A Survey of Energy Harvesting Technologies for Wireless Sensor Networks

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Abstract - **With the development of the wireless sensor networks, more complicated and challenging applications can be targeted by small but smart systems. Although most of these applications require little power, the lifetime of the system is thereby limited by the energy capacity of the batteries used. Gradual degradation of the batteries further decreases the useable lifetime of the WSN systems. Aside from relying on revolutionary development of battery technologies, one of the most important ways to improve the system lifetime is to "harvest" energy from ambient environmental energy sources. Several common energy sources are targeted, namely, light (both indoor and outdoor), thermal energy (waste heat from AC/heating system/ body heat), vibration (electromagnetic and piezoelectric), and Radio frequency Energy Harvesting (RFH). Finally, it is shown that RFH with super capacitor storage has maximum gain (up to 50%) above all wireless energy harvesting technologies.**

Keywords: Energy Harvesting Technologies, Piezoelectric Energy, Vibration Energy Harvesting, Ambient Energy, Super-capacitors.

I. INTRODUCTION

WIRELESS Sensor Networks (WSN) are spatially distributed autonomous sensors used to monitor physical or environmental conditions, such as temperature, sound, pressure, etc. and to cooperatively pass their data through the network to a main location. Traditionally, energy has been taken from fuels that occur in the ground - coal, gas, etc. However to ensure that greenhouse gasses and other forms of pollution are not created, energy harvesting techniques can be used. These have a much smaller impact on the environment as shown in Figure 1.

Energy harvesting technology aims to convert ambient energy into electrical energy that can be used for a variety of purposes. There are many energy harvesting techniques that are available. The actual techniques to be employed will obviously vary according to the source and the form of energy to be harvested and also the load to be supplied - some will be very small (*e.g.* remote wireless sensors, etc.) others will be much larger (*e.g.* to provide energy for motors, etc.) as discussed in [1].

II. SURVEY OF ENERGY HARVESTING SOURCES FOR WIRELESS SENSOR NETWORKS

Figure 2 shows different forms of energy harvesting sensor platforms from which we extract energy and their related nodes [2]. There are following types of energy sources suitable for wireless sensor nodes:-

Mechanical energy harvesting nodes: The sum of the kinetic and potential energy in any object that is used to do work is called mechanical energy. Basically, it is the energy in an object due to motion or position, or both.

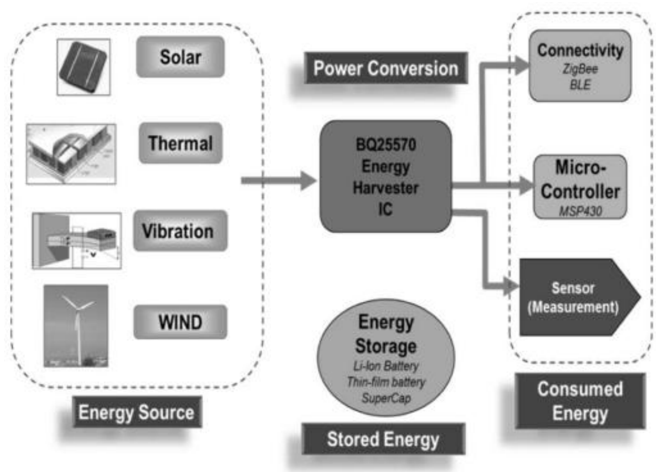

Figure 1. Energy scavenging from different energy sources suitable for Wireless Sensor Networks.

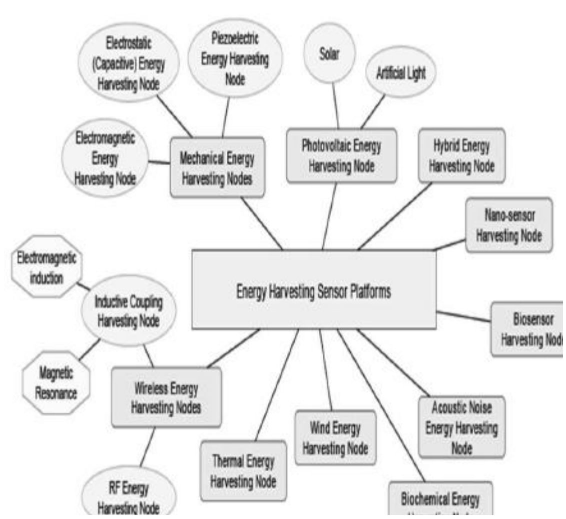

Figure 2. Different energy types and their sources.

