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TOPICAL REVIEW

A comparative evaluation of IoT electronic solutions for energy harvesting

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Abstract

This review synthesizes the current scenario of Internet of Things (IoT) electronic solutions for energy harvesting, presenting an extensive analysis of existing technologies, trends, and emerging paradigms. The study examines various energy harvesting methods, including solar, vibration, and thermal technologies, and evaluates their efficiency, scalability, and applicability to indoor IoT applications. Special emphasis is placed on the integration of power storage systems, with a comparative assessment of traditional batteries, supercapacitors, and hybrid configurations. In addition to exploring energy sources, the review investigates strategies to optimize IoT device power consumption. This encompasses an examination of low-power design techniques such as impedance matching circuits, rectifiers, voltage multipliers, and DC-DC or AC-DC converters, along with an exploration of sleep modes and wake-up mechanisms. Communication protocols within the IoT domain are scrutinized for their energy efficiency, analyzing the trade-offs between data transmission overhead and power consumption. The study further explores techniques for aggregating energy from multiple sources within energy harvesting systems. This comprehensive investigation significantly contributes to existing knowledge by providing insights into the intricacies of energy-harvesting devices.

1. Introduction

In recent years, indoor environment monitoring systems based on Internet of Things (IoT) sensors have been widely employed for various purposes, including ensuring occupant thermal comfort, implementing energy-saving strategies, as well as health and indoor air quality monitoring [1–8]. However, most commercial applications of sensors and control systems are limited to one-way sharing of measurement data and simple control of related equipment [5, 7, 8]. Effective control of a comfortable indoor environment requires integrated management of devices that monitor a series of parameters, including temperature, humidity, noise, lighting and the presence of pollutants such as particulate matter (PM) suspended particles, carbon dioxide (CO_2) and formaldehyde [5]. These needs have become increasingly critical, especially in multi-purpose buildings and public transport [9–11].

Recently, energy harvesting boards that exploit renewable energy sources present in the surrounding environment, such as sunlight or heat, to power the sensors have begun to be used. These devices have the advantage of being energy-autonomous, thus helping to reduce energy consumption and CO_2 emissions. They can be installed in places that are difficult to access or without an electricity network and require low maintenance and operating costs. Furthermore, thanks to low-power data transmission systems, such as Wi-Fi, Bluetooth low energy, ZigBee and Long Range (LoRa), they can send the collected data to a cloud platform or a mobile device, allowing easy consultation and analysis of the gathered information [8, 12–14].

However, capturing and using renewable energy from the environment imposes serious challenges in the design of electronics and systems for its storage and use. Furthermore, it is not only the amount of energy that matters, but also its availability and how it is distributed and fluctuates over time, the so-called energy profile [7, 8, 15].

Recent developments have highlighted interesting opportunities to improve the efficiency of energy recovery devices through different strategies, including the design of dedicated converters [8], the integration of converters in hybrid solutions and the adoption of different wireless energy transmission systems [16]. The evolution in microelectronics has significantly contributed to reducing energy consumption, making power supply from environmental sources increasingly feasible [17]. For example, the use of wake-up receivers allows non-essential parts of the system to be completely turned off, significantly reducing energy consumption during inactivity phases [18]. Furthermore, the application of data aggregation techniques, clustering and intelligent routing, significantly contribute to energy savings at the network level [19].

This paper aims to provide an exhaustive and comprehensive review of academic studies on electronic solutions for energy harvesting. It presents an extensive analysis of current technologies, identifies prevailing trends in the field, and discusses emerging paradigms or new approaches that are gaining traction. Barriers and gaps in knowledge are explored, thus suggesting potential scenarios for future research and investigation on the topic. In particular, the review starts with a brief description of the state-of-the-art and commercial solution for energy harvesting and environmental parameter monitoring. Subsequently, an overview of real indoor energy sources and management in harvesting boards has been presented. The last section deals with the complex problem of energy consumption. Specifically, hardware architectures and operating strategies to reduce energy use in environmental monitoring boards based on energy harvesting have been discussed.

2. State-of-the-art and commercial solutions

To implement a system that collects and monitors information from IoT sensors, it is necessary to precisely outline aspects related to the network, the method of data transmission and their storage. Several studies in the literature reported various wireless communication methods adopted in the field of sensor networks, including LTE (Long-Term Evolution), the 3G cellular network, the WPAN (Wireless Personal Area Network), Wi-Fi, ZigBee and visual light communication [1, 5, 13, 20, 21].

