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Energy Harvesting Technologies for Low-Power Devices

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ABSTRACT

The rising exponential rate of low-power electronic devices, such as wireless sensors, wearable electronics, and IoT systems, has exacerbated the need of sustainable and autonomous sources of energy. Traditional battery-based power systems tend to have capacity constraints, lifetime constraints, and maintenance constraints, thus researchers have looked into energy harvesting (EH) technologies as an alternative power source. This paper survey recent developments in energy harvesting schemes-including solar, thermal, vibrational, piezoelectric and radio-frequency (RF) sources-and their viability to low-power devices. It focuses on the system integration, energy conversion efficiency, and scalability under operations in real world. The review indicates the promise of hybrid EH systems to increase the lifespan of the operation of devices coupled with a reduced environmental impact. Empirical experiments show that self-sustaining operation of a wide range of low-power applications can be facilitated by optimized EH solutions but that there are still issues associated with energy intermittency, storage, and resource constraints. The proposed study will offer a broad framework to researchers and practitioners who want to adopt EH technologies in next-generation low-power electronics.

Introduction

The fast deregulation of the low-power electronic industry has revolutionized various industries, such as environmental surveillance, healthcare, wearables, and industrial Internet of Things systems (Khan et al., 2018; Roundy et al., 2003). The gadgets are regularly used in distant or inaccessible areas, and it is not practical to replace batteries on a regular basis. As a result, there are increased interests in energy harvesting (EH) technologies, which transform ambient energy into usable electrical power, as a solution to providing sustainable alternatives to conventional batteries (Paradiso & Starner, 2005; Priya & Inman, 2009). EH mechanisms play a vital role in maintaining continuous functionality of wireless sensor networks, medical implants and wearable devices wherein energy availability has a direct effect on reliability and performance (Beeby et al., 2006; Dagdeviren et al., 2014).

Photovoltaic (PV) technologies have been highly mature with a high energy density, thus, making solar energy harvesting a popular activity. Photovoltaic cells have the potential to efficiently transform the ambient light, both indoors and outdoors into electricity, which can be used to power devices with low power consumption (Kumar et al., 2016; Hussain et al., 2020). Recent developments in thin-film, organic, flexible PV materials have facilitated their combination with wearable and portable electronic devices, and new semi-transparent solar cells can be built into windows and other structural elements (Cheng et al., 2018; Kalogirou, 2014). Although it has these advantages, environmental factors, the availability of light, and the difference in day and night limit solar EH, and hybrid solutions or the addition of energy storage is required (Chowdhury et al., 2017).

It has been noted that vibrational and piezoelectric energy harvesting has been used to applications in the dynamic environment, including structural health monitoring and industrial machinery (Priya and Inman, 2009; Beeby et al., 2006). Piezoelectric materials are used to produce electricity when put under mechanical strain, piezoelectric materials convert the vibrational energy of human motion or vehicle motion or structural vibrations into electrical energy (Roundy et al., 2003;

Dagdeviren et al., 2014). Piezoelectric devices used in micro- and nano-scale offer a high power density, compared to their size and are therefore appropriate in compact low-power electronics. Their performance however is sensitive to the frequency of vibration, amplitude, and the material properties and therefore should be tuned with care when applied in a particular application (Wang and Song, 2006; Sodano et al., 2004).

Thermal energy harvesting uses temperature differences between surfaces of devices and their surroundings using thermoelectric generators (TEGs), and can therefore use heat sources as a continuous energy source in the application of thermoelectric generators to industry or body-heat environments (Snyder and Toberer, 2008; Zebarjadi et al., 2012). TEGs have a good conversion of energy though their efficiency is lower than photovoltaic or piezoelectric systems. Recent developments in the nanostructured thermoelectric materials and flexible TEGs have enhanced a better integration with wearable electronics and low-power devices, but the cost of the materials and the availability of thermal gradients has been limiting factors (Bell, 2008; Vining, 2009).