It has two different nodes:

Piezoelectric Energy Harvesting Node: The use of piezoelectricity to convert mechanical to electrical energy can be shown through a example described in [4] as the proposed floor tile energy harvester can be replaced on the ground as a regular floor tile would be, but has the ability to capture the kinetic energy carried in a footstep and convert that energy into electric power. This device can act as a localized energy source, which can be used to power nearby electronic device.

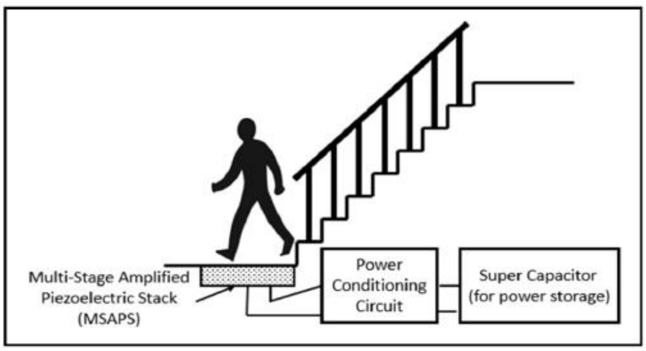

Figure 3. Floor tile piezoelectric energy harvesting system.

Ultimately, the energy harvesting system includes a power conditioning unit and a super capacitor in order to store the generated electric power, as shown in Figure 3. The concept of Vibration Energy Harvesting is to convert vibrations in an electrical power. Actually, turning ambient vibrations into electricity is a two steps conversion in Figure 3 as discussed in [9]. Vibrations are first converted in a relative motion between two elements, and then converted into electricity that is mechanical-to-electrical converter (piezoelectric material, magnet-coil, or variable capacitor). An equivalent model for a piezoelectric vibration energy harvesting system is shown in Figure 4. The output power is given as:

$$P_{max} = \frac{1}{2}\omega_{max} V^2{}_{max} \sum_{i=1}^{n} C_i \quad (1)$$

where P_{max} is the maximum power required to control vibration on a large airplane wing, is the frequency of the control law output signal, C_i is the effective capacitance of actuator *i, n* is the number of actuators being used, v_{max} is the maximum voltage the piezoelectric actuator can withstand before it breaks down.

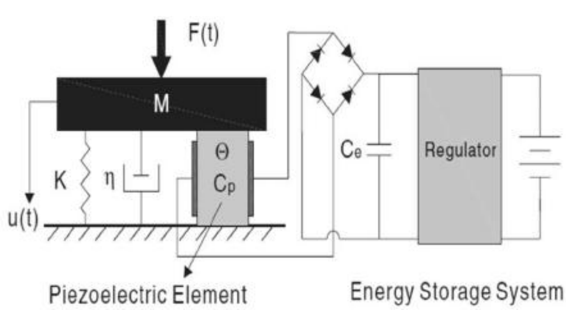

Figure 4. An equivalent model for a piezoelectric vibration energy harvesting system.

Electromagnetic Energy Harvesting Node: A low power clock synchronization using electromagnetic energy radiating from AC power lines is proposed in Fig.5 as discussed in [3].The equivalent circuit of the experiment expressed in Fig.5 is shown in Fig.6. There are also sensor network systems that harvest energy from the visible part of the electromagnetic spectrum.

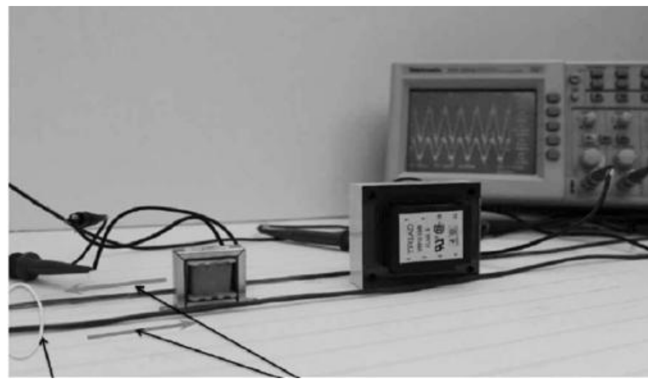

Figure 5. Experimental setup showing the inductors placed in between two parallel conductors carrying the live and return current. We measured the voltage across the inductors to estimate the maximum power available from the magnetic field.