In detail, Komuro and Suzumaru developed a time series data collection system for indoor environments using the ZigBee wireless communication standard together with a compressed transmission of measurement data to reduce network energy consumption [20]. In contrast to the traditional approach of using a gateway and a data logger, Jo *et al* conceived a microcontroller-based sensor node, adopting a data collection methodology using a cloud web server and LTE communication to build an IoT-based indoor air quality monitoring platform [1]. Benammar *et al* have developed a modular IoT platform consisting of a gateway with Raspberry Pi 2 and sensor nodes for real-time monitoring of indoor air quality. However, the study highlights that the data storage cycle, storage capacity and processing power of the gateway must be taken into consideration for the successful operation of the developed device [21]. Moreover, from the literature analysis, it emerged that the most recent monitoring solutions and platforms back up the data on a cloud storage server, while a minority adopt on-board storage [5].

According to recent studies on the energy requirements of sensors and monitoring systems [9], over 60% of the energy is consumed during wireless data transmission, thus underlining the importance of configuring the system to minimize the total transmission data. Moreover, the wireless communications are of paramount importance in monitoring system to remotely access to the data and, therefore, it is difficult to avoid it. However, the amount of data transferred per transmission varies significantly between technologies. Wi-Fi requires the most energy, with a minimum of 670 mJ per transmission, followed by SigFox at 350 mJ, and LoRa with the lowest energy requirement of 140 mJ per transmission. In contrast, short-range, low-power wireless technologies such as BLE and Zigbee are well-suited for indoor photovoltaic systems, as they have very low energy requirements of 44 μJ (BLE) and 152 μJ (Zigbee) per transmission [22]. Figure 1 shows a general diagram of an energy recovery sensor node for environmental monitoring purposes. This sensor node can gather data from various sensors, process the electrical signals generated from them, harvest energy from the ambient surroundings through AC/DC or DC/DC modules, store the acquired energy in either a battery or supercapacitor, and finally, transmit the collated data to a monitoring platform or central server via Wi-Fi or analogous wireless communication protocols. A brief description of the main components of an energy recovery sensor node is provided below [7, 23]:

- The measurement unit is responsible for measuring the desired environmental parameters, such as temperature, humidity, brightness, or any other quantity one wants to monitor. Sensors are designed to detect these quantities and transform them into electrical signals.

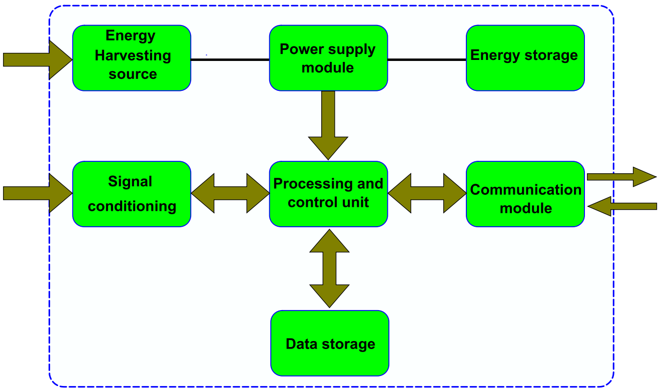

Figure 1. General block diagram of the node with the main subunits [7, 23]. Reproduced from [7]. CC BY 4.0.

- The energy harvesting source is responsible for capturing energy from the surrounding environment to power the sensor node. It can use different energy sources, such as solar energy (via photovoltaics), thermal energy (via thermoelectric), kinetic energy (via piezoelectric generators), etc
- A signal conditioning system that is necessary to condition the electrical output generated by the sensors to obtain clean and reliable signals. This phase involves the amplification, filtering and analog-digital conversion (ADC) of the signals, if necessary, to adapt them for subsequent processing.
- The energy storage unit is responsible for storing the recovered energy within a battery or supercapacitor. This component serves to ensure that the sensor node can operate even when energy from environmental sources is unavailable or insufficient. The choice between battery and supercapacitor depends on energy autonomy requirements and charging speed. This unit is strictly correlated to the energy harvesting source and the power supply module that regulates the voltage level to power the node.
- Data storage and communication unit is dedicated to store the collected data and transferring it to a desired destination. Data can be stored locally and then sent periodically over a Wi-Fi connection or similar. This enables remote monitoring and management of data.
- Processing and control unit processes sensor data and manages energy recovery, power consumption and data transfer. It can be a dedicated microcontroller (MCU) or a more general structure that combines multiple sub-blocks.

In addition, a fundamental element is represented by the implementation of management algorithms. These algorithms control energy harvested, energy consumed, and data transmission operations to maximize energy efficiency and extend the overall operating life of the node.