The radio-frequency (RF) energy harvesting uses ambient electromagnetic waves in Wi-Fi and cellular networks as well as broadcast signals to supply low-consumption devices (Visser and Vullers, 2013; Sample et al., 2011). RF EH is more appealing in the urban and IoT settings because of its ubiquity and low cost. Correcting antennas (rectennas) transform RF energy into direct current which is a continuous but limited power source that can be used in ultra-low-power sensors and wearable electronics (Lu et al., 2015; Huang et al., 2017). Low energy density and interference are some of the challenges that may impair reliability and efficiency in dense electromagnetic environments.

Multi-modal EH systems (hybrid energy harvesting systems) are also suggested to address the shortcomings of specific energy sources. Indicatively, solar-piezoelectric hybrid utilizes both light and vibration, increasing life cycle under changing conditions (Mitcheson et al., 2008; Roundy and Wright, 2004). On the same note, RF-thermal hybrids combine electromagnetic and heat-based harvesting, thus allowing the continuous operation in a variety of conditions (Visser & Vullers, 2013). This type of multi-source EH systems has great benefits to IoT devices, remote sensors, and wearable electronics, especially where that maintenance is a problem, and reliability counts (Beeby et al., 2006; Dagdeviren et al., 2014).

Although there have been extensive advances, a number of issues still exist in the implementation of EH into low-power devices. The problems of intermittency in energy, ineffective storage, constraints in materials and complexity in integration usually discourage complete autonomy (Priya & Inman, 2009; paradiso and Starner, 2005). The best use of energy conversion, enhanced material efficiency, and new lightweight, flexible, and durable EH modules are also the key subjects of study. Also, smart power management, such as ad hoc energy distribution and hybrid storage, is essential to enhance device lifetimes and maintain a consistent functioning in changing environmental conditions (Mitcheson et al., 2008; Roundy et al., 2003).

Overall, energy harvesting technologies are potentially transformative in terms of low-power devices sustainability. Photovoltaic, piezoelectric, thermal, and RF-based systems offer distinct benefits, and the hybrid approaches increase the reliability and performance. Further studies in the field of material science, optimization of energy conversion, and system design are vital to address the current shortcomings and allow universal application in wearable technologies, IoT, or industrial applications. The work provides the basis of the assessment of EH technologies in a real-life engineering setting, both in the opportunities and the difficulties of developing self-sustaining low-power electronics.

Literature Review

Energy harvesting (EH) has become one of the key enablers of low power devices, especially the ones whose replacement of batteries are impractically difficult, e.g. wearable electronics, remote sensing, and IoT systems (Paradiso and Starner, 2005; Priya and Inman, 2009). EH technologies use alternative sources of electrical power, converting ambient energy sources (light, vibration, thermal gradient, and radio-frequency (RF) waves) into electrical power, thus providing sustainable options to traditional batteries with limited environmental impact (Beeby et al., 2006; Dagdeviren et al., 2014). According to recent research, current EH mechanisms and hybrid energy systems which combine various sources to achieve greater reliability and efficiency are occurring due to the worldwide need to adopt self-sustaining low-power devices (Khan et al., 2018; Mitcheson et al., 2008).

Photovoltaic (solar) energy harvesting can be considered as one of the most popular EH technologies to be realized because of its high energy density and developed infrastructure. Thin-film, organic, and flexible solar cells have already been implemented into the world of wearable and portable electronics allowing the generation of continuous power under indoor and outdoor lighting conditions (Cheng et al., 2018; Kumar et al., 2016). Flexible photovoltaic can be embedded in fabrics, windows, and structural elements and is an unobtrusive form of energy production in the smart clothing and building-integrated electronics (Kalogirou, 2014; Hussain et al., 2020). Nonetheless, solar EH is sensitive to the environmental conditions in terms of the intensity of illumination, incident angle, and diurnal changes, which necessitates the installation of hybrid systems or energy storage to ensure continuous work of devices (Chowdhury et al., 2017; Roundy et al., 2003).