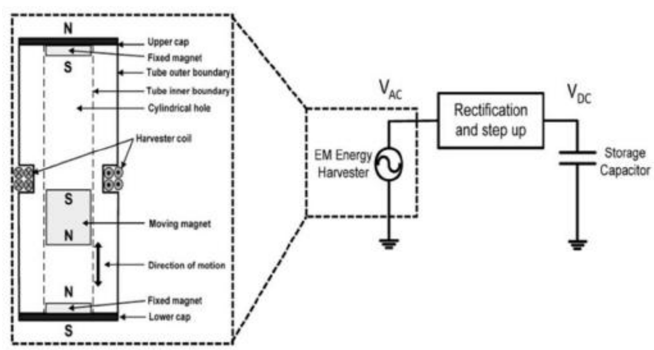

Figure 6. Equivalent circuit of experiment shown in Figure 5.

The maximum available average power is given as:

$$P = \frac{V^2{}_{rms}}{R_s} \quad (2)$$

where P is the available power delivered, R_s is the series resistance of the inductor, and V_{rms} is the effective value of varying voltage.

Photovoltaic energy harvesting nodes: It involves energy harvesting from light whether it is solar or artificial light. Solar energy is the most prominent source today. Figure 7 shows a circuit implementation of photovoltaic energy harvesting system. Designing most of the research in routing in WSN assumes that all nodes are battery driven. Some of these nodes can be powered by solar or gravitational power. Nodes powered by these sources can transmit and receive packets without consuming battery energy. Therefore routing packets through these solar powered nodes is made use of in a simplified version of directed diffusion [5] as shown in Figure 8.

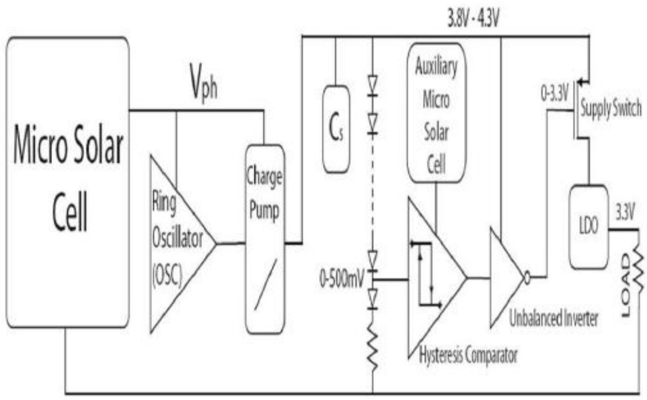

Figure 7. Circuit diagram of photovoltaic energy harvesting.

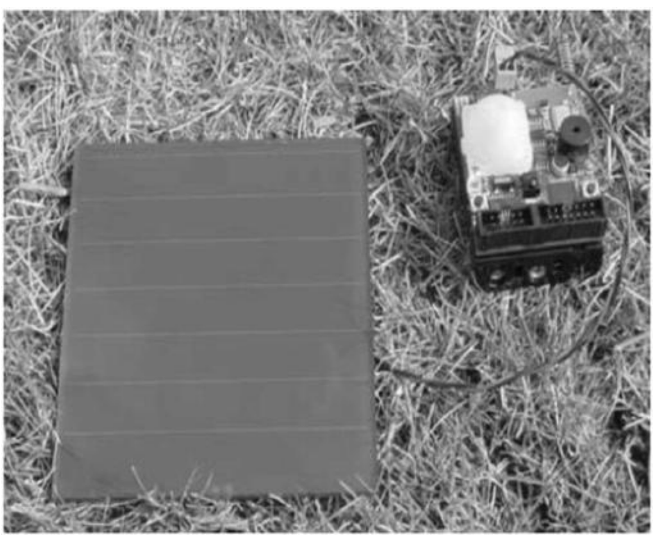

Figure 8. Solar Panel connected to sensor board.

