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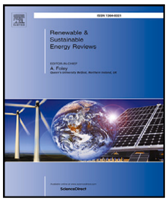

Design architectures for energy harvesting in the Internet of Things

Sherali Zeadally [a,*], Faisal Karim Shaikh [b], Anum Talpur [b], Quan Z. Sheng [c]

[a] *College of Communication and Information, University of Kentucky, Lexington, KY 40506-0224, USA*
[b] *Department of Telecommunication Engineering, Mehran University of Engineering & Technology, Jamshoro, Pakistan*
[c] *Department of Computing, Macquarie University, Sydney NSW 2109, Australia*

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ABSTRACT

An increasing number of objects (things) are being connected to the Internet as they become more advanced, compact, and affordable. These Internet-connected objects are paving the way toward the emergence of the Internet of Things (IoT). The IoT is a distributed network of low-powered, low-storage, light-weight and scalable nodes. Most low-power IoT sensors and embedded IoT devices are powered by batteries with limited lifespans, which need replacement every few years. This replacement process is costly, so smart energy management could play a vital role in enabling energy efficiency for communicating IoT objects. For example, harvesting of energy from naturally or artificially available environmental resources removes IoT networks' dependence on batteries. Scavenging unlimited amounts of energy in contrast to battery-powered solutions makes IoT systems long-lasting. Thus, here we present energy-harvesting and sub-systems for IoT networks. After surveying the options for harvesting systems, distribution approaches, storage devices and control units, we highlight future design challenges of IoT energy harvesters that must be addressed to continuously and reliably deliver energy.

1. Introduction

The Internet of Things (IoT) has brought about a large network of objects that include a wide range of devices with varying networking, computing, and storage capabilities. IoT enables networked objects to interact with each other and exchange various types of information (e.g., sensor data, multimedia data). These objects range from sensors, actuators, and mobile phones to vehicles, televisions and so on. According to [1], by 2022, there will be 29.7 billion devices connected to the Internet, out of which 18.1 billion will be related to the IoT. IoT enables smart communication capabilities for objects using ubiquitous computing, embedded networks, communication technologies, and Internet protocols [2,3]. An increasing number of Internet-connected objects are being integrated into IoT. This ecosystem continues to grow and expand as it incorporates new technologies such as smart cities [4,5], smart transportation, and smart grids, are being integrated [6,7] (as shown in Fig. 1). IoT has already started to have an impact on various application domains, and many more changes will emerge that will drastically affect the quality of our daily lives in terms of improved convenience, ubiquitous access to a range of services anytime, anywhere, and from any device. To achieve these goals, several research challenges, including security, reliable data transfer, energy consumption, and interoperability must be addressed.

However, according to [9] the most important challenge is smart energy management. Every active component in the IoT network consumes a certain amount of energy to perform its functionality. Recently, we have witnessed a significant increase in the amount of data produced by IoT [10,11] despite the use of scarce energy resources [12]. This results in communicating objects' batteries rapidly draining over the wireless channel, requiring battery replacement frequently. In a deployed network, changing batteries can also be risky for scenarios that require continuous monitoring. In such cases, battery replacement can be an expensive, laborious process. Thus, energy harvesting is the only likely option to provide unlimited energy resources to such low-powered devices in IoT [13]. An added benefit is that energy harvesting requires little to no servicing for long time periods. As energy consumption is such a crucial issue, this paper surveys the state-of-the-art results in the area of IoT energy harvesting and explores its feasibility for various IoT applications.

This paper is organized as follows. Section 2 explores how energy harvesting is utilized in areas related to the IoT. Section 3 overviews a general energy-harvesting system for the IoT. Section 4 presents the various types of energy sources that can be used to harvest energy. Section 5 describes various energy harvesters for IoT. Section 6 discusses the storage of harvested energy. Finally, Section 8 concludes the paper.

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[*] Corresponding author.

E-mail addresses: szeadally@uky.edu (S. Zeadally), faisal.shaikh@faculty.muet.edu.pk (F.K. Shaikh), anum.talpur@faculty.muet.edu.pk (A. Talpur), michael.sheng@mq.edu.au (Q.Z. Sheng).

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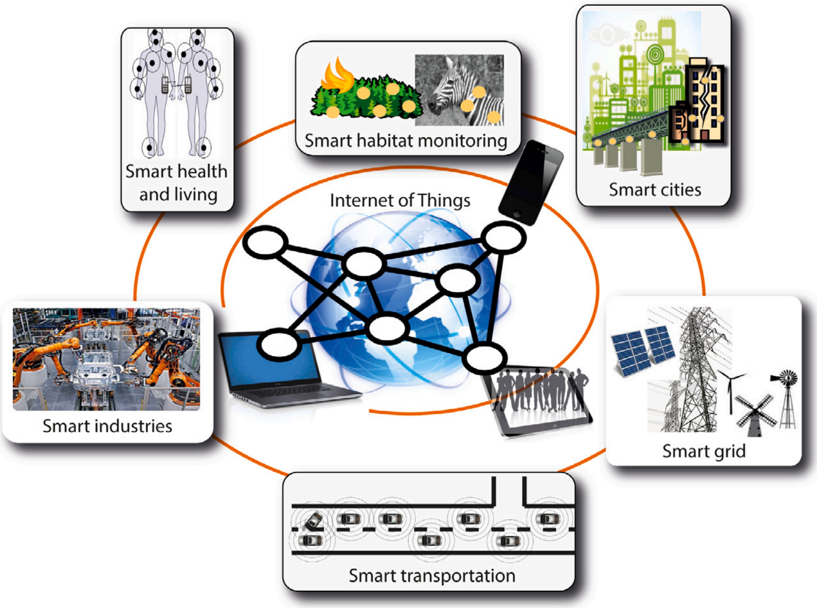


Fig. 1. Applications of the Internet of Things (IoT).
Source: Adapted from [8].

2. Energy-harvesting trends in related fields

Increasingly, researchers use energy-harvesting techniques in many Information and Communications Technologies (ICT) based systems. The scope of energy harvesting for Wireless Sensor Networks (WSNs), Cyber–Physical Systems (CPS), and Machine to Machine (M2M) communications offers many benefits. Next, we explore in detail energy-harvesting trends in these domains.

2.1. Wireless sensor networks

WSNs have been studied and deployed for a long time [14]. Typically, a WSN is a network of distributed sensor nodes that monitor physical or environmental parameters such as temperature, humidity, vibration, and pressure. Each sensor node consists of a sensor, microcontroller, storage capability, a radio transceiver and a battery [13,15]. Mostly, the sensor node uses a battery as its energy resource. However, the battery power's limitation is a major bottleneck for WSNs. Today, WSNs often use harvesters as an energy resource [13]. In [16], the authors used Radio Frequency Identification (RFID) for harvesting energy in a WSN, and a variety of WSN applications have reported using energy harvesters as a basis for efficient WSN system design [17,18]. The type of energy harvester and energy resource varies from application to application and system to system [19].

Health-monitoring applications consist of a low-power wearable or implantable nodes, which collect physiological parameters of the human body [20–22]. These systems are useful for patient monitoring in hospitals, especially tracking of patients in emergency situations [23]. An energy-harvesting system in healthcare applications [24] utilizes body heat, bio-energy, body friction, body movement [24], and ambient light from surroundings [25] as an energy resource. In [26], the authors present a review of different available energy-harvesting resources for health applications.

Environmental monitoring is the most significant application of WSNs [27–29]. Since, WSNs can be deployed in a variety of environments for monitoring purposes, various energy-harvesting techniques exist that can utilize the appropriate energy resource and harvester [30]. Several environments can be monitored by observing different parameters, whether for measuring glacier dynamics, turbidity monitoring, agricultural monitoring, underground water-level monitoring, atmospheric humidity, temperature and pressure monitoring, rainfall monitoring, or wind-speed monitoring; in all aspects of the environment, WSN is used for monitoring purposes [27–29]. This requires battery reservoirs and complex protocols to enable the efficient working of sensor networks. One way to ease sensor networks' usage is through different types of energy-harvesting techniques. The authors of [31] proposed modular WSN nodes that support energy harvesting to provide a constant power supply of the node. A recent survey describes in detail energy-harvesting techniques in environmental monitoring for WSNs [30].

The increasing number of vehicles around the world give rise to the safety and congestion concerns on the road. We visualize this easily, using road accidents and traffic jams. WSN-based Intelligent Transportation Systems (ITS) are also playing a significant role in improving road safety and traffic management [32–36]. Many ITS applications employ energy-harvesting techniques [37]. In [38], the authors have proposed an energy-harvesting technique to power on-board train systems. In [39], the authors used the vibrations of train wheels to harvest the energy for condition monitoring. In [40], a mobile energy-harvesting node is used for road surveillance purposes.

Tracking and monitoring animals has been a challenge for WSN [41]. The continuous movements and roaming of animals throughout the day involves an abundant generation of kinetic energy which can be exploited for energy harvesting [42–44].

2.2. Cyber–Physical Systems

A Cyber Physical System (CPS) controls and monitors the physical devices using cyber-space. It integrates the controlling factors with the physical components. The controlling factors communicate with sensors and actuators to alter the cyber and physical environments [45]. Several CPS applications employ various types of harvesting techniques to guarantee a continuous supply of energy [46,47]. In [46], the authors addressed the energy allocation problem for a single energy-harvesting sensor for source channel coding in CPS. They solve this problem using sub-optimal policies and dynamic programming. In [47], the author proposes a non-volatile register size-reduction technique that efficiently manages the harvesting process. Flow-induced oscillations-based energy harvesting for CPS is proposed in [48]; the results obtained show that a reasonable amount of energy can be harvested from a steady air flow. A review of energy sources from the perspective of CPS [49] compares and contrasts these sources and shows which sources are good for which environment.

2.3. Machine to machine communication

M2M communication has attracted the attention of many researchers working in different application domains [50]. M2M focuses on machine connectivity to enable the transfer of data between mobile nodes and remote locations using licensed cellular wireless access [50,51]. In [52], the limitations of energy harvesting in M2M are highlighted using numerical methods. The authors in [53], presented limits of solar and photovoltaic harvesting in M2M. To facilitate energy harvesting for M2M wireless communication, IEEE 802.11 power-saving mode enhancements have been proposed in [54]. Energy-harvesting methods are still being researched and remains a technological challenge for M2M and wireless networks [55].

3. Overview of the IoT energy-harvesting

Energy harvesting (also known as energy scavenging) is a process of converting readily available energy from environment to usable electrical energy. This provides a viable solution for continuous powering of various loads. There are many natural and man-made resources present in the environment that we can use to harvest energy. These resources include: motion, light, heat, electromagnetic effect, and many more. Generally, the energy-harvesting process includes four phases as shown in Fig. 2.

Energy resource: The first phase is energy resource availability. It is important to choose an appropriate and abundantly available energy resource in the deployed system's environment.