Recent advancements in environmental monitoring IoT solutions have focused on enhancing sustainability by integrating low-power and eco-friendly sensors produced from sustainable materials (e.g. gelatin, zein and chitosan) [24–35]. This approach aims to mitigate the environmental impact of monitoring systems by minimizing energy consumption and reducing the overall lifecycle footprint of the devices, from manufacturing to disposal.

The environmental parameters of interest in buildings (such as temperature, humidity, indoor air quality, ambient light and sound level) may vary based on specific monitoring needs and applications [36]. Table 1 shows a list of commercial sensors that can be used for indoor monitoring [37].

3. Overview of real indoor energy sources for harvesting

In general, the goal of using environmental energy sources through energy harvesting is to convert energy from one form to another that can be used to power electronic devices. Energy harvesting sources can be divided into categories of environmental sources (e.g. solar, thermal and radio frequency) [10, 38] and external sources (e.g. vibrational and human-generated) [11, 15]. Harvesting energy from environmental sources, despite the existence of different harvesting principles and technologies, still presents several challenges due to the limited amount of energy generated and the instability of the sources, which vary based on the application and environmental conditions. To increase the energy available for energy harvesting monitoring nodes, numerous studies have been conducted aimed at improving the performance of energy harvesting systems, considering the

Table 1. List of representative sensors for some target gases [37].

Sensor name	Target gas	Sensing range
CDM 4161	CO_2	400–2000 ppm
TGS 5342	CO	0–100 ppm
TGS 2602	VOCs	0–30 ppm
MiCS-2610	O_3	0.01–1 ppm
MiCS-2710	NO_2	0.01–5 ppm
KE-25	O_2	0%–100%
HSM20G	Humidity	20%–95% RH
HSM20G	Temperature	0 °C–50 °C
GP2Y1010AU0F	PM 10	0–0.5 mg m^{-3}

Table 2. Comparison between energy harvesting sources [7, 8, 62].

Source type	Harvesting method	Power density
Solar	Photovoltaic	15 mW cm^{-2}
Wind	Electromechanical conversion	0.1–6 mW cm^{-3}
Vibrational	Piezoelectric/electromagneti/ electrostatic/magnetoelectric/ triboelectric vibration conversion	0.1–300 mW cm^{-3}
Thermal	Thermoelectric conversion	15–40 μW cm^{-3}
Radio frequency	Electromagnetic conversion	1 μW cm^{-2} (WiFi)

characteristics of real environmental sources [8, 39, 40]. Each environmental source and conversion principle has its peculiarities and a specific power density. Table 2 provides a summary of the most common environmental sources found in indoor environments, including solar energy, wind, vibrational, thermal, and radio frequencies (RF). Solar cells emerge as a major source of energy within indoor environments (see table 2). Mechanical energy (wind and vibrational) also arouses considerable interest since it offers the possibility of extracting a high level of energy [41–43]. This source is interesting both from the point of view of availability and applications, for example, in environmental and industrial contexts, generating energy density lower than 300 mW cm^{-3}. It is worth noting that the triboelectric and piezoelectric mechanisms are widely used for sensing applications [44–46]. Acoustic noise is widely recognized as a source of energy harvesting and it is used in industrial plants, transportation (such as airplanes, vehicles, and high-speed trains), and loudspeakers [47, 48]. Thermal energy recovery systems, on the other hand, have an energy efficiency of 40 μW cm^{-3} and are interesting in situations where they can be applied to a large surface or in environments characterized by high-temperature differences [49, 50]. Recently, thermoelectric conversion has found application in the realm of low-grade heat harvesting, particularly targeting temperatures below 100 °C, for integration within smart building and wearable technologies [38, 51, 52]. To evaluate different energy harvesting device strategies, including the types of electrodes and active materials, as well as the layout and geometry for solar cells, thermoelectric, triboelectric, and piezoelectric generators, readers can refer to several comprehensive reviews published in recent years [49, 52–56]. To make IoT electronics boards for energy harvesting more environmentally sustainable, even the energy harvester devices such as solar cells, and triboelectric and thermoelectric generators have been fabricated with sustainable materials and processes [57–61].