Power generated by solar energy is given as:

$$P = A \times r \times H \times PR \tag{3}$$

where, E = Energy (kWh)

A = Total solar panel Area (m²)

r = solar panel yield (%)

H = Annual average solar radiation on tilted panels

PR = Performance ratio, coefficient for losses

(Range between 0.5 and 0.9, default value = 0.75)

Hybrid energy harvesting nodes: Devices that harvest energy from the environment require specific environmental conditions; for instance, solar cells and piezoelectric generators require sunlight and mechanical vibration, respectively. Figure 9 shows a basic format of hybrid energy combining vibration, solar, wind and hydro. Since these conditions don't exist all the time, most energy harvesters don't generate a constant stream of electricity. In order to harvest ubiquitous energy continuously, researchers have designed and fabricated a hybrid energy harvester that integrates a solar cell and piezoelectric generator, enabling it to harvest energy from both sunlight and sound vibration simultaneously. Figure 10 shows such type of this combination as described in [6].

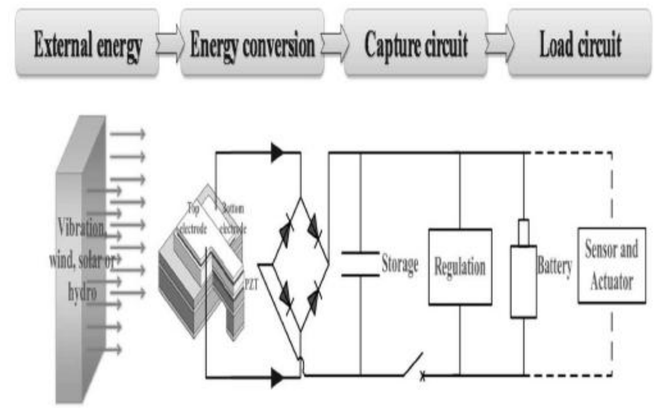

Figure 9. Basic form of hybrid energy.

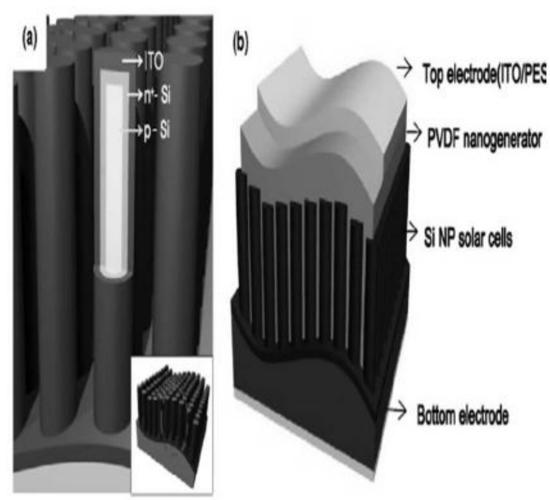

Figure 10 (*a*) Diagram of the silicon nano-pillar solar cell, (*b*) Diagram of the hybrid energy harvester consisting of a piezoelectric nano-generator integrated on to of a silicon nano-pillar solar cell.

Nano-Sensor harvesting nodes: A piezoelectric nano-generator is an energy harvesting device converting the external kinetic energy into an electrical energy based on the energy conversion by nano-structured piezoelectric material. Although its definition may include any types of energy harvesting devices with nano-structure converting the various types of the ambient energy (*e.g.* solar power and thermal energy), it is used in most of times to specifically indicate the kinetic energy harvesting devices utilizing nano scaled piezoelectric material.

Figure 11 shows the working principle of nano-generator where an individual nano-wire is subjected to the force exerted perpendicular to the growing direction of nano-wire. (*a*) An AFT tip is swept through the tip of the nanowire. Only negatively charged portion will allow the current to flow through the interface. (*b*) The nano-wire is integrated with the counter electrode with AFT tip-like grating. As of (*a*), the

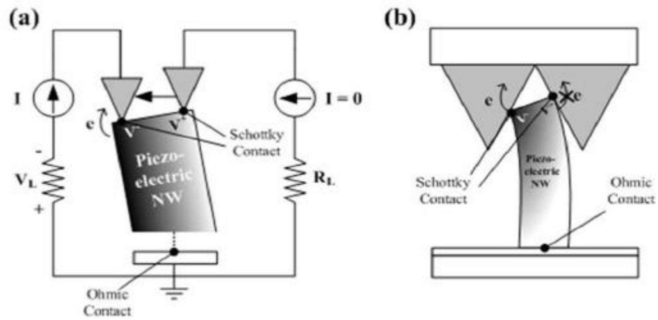

Figure 11. Working principle of Nano-generator.

electrons are transported from the compressed portion of nano-wire to the counter electrode because of Schottky contact. The maximum voltage generated in the nano-wire can be calculated by the following equation:

$$V_{max} = \pm \frac{3}{4(k_0+k)}\left[e_{33} - 2(1+v)e_{15} - 2ve_{31}\right]\frac{a^3}{l^3} v_{max} \quad (4)$$

where κ_0 is the permittivity in vacuum, κ is the dielectric constant, e_{33}, e_{15} and e_{31} are the piezoelectric coefficients, ν is the Poisson ratio, *a* is the radius of the nano-wire, *l* is the length of the nano-wire and ν_{max} is the maximum deflection of the nanowire's tip.