Energy conversion: The second phase involves energy-transformation mechanisms. The harvester or transducer is used to detect and convert the energy. In this phase, a converter circuit is also used to provide rectification.

Energy storage: The third phase exploits the use of super capacitors or batteries to store the energy. The power management and control unit are also associated with this phase. The power management unit includes regulators or control equipment to contend with the power need, based on available power.

Energy consumption: The last phase is energy consumption, where harvested energy is consumed by a suitable device for the application.

Deploying a sustainable IoT system is a challenging task. Numerous techniques are proposed to maintain and optimize energy usage. Different energy-management techniques are applicable in different domains of IoT by considering application requirements. Next, we describe the various phases of energy harvesting for IoT in detail.

4. Energy resources for IoT

This section describes the energy sources (present in our environment) that can be used to harvest the energy and supply it for IoT systems as depicted in Fig. 3. Different energy sources exist in different environments that we can harness to power different IoT applications. Here, we introduce different types of energy resources and analyze what we can extract from which local sources for energy harvesting.

4.1. Thermal energy

Thermal energy or heat energy are ubiquitous in indoor as well as outdoor environments. It can be extracted from electrical appliances (engine heat), the human body (body heat or skin heat), or through temperature gradients. Thermal energy can take different forms such as sunlight heat, exhaust gas heat, internal resistance heat, or heat flux. Temperature availability also varies with time. We can transform the change in heat or heat produced from different sources into electrical energy to provide a consistent supply to IoT networks. Extracting heat energy is cost effective because the system output often also generates heat as a by-product. In industrial applications, thermal energy harvesting is a prominent method of generating energy. Thermal energy harvesting devices have the advantage of reliability and a long lifetime, but with a low efficiency of energy conversion [56].

4.2. Light energy

Light energy is the most commonly available type of energy source. This energy is widely used in a number of applications. For an outdoor environment, solar light is the most obvious source, and for indoor, artificial light is used. Solar energy can be used for daytime with power density of $100\ \mathrm{mW/cm^2}$ and zero energy for night [56]. Artificial light can be available around the clock, though, depending on environmental and application requirements. Solar energy also results in fluctuated extraction because of its intensity variation with the time of day and seasonal weather of the year. However, it has the advantage of providing infinite potential energy and high-power density compared to artificial light. The energy-harvesting efficiency of artificial energy is one-third of solar energy efficiency. The unexpected changes in availability of solar energy make harvested energy relatively small compared to its density. Apart from these challenges, light energy harvesting is promisingly used in many low-powered IoT applications, ranging from smart homes to large-scale agricultural applications [57]. The Waspmote (by Libelium), widely used IoT sensing node, also contains a solar panel that produces 12 volts (V) to 500 milliampere (mA) of supply energy [58]. Solar biscuit is another widely available solar-powered sensor network system containing a 5 × 5-centimeter(cm) solar panel and 1 Farad (5 V) super capacitor [57].

4.3. Electromagnetic (EM) energy

EM energy is locally available in form of Electric (E) field, Magnetic (M) field and ElectroMagnetic (EM) field. EM energy harvesting is attracting most of the IoT applications because of the ubiquitous availability of EM radiations and wireless communications. According to the application's size and scope, it uses either near-field or far-field radiations. In near-field, magnetic and EM fields are induced to generate electric energy and power devices wirelessly. But, in far-field, EM radiation (in the form of microwave signals) is used to convert signals, received by antenna, and rectified to power DC-operated nodes. Far-field means a distance of a few kilometers and near-field is within one kilometer. EM energy-harvesting efficiency is more than 80% [56]. The most common source of EM energy is TV broadcast and cellular broadcast.

4.4. Radio Frequency (RF) energy

In contrast to other energy resources, Radio Frequency (RF) energy is the most commonly available, ubiquitous and reliable source of energy. It is an ambient source of energy, because of signal radiations from some usual transmitters such as Frequency Modulation (FM)/ Amplitude Modulation (AM), TeleVision (TV) broadcast, Wireless Fidelity (Wi-Fi), and cellular transceiver stations [59,60]. RF energy is significant in urban areas, whereas availability is low in rural areas. An RF harvesting system only transfers power wirelessly to devices

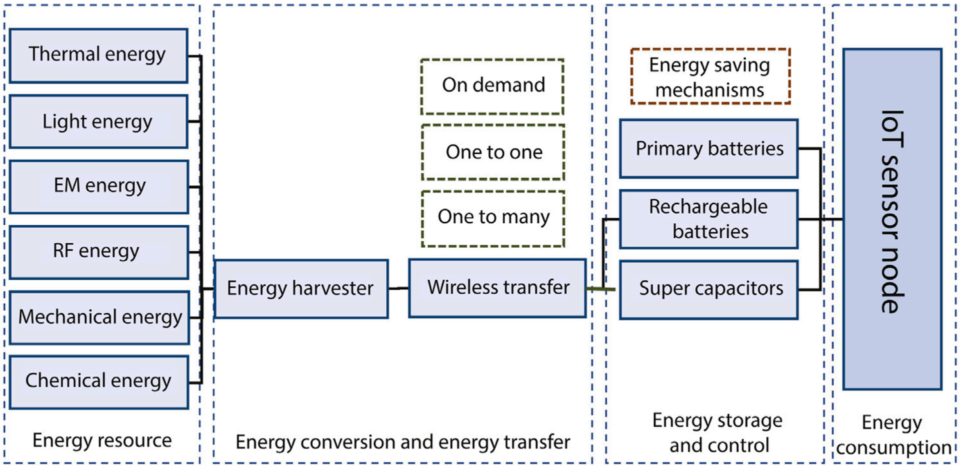


Fig. 2. A block diagram of an energy-harvesting system.

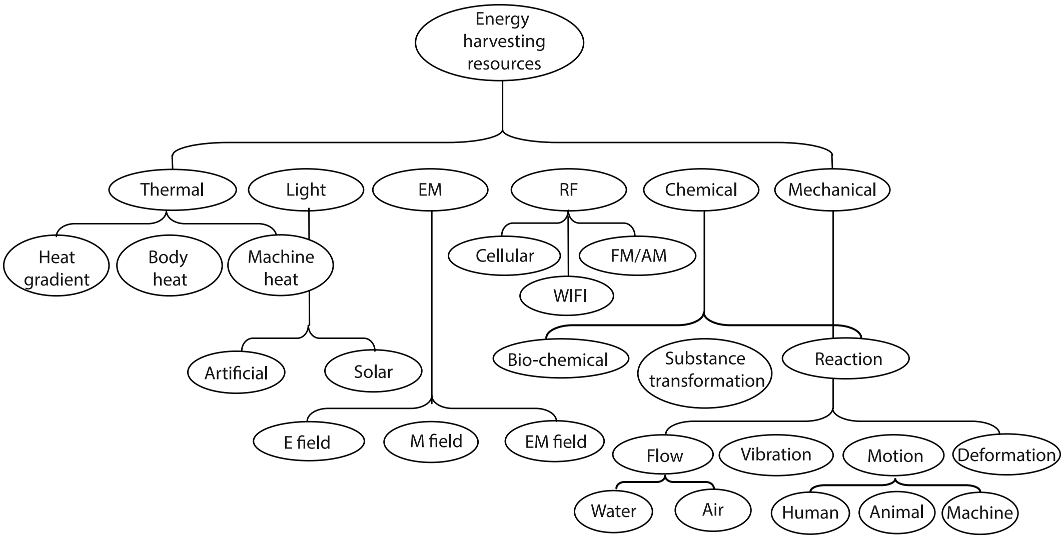


Fig. 3. Classification of energy resources for IoT.

within a 15-meter (m) range [61]. As the power level of RF harvested energy (i.e. −40 decibels per meter (dBm)) [62] is low, the range of energy transfer can be managed by taking the antenna size into account. Other drawbacks of RF energy harvesting include low energy density (≈ .50 $\mu W/cm^2$) and low efficiency (≈ .45%) [63]. We can increase the energy density by using a dedicated RF energy supply. This requires extra circuitry and a dedicated system. In this context, RF energy actually has a major advantage of using simple and small harvesting circuitry. The most common example of RF harvesting is RFID, which is slightly larger than a grain of rice.

4.5. Chemical energy

Chemical energy is a type of energy that is readily available from chemical reactions, chemical substance transformations, or biochemical processes. The human body is an ideal representation of the biochemical process where food breaks into energy. Battery construction is a rather different example of converting a chemical reaction into electric energy. Similarly, we can use chemical energy to power IoT sensor nodes and the most common and easily available source for chemical energy is biological waste and corrosion.

4.6. Mechanical energy

Mechanical energy is the most prevalent energy source in an IoT environment, with a wide range of local sources available. These local sources include the following:

- *Vibration and motion*: Vibration is a readily available energy source found from a wide array of creatures, existing facilities, and productions. The vibration from appliances, rotation, human/animal motion, pressure, and kinetic energy are intense mechanical resources. All of these can be scavenged from roads, electric appliances, buildings, vehicles, bio-motion, bridges, industrial machinery, and so on. Vibrational energy is also a high-density source which we can generate in different power densities [64,65]. The harvested energy depends on amplitude and frequency of vibration. The majority of vibrational sources have amplitude and fundamental frequency in between 0.5–10 m/s^2 and 60–200 Hertz(Hz), respectively [17]. This is also contingent on the harvesting device's mass and vibrating mass. Most of the vibrations are made of multiple frequencies instead of having a single frequency. Vibrational energy is sometimes unpredictable, but easily controllable in the conversion process.

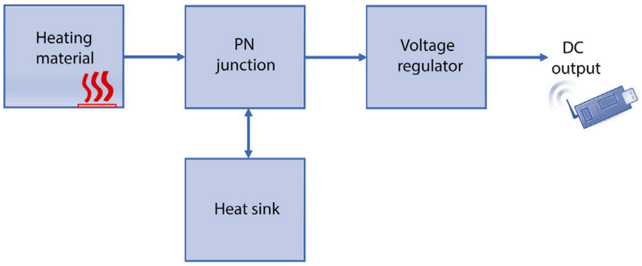


Fig. 4. Block diagram of the typical thermal energy harvester.

- *Wind and water*: Wind and water are the natural resources used for production of electric energy. Wind turbines and hydroelectric turbines are the oldest known mechanisms used in power electronics to harvest electric energy from air and water flow. An exorbitant amount of energy is produced through turbines. Wind and water usage is not limited to power systems. Miniaturized turbines are designed as micro harvesters to power low-energy sensor nodes (as Section 5.6 discusses). Wind availability depends on an areas' climatic changes whereas water's presence depends on the region. A human's body blood flow can also be used by a water harvester to extract energy and power e-health monitoring wearable systems. Wind's and water's existence is predictable, but the speed of flow is sometimes unpredictable [66] leading to uncontrollable situations.
- *Deformation*: A deformation in a material's internal molecular structure is also a reason for generating electricity. This deformation energizes the motion of electrons and protons within material, which results in the flow of electricity.