4. Energy management in harvesting boards

The concept of energy storage arises from the necessity to convert energy from challenging-to-store forms, such as electrical energy, into more easily storable forms, typically of an electrochemical nature [63, 64]. The energy stored in this way can subsequently be converted back into directly usable form. There are different types of energy storage systems, or accumulators, characterized by different properties, including capacity, power and charge/discharge speed [65–72]. The selection of a particular storage technology depends on the specific requirements of the application in question. In the context of environmental monitoring, energy storage units must meet specific criteria relating to small size [68], adequate capacity and limited environmental impact [73–76]. In powering sensor nodes used for environmental monitoring, the following types of energy storage devices are commonly used [63, 69, 77–79]:

> Primary or secondary batteries can be disposable or rechargeable and are commonly used for energy storage in sensor nodes. However, their choice can significantly influence the size, cost and overall operational life of the node.
>
> Supercapacitors are devices capable of accumulating energy in the form of electric charge. They are known for their fast charge and instant discharge capabilities but may have a lower overall capacity than batteries.
>
> Hybrid combinations of supercapacitors and rechargeable batteries, in some applications, can be used to exploit the advantages of both technologies, thus obtaining a balanced energy storage solution in terms of capacity and charge/discharge speed.

The energy storage subsystem plays an extremely important role within a sensor node, as it significantly influences its overall efficiency. The choice of energy storage technology has a significant impact on the physical dimensions of the node, its implementation costs and its overall operational lifetime [80]. Moreover, precise estimation of the state of charge (SOC) plays a fundamental role in any application involving energy storage devices. However, it is a complex task due to the diversity of phenomena that contribute to the ageing of such devices. These phenomena include the loss of charge accumulation capacity of the active material on the electrodes, changes in the physical properties of the electrolyte and corrosion of the current conductors [81]. In the context of power supplies for sensor nodes, accurate estimation of SOC is essential to correctly configure operational parameters, such as measurement and data transmission times. There are several common methods for estimating SOC, and these methodologies have been thoroughly covered and are reported in these references [7, 81, 82]. Furthermore, it is common to monitor an additional measurable parameter that reflects the overall physical state of the storage devices, known as the state of health (SOH) [82].

More recently, several studies reported in the literature show the utilization of environmentally friendly and/or biodegradable materials in the fabrication of energy storage devices [76, 83–93]. These efforts have been motivated by a collective aim to mitigate the environmental impact associated with energy storage technologies, particularly in light of their widespread application across various domains such as consumer electronics, medical devices, remote sensors, wearable technologies, and transient electronics [94, 95]. The adoption of these materials, such as gelatin, chitosan and casein, characterized by their inherent biodegradability, serves to facilitate natural decomposition processes, thus minimizing adverse environmental effects [90–92]. However, despite their promising attributes, biodegradable batteries and supercapacitors encounter challenges in performance optimization, lifetime, energy density, stability, and cost-effectiveness [76, 83, 85].

4.1. Batteries

The choice of batteries can be approached from different perspectives [64, 69]. The most significant factors influencing the choice are the needs of the application (for example, the need for fast charging/discharging, durability, life cycle, size and weight). Batteries not only serve to provide energy to the system but also to efficiently store energy collected from the environment. In this way, energy can be conserved for periods when it cannot be directly extracted from the surrounding environment.

Important battery specifications include storage technology, energy density, internal resistance, depth of discharge, self-discharge, and overcharge tolerance [96, 97]. From an application perspective, it is crucial to specify operating conditions and choose appropriate battery devices to avoid operational problems. One example is the selection of batteries based on different climatic conditions (e.g., tropical versus arctic regions) [98].

Most batteries, except for lithium batteries, do not perform well at cold temperatures due to the increase in their internal resistance, which leads to a loss of capacity [63, 64]. Conversely, they operate better at high temperatures but at the cost of a significant shortening of their service life or even permanent damage. The estimated overall efficiency of the battery storage system varies between 60% and 80%, depending on the operating cycle and the type of electrochemistry of the batteries [99]. The specific energy (Wh/kg) indicates the maximum density of energy stored in the battery per unit mass and is different for different types of batteries [100]. Battery capacity is the amount of energy that can be stored in the cell when fully charged. The life of most electrochemical batteries is hundreds or thousands of charge/discharge cycles. During this period, the capacity of the battery gradually decreases due to chemical corrosion of its electrodes. Lifetime is strongly influenced by charging and discharging, as well as operating temperature [7]. The basic parameters of the evaluated battery types are reported in table 3.

Ambient temperature plays a very important role in analyzing the actual life of a battery. Conventional batteries tend to express their nominal performance in temperature conditions close to around 20 °C [63]. Any significant deviation from this reference temperature can lead to a reduction in battery life and a higher

Table 3. Basic parameters of the evaluated battery [7, 100].