Biosensor energy harvesting nodes: A biosensor is an analytical device which converts a biological response into an electrical signal. The term 'biosensor' is often used to cover sensor devices used in order to determine the concentration of substances and other parameters of biological interest even where they do not utilise a biological system directly. The biological response of the biosensor is determined by the bio-catalytic membrane which accomplishes the conversion of reactant to product. Immobilised enzymes possess a number of advantageous features which makes them particularly applicable for use in such systems. Figure 12 shows implantable sensor, having 1-mm diameter, to measure and monitor blood pressure.

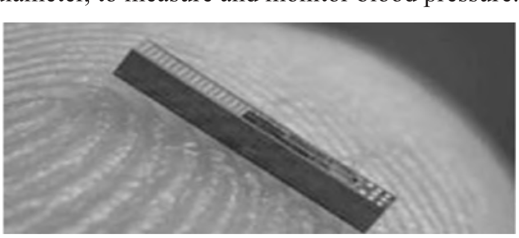

Figure 12. (*a*) Implantable sensor, having 1-mm diameter, to measure and monitor blood pressure.

Figure 12. (*b*) human leg having sensors to extract energy while walking.

The power delivered by the thermopile to a matched load is given as [7]:

$$P = \frac{\Delta V^2}{4R} \quad (5)$$

where Δ V is the voltage generated across a thermocouple due to a temperature difference (T_1 - T_2).

Acoustic Noise energy harvesting nodes: Energy harvesting systems based on the transformation of acoustic vibrations into electrical energy are increasingly being used for niche applications due to the reduction in power consumption of modern day electronic systems [8]. These type of applications involve extracting energy at remote or isolated locations where local long term power is unavailable or inside sealed or rotating systems where cabling and electrical commutation are problematic. The available acoustic power spectra can be in the form of longitudinal, transverse, bending, hydrostatic or shear waves of frequencies ranging from less than a Hz to 10's of kHz. Figure 13 shows a photograph of a high power acoustic electric feed-through prototype. The final design had six piezoelectric rings.

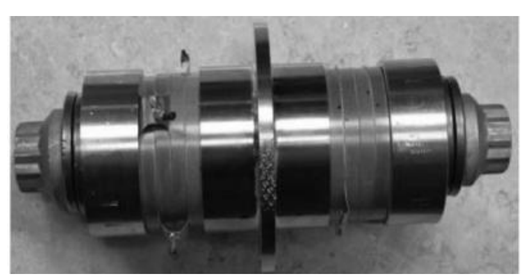

Figure 13. A photograph of a high power acoustic electric feed-through prototype.

The maximum power using impedance for lossless case discussed in [8] is given as:

$$P \propto \frac{{k_t}^2}{(1-{k_t}^2){c_{33}}^E} \quad (6)$$

where, P = Maximum power, k_t open circuit elastic stiffness, material constant whose value is given by

$$k_t = 0.526\ (1 + 0.0296\ i).$$

Wind energy harvesting nodes: In wind energy harvesting large wind turbine generators (WTGs) are used for supplying power to remote loads and grid-connected applications. A wind turbine is essentially a very large, inverse fan: the wind produces electricity instead of electricity producing wind. However, because wind turbines run 'backwards' and are several thousand times larger than most fans (~85-400 tons), they are much more complicated, especially since it is necessary to get the greatest efficiency and quality at the least cost. Modern wind turbines range from about 40 – 80 m in height, 50 – 85 m in span, and 850 kW to 4.5MW in power. They usually have three blades and almost always have a horizontal axis shaft (like old European windmills). Figure 15 shows basic wind mills fans structure, while Figure 14 shows wind energy harvesting.