5. Energy conversion and transfer in IoT

5.1. Thermal energy harvesters

Different harvesters are introduced in literature to harvest thermal energy [57]. Thermal energy can be directly converted to voltage energy through a seeback method. In a seeback method heat flow is induced by using a suitable ThermoElectric (TE) generator. The thermoelectric and pyroelectric technique is a most commonly and widely used technique for heat extraction. Fig. 4 shows the block diagram of the TE energy harvesting process. A TE generator uses P-type and N-type junctions that are connected with heating material. When heat is induced over heating material, this results in movement of carriers from one junction to another. The most common heating materials used are aluminum oxide and silicon wafer, because of their high thermal conductivity [67]. This develops a current and voltage potential that is then transferred to a voltage-regulating circuit. By increasing the number of PN junctions across heating material, the quantity of harvested energy can increase proportionally. The regulated voltage can be wirelessly transferred to energize one or many IoT sensor nodes.

In contrast, another commonly used thermal energy-harvesting technique is the pyroelectric technique. This approach uses a special crystalline material that generates potential when it undergoes a temperature variation in its environment [57]. The difference in temperature causes the atoms to reposition and change material's polarization. This produces a voltage energy across the crystal. The pyroelectric method is of no use in constant temperature environments. Both thermal extraction methods are micro-level harvesters with long life, because of its simple and robust circuitry. Currently this method plays a significant role in IoT applications such as industrial, healthcare, and wearable technologies (for example, smart watch and fitness band).

A thermal harvester design is not limited to TE and pyroelectric only. As Table 1 shows, several other techniques have been proposed over time to perform thermal harvesting for IoT applications. It is worth noting that for efficiency in Table 1, medium and high correspond to 41%–75% and 76%–90% respectively as discussed in [72,73,76]. In [68], Vahid at el. present a simple fabrication design of a nano-antenna for use in IoT applications to harvest thermal energy. They claim this is the first nano-thermal energy-harvesting antenna. The performance results of the nano-antenna exhibit high gain at 30 Terahertz (THz), which makes it a best choice for infrared (IR) technologies. IR's use could portend a promising application in IoT-based health monitoring systems. This makes the thermal harvester a key technology of wearable devices.

In [69], the authors investigate harvesting body heat for IoT and medical usage. This work proposes two approaches: an mTE generator and μTE generator, as low- and high-output voltage designs, respectively. In the μTE generator, a single inductor DC–DC converter is used to achieve low thermal resistance and high efficiency, and in the mTE generator, use of the coupled inductor Direct Current to Direct Current (DC–DC) converter achieves high thermal resistance and low electric resistance. The experimental results of a wrist-worn harvesting unit achieves an average power of 260 and 280 μW, and power densities of 13 $\mu W/cm^2$ and 14 $\mu W/cm^2$ for the μTE and mTE generators respectively. Both designs are cheap, with low-cost components for a human-friendly and lightweight wearable medical system. Another wearable IoT design is proposed in [70], which develops a silk fabric-based body heat harvester. The number of thermocouplers are fabricated with nano-plates of hydrothermal P-type and N-type materials. The dense packing of couplers results in an efficient TE generator design. This design converts thermal energy ($\approx$ heat of 5 K to 35 K range) into maximum power of 15 nW and voltage of 10 mV. These harvesters can be fabricated easily over silk clothes using conventional printing machines. Such designs can be used with rechargeable batteries to achieve continuous monitoring of health parameters. Other experimental results in [71] are presented for fabric-printed thermal harvester. This design works by utilizing a seeback effect. The circuit can generate power in the range of 2.21 nW to 23.9 mW at a temperature of 22.5 C. Based on the number of experiments, the authors demonstrate this design as durable, flexible, and well-conditioned, with the human body at different active conditions. One of the latest works [72] has presented a μW sized biochip that can be used efficiently in wearable IoT applications. It is a lightweight and miniature chip, with an area of 0.46 mm^2. Experimental results confirm an efficiency of 65%–71%, with a power reading of 42–182 μW.

Mckay and Wang [73] has proposed the design of mechanical thermal switch that introduces a pulse mode of operation, where a periodic phase shift increases heat concentration. This effect lets the harvester work with maximum efficiency. This design has improved thermal scavenging efficiency up to 80%, but at reduced total power. One of the simplest thermal-harvesting concepts is given in [74], which we use extensively in IoT applications, including sensing and IR detection. The concept uses a pyroelectric effect, along with IR rays for thermal energy harvesting. The material, called ceramic lead zirconate titanate (PZT) pyroelectric buzzer, is used to harvest power in the range of 0.80 to 2.40 mW for an area of 5 cm^2 and 20 cm^2, respectively. These results show that the pyroelectric effect (which is subject to mechanical harvesting) is also an efficient thermal harvester.

The authors in [75] proposed a design to power smart IoT nodes through thermal energy. Their work describes the advanced design of communicating the temperature through a coordinating node. They implemented the experimental network scenario using autonomous IoT nodes. They also discussed the sustainability and service availability of a network while using thermal energy.

Table 1
Existing thermal harvesters used in IoT Networks. (NA = Not applicable).

Reference	Harvester type	Average Power/Voltage	Efficiency	Circuit complexity	Others	Application domain
[68]	Nano	NA	Medium	NA	High gain	IR-based E-health IoT
[69]	Single and coupled inductor	260–280 μW	NA	Low	Light weight	Wearable IoT
[70]	Thermo-coupler	15 nW/10 mV	NA	Low	Flexible and easy fabrication	Wearable IoT
[71]	Fabric-printed	2.21 nW–23.9 mW	NA	NA	Flexible and durable	Fabric-printed IoT
[72]	Biochip	42–182 μW	Medium	NA	Light weight	Wearable IoT
[73]	Thermal switch	NA	High	NA	NA	Smart IoT
[74]	Lead Zirconate Titanate (PZT)	0.8–2.4 mW	NA	Low	NA	Sensing and IR detection
[75]	DASH7 Coordinating	NA	NA	Medium	High sustainability and availability	Smart IoT

5.2. Light energy harvesters

The photoelectric effect or photovoltaic is the most commonly used harvesting method for light energy source. The first time PhotoVoltaic (PV) cells were used in sensor networks was for the smart dust program at the University of California, Berkeley [77]. The smart dust program used light-harvested energy to communicate with laser-based transceivers using an optical channel. The different versions of photovoltaic cells are available in the market that differentiates the construction material. Different materials are used to offer different efficiency and cost. The most common type is a silicon-based PV cell. Three significant categories of silicon-based photovoltaic cells are polycrystalline, mono crystalline, and amorphous [77], as Table 2 shows. Polycrystalline cells are cheaper and provide only 20% efficiency. However, mono crystalline reaches 25% efficiency, with more expensive rates than poly crystalline. Amorphous cells are cheapest of all, with quite smaller efficiencies (i.e, 10% for outdoor and 3%–7% for indoor). Amorphous cells are used with very low-powered nodes of IoT networks. Amorphous cells are also good absorbers of low-intensity artificial lights.

Photovoltaic cells are also known as solar cells. A typical cell consists of two layers of semiconducting material (such as silicon) and each layer is doped with P-type and N-type materials respectively [67]. The N-type layer is made to contact light energy. The light strikes the material, and photons are absorbed which free electrons to travel through the PN-junction. This fills up holes in the P-type material. Some electrons that are not used are released back toward the N layer. This results in generating a current around the PV cell. In this way, light energy is transformed into electric energy as shown in Fig. 5. Light energy harvesting is considered source of great potential for IoT applications. Photovoltaic cells are popular for environmental monitoring, military systems, smart homes, and commercial buildings to harvest light energy that can provide power to all of the given IoT networks.

There has been exponential growth in the use of light energy for powering different IoT systems as Table 3 shows. Using Table 2, the value of high efficiency in Table 3 corresponds to 21%–30%. Similarly, researchers are making concerted efforts to utilize light energy to power IoT networks' miniaturized circuitry. The authors in [78] have showed experimentally that IoT nodes are more responsive toward light energy. In this work, an EcoSense sensing technique is utilized to offer good reaction distances for light energy harvesting. In [79], the authors have proposed a light-harvesting circuitry for powering Bluetooth Low Energy (BLE) beacons. BLE beacons are low-cost devices used to transfer basic contextual information (such as location, advertisement, acknowledgment and so on) between different IoT nodes. A huge number of beacons are required for large IoT networks to work efficiently. Powering these networks with a battery is an expensive task; therefore, a harvester plays a vital role in such scenarios. In [79], they experimented with the design of a light harvester as a promising, energy-efficient solution for processing BLE beacons. In [80], the authors outlined the concept of an Eco-node for IoT applications. The Eco-node is a sensing node with harvesting circuitry that is battery-independent and gets its energy from light. Meanwhile, in [81], the authors proposed a Current-Starved Voltage-Controlled Oscillator (CS-VCO) design that produces an output power of 833 μW with a light intensity of 600lx. They also researched designing a power controller for maintaining adequate output power. In their work, they found that the light energy available in the environment is not uniform. It results in highly fluctuated power generation from the harvester. The feedback control concept is adept at maintaining uniformity in the harvested power and maintains an adequate level of energy to power IoT. Another recent research effort designed a feed-forward quasi-universal circuit by using boost converters, to control the excess voltage and current flow in the IoT network [82]. Different parameters are analyzed that will be chosen properly to have targeted output power.

The intensity of light for indoor and outdoor environments is different. The light-harvesting circuits work well for outdoor whereas for indoor, it generates less energy. Masoudinejad et al. have proposed a design of high accuracy indoor light measurements to get an adequate level of power generated at output [83]. This makes it suitable for indoor IoT applications. Another indoor application harvester is proposed [84], in which photovoltaic cells are utilized with some light intensity-adjustment techniques. With different light densities, output power of up to 400 μW is achieved. In addition, Shin and Joe have worked to propose a light-energy prediction algorithm for IoT networks with 0.5% of error [85]. In the literature, the number of other researches exist but their percent of error was very high and makes it unsuitable in many IoT applications [92–94]. The concept of weighted average is utilized by Shin and Joe to estimate more results [85]. One other indoor PV energy-harvesting design is proposed for smart building IoT application which generates 3.6–4.2 V output voltage, with 100 mA of pulse current [86].

The design of light harvesters for IoT is not limited to this. Multiple experiments are performed to use light, along with many other harvesters and propose a hybrid harvesting design [87–91]. In [89], EM energy is harvested for an IoT network, but in the vicinity of light. In many applications, a hybrid harvester has demonstrated a highly efficient result. The authors in [95] presented two-stage performance maximization systems of a hybrid energy harvester. This paper also demonstrates the advantages of using hybrid energy compared to a single energy source.

