated in the last decade, especially for triboelectric and piezoelectric EH. In the last five years the system level implementation has been prioritized and a few systems have been demonstrated.

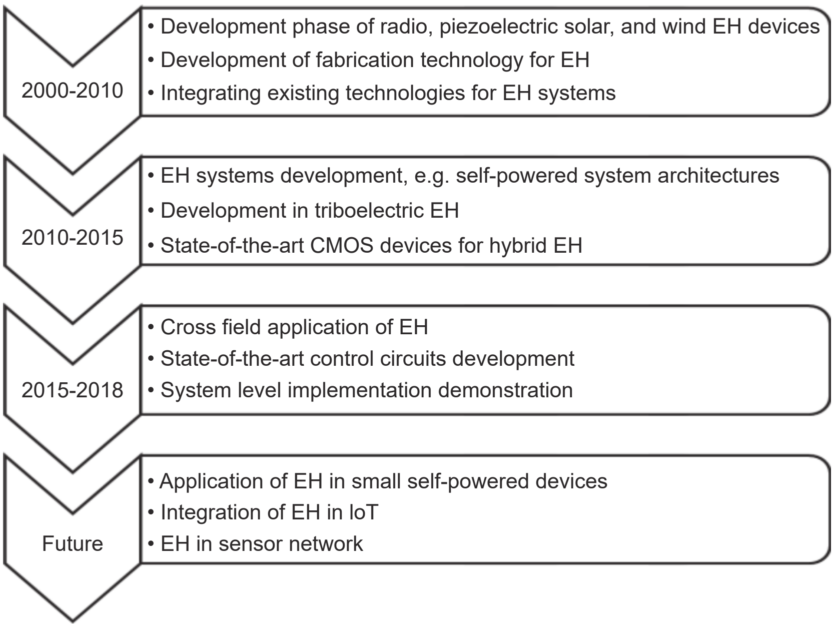

Fig. 4. Trend analysis of the reviewed literature.

6. Conclusion

In this paper different types of EH technologies have been reviewed, four renewable EH technologies are covered, along with the most important non-renewable EH technique. The topics covered small scale EH for self-dependent low powered electronics. The literatures reviewed here are recent and it can be observed that there have been demonstrations of self-powered devices. Compared with the technological know-how in this field in around year 2000, currently, the state-of-the-art technologies are much improved and suitable for implementation. The natural consequence of this is the development of commercial applications using the state-of-the-art technologies. Thus it is expected in the coming decade to see the penetration of more self-powered small electronic devices in different arenas of applications including sensor networks, IoT, health monitoring, and security applications.

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