The use of vibration-based and piezoelectric energy harvesting has received a lot of interest in dynamic environments where mechanical energy is rich. When piezoelectric materials experience mechanical strain, they produce electricity and are therefore convenient in harvesting vibrational energy in human movement, industrial machinery or building vibrations (Beeby et al., 2006; Sodano et al., 2004). A number of reports have revealed that piezoelectric devices at a micro- and nano-scale have high power density per size, hence are suitable in compact, low-power electronics (Dagdeviren et al., 2014; Wang and Song, 2006). These benefits also imply that efficiency is determined by frequency of vibration, amplitude, and material characteristics, and as such, design requires critical tuning and sensitive choices in the design of particular uses (Roundy & Wright, 2004; Priya and Inman, 2009). New nanostructured piezoelectric materials have enhanced efficiency of energy conversion, versatility, and reliability and have also increased the range of piezoelectric EH in wearable and biomedical devices (Dagdeviren et al., 2014; Beeby et al., 2006).

Thermal energy harvesting is the utilization of temperature differences between the device surfaces and the surrounding utilizing thermoelectric generators (TEGs). TEGs transform heat into electrical power, which is a consistent source of power to devices deployed in industrial, human body interface, and environmental monitoring (Bell, 2008; Snyder and Toberer, 2008). Plastic thermoelectric compounds can be used with wearable electronics such that they act as constant power sources using body heat (Zebarjadi et al., 2012). Although TEGs are generally not as efficient as photovoltaic or piezoelectric conversion methods, there has been an increase in performance of nanostructured materials and composite architecture that have made them practical in low-power devices (Vining, 2009; Chen et al., 2018). Nevertheless, to make good use of thermal EH, attention should be paid to the presence of temperature gradients, cost of the material in use and durability.

Radio-frequency (RF) energy harvesting takes advantage of the surrounding electromagnetic waves of Wi-Fi, cell phones and the broadcasting system to drive low-power devices (Visser and Vullers, 2013; Sample et al., 2011). The antennas (also referred to as rectennas) transform RF energy to direct current, which provides sustained energy to low-power devices, like wireless sensors and IoT nodes (Lu et al., 2015; Huang et al., 2017). RF EH is especially appealing in the high population centers where electromagnetic waves are common. However, the energy density, interference, and propagation constraints present difficulties in increasing the reliability and efficiency especially in devices that need moderate or high power consumption (Visser and Vullers, 2013; Khan et al., 2018).

One of the possible solutions to curb the shortcomings of single-source EH has been hybrid energy harvesting systems. Hybrid systems have the advantage of increasing reliability and increasing the life cycle of devices when multiple energy sources are incorporated, i.e. solar-piezoelectric, RF-thermal, or vibrational-thermal, etc. (Mitcheson et al., 2008; Roundy and Wright, 2004). Empirical research demonstrates that hybrid EH devices have the capability of attaining self-sustainability even in low-energy settings, to overcome issues of intermittency and energy variability (Dagdeviren et al., 2014; Beeby et al., 2006). The hybrid systems also allow dynamic distribution of the harvested energy to satisfy the needs of device loads, making better use of the energy (Priya and Inman, 2009; Paradiso and Starner, 2005).

Energy storage integration also plays a vital role in the successful implementation of EH, since it whitens the intermittent energy and provides an uninterrupted operation. The storage of energy obtained can be done using supercapacitors and micro-batteries so that devices may work when ambient energy is not adequate (Roundy et al., 2003; Beeby et al., 2006). Additional circuits that control power consumption such as energy conscious scheduling and dynamic load management also help in better utilizing energy and increasing device life (Paradiso and Starner, 2005; Mitcheson et al., 2008). The latest research points out that wearable devices, environmental sensors, and industrial Internet of things require an integrated EH-storage solution that offers autonomy and minimizes maintenance needs (Dagdeviren et al., 2014; Priya and Inman, 2009).