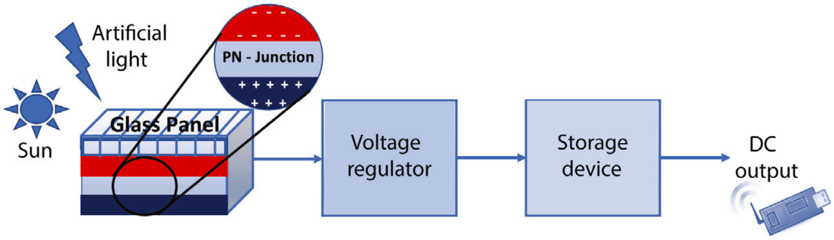


Fig. 5. Diagram of a typical photovoltaic energy harvester.

Table 2
Silicon-based PV cells [77].

Type of cell	Efficiency	Characteristics
Polycrystalline cell	20.4%	Cheaper and good level of output power
Monocrystalline cell	25%	Costly and highly efficient
Amorphous cell	3%–10%	Cheapest, good absorber of low-intensity light and low output power

Table 3
Existing light harvesters used in IoT networks. (NA = Not applicable).

Reference	Harvester type	Average Power/Voltage	Efficiency	Circuit complexity	Others	Application domain
[78,79]	Ecosence and econode	NA	High	NA	Highly responsive	Long-distance IoT networks
[80]	BLE beacon	NA	NA	NA	NA	Transferring small information
[81,82]	Current Starved-Voltage Controlled Oscillator (CS-VCO) feedback quasi PV	800 μW	NA	NA	Power uniformity and controlled voltage/current.	NA
[83,84]	Simple PV	400 μW	High	Medium	High accuracy	Indoor IoT applications
[85]	Prediction algorithm	NA	High	NA	High accuracy	NA
[86]	PV indoor	3.6–4.2 V	High	Low	NA	Smart Buildings
[87–91]	Hybrid	NA	High	Medium	NA	Used in number of IoT applications

5.3. EM energy harvesters

The harvesting process for EM resources is based on inductive transfer and resonant coupling [57]. In an inductive transfer mechanism, a time-varying voltage is applied to the coil used to generate variable EM fields. Another coil is used in proximity of the first coil to induce voltage across the terminals of the second coil as shown in Fig. 6. This process does not require any wired connection between two stages of the harvesting system. Inductive transfer of EM energy into electric energy is a simple, durable, and efficient method of harvesting. Due to its portable size and durability, inductive coupling method can be highly utilized for IoT applications to power sensor nodes.

Another EM energy-harvesting technique is achieved through magnetic resonance. This method is similar to an inductive coupling technique. When a time-varying voltage is applied to the first coil or primary coil and a resonant frequency that is tuned, it generates a variable magnetic field. To couple it with a second coil, it is important to tune the second coil with the same resonant frequency. Both coils will start exchanging energy — a process known as magnetic resonance coupling. This process is continuous as long as the same resonant frequency is at both coils. Both methods are simple and highly efficient, with an efficiency of up to 70%. The EM energy-harvesting method has an alignment problem and weak power. Researchers used this technique to power AA batteries of sensor networks [67]. This makes it efficient to use in IoT applications.

The EM harvester works well with several energy resources for efficient induction using EM waves within the system [96–98]. Researchers have proposed a smaller number of independent EM harvesters. Most of the works experimented with joint designs. In [99], Cho et al. presented the design of an EM harvester along with a piezoelectric harvester to power a smart watering IoT system. The system measures the water flow rate and detects leakage points in the water pipe. Replacing batteries frequently for such applications is inadequate. Therefore, a harvester is designed to power a system from harvested EM energy [99]. It uses a tiny waterwheel with a DC motor in the circuitry to achieve maximum output power of 648 mW.

In addition, EM harvesters are also combined with MEMS to create an enhanced harvesting design [100]. The design considers various parameters of coil and magnet to optimize the output power of harvester for different IoT applications. Another MEMS EM harvester [101] magnetically induces a tuning effect, which applies to the circuitry for efficient results. The magnet and tuning effect help control the output

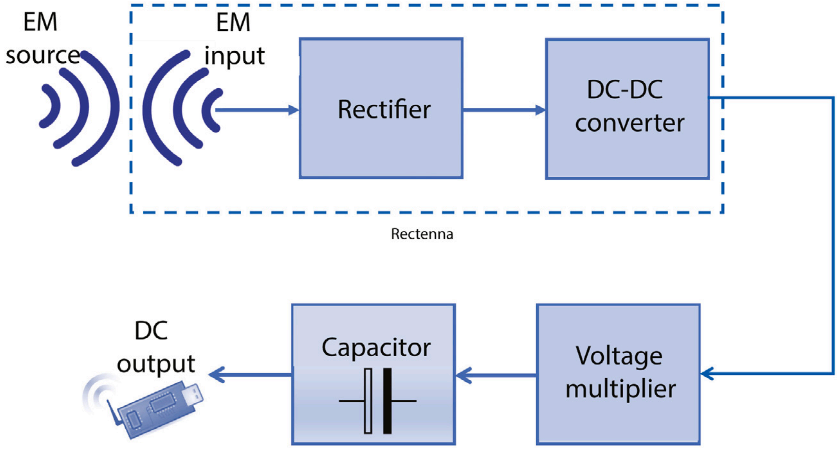


Fig. 6. Block diagram of a typical EM energy harvester.

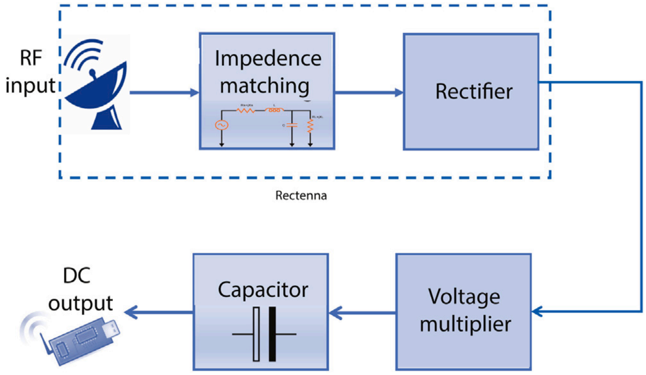


Fig. 7. Block diagram of a typical RF energy harvester.

power spectrum. This design shows great potential for IoT networks. In [88], the authors discussed a novel dual-harvesting design for an ISM band-based IoT communication. A 3-D package of slot antenna is used along with a PV cell and DC converter to harvest EM as well as light energy simultaneously. A tiny, and miniature design was proposed with 50% greater efficiency compared to conventional harvesters. In [102], Takacs et al. have addressed latest research related to the design of small and highly efficient EM harvesters and their applicability to IoT networks.

5.4. Radio Frequency (RF) energy harvesters

RF energy-harvesting systems have garnered significant attention because of the consistent and ambient presence of RF energy from Wi-Fi, cellular, and radio stations. The key elements of an RF energy-harvesting system is a rectenna, a voltage multiplier, and a storage/controlling unit, as Fig. 7 shows.

- A rectenna consists of an antenna and a rectifier. The rectifier circuit has one or multiple Schottky diodes to maintain a switched-mode power supply. The fast switching of diodes results in rectification. The RF signal's presence in the environment is first detected by the antenna. This induces voltage in the antenna and results in generating an Alternating Current (AC) signal. The AC signal is received by the rectifier which converts the AC signal into a Direct Current (DC) signal. To efficiently design the rectenna, different antenna types are considered such as dipole, planer, and patch. Most of the time, the dipole antenna is used, and in some cases a combination of different antennas is also used.
- A voltage multiplier maintains DC–DC conversion while increasing voltages level, to facilitate applications where low voltage is not enough [103].
- The last element of an RF harvesting system is the storage and controlling unit. This unit is important because it maintains an uninterrupted and continual supply of power to the end node.

The RF harvester has a challenge of impedance matching. RF signals are available with a wide range of frequencies. The circuit's impedance must be adjusted with respect to the frequency of the resource signal. The circuit antenna should be designed to induce most of the RF energy frequencies [77], to ensure maximum power transfer. Increasingly, researchers have been paying more attention to designing a system that assesses the entire band of RF energy. The RF energy conversion system does not require any mechanical action as it used to in other harvesters. This results in high robustness of an RF harvester.

RF energy harvesters are widely used in powering IoT sensor networks, as Table 4 shows (here, low, medium, and high efficiency, as in [116], correspond to 10%–30%, 31%–60%, and 61%–90% respectively). The demand for power requirements keeps increasing with ever-expanding IoT networks. However, the RF harvester has a challenge of relatively low-power densities ($0.2\ \mathrm{nW/cm^2}$–$1\ \mu\mathrm{W/cm^2}$). The small-sized, high-gain antennas also cannot generate enough power densities, the way that other harvesters can. A high-gain antenna only acts as a solution for maintaining good levels of power at the harvester's output. Using RF harvesters in proximity to RF towers also generates high-power densities. A typical RF harvester and conversion circuit achieves 10%–30% of efficiency and 1.8–4.0 V of output voltage (with input power levels from 30–20 dBm and output 100μW) [104]. In [104], the benchmarking design of an embedded harvester is proposed that powers the sensor platform from Ultra High Frequency (UHF) TV signals. Their experimental results were for a harvester kept at 6.3 kilometers (km) away from an RF source. The authors suggest using this circuit in IoT-enabled smart skin applications. However, the authors in [105] has experimented with an antenna design with an airgap to control the output power. Using an airgap increased efficiency up to 36%. The antenna size is miniaturized, while the high gain is maintained at a 5 GHz ISM band. This makes the design a good source of power for IoT networks. A new concept of the cooperative communication based harvesting is proposed in [117] for IoT networks' efficient power usage. In this work, the idea of a discrete phase-type distribution (D-PHD) is evaluated in the relay device of an RF energy harvester. An analytical model proves the proposed policy effective in maximizing the network's lifetime.

The work carried out in [106] has proposed a three-chip RF harvesting system by using a commercially available DC–DC boost converter

Table 4
Existing RF harvesters used in IoT applications. (NA = Not applicable).