Type	Nominal voltage(V)	T range (°C)	Cycle stability	Specific energy (Wh/kg)
Lead-Acid	2	−20−> 60	500/1000	30/50
MnO_2Li	3	−20−> 60	1000/2000	280
NiCd	1.2	−40−> 70	10000/20000	50/60
NiMH	1.2	−20−> 40	1000/20000	60/70
Li-Ion	3.6	−30−> 45	1000/100000	75/200

frequency of charging cycles [101]. To extend the operating time, rechargeable batteries can be integrated with supercapacitors, thus creating a hybrid storage system [63, 102, 103].

Lead-acid batteries are a common choice for medium-sized devices because of their low cost, high reliability and appreciable efficiency. However, they have limited cycling capacity and poor performance under extreme environmental conditions [104]. Nickel-cadmium (NiCd) batteries offer long life, fast charging times and vibration resistance, but their main disadvantage is low capacity [64]. Nickel-metal hydride (NiMH) batteries boast a higher capacity than NiCd and are less toxic, making them more suitable for environmental monitoring applications [64]. Lithium-ion batteries are well known for their high efficiency, power density and cell voltage [63]. However, their use is limited by their high cost and propensity to start fires in the presence of humidity [104]. Finally, MnO_2 alkaline batteries have the lowest self-discharge rate among the available options [7].

4.2. Supercapacitors

Supercapacitors are devices characterized by high power density compared to traditional batteries and conventional capacitors. They are constructed as electrochemical double-layer capacitors (EDLC) or pseudocapacitors [76, 79, 91, 92, 105]. EDLCs work on the electrochemical principle, where electric charge accumulates between electrodes with a large surface area separated by a thin electrolytic dielectric layer. The maximum operating voltage is determined by the breakdown parameters of the dielectric material, while the nominal voltage considers a safety margin to prevent the decomposition of the electrolyte and the consequent short circuit [80]. Pseudocapacitors, on the other hand, have a lower power density than EDLCs but offer higher specific capacitance and energy density [79]. These devices exploit a redox reaction that occurs at an electrode, generating charges and allowing their transfer across a layer. Supercapacitors have various advantages over rechargeable batteries, including [7]:

- High number of charge/discharge cycles without a significant decrease in performance and storage capacity, which varies from 100000 to 1000000 cycles depending on the manufacturer [80, 106].
- High charging/discharging efficiency, which can reach up to 98%, and fast charging process [80].
- Wide operating temperature range, ranging from −40 °C to +65 °C for EDLC supercapacitors and pseudocapacitors [106]. Some sources report an even wider range, from −55 °C to 85 °C.

However, the use of supercapacitors can be affected by the phenomenon of self-discharge, which is related to the terminal voltage of the energy stored in the element. The extent of this problem depends on the capacity of the device and can vary between manufacturers and even between production batches. Several studies have recorded self-discharge rates ranging from 50%–60% per month to 5.9% or even 11% per day [7, 80, 106]. If not addressed, this phenomenon can significantly reduce the operational life of powered devices. However, this issue can be mitigated through fast charging. Fast charging can provide an estimated operational life of 20 years [107].

Initially, it has been believed that all energy losses in supercapacitors have been due to self-discharge. However, it has been observed that the voltage decreases much more rapidly with shorter charging times [108]. Since the digital electronic circuits of typical sensor nodes can only operate up to a certain voltage threshold (usually on the order of 1–2 V), longer charging times can provide usable voltage for longer periods. Secondly, this effect is accentuated when the supercapacitor is being charged. Further testing on sensor nodes with a duty cycle of 0.1% confirmed that supercapacitor-powered devices can operate for significantly longer periods when charged for more extended times [7]. The basic parameters of the evaluated types of supercapacitors are listed in table 4 [7, 80, 106].

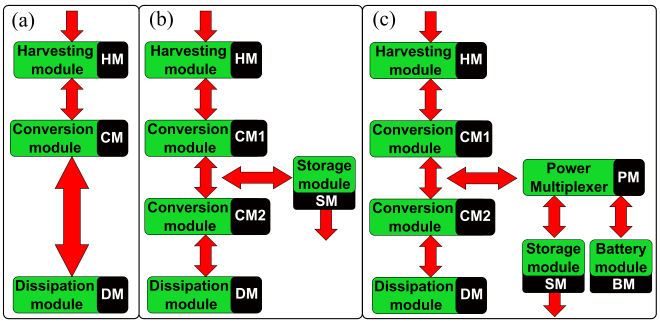

Figure 2. Harvesting system topologies: (a) standalone (b) hybrid standalone and (c) battery-supplemented. Reproduced from [7]. CC BY 4.0.