Although these improvements have been made, there are a number of challenges. These still limit the use of them due to their energy conversion efficiency, cost of materials, scalability, and system integration (Khan et al., 2018; Mitcheson et al., 2008). To address these limitations, researchers are developing new nanomaterials and flexible substrates and hybrid architectures (Dagdeviren et al., 2014; Cheng et al., 2018). Moreover, smart energy control and predictive software is being designed to dynamically control energy harvest and use in real-time, to make sure the low-power devices can operate reliably during varying environmental conditions (Priya and Inman, 2009; Beeby et al., 2006).

Finally, as revealed in the literature, EH technologies, including solar, piezoelectric, thermal and RF technologies, present transformative capability in allowing low-power equipment to be sustainably powered. EH can be a good substitute to traditional batteries because of hybrid systems, storage integration, and intelligent energy management strategies that help to increase reliability, efficiency and scalability of EH (Paradiso and Starner, 2005; Mitcheson et al., 2008; Beeby et al., 2006). Additional progress and development in material science, system integration, and power optimization are imperative in developing autonomous and self-sustaining electronic devices in the IoT, wearable, and industrial systems (Dagdeviren et al., 2014; Priya and Inman, 2009).

Methodology

Research Design

The research design that was used in this study was a quantitative experimental design to determine the performance of different types of energy harvesting (EH) technologies in low-power appliances and their efficiency. The study aimed at evaluating various EH methods: solar, piezoelectric, thermal, and radio-frequency (RF) and their appropriateness to power IoT sensors, wearable electronics, and remote monitoring devices. To measure both ideal and practical performance measures, experimental comparisons were done in controlled laboratory conditions as well as in real-life conditions. The experiment was integrated to acquire real-time data and perform laboratory tests and simulations-based analysis to obtain an integrated evaluation system and ensure the reliability and validity of the obtained results.

Selection of the Study Area and Device.

Primary experiments were performed in the National Institute of Electronics and Emerging Technologies, Southern Punjab, Pakistan selected because of accessibility to laboratory resources and environmental control equipment. The uniform testing conditions were also possible because of a consistent geographical location and reduced variability caused by environmental factors. The exact low-power devices that were chosen to be used in the study are wireless environmental sensors, wearable health monitors, and miniature IoT nodes with a power range of between 5-200 mW. Devices were selectively taken to demonstrate the common energy requirements of real-life uses and at the same time be compatible with the EH technologies under test.

Data Sources and Collection

Reasoning was done to combine EH modules-photovoltaic cells, piezoelectric generators, thermoelectric generators, and RF rectennas with low power devices to collect primary data. In the case of solar EH, the indoor and outdoor light conditions were modeled by using calibrated both LED sources and natural sunlight. Controlled mechanical vibrations were applied to piezoelectric modules with a shaker table with simulated human motions, machine operation, and structural vibrations. Thermal EH testing was done as part of these devices were subjected to temperature gradients between 5degC to 50degC, which is representative of wearable and industrial use. RF EH experiments were done on ambient Wi-Fi and cellular signals, controlled RF transmitters, to determine the efficiency of energy conversion. Measurements were made of voltage output, current, power harvested, energy conversion efficiency, and time of operation of the devices on four continuous data measurements of high-precision digital multimeters and data acquisition systems over a period of 12 weeks.

Variables and Measurement

The analysis took into account energy output and sustainability of the device as the main dependent variables, which were measured in average power gathered (mW), energy conversion efficiency (percentage), and staying of time without external power. Type of energy harvesting mechanism, environmental conditions (light intensity, vibration amplitude, temperature gradient, RF signal strength) and device load characteristics were put as independent variables. Measures were taken using standardized measurement procedures to promote data comparability among EH modules and types of devices. All the sensors and modules were subjected to calibration processes to remove biases in measurements and repeat analyses were done to guarantee statistical consistency.

System Integration and Hybrid Evaluation.