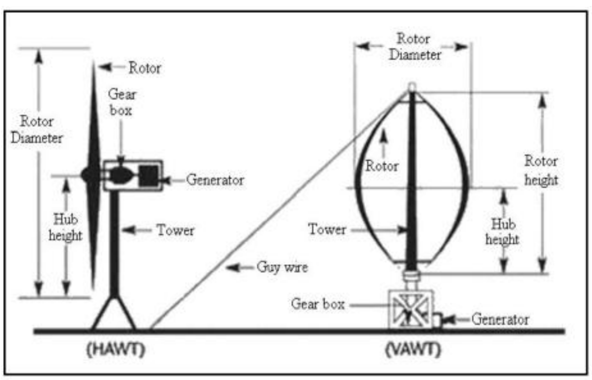

Figure 14. Wind energy harvesting.

Figure 15. Basic wind mill.

The power contained in the moving mass is the time rate of change in kinetic energy, given as:

$$P = \frac{d(kE)}{dt} \qquad (7)$$

Wireless energy harvesting nodes: Wireless energy can be absorbed by two different nodes that are inductive coupling harvesting node and other one is RF energy harvesting node. Inductive coupling harvesting node is further divided into two as Electromagnetic induction and Magnetic Resonance. The most widely used wireless energy harvesting node is RF energy harvesting. It uses super-capacitors to absorb the energy for regulates the wireless sensor nodes. The RF radiation pattern is generally wide angled; radio waves can simultaneously carry information and energy, and the radiation directivity can be electronically steerable. In a typical energy harvesting system, energy is generated from motion, a thermal source, a photoelectric source, or magnetic activity. This energy is then captured, stored, managed, and fed to a sensor for transmission. Figure 16 shows a typical Energy Harvesting powered WSN node .

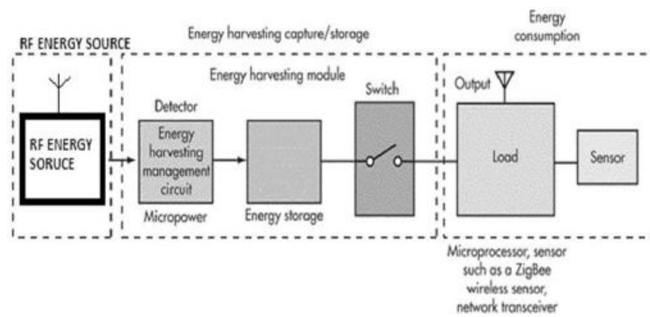

Figure 16. A typical RF Harvesting powered WSN node with a super-capacitor used as energy storage element.

Amount of electrical energy that can be harvested is dependent on the power emitted from the RF source, the antenna gains of the RF source and the receiving device, the distance of the receiving antenna from the RF source antenna, path loss exponent, and the RF-to-DC rectification efficiency η_{RF-DC}. The received electrical power is given in [8] as:

$$P_R{}^{DC} = (\eta_{RF-DC})P_R \qquad (8)$$

where, P_R is the received RF power that can be calculated using the Friis transmission equation.

TABLE 1-PERFORMANCE TABLE OF VARIOUS ENERGY HARVESTING TECHNOLOGIES

S.N.	Energy Harvesting source	Performance (Power Density)	Efficiency
1.	Solar-Direct sunlight	15mW/cm^2	Typically 25±1.5%
2.	Electrostatic	15 - 100	x
3.	Electromagnetic (Human Motion)	1 – 4	x

4.	RF energy	0.1mW/cm^2 (GSM 900/1800 MHz) 0.01mW/cm^2(WiFi 2.4 GHz)	50%
5.	Piezoelectric	250	x
6.	Wind	380 at speed of 5m/s	5%
7.	Acoustic noise	0.96 at 100dB 0.003 at 75dB	x

where x: Maximum power and energy are source dependent

III. CONCLUSION

In this paper, comprehensive review on some common energy harvesting technologies of wireless sensor networks was provided. A brief comparison table is also shown on the basis of their performance parameter. It is concluded that the sunlight provides maximum power density (15 mW/cm^2) whereas Radio Frequency (RF) energy radiated from Radio/TV transmitters, Mobile towers, Wi-Fi routers and other electronics RF devices used in our daily life provide greater efficiency. Therefore, a hybrid Solar-RF energy harvesting approach can provide best optimal design solution for of Energy Harvesting Wireless Sensor Networks (EHWSN) for indoor and outdoor applications.

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