Table 4. Basic parameters of the evaluated supercapacitor [7, 80, 106].

Supercapacitor	Cycle stability	Specific energy (Wh/kg)
Maxwell PC10	500	1.4
Maxwell BCAP0350	500	5.1
Green-cap EDLC	>100000	1.5
EDLC SC	1000000	3/5
Pseudo SC	100	10
Hybrid SC	500	180

4.3. Energy harvesting system topologies

Three primary topologies exist for energy harvesting systems: standalone, hybrid standalone, and battery-supplemented [7]. Depending on the configuration, energy management strategies with different design objectives are required [37, 109].

Autonomous energy harvesting systems fulfill their energy requirements exclusively from ambient environmental sources, without reliance on auxiliary batteries. Operationally, these systems are contingent upon the availability of ambient energy and are not constrained by limitations associated with energy storage, such as self-discharge and degradation. Adopting the principle of energy neutrality, these systems are engineered to consume only the energy that can be harvested by their energy recovery unit. To realize these design goals, autonomous energy harvesting systems necessitate the integration of prediction algorithms capable of forecasting future energy availability over time [7, 22].

The structure of an autonomous energy harvesting system is shown in figure 2(a), representing the simplest case comprising three main modules [110]: an energy harvesting module (HM), an energy conversion module (CM) and a power dissipation module (DM). A significant limitation of this energy harvesting system type is the potential waste of surplus energy beyond the immediate load consumption. The energy harvester module serves as the sole energy source for the system, lacking any buffering mechanism. The CM, typically facilitated by a DC/DC converter, directly delivers energy to the downstream module, namely the load [7].

In a hybrid autonomous energy harvesting system, the device uses ambient energy sources and a battery or other energy storage device (supercapacitor). This configuration offers greater flexibility, allowing the device to operate when ambient energy is not sufficient or unavailable.

The main objective is to balance the use of collected energy with stored energy to maximize autonomy and ensure a continuous supply of energy even in conditions of low environmental energy availability. However, it is important to maintain low power consumption and use energy management strategies to extend battery life. A hybrid autonomous energy harvesting system is described in figure 2(b). The system contains three autonomous system modules (HM, CM and DM) and an energy storage module (SM) [7, 110].

In an energy-harvesting battery system, the device is primarily powered by a battery, while ambient energy is used to extend battery life or provide additional power input.

This configuration offers greater reliability, as the device can operate continuously even when ambient energy is unavailable. The main goal is to reduce dependence on the battery and extend its useful life. The energy collected from energy harvesting can be used to periodically recharge the battery or to support peak power consumption. In figure 2(c) the block diagram is shown. In addition to the components of an autonomous hybrid collection system (HM, CM, DM and SM), there are a primary (non-rechargeable) battery module (BM) and a power multiplexer (PM) [7].

5. Low energy consumption hardware architectures and operating strategies

In general, sensor nodes consume energy during different phases, such as sensing, processing, data transmission and reception, and this can be called operational energy consumption. It is interesting to note that, as reported in [9], over 60% of this energy is allocated to the radio aspect of communications. The growing evolution of computational and memory demands, the need to maintain connectivity, compliance with design constraints, the search for low energy consumption and low costs, as well as the need to respect the time constraints typical of applications in wireless sensor networks (WSNs) are pushing the development of new solutions for more efficient hardware architectures.

An important challenge is represented by the design of applications that require high computing capabilities with limited resources. Therefore, it is crucial to find a balance between processing performance and power consumption. Choosing a low-power microcontroller plays a major role in the design of any wireless sensor node. In this perspective, to identify the most suitable choice for WSN wireless sensor networks, a comparative analysis to evaluate the energy efficiency of various microcontrollers, has been conducted [111]. This investigation examines the energy consumption of different microcontrollers in different operating modes. The primary objective is to identify those microcontroller alternatives that are optimal for applications characterized by stringent prerequisites of minimal energy consumption and cost-effectiveness [8].

5.1. Microcontroller, RF transceiver and memory

As shown in figure 1, the architectures designed for IoT applications consist of a sensing system for data acquisition, low-power microcontrollers for digital processing and a low-energy wireless communication system (RF transceiver). Currently, the predominant market direction is to unify these three subsystems into a single, fully integrated chip. Although several strategies have been adopted to mitigate energy consumption in wireless subsystems, the issue remains of great relevance [22, 112]. An innovative perspective for an overall reduction of energy consumption in a wireless subsystem is to increase the computational power and complexity of the processing subsystem. This approach has the potential to significantly reduce the volume of data transmitted and, consequently, the overall energy consumption, especially in IoT application contexts. Therefore, there is a need to equip the sensing system with digital processing architectures that are robust, efficient, flexible and, characterized by low energy consumption [8, 113].