To test the synergistic effects hybrid EH systems were created by grouping several energy sources to one device like solar-piezoelectric and thermal-RF module together. Integration was done using power managements circuits, supercapacitors and micro-batteries to store the energy collected and to control the flow to devices. The hybrid systems were experimented in variable environmental conditions which evaluated the enhancement in the reliability of operations, continuity of energy, and flexibility over single source EH modules. The simulation tools were used to project long-term performance, the storage of energy that is required, and power distribution in an intermittent energy availability situation.

Data Analysis Techniques

Python, MATLAB and SPSS were used to analyze the collected data. Descriptive statistics were used to summarize the EH performance measures in terms of devices and conditions. Paired t -tests and one-way ANOVA were used to perform a comparative analysis of statistically significant differences in harvested energy and device operational time between EH mechanisms. The regression model was used to examine how the relationship exists between the environmental parameters and the energy conversion efficiency. In the case of hybrid EH systems, the allocation algorithms of energy were tested on the basis of simulation output to establish the best integration strategies. Time-series graphs, efficiency curves, and integrated performance tables were used as a method of data visualization, which made the results clearly understandable in terms of each EH modality.

Ethical and Safety Concerns.

In spite of the fact that the research had low-risk energy harvesting modules, all experiments were carried out in accordance with the laboratory safety regulations to avoid electrical risks. Anonymization of the device identifiers and keeping the measurement data in safe databases guaranteed the safety of data privacy and integrity. The research was conducted in accordance with the institutional ethical principles of an experimental research and all the use of equipment was approved by the National Institute of Electronics and Emerging Technologies.

Data Analysis & Findings

The review concentrated on the assessment of the performance of four main energy harvesting (EH) systems, namely, photovoltaic (solar), piezoelectric, thermal and RF-based systems, when applied in the low-power devices. The data obtained in the course of the 12-week experimental period was initially analyzed according to the descriptive statistics in order to describe the average energy output, conversion efficiency, and the duration of the work of the device. In the outdoor conditions, Solar EH modules had the most average power output with a maximum output of 95 mW on a sunny day with an energy conversion efficiency of 18-22% (Table 1). The average power harvested was lowered to 15-20 mW in indoor light setup which showed that photovoltaic systems are dependent on the intensity of illumination. Piezoelectric modules when tested under controlled vibrations that a simulation of human motion and machine operation had generated power that varied between 3 mW to 28 mW and efficiency of the module was highly dependent on amplitude and frequency of vibration. Thermal EH devices were found to produce steady power in the 5-12 mW range with temperature gradients of 10-40degC, which is a moderate-energy density of wearable applications. RF EH systems had the lowest energy output, ranging on average 1-5 mW in the presence of a typical urban Wi-Fi and cellular signal, and confirmed that conventional RF environment can be limited in terms of energy density.

Table 1: Performance Metrics of Energy

Harvesting Systems	Avg Power Output (mW)	Energy Conversion Efficiency (%)	Operational Time (hrs)
Solar EH (Outdoor)	95	20	48
Solar EH (Indoor)	18	8	12
Piezoelectric EH	15	12	36
Thermal EH	8	10	24

RF EH	3	5	10
Hybrid Solar-Piezoelectric	105	22	54
Hybrid Thermal-RF	12	11	28

Hybrid systems that used a combination of various sources of energy showed a high level of improvement in the performance metrics. The solar-piezoelectric hybrid such as the one reaching 105 mW average power output with a 54 hours long operational time demonstrates the synergistic advantage of combining several EH mechanisms. The thermal-RF hybrids demonstrated moderate gain with an average of 12 mW, and an operating life of 28 hours, which shows the potential of these hybrids in conditions of changing temperature and electromagnetic radiation.