Reference	Harvester type	Average Power/Voltage	Efficiency	Circuit complexity	Others	Application domain
[104]	Embedded RF	100 μW/1.8–4 V	Low	High	Benchmark design	Smart skin IoT
[105]	Air-gap-based power controllable RF	NA	Low	Low	High gain and small size	5 GHz ISM-band IoT networks
[106]	Three-chip RF	NA	Medium	NA	Small size	Power battery-less IoT
[107]	Adaptive MAC-based RF	NA	High	High	Highly responsive and high Quality of Service	Variable traffic IoT networks
[108–110]	Cellular RF	NA	High	NA	NA	Cellular and 5G IoT networks
[111]	Dipole antenna-based UHF	NA	High	NA	Long distance harvesting	Large IoT networks
[112]	Game theory-based	NA	NA	NA	Stochastic-based power prediction	Input-sensitive IoT networks
[113]	Adaptive rectenna RF	NA	NA	High	High gain and wide frequency band	Satellite health-monitoring smart IoT system
[114]	Ink-jet-printed RF	2.5 V	NA	NA	Flexible and robust	Next-generation IoT
[115]	Commercial RF	Sub-milli watts	Medium	NA	NA	Wide range of IoT networks

and a micro-controller. The third chip is designed and works on ultra-low power measurements. This chip works as an RF DC rectifier, converter, and Resistor Emulation Circuit (REC). The REC helps enhance efficiency. This chip is of 1.5 × 1.5 mm and designed with Complementary Metal Oxide Semiconductor (CMOS) technology. It fully powers a batteryless sensor node in the IoT. Despite enhancing the hardware design, some researchers are working to use an additional protocol and algorithms with RF harvesters to increase system efficiency. In [107], the authors proposed an energy-efficient design, which works to improve the QoS of an RF harvester. Maintaining higher efficiency with a high QoS is a difficult task. The authors in [107] proposed an adaptive Media Access Control (MAC) protocol that works over an RF-harvesting system and adjusts the sleeping modes in sensor nodes. The system is responsive and varies the performance based on traffic load, available RF power and residual energy. The simulation results confirm it as an energy-efficient and high-quality system for variable traffic in IoT networks.

Cellular-based IoT networks also often implement RF harvesters in their system design [108,109]. In [108], the authors have powered receiving nodes on a downlink channel with an RF harvester. Since cellular networks are surrounded by a rich quantity of RF energy, using the same energy for powering the system is an economic solution. In [109], the authors introduced the concept of a slot-synchronous, IoT-based cellular network. A cluster head is used that plans the RF harvesting and transferring of energy based on schedules of cellular traffic. The schedules of energy, spectrum, and information availability are estimated by Markov chain analysis. The author considers its design as a feasible solution for green Fifth-Generation (5G) networks. Another schedule-based energy transfer is presented in [118]. In this work, the authors introduced the concept of a software-defined energy-harvesting for IoT that combines the data plane, energy plane and control plane together to better utilize energy and reduce packet loss. In addition, the authors in [119] also emphasizes the role of power management as a key player in the design of an efficient IoT energy harvester. The RF harvesters were also used with MEMS and are referred as Radio Frequency MicroElectroMechanical-Systems (RF-MEMS). The concept of RF-MEMS came about in the late 90s. However, a mature and efficient design of RF-MEMS that can be used in future IoT applications was just developed in 2014 [120].

Additionally, the authors worked to design long-distance power for IoT networks using RF harvesters. In [111], the authors proposed a single-dipole antenna-based UHF energy-harvesting unit. Not limited to this, the authors also proposed an innovative design of RF harvesters that work on game theory and stochastic geometries [112]. In [113], several rectenna designs are proposed to power satellite health-monitoring systems and IoT applications. A low-cost rectenna design is also proposed in [121] to power different IoT applications. It achieves a received measured power of 64.4 dBm at 2.4 GHz. Meanwhile, in [114], the authors proposed the design of an inkjet-printed mm-wave rectenna to power next-generation IoT networks. It achieves 2.5 V of DC output voltage with 18 dBm of input power at 24 GHz. Apart from this, multiple commercial RF harvesters are also present today that can produce sub-milliwatt power and achieve up to 50% efficiency [115]. However, efficiency and power levels can still be increased through beamforming, multiband and high-gain antennas for IoT applications.

5.5. Chemical energy harvesters

Many chemical energy harvesters have been in use for quite some time [122]. Microbial Fuel Cells (MFC) are mostly used for converting chemical energy to electrical energy. In MFC, biological waste is used as a resource for electrical energy generation. Here, bacteria break the waste into ions and free electrons using an oxidization process. Then free electrons are picked up by the anode and transformed to cathode. This results in a flow of electric voltage as shown in Fig. 8. MFCs are characterized as a robust and low-maintenance voltage source. In many WSN-based IoT applications [123–125], they use MFCs to power medium to large-scale electronic systems. For small-scale systems (such as biomedical sensor systems), enzymatic biofuel cells are used as energy-harvesting devices [126]. Unlike MFCs, enzymatic biofuel cells use the same harvesting process, except for the oxidization source's process. Enzymatic cells use proteins for triggering oxidization process. These cells are costly, with an advantage of higher efficiency and a smaller size than MFCs [127].

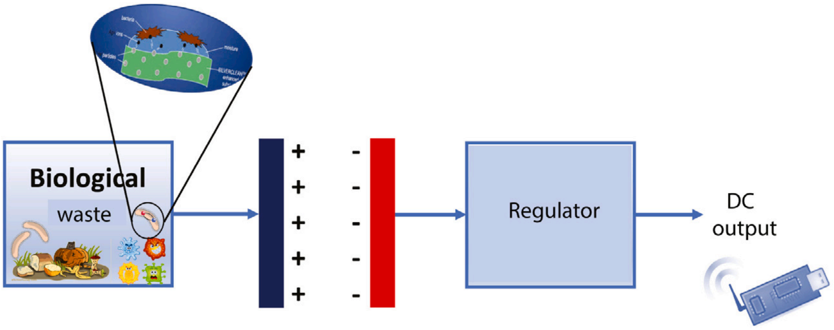


Fig. 8. MFC-based chemical energy harvester.

Another source of extraction based on a chemical source is corrosion [128]. In corrosion phenomena, carbonation and oxidization forms a compound (known as rust) in the presence of water or humidity. This compound releases electrons while reacting with iron metal. The part of metal that releases electrons works as an anode, and the part of metal that accepts electrons works as a cathode. This generates electric voltage. In [128], the authors designed a system for corrosion monitoring where they powered their system using the same corrosion process.

The use of waste is also a source of energy generation for low-power IoT applications. The single unit of MFC generates an extremely low output power, but the proper combination of MFCs in series and parallel can produce a sufficient amount of voltage and current [129]. A management unit will be used for further conversions. In [130], four MFCs are combined to get 1.5 mW of output power. In [131], the authors proposed a voltage balancing circuit for MFC stacks. They also proposed a balancing method to combine a serial stack output with a DC converter. This circuit works quite well to power IoT network nodes for different applications.

MFC is also useful in underwater IoT applications. However, such designs require robustness in MFCs' usage. In [132], they utilize the new concept of Benthic MFCs, known as BMFCs. Multiple anodes and cathodes are used for the distributed design of a BMFC-based harvester. A power-management system is a must in BMFCs, to have adequate control over power generation and remove system impairments. In the end, the experiments prove it as an efficient chemical harvester. However, conventional BMFCs have a limiting factor of low-power density and low-output voltage [133–135]. Most of the work has achieved effective output power, though, by using large parallel electrodes. This does limit a harvester's use in IoT networks. Thus, miniaturizing MFCs is necessary. Another innovative use of MFCs is found as a Plant MFC (PMFC) [136]. Power generation from an PMFC is extremely low, which makes it useful for triggering IoT networks' nodes. This design shows great utility in environments surrounded with plants. In [136], the authors powered an IoT node for sensing applications by using additional circuitry and protocols with the harvester.

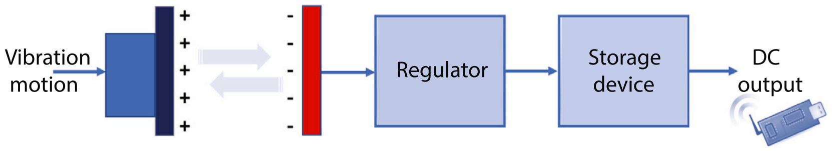
5.6. Mechanical energy harvesters

Today, several methods are available to provide mechanical to electrical energy conversion. Some well-known transduction methods to scavenge mechanical energy include, electrostatic, piezoelectric, and electromagnetic method [13,137,138], as Fig. 9 shows.

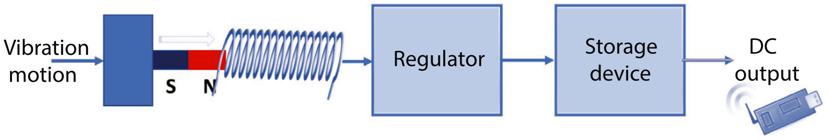
An electrostatic harvesting technique uses two electrodes of positive and negative charge. The production of electricity is based on relative motion in between two plates/electrodes of a capacitor [139]. The vibration or motion from an external source results in voltage variation, because of the distance change in between two electrodes. This results in electrostatic transduction around capacitive plates/electrodes and makes the flow of current in a circuit [139]. The electrostatic harvesters are characterized as current source devices. The generated current oscillates in between maximum and minimum values. It has the advantage of easy micro-fabrication manufacturing over two other harvesters [140]. However, the initial charge of capacitors is a must in electrostatic harvesters. Another common mechanical harvester is the electromagnetic harvester. In the electromagnetic method, the harvesting process follows Faraday's law of induction [141]. As with Faraday's law, the magnet's displacement around a coil helps in current generation at the coil's end. Similarly, in a harvester, a permanent magnet oscillates inside the coil to induce a current in it. The efficiency of electromagnetic harvesters can be controlled by properly choosing magnet bar's material, number of coil winds, and coil thickness [67]. The micro-fabrication process is also convoluted because of its complex assembly and alignment of the magnet bar with the coil. This makes the harvester's robustness poor.

Moreover, the piezoelectric mechanical harvesters got its name from the property of using a special crystal of piezoelectric material [142]. The power is generated when piezoelectric material is compressed and deformed by an external source's vibrations or motions. The applied force deforms the material's internal structure and causes modifies positive and negative particles. This results in polarization and generates a voltage difference across the material. The generated potential difference is directly proportional to the production of AC current. Piezoelectric materials are used extensively because of their direct conversion from mechanical to electric energy [142]. The use of piezoelectric materials in the harvesting process exhibits high power densities when compared to other macro-harvesting techniques [145]. One of the best exhibited power densities is 250 μW [143]. On the other hand, MEMS can reach a power of 10–100 mW for typical and high accelerations [147,148]. Further, the harvesting process's efficiency is directly related to the type of material used. Natural as well as artificial piezoelectric materials are available. The most commonly used piezoelectric materials are PZT, zinc oxide (ZnO) and Poly Vinylidene Fluoride (PVDF) [143,144]. Compared to PZT, ZnO and PVDF are flexible and more robust. However, all of the piezoelectric harvesters are simple and easy to fabricate. In [149], a Ytterbium (Yb3+)-assisted PVDF design is proposed with Ferroelectric NanoGenerator (FTNG) in piezoelectric harvester. The FTNG-based harvesters are considered to be highly efficient designs that can be used with low-power networks. Li et al. proposed a bi-resonant structure of PVDF that achieves 40%–81% efficiency [150]. In [151,152], a novel MEMS-based piezoelectric design is proposed that harvests vibrational energy and powers remote IoT nodes. In [151], the authors proposed a concept of a resonator-based Four-Leaf Clover (FLC) design. This offers the major advantage of providing high efficiency over a wide band of frequencies. However, in [146], the authors proposed a data-driven probability structure that estimates the energy production for the piezoelectric harvester.