To limit processing unit power consumption in wireless network nodes, several techniques have been implemented, including clock gating, power gating, and Dynamic Voltage and Frequency Scaling (DVFS) [113, 114]. DVFS has been developed to minimize energy consumption during task execution by dynamically adjusting operating voltage and frequency based on real-time system performance demands. When the MCU is in a state of light computational load, the frequency and voltage are gradually reduced to ensure that the execution latency of the MCU remains acceptable. The MCU operates at maximum frequency only when considerable computational power is required [8].

Furthermore, it is crucial to conduct a detailed analysis of the wireless node energy consumption during different activities, since each sensor node can operate in different operating modes, each characterized by a specific energy consumption based on the function performed [38]. Five main activity modes have been identified for each wireless sensor node: ‘off’, ‘idle’, ‘sleep’, ‘transmission and reception’, and ‘processing’ which correspond respectively to ‘off’, ‘inactive’, ‘in sleep’, ‘transmission and reception’, and ‘processing’ [8, 115]. The ‘off’ mode represents the node in an idle state, with minimal power consumption compared to other modes, which allows an efficient transition to ‘sleep’ mode when necessary. Once turned on, the node switches to ‘sleep’ mode to optimize energy savings, waiting for the next scheduled activity cycle. During the listening period, the ‘idle’ mode is activated. It continues with the full operating mode, in which the node can operate in ‘transmission and reception’, and in both cases, the energy consumption is higher than the previously described phases. It is important to note that the energy consumption in each of these phases is intrinsically connected to the electronic components present within the node itself [8]. Table 5 shows the comparison in terms of current consumption of a low-cost and low-energy 2.4 GHz RF transceiver model CC2500 [115].

Some radio transceivers used in WSN applications require an average current of approximately 10 mA for reception and 20–30 mA for transmission, generating an antenna radiated power (ERP) of 10–12 dBm [8]. In low-energy WSNs, an energy management strategy based on intermittent cycles or duty cycling is typically used. This means that there are specific time slots dedicated to transmitting and receiving data while alternating with long periods of sleep to save energy. To meet response time needs and maintain low power consumption, a separate wake-up receiver (WuRx) is often used, as shown in figure 3. This component features extremely low power consumption, allowing it to shut down the rest of the system. Therefore, it is possible to maintain communication that is always active on demand, maintaining energy consumption in the μW range.

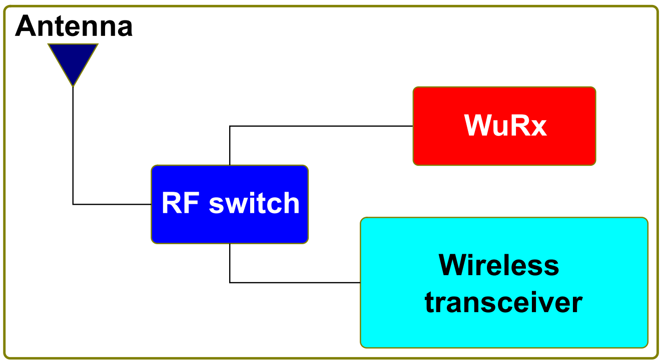

Figure 3. Block diagram of a typical WuRx receiver. Reproduced from [8]. CC BY 4.0.

Table 5. Power consumption of a low-cost, energy-efficient 2.4 GHz RF transceiver model CC2500 in its different operating modes. The MCU considered is the MSP 430 model [115].

Working mode	Current
Radio (sleep)	0.9 μA
Radio (idle)	1.5 mA
Radio (transmit)	22 mA
Radio (receive)	14 mA
MCU (active)	8 mA
MCU (idle)	2 mA

Wake-up receivers are used in addition to the main receiver and are activated only when there is a communication request. When a wake-up signal with a unique identifier is received, it activates the main processor and other peripheral devices. Detection of wake-up packets can be accomplished via specially designed circuitry to consume a minimal amount of power. It is important to note that improving the sensitivity of the main receiver or increasing the transmission speed would inevitably lead to an increase in overall power consumption.