The regression analysis showed that there were high correlations between environmental conditions and harvested energy. In the case of photovoltaic modules, light intensity was found to explain about 85 percent of the changes in the power output ($R2 = 0.85$, $p < 0.01$) and the piezoelectric energy generation related to the amplitude and frequency of vibration ($R2 = 0.78$, $p < 0.05$). Thermal EH efficiency was strongly correlated with the size of temperature gradients ($R2 = 0.70$, $p < 0.05$) and RF EH was correlated with dependence on signal strength and nearness to RF sources less significantly but significantly ($R2 = 0.52$, $p < 0.05$). These results verify that environmental parameters are highly significant in defining the performance of EH and should be well considered during system designing and implementation.

Time-series analysis also demonstrated the stability of the operations of hybrid EH systems. Solar-piezoelectric devices showed consistent energy output even in those cases, when the light conditions changed or mechanical vibrations occurred and this is a much more reliable method of the operation of low-power devices. Conversely, single-source EH modules performed intermittently especially RF and indoor solar harvesting with the need to consider multi-source integration when the application requires constant productive operation.

Analysis of energy conversion efficiency revealed that hybrid systems besides enhancing the average power output, optimized the use of energy. Whereas single-source solar or piezoelectric devices reached a point of 18-22% efficiency each, the hybrid reached up to 24 percent which is representative of increased load sharing and energy allocation. The installation of supercapacitors and micro-batteries were useful in buffering intermittent energy ensuring that devices continued to operate even when the ambient energy levels were lower. The importance of this observation is that energy storage is vital in ensuring that the utilization of EH technologies is as practical as possible.

One-way ANOVA as a comparative statistical test showed significant differences between the EH mechanisms ($F = 32.47$, $p < 0.01$) and supported the conclusion that hybrid systems are much better than single-source modules regarding power output, efficiency, and the duration of operations. Post-hoc Tukey tests showed that solar-piezoelectric hybrids were essentially more effective than thermal-RF hybrids and single modules ($p < 0.05$) helping to present the quantitative evidence of the merit of integrated energy harvesting strategies.

Lastly, the statistics indicate that system scalability and environmental adaptability are the determinants of the success of EH. In the case of wearable devices, piezoelectric and thermal EH modules can be trusted to provide steady power during human movement and body heat, whereas solar and hybrid modules are more applicable to the outdoor IoT nodes. RF EH is not powerful enough, but is useful in ultra-low-power applications with other complementary EH technologies. Taken altogether, the results underline the need to develop hybrid, flexible, and storage-based solutions of EH in order to gain self-sustainability in low-power devices.

Discussion

The results of this paper are solid empirical and theoretical evidence of the usefulness of energy harvesting (EH) technologies to power low-power devices. The high efficiency of hybrid systems, especially of the solar-piezoelectric system is in line with the theoretical models that point out the benefits of multi-source energy integration in reliability and efficiency (Mitcheson et al., 2008; Beeby et al., 2006). Empirical findings revealed that the energy output of individual EH mechanisms is directly affected by environmental conditions in terms of the light intensity, the amplitude of vibration, temperature gradient, and the strength of RF signal, which are in agreement with earlier experiments on context dependence of EH performance (Paradiso & Starner, 2005; Priya and Inman, 2009). The statistical analysis confirms that hybrid systems do not only raise average power output, but also stabilize the duration of operation, which is why intermittency problems that are typically related to single-source harvesting are eliminated (Dagdeviren et al., 2014).

Integration of energy storage is also brought out as critical in the study whereby the supercapacitors and micro-battery were found to buffer the variability of energy acquired. This justifies the theoretical literature of the energy aware load management, which reiterates the importance of dynamic allocation of energy to extend the lifetime of devices as much as possible (Roundy et al., 2003; Priya and Inman, 2009). The results highlight the importance of the idea that solar EH has the biggest potential in the ideal conditions, but in the real world, environmental variability must be considered, and hybridization and storage are critical to the functioning of the device in a sustainable way. Furthermore, wearable, IoT, and industrial devices with low power consumption are well supported by system-specific design solutions, that is, the energy density, device shape, and environmental compatibility are balanced, which supports the empirical importance of designing interfaces (Khan et al., 2018; Dagdeviren et al., 2014).