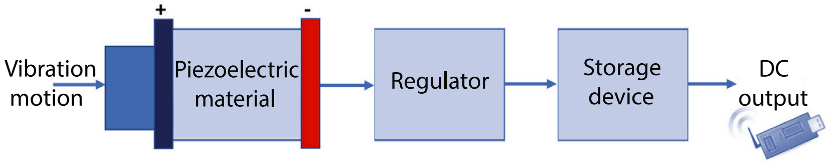
Mechanical harvesters are the most widely used harvesters in IoT applications as depicted in Table 5, where high efficiency corresponds to 80%. The aforementioned methods are applicable for converting vibration and motion into electric energy. In contrast, for harvesting



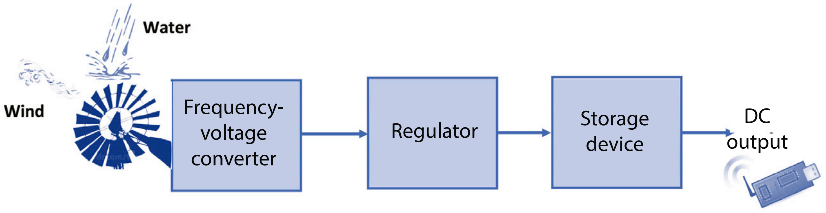
(a) Electrostatic harvester



(b) Electromagnetic harvester



(c) Piezoelectric harvester



(d) Spinning turbine harvester

Fig. 9. Block diagram of mechanical energy harvesters.

Table 5
Existing Mechanical harvesters for IoT networks. (NA = Not applicable).

Reference	Harvester type	Average Power/Voltage	Efficiency	Circuit complexity	Others	Application domain
[139,140]	Electro-static	NA	NA	Low	Micro fabrication	IoT networks with a low-level of vibration
[67,141]	Electro-magnetic mechanical	NA	High	High	Poor robustness and alignment problem	Industrial IoT and vehicular networks
[142–146]	Piezoelectric	250 µW	High	Low	High-power densities and easy fabrication	Industrial IoT and vehicular networks
[147,148]	MEMS	10–100 mW	High	NA	NA	Industrial IoT
[149,150]	Poly Vinylidene Fluoride (PVDF) piezoelectric	NA	High	NA	NA	Low-powered IoT networks
[151,152]	MEMS-based piezoelectric	NA	High	NA	NA	Industrial IoT and vehicular networks
[67,153–155]	Spinning turbine	900 mW (Water)	NA	High	NA	Irrigation and outdoor IoT networks
[156–158]	Statistical data-driven	4 pW–2.75 W	High	High	High-speed switching and flexible	Wearable IoT

energy from wind or water, most prefer a miniaturized spinning turbine [67,154,155]. Some harvesters also exploit an anemometer to convert wind energy into electric energy. Azevedo and Sentos [153] have proposed a harvester design for extracting wind and water energy to power wireless nodes on an IoT network. The system design is composed of propeller turbines. With water as the resource energy, the turbine produces an output power of 900 mW, which is highly suitable for irrigation applications. However, in [156], the authors proposed the design of movers and shakers to power the IoT network. The kinetic or motion energy is used as a source of power. Human activities also release bulk mechanical energy that we can harness to power nodes. Often such harvesters are used in wearable IoT networks [156–158]. The authors in [158] consider their design as a rocket logger due to its high switching speed. The high speed switching also makes it a remarkable research for the IoT networks. In this work, the experimental results obtained demonstrated guaranteed power measurements from 4 petawatts (pW) at 1 mV, and up to 2.75 W at 5.5 V.

5.7. *Application classification and cost analysis for energy harvesters*

Based on the analysis above, Fig. 10 classifies various IoT applications/services that can benefit from specific types of energy harvesters. Furthermore, the cost associated with the design of an energy harvester may vary according to the impedance, voltage, and output power required by the IoT application/service. Table 6 [159] presents the typical costs associated with various types of energy harvesters.

5.8. *Energy transfer*

Energy transfer is the process of transferring electrical energy from the harvesting source to the deployed IoT nodes. For IoT systems, the preferred medium of energy transfer is wireless. The concept of wireless energy transfer is quite old, initially proposed in 1914 by Tesla [160]. Since then, many research efforts have refined and increased the efficiency or reachable distance of transfer. A detailed recent survey contemplates efficient wireless transferring methods [57, 161–165]. Thus here, we do not discuss the methods used. Instead, we explore the arrangement and distribution approaches of wireless transfer for the IoT, which we can classify into three categories as shown in Fig. 11, i.e., (a) one-to-one; (b) one-to-many and, (c) on-demand. The choice of distribution approach depends on the type of application.

One-to-one: The first and most commonly used approach is one-to-one energy distribution. In this arrangement, a separate harvesting unit would be deployed for each node of an IoT system. The circuitry of harvesting is wirily fabricated with a sensor node. The failure of any single harvesting system will only affect that particular node. All other system nodes, however, will work smoothly. This approach operates efficiently for small networks. In large networks, though, deploying a separate harvesting unit for each node is not economically viable.

One-to-many: Another distribution approach is one-to-many energy transfer. In this arrangement, a single harvesting unit will be used to power a group of nodes. All nodes of a group will receive harvested energy periodically and wirelessly. Depending on the node's energy expenditure, the amount of energy transfer may vary for all nodes. The failure of a single harvesting unit affects multiple working nodes. For mobile nodes, the wireless energy transfer's efficiency will also be affected by the frequent distance changes. This arrangement works well for small as well as large networks. The one-to-many energy transfer is also an economic way of powering IoT nodes using harvested energy.

On-demand: The third and last approach of energy transfer is on-demand energy transfer. This distribution approach resembles a one-to-many energy transfer. As a result, some drawbacks from one-to-many are also present in the on-demand approach. The one-to-many energy transfer has one major drawback of unwanted distribution of energy: sometimes, a node does not need it, but unwanted energy may be transferred to the node by the harvesting unit. At other times, high node usage requires more energy to work efficiently, but only a fixed amount of energy is always allocated. This results in a loss of energy or system efficiency. In such scenarios, an on-demand distribution approach works well. A single harvesting unit can be used to power a group of nodes, similar to the one-to-many approach. However, the power distribution will not be periodic. Power will be distributed according to the demand of an IoT node. Each node will keep an eye over its storage device, and if power falls below a certain threshold level then a request is made to the harvesting unit. This approach works well for large IoT networks.

6. Energy storage, management, and consumption in IoT

In recent years, energy storage and control methods are progressing dramatically [166,167]. A reservoir can be used to store the energy to contend with the power need of a consumption unit, based on available power. However, the lifetime of reservoirs and storage units depends on the capacity of energy it can store. The consumption of power in IoT can also be optimized by using energy harvesting and saving techniques. Energy management is controlled in IoT using an energy control unit. The energy control unit can be hardware or software-based. We present a comprehensive review of energy storage units (classified into three different buffering types), energy management mechanisms, and energy consumption in the following sub-sections.

6.1. *Energy storage in IoT*

6.1.1. *Primary batteries*

Primary batteries are also known as conventional or non-chargeable batteries. Battery usage is quite old, and the most common type of power supply unit for IoT-based systems. The batteries are intended to operate a system for a long duration. It becomes difficult to maintain longevity when the user deals with a large network. IoT-based systems consist of low-power nodes and sensors. The consumption of power in the IoT can be optimized by using energy-saving techniques, as Table 7 shows. When an energy-saving mechanism is not used, non-chargeable or conventional lithium batteries provide a lifetime of one year with a power density of 45 $\mu W/cm^3$, and a lifetime of 10 years with a power density of 3.5 $\mu W/cm^3$ [168]. So, if an IoT network is small and deployed in a less-demanding environment, then batteries are the most economic and simplest choice to supply power. However, when the size of the network increases or the IoT network must work for a very long time, or the deployment place is not conducive for easily replacing batteries (such as environmental monitoring and military applications) [169], conventional batteries cannot be used to power such systems. Thus, the network size, number of nodes and type of application limits primary battery usage. In such a scenario, conventional batteries create a bottle neck for continuous operation and network life. The second most-convenient method to increase the lifetime of a network is the use of rechargeable batteries. We present a detailed description of rechargeable batteries in the next section.

6.1.2. *Rechargeable batteries*

In order to efficiently provide power to a network, rechargeable batteries can be used. Rechargeable batteries minimize the problem of battery replacement. Despite replacing a battery or a power supply unit, a recharging technique is still needed along with a rechargeable battery to maintain continuous network power. Rechargeable batteries also enhance an IoT system's economic design because this limits the cost of buying multiple batteries repeatedly over the time. Different rechargeable batteries (of different efficiencies) are available on the market [77]. One survey [167], describes rechargeable batteries' high use in IoT-monitoring applications (as Fig. 12 shows). Lead–acid, Nickel–Cadmium (NiCd), Lithium-Ion (Li-ion), and Nickel-Metal Hydride (NiMH) are the most common rechargeable batteries [170, 171].

- *Lead–Acid*: This battery is the oldest and the most widely used type of rechargeable battery in sensor networks [170]. We can find lead–acid batteries ranging from 1 to 3000 Ampere hours (Ah). The potential voltage of a lead–acid battery is 2.048 V (at 25 °C). One of the biggest advantages of this type of battery is that most of its life, the expected voltage does not fluctuate. Eventually, with time and age, it starts losing some of its capacity. Lead–acid batteries are also highly versatile.

Table 6
Cost associated with different energy harvesters [159].