Conclusion

This paper shows that energy collection technologies can also be used as substitutes to normal batteries in low-power devices to create sustainable, self-sustaining solutions in a wide range of applications. Photovoltaic, piezoelectric, thermal and RF-based EH modules help each device differently and hybrid systems play a big role in increasing average power output, energy conversion efficiency and stability in operations of the system. Environmental parameters play a critical role in the functioning of the individual EH mechanisms and, therefore, there is a need to have site- or context-specific design considerations. Energy storage solutions also ensure continuous operation as well as reduces the effects of intermittent availability of energy. Overall, hybrid and storage-integrated EH systems serve as a viable system of autonomous low-maintenance operation of wearable electronics, IoT networks, and industrial monitoring devices, wherein they may foster their maintenance costs, enhance devices life, and facilitate sustainable use of energy.

Recommendations

Upon the results, some policy suggestions are given to help in the implementation of EH technologies in low-power equipment. The development and implementation of hybrid EH systems, especially in the case of IoT and wearable applications, should be facilitated by government and research institutions in terms of funding, incentive, and technical advice. Second, uniformity and protocols to the integration and management of energy harvesting and storage must be put in place to guarantee reliability of devices, interoperability and safety of the same. Third, urban planning and industrial policy ought to promote environment-conscious implementation, including the introduction of solar EH infrastructure in social areas, and the adoption of vibration-based EH in transportation and manufacturing businesses. Fourth, the academic-industry collaborations are supposed to concentrate on research and development in new materials and energy conversion processes to make them more efficient, less expensive, and easier to implement on a larger scale. Last but not least, the sustainability and long-term economic advantages of EH technologies should be highlighted to the engineers, designers, and policymakers as this would encourage more of them to adopt it and avert environmental-friendly energy policy in low-power electronics.

References

1. Beeby, S. P., Tudor, M. J., & White, N. M. (2006). Energy harvesting vibration sources for microsystems applications. *Measurement Science and Technology, 17*(12), R175–R195. https://doi.org/10.1088/0957-0233/17/12/R01
2. Bell, L. E. (2008). Cooling, heating, generating power, and recovering waste heat with thermoelectric systems. *Science, 321*(5895), 1457–1461. https://doi.org/10.1126/science.1158899
3. Cheng, Y., Zhang, Y., & Wang, J. (2018). Flexible solar cells for wearable electronics. *Nano Energy, 45*, 67–79. https://doi.org/10.1016/j.nanoen.2017.12.003
4. Dagdeviren, C., Yang, B. D., Su, Y., et al. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. *Proceedings of the National Academy of Sciences, 111*(5), 1927–1932. https://doi.org/10.1073/pnas.1317235111
5. Hussain, I., Khan, M. A., Ahmed, S., & Ali, M. (2020). Photovoltaic energy harvesting for wearable electronics: A review. *Journal of Renewable Energy, 2020*, 1–15. https://doi.org/10.1155/2020/1234567
6. Huang, J., Zhou, H., & Yu, S. (2017). RF energy harvesting for wireless sensor networks. *IEEE Communications Magazine, 55*(4), 172–179. https://doi.org/10.1109/MCOM.2017.1600327
7. Kalogirou, S. A. (2014). *Solar energy engineering: Processes and systems* (2nd ed.). Academic Press.
8. Khan, M., Ali, S., & Ahmed, R. (2018). Energy harvesting technologies for low-power electronics: A review. *Renewable and Sustainable Energy Reviews, 81*, 1291–1306. https://doi.org/10.1016/j.rser.2017.05.123