Type of harvester	Cost
Light	\$0.5–\$10
Mechanical	\$2.5–\$50
Thermal	\$1–\$30
RF & Inductive	\$0.5–\$25

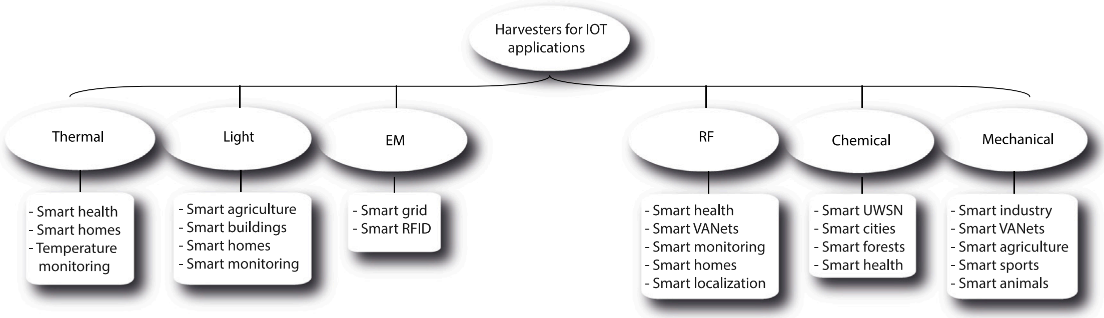
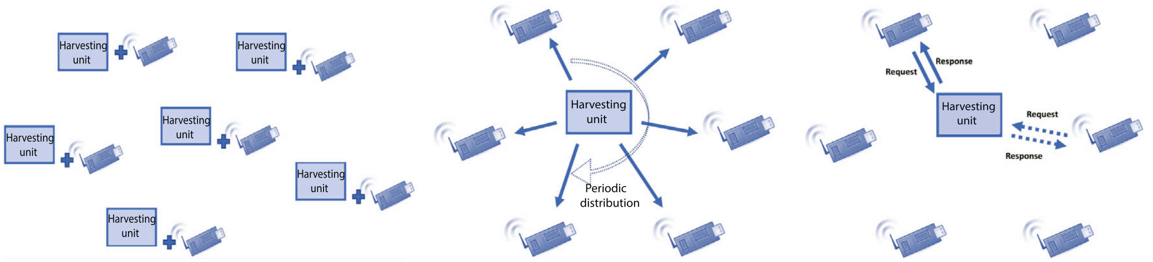


Fig. 10. IoT applications for various energy harvesting systems.



(a) One-to-one distribution approach (b) One-to-many distribution approach (c) On-demand distribution approach

Fig. 11. Energy transfer for IoT harvesting systems.

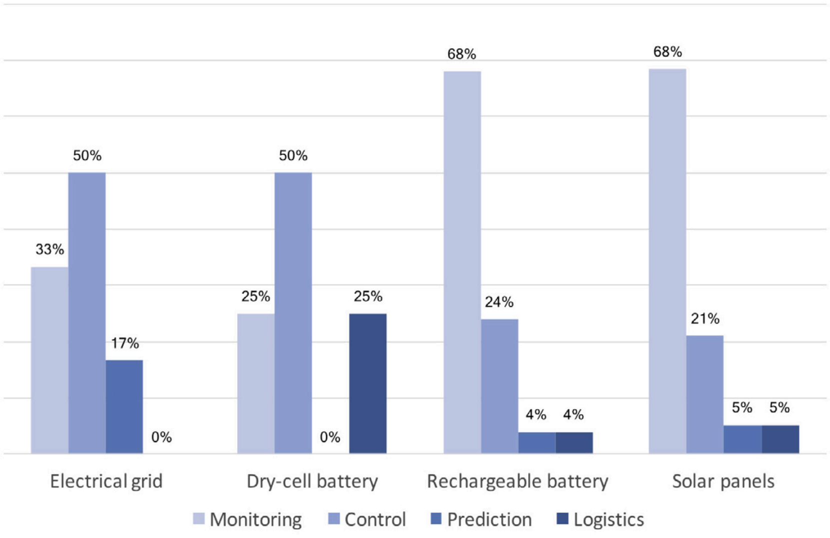


Fig. 12. Usage of energy resources [167].

- *Nickel–Cadmium (NiCd)*: This is another mature and popular battery-type which is commonly used in health applications to power medical tools [172]. Such batteries have low energy and low gravimetric energy density; other batteries are replacing NiCd in most applications. But because of its cost, many researchers still use NiCd in network design.
- *Lithium-Ion (Li-ion)*: This rechargeable battery is often used in consumer electronics. These batteries are well-known for retaining charge, with very small voltage depression and high energy

Table 7
Taxonomy of energy-saving mechanisms in the IoT.

	Classification		Reference
Energy-saving mechanisms	Wireless standard	Application-based selection	Table 8
	Radio optimization	Tx power control	[174–176]
		Directional antenna	[177,178]
		Cognitive radio	[179–181]
	Data optimization	Modulation and coding scheme	[182–186]
		Compressive sensing	[187–191]
		Aggregation and clustering	[192–195]
		Probability structure	[196–199]
	Scheduling schemes	Sleep scheduling	[200]
		Message scheduling	[201,202]
		Traffic scheduling	[203]
		Wake-up radio scheduling	[204–208]
		MAC duty-cycling	[206,209,210]
	Routing and topology control	Energy efficient routing	[211–213]
		Multipath routing	[214–216]
		Distributed topology Control	[207,208,217]
	Messaging protocols	MQTT	[218]
		AMQP	[219]
		CoAP	[220]

density [171,172]. After a full charge, a Li-ion battery discharge 5% in its first 24 h and then 1% to 2% after every month. Li-ion is considered dangerous because it is highly flammable. Li-ion batteries are classified further into six types, and each one shows great utility for different applications of portable consumer electronics and distributed networks [77].

- *Nickel-Metal Hydride (NiMH)*: This battery became popular in 1989, because of its array feature, which is advantageous for multiple applications [173]. NiMH is an advanced version of NiCd. It has 40% greater specific energy over NiCd, and it is environmentally friendly, because of its wide range of cell sizes [173]. Apart from this, NiMH also has high energy density, low maintenance costs and is safe to use at high voltages. Such features make these batteries ideal to use in distributed networks [77].

6.1.3. *Super capacitors*

A capacitor with high power or energy density compared to an ordinary battery or capacitor, is known as a super capacitor. Super capacitors have the advantage of a huge number of charge and discharge cycles. The charging mechanism of a super capacitor is simple and does not require any extra circuitry. Extra circuitry can be used sometimes, to efficiently transfer energy (depending on the type of energy input). However, in conventional situations, direct connection of voltage terminals is enough to store energy in the capacitor. Different harvesting resources (such as solar energy) work efficiently with super capacitors to buffer energy in it [77]. Their charging efficiency of super capacitor is 98%, so they recharge expeditiously [57]. This makes super capacitors the best energy-storage choice for energy harvesting in the IoT. Having simple or no circuitry is advantageous when using super capacitors with the IoT sensor nodes in harsh environments [57].

6.2. *Energy-management in IoT*

In this section, we present a taxonomy of energy-saving mechanisms for IoT networks as Table 7 shows. Energy efficiency has become an important research topic not just for IoT but for several other application domains [8,221–223]. In addition to the use of harvesters, it is even more important to handle the harvested power efficiently [224]. Over the last few years, several energy-efficient strategies have emerged and they will play a vital role in IoT systems. An energy-efficient IoT can be implemented by using energy-saving mechanisms in the storage and control unit as discussed in Section 3 of the IoT system. We classify the energy-saving mechanisms as follows:

(a) **Radio optimization:** to optimize the radio, its transmission power can be controlled [174–176], i.e., if the nodes are close by, the power will be tuned to low (consuming less energy) and if they are far away the power can be tuned to full (consuming the maximum energy). For scenarios where the direction of communicating nodes in an IoT network is known apriori, directional antenna consumes less energy for communication [177,178]. Furthermore, to avoid interference and congestion (which results in unnecessary retransmissions of data and increases the energy consumption) cognitive radios can be utilized [179,180]. Cognitive radios can be dynamically configured and programmed to utilize the spectrum efficiently and concurrently [181].

(b) **Data optimization:** to optimize data collection, different modulation and coding schemes are used to transmit optimal amounts of data across nodes despite unreliable wireless links [182–186]. Another promising technique is compressive sensing [187–190] which reconstructs the original data using fewer samples which the node has acquired in compressed format. Thus, in an IoT network, a node uses compressive sensing performs sensing and compression simultaneously. In [191], the authors present a good review of IoT applications/services that use compressive sensing. In addition, in order to transmit data efficiently to central data centers only the aggregated data is transmitted using various techniques such as clustering [192–195]. Similarly, bloom filters [196,197] or named data networking [198,199] can also be used to reduce the amount of traffic flowing across the IoT network.

(c) **Scheduling techniques:** they schedule the data to be transmitted in a way that saves energy. Some approaches put nodes to sleep to conserve energy [200,225] when there is no data to send. Other approaches wake up nodes to either receive or transmit the data [204–208]. Some techniques schedule the data in such a way that it will reach the edge node with high energy efficiency [201,202] and some schedule the traffic flows across the network [203]. Duty cycling is another approach that consumes less energy wherein the node goes into an idle mode when there is no operation to perform [206,209,210].

(d) **Routing and topology control:** routing plays an important role in the transmission of data from one node to another node or to some edge node. There are many energy-efficient routing schemes [211–213] that have been proposed in the literature. Several energy-efficient multipath routing schemes have also been proposed to transmit the data [214–216] so as to balance the energy consumption across the IoT network. Other techniques [207,208,217] that extend the lifetime of an IoT network control the topology of network in a distributed manner by altering the underlying physical network to create a connected virtual network that minimizes the cost of data transmissions.

(e) **Messaging protocols:** various messaging protocols have been developed to support the idea of connecting devices anytime and anywhere with high energy efficiency. Message Queue Telemetry Transport (MQTT) [218] is based on a lightweight publish/subscribe model that allows a node (edge node) to publish a broker. Client nodes subscribe to the broker, which then establishes communication among the nodes. Advanced Message Queuing Protocol (AMQP) [219] is an open access client/server based application layer protocol to support messaging among nodes in an IoT network. Another well-known application layer protocol is the Constrained Application Protocol (CoAP) [220] which is described in RFC 7252. CoAP supports Hyper Text Transfer Protocol (HTTP) for seamless integration with the Internet.

Table 8
Comparison of wireless technologies for IoT.

Wireless technology	TX Range	Data rate	Lifetime	IoT application
Wi-Fi (IEEE 802.11)	20–100 m	1 Mbs–6.75 Gbits/s	Days	Used at Gateway to connect IoT nodes to the Internet
Zigbee (IEEE 802.15.4)	10–20 m	40–250 Kbits/s	Years	Smart health, smart home, and smart parking
WiMAX (IEEE 802.16)	<50 Km	1 Mbit/s–1 Gigabit/s	Hours	Large-scale outdoor applications such as smart grid, environmental, and agriculture monitoring
Bluetooth (IEEE 802.15.1)	10–100 m	1–24 Mbits/s	Months	Smart health, smart retail, and smart home
BLE IEEE 802.15.6	30 m	1 Mbit/s	Years	Smart health, industry
Cellular	Cell area	200 Kbits/s–1 Gigabit/s	Hours	Smart cities and automotive
LoRa	<30 Km	0.3–50 Kbits/s	Years	Smart cities, automotive, industry
Sigfox	<40 Km	0.1–1 Kbit/s	Years	Smart cities, agriculture, industry

These mechanisms and protocols are used by different researchers in different ways to design and implement energy-efficient models for IoT systems. Employing energy-saving mechanisms within an IoT harvesting system not only improves energy use but it also enhances other parameters such as QoS, privacy, transmission latency, and system cost [212,226].

Furthermore, the appropriate selection of wireless standards (based on the requirements of the specific IoT application) is also important for energy-efficient IoT systems [227,228]. Table 8 compares wireless standards and their usage in IoT applications. The IoT wireless communication standards include (a) Wi-Fi, (b) Zigbee, (c) Worldwide Interoperability for Microwave Access (WiMAX), (d) Bluetooth and Bluetooth Low Energy (BLE), (e) Cellular networks, (f) Long range (LoRa), and (g) SigFox. Table 8 presents various wireless technologies (along with their characteristics such as transmission range, data rate, and lifetime)that could be deployed in an IoT environment. This information will help select the most appropriate wireless technology to meet the requirements of a specific IoT application.

6.3. Energy consumption in IoT

An energy-consumption unit can consist of an IoT sensing device, IoT node, and/or an IoT gateway node. Table 9 shows the energy consumption of various components used in IoT. Depending on the application, each network consists of one or more IoT nodes. Each IoT node can use one or more transmission devices, a few sensors, memory and a processing unit [229]. Generally, an IoT node is powered by 3-5V batteries [230]. A review of various types of nodes and their energy consumption is presented in [231]. A gateway node manages the communication between end nodes and Internet devices. In [232], the author presents a comprehensive overview of energy consumption by IoT applications and services. All IoT devices and nodes use a wireless interface to communicate with each other. Table 9 can be used as a reference to better understand the amount of energy that will be required from the harvesters. A full discussion of energy consumption in the IoT environment is beyond the scope of this paper but can be found in recent publications [8,22,233–236].

Table 9
Energy consumption of various components used in IoT [237–244].

	Component	Power/Current consumption
Wireless technology	Wi-Fi	835 mW
	Zigbee node	36.9 mW
	MiMAX node	36.78–36.94 W
	Bluetooth	215 mW
	BLE	10 mW
	Cellular	0.1–0.5 W
	LoRa	100 mW
Typical sensing devices	Temperature/humidity	0.2–1 mA
	IR	16.5 mA
	Ultrasonic	4–20 mA
	PIR	65 mA
	Light	0.65 μA
	Camera	270–585 mA
IoT node/gateway	WASP mote	9 mA
	Pi	100–500 mA
	Xbow	17.5–19.7 mA
	Arduino	3.87–13.92 mA

7. Future research challenges for energy harvesting design architectures in Internet of Things

IoT is a revolution in the IT industry. Battery-operated IoT poses a challenges to manage the energy budget. Energy harvesting in an IoT system brings about several challenges. Based on the above research results and observations, this section discusses major design issues for an IoT-harvesting system.

7.1. Hardware design

Every aspect of a node's hardware is affected by the underlying harvesting circuitry. A hardware design is required to cope with multiple issues. The power generated by the harvesting circuit is highly variable.

Sometimes the power obtained from the environment is inferior or superior to the power delivered to the IoT node circuitry. Therefore, the harvested energy relies on the energy availability in the environment. This often results in heavy fluctuations of energy within the node's circuitry. Traditional IoT node designs are unable to handle the fluctuations [245]. This requires a hardware design that can withstand a wide range of power inputs. Advanced power management can be a solution to handle the varying levels of harvested power.

In many harvesting systems, often, there is less harvested power than needed for large IoT networks. One-to-one deployment can address the network need. For one-to-many and on-demand deployments, a multiple antenna technology in the harvesting circuitry can be a viable solution. Multiple antennas such as massive Multiple Input Multiple Output (MIMO) and distributed antennas, can efficiently compensate for IoT system requirements. For RF harvesters, using multiple antenna technologies increases the energy-scavenging efficiency and distance of RF energy transfer [246,247]. Using multiple antennas also caters to two-way channel interference and improves functioning where power and information are transferred simultaneously [248].

The harvester's bulky circuitry is another challenge, and unlikely to work with traditional IoT sensor nodes. A robust nanoscaled and low-cost harvesting circuit is required to provide sufficient power to IoT nodes. Some prior miniaturized harvesting circuits are available on the market, but with only a low range of supply power. This range of power is not sufficient to handle sensing and monitoring simultaneously. Therefore, future work should focus on a nano design that fully addresses the power requirements and efficiently handles the harvested power's variable nature of power.

7.2. Software design

Software developers should focus on designing software for harvesting systems where energy's unavailability for a short period of time is managed smartly. Such an operating system should be able to resume the task from the point where it was left. This will ensure that resumed state is meaningful. There must be no restarting a task because it can result in data loss. The idea is to design a system capable of extending its functionality with regard to the variable nature of scavenging power.

A robust simulation software is also a future challenge in the field of harvesting systems. A simulation model is required that covers the feature of harvesting parameters. Such a simulator will be an efficient tool to simulate the impact of the variable nature of harvested power over existing energy models. Prior testing of large energy-harvesting networks is always an intelligent step toward designing them.

7.3. Battery storage

As discussed in previous sections, there are two storage technologies (i.e., battery and capacitor), that can be used to store energy in sensor systems. Selecting a proper storage device is crucial for a long-lasting network. Both a rechargeable battery and a super capacitor have some limiting factors that hinder their use in many IoT applications. Lead–acid battery is the most widely used rechargeable battery in sensor network applications. It comes with the drawback of quickly draining the energy capacity. This makes it a poor choice for large-scale IoT networks. An NiCd rechargeable battery is cheaper in cost, but has low energy density. However, Li-ion and NiMH batteries have high energy density as well as low discharge rates. The highly flammable nature of these batteries, though, makes them worst to use in most of IoT applications. Super capacitors, with their numerous advantages, are one of the best choices to use for IoT networks. However, a super capacitor is still an immature technology. Despite their high energy density and simple circuitry, super capacitors have a high self-discharge rate which limits their use for the long-lasting applications. A highly efficient, long-lived, miniaturized and economic battery and capacitor is still a challenge for researchers.

Conventional rechargeable batteries and capacitors can also be used efficiently in IoT sensor networks by designing additional charging circuits to control their limiting parameters. Therefore, future research should focus on conventional batteries to make them better-suited for IoT harvesting networks.

7.4. Reliable delivery

Reliable delivery is crucial for wireless energy transfer in harvesting systems. Understanding the notion of energy distribution is the first step of reliable delivery. Section 5.8 explains the energy transfer and distribution techniques for IoT systems. Designing an all-inclusive reliable transport protocol is a challenge where the harvesting unit first needs to acquire tenable information from the node. This information includes learning the rate of data flow from the node; how much energy must be transferred; knowing the node's location; and discerning the node's distance from harvesting unit. Based on this information, the system must schedule an adequate transfer of energy for reliable functioning. The protocol should also ensure a suitable sharing of bandwidth.

The reliable networking of energy is also considered a pre-requisite for data networking. Therefore, an energy-management model must also be designed to assure and cope with energy requests from the IoT nodes. As Section 5.8 discusses, on-demand energy distribution is not periodic, and power will be distributed on-demand for IoT nodes. So, the energy-management model will play a key role.

7.5. Environmental models

Free space models and wireless propagation models are available to examine generic IoT systems. In a similar way, an environmental model design for energy prediction in harvesting systems is a challenging future task. Based on multiple general environmental parameters such as intensity, pressure, flow rate, speed, distance, height, and frequency, an environmental model can be designed that predicts the energy-generation rate for particular energy resources. This will help articulate and plan energy's nature for different regions of interest. Then, a network designer can pre-deploy calculations to investigate a harvesting system's performance in a particular environment.

7.6. Protocol design

To address the issue of unwanted consumption of battery-powered nodes, using an energy-efficient strategy plays a vital role in IoT systems. In addition to energy-saving and energy-aware protocols, harvesting systems require a supply-aware protocol. Such a supply-aware protocol must be able to handle the highly variable nature of harvesting power and long energy outages. Therefore, a redefinition of existing energy-saving protocols is significant for future research.

8. Conclusion

Today, IoT is playing a pivotal role in our daily lives, making headlines globally opening up many new possibilities. It is a fascinating concept of networking devices, where the scope of devices' interactions increases every year. However, every added IoT device comes the consequence of growing energy needs. In this paper, we present the fundamental components of an energy-harvesting system for the IoT. We evaluate the different aspects of each component in the context of IoT networks. We reviewed six major energy resources along with their environmental locality, to be used by energy-harvesting systems deployed in an IoT environment. Furthermore, in this review, we identified different types of hardware that could be used in harvesters' designs. Correspondingly, each harvester's efficiency also varies based on different parameters. This leads to IoT systems that schedule different distribution approaches for different deployments. In our review, we also looked at energy storage and control units. We surveyed typical storages devices along with their recharging features. We have also presented a taxonomy of energy saving mechanisms in the IoT.

From this work, we found that an IoT network's node has limitations in terms of computation, power, and storage. These limitations make existing harvesting systems' deployments difficult in the IoT. This, future research efforts should focus on creating and outfitting new frameworks on protocol designs that operate efficiently in IoT nodes' resource-constrained environment. It is our hope that this review of existing works and research efforts gives focus to future research that opens up new opportunities to overcome some of the current challenges we have identified in this work.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acronyms

5G Fifth-Generation

AC Alternating Current

AM Amplitude Modulation

AMQP Advanced Message Queuing Protocol

BLE Bluetooth Low Energy

cm centimeter

CMOS Complementary Metal Oxide Semiconductor

CoAP Constrained Application Protocol

CPS Cyber-Physical Systems

CS-VCO Current Starved-Voltage Controlled Oscillator

dBm decibels per meter

DC Direct Current

DC-DC Direct Current to Direct Current

D-PHD Discrete Phase-type Distribution

EM ElectroMagnetic

FLC Four-Leaf Clover

FM Frequency Modulation

FTNG Ferroelectric NanoGenerator

Hz Hertz

ICT Information and Communications Technologies

IoT Internet of Things

IR Infrared

ITS Intelligent Transportation Systems

Li-ion Lithium-Ion

LoRa Long Range

M2M Machine to Machine

mA milliampere

MAC Media Access Control

MFC Microbial Fuel Cells

MIMO Multiple Input Multiple Output

MQTT Message Queue Telemetry Transport

NiCd Nickel-Cadmium

NiMH Nickel-Metal Hydride

PMFC Plant Microbial Fuel Cells

PV PhotoVoltaic

PVDF Poly Vinylidene Fluoride

pW petawatts

PZT Lead Zirconate Titanate

QoS Quality of Service

RF Radio Frequency

RFID Radio Frequency Identification

RF-MEMS Radio Frequency MicroElectroMechanical-Systems

TE ThermoElectric

THz Terahertz

UHF Ultra High Frequency

V volts

Wi-Fi Wireless Fidelity

WiMAX Worldwide Interoperability for Microwave Access

WSNs Wireless Sensor Networks

Yb3+ Ytterbium

ZnO Zinc Oxide

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