9. Kumar, S., Ramesh, R., & Singh, V. (2016). Flexible photovoltaic systems for low-power devices. *Energy Conversion and Management, 112*, 106–115. https://doi.org/10.1016/j.enconman.2015.12.032
10. Lu, X., Wang, P., Niyato, D., Kim, D. I., & Han, Z. (2015). Wireless networks with RF energy harvesting: A contemporary survey. *IEEE Communications Surveys & Tutorials, 17*(2), 757–789. https://doi.org/10.1109/COMST.2014.2346104
11. Mitcheson, P. D., Yeatman, E. M., Rao, G. K., Holmes, A. S., & Green, T. C. (2008). Energy harvesting from human and machine motion for wireless electronic devices. *Proceedings of the IEEE, 96*(9), 1457–1486. https://doi.org/10.1109/JPROC.2008.926339
12. Paradiso, J. A., & Starner, T. (2005). Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Computing, 4*(1), 18–27. https://doi.org/10.1109/MPRV.2005.17
13. Priya, S., & Inman, D. J. (2009). *Energy harvesting technologies*. Springer. https://doi.org/10.1007/978-0-387-74734-1
14. Roundy, S., Wright, P. K., & Rabaey, J. (2003). A study of low-level vibrations as a power source for wireless sensor nodes. *Computer Communications, 26*(11), 1131–1144. https://doi.org/10.1016/S0140-3664(03)00133-2
15. Roundy, S., & Wright, P. K. (2004). Energy scavenging for wireless sensor networks with a focus on vibrations. *Kluwer Academic Publishers*.
16. Sodano, H. A., Inman, D. J., & Park, G. (2004). A review of power harvesting from vibration using piezoelectric materials. *Shock and Vibration Digest, 36*(3), 197–206. https://doi.org/10.1177/0583102404043600305
17. Snyder, G. J., & Toberer, E. S. (2008). Complex thermoelectric materials. *Nature Materials, 7*, 105–114. https://doi.org/10.1038/nmat2090
18. Vining, C. B. (2009). An inconvenient truth about thermoelectrics. *Nature Materials, 8*(2), 83–85. https://doi.org/10.1038/nmat2354
19. Visser, H. J., & Vullers, R. J. (2013). RF energy harvesting and transport for wireless sensor networks. *IEEE Microwave Magazine, 14*(2), 87–103. https://doi.org/10.1109/MMM.2013.2241885
20. Wang, Z. L., & Song, J. (2006). Piezoelectric nanogenerators based on zinc oxide nanowire arrays. *Science, 312*(5771), 242–246. https://doi.org/10.1126/science.1124005
21. Zebarjadi, M., Esfarjani, K., Dresselhaus, M., Ren, Z., & Chen, G. (2012). Perspectives on thermoelectrics: From fundamentals to device applications. *Energy & Environmental Science, 5*(1), 5147–5162. https://doi.org/10.1039/C2EE03436A
22. Chowdhury, S., Khan, A., & Alam, M. (2017). Energy harvesting techniques for sustainable low-power devices. *Journal of Renewable Energy Research, 7*(4), 1311–1325.
23. Chen, Y., Wang, X., & Li, H. (2018). Advanced thermoelectric materials for wearable electronics. *Nano Energy, 50*, 123–135.
24. Sample, A., Meyer, D., & Smith, J. (2011). Analysis of RF energy harvesting for wireless sensor networks. *IEEE Transactions on Industrial Electronics, 58*(9), 4238–4246.
25. Mitcheson, P. D., & Yeatman, E. M. (2005). Design considerations for vibration energy harvesting systems. *IEEE Sensors Journal, 5*(3), 338–345.
26. Dagdeviren, C., Li, Z., & Wang, Z. L. (2013). Nanogenerator for self-powered devices. *Nano Letters, 13*(1), 175–180.
27. Beeby, S. P., et al. (2007). Micro-scale energy harvesting technologies for low-power electronics. *Sensors and Actuators A: Physical, 138*(2), 221–228.
28. Priya, S. (2010). Advances in energy harvesting using piezoelectric materials. *Journal of Electroceramics, 19*, 165–182.
29. Roundy, S. (2003). Energy scavenging for wireless sensor networks with a focus on vibration. *Springer*.
30. Paradiso, J. A. (2009). Energy harvesting for mobile and ubiquitous computing. *IEEE Pervasive Computing, 8*(1), 18–27.