To further reduce power consumption in wake-up receivers and wireless systems, new integrated circuits optimized for power efficiency can be developed in different frequency bands. Another approach is to use existing components, designed for short-range applications. In particular, some architectures based on passive components allow for improving the sensitivity of the receiver without significantly increasing the overall power consumption. These circuits can be based on a passive architecture that includes, for example, a Schottky diode-based envelope detector followed by a 16-bit serial D-Flip-Flop detector. With this approach, a sensitivity of −52 dBm can be achieved with a power consumption of only 45 μW at a voltage of 3 V. The detection latency is on the order of 80 μs, and the transmission rate reaches 100 kbit/s [8, 116].

Table 6 provides a summary of the power consumption of wireless sensor nodes present in commercially available platforms during different operating modes [113]. The accurate estimation of the energy consumption associated with each operating mode is closely linked to the transmitted data, with particular emphasis on the data reception and transmission phases. In these devices, to obtain low energy consumption calculations, the use of ARM processor cores is preferred. Hybrid architectures involving both hardware and software components are adopted, with on-chip hardware accelerators inserted into integrated circuits. Furthermore, multicore systems are exploited for parallel processing, helping to optimize the overall energy efficiency of the system. In recent years, there has been notable progress in CPU architecture, moving from simple 8-bit microcontrollers to complex 32-bit ARM Cortex-M architectures. Most microcontrollers used in low-power IoT applications have a single-issue CPU, capable of executing instructions sequentially (only one instruction per cycle), thus improving the overall energy efficiency of the target system [113].

The type of memory used to store data within a microcontroller plays a significant role in the overall energy efficiency of the system since switching between power modes requires storing or restoring the system state in memory. In general, a Static Random-Access Memory (SRAM) module consumes less power than a Dynamic

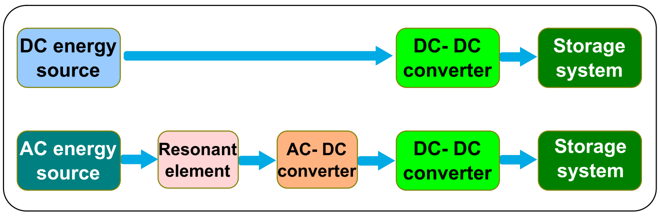

Figure 4. General structure of circuits for managing energy from DC sources (top) and AC sources (bottom). Reproduced from [8]. CC BY 4.0.

Table 6. Summary of low-power microcontrollers available on the market [113].

MCU	Instruction set architecture	Max. frequency (MHz)	Memory	Datapath	Current (μA/MHz)	Working voltage (V)
ESP 32 - family	Tensilica processor	80, 160 or 240	520 kB SRAM 16 MB FLASH	32-bit	125	2.3–3.6
SAML21E	ARM Cortex M0+	48	64 kB SRAM 256 kB FLASH	32-bit	35	1.62–3.63
MSP430FR6x	MSP430	16	128 kB SRAM	16-bit	100	1.8–3.6
Kinetis KL8x	ARM Cortex M0+	72	96 kB SRAM 128 kB FLASH	32-bit	120	1.71–3.6
STM32F745xx	ARM Cortex M7	216	340 kB SRAM 1 MB FLASH	32-bit +FPU	700	1.7–3.6
PIC32CM LE00	ARM Cortex M23	48	64 kB SRAM 512 kB FLASH	32-bit	54	1.62–3.63

Random-Access Memory (DRAM) module. This disparity is attributable to the fact that SRAM requires only a modest constant current, while DRAM requires current pulses at regular intervals, every few milliseconds, for the refresh process. The refresh current required by DRAM is significantly higher than the low standby current typical of SRAM. Static RAM uses a transistor to store information, while DRAM makes use of a separate capacitor, which justifies the need to perform refresh cycles periodically [113, 117].

Microcontrollers used in IoT environments for energy harvesting applications, characterized by limited energy resources, require certain specifications: reduced occupation of physical space, considerable energy efficiency, programmability and high reliability. In recent years, integrated circuit design has favored the optimization of the physical area and performance, aimed at reducing costs and increasing the efficiency of microcontrollers. However, the emergence of the IoT and the concept of 'edge processing' (i.e. processing data directly at the data generation source itself, the sensor nodes) has required a revolution in the design of integrated circuits. This new trend focuses less on intensive computation and more on processing large volumes of data, representing a significant breakthrough [113].

Nowadays, improving the energy efficiency of microcontrollers has become the main driver in hardware design [118, 119]. Fine-tuning the operating and sleep modes of microcontrollers requires particular attention to obtain maximum results in terms of energy efficiency in IoT applications.

5.2. Impedance matching circuits, rectifiers, voltage multipliers and DC-DC or AC-DC converters

Power management circuits are complex components that are a crucial element in energy harvesting applications [120]. These circuits are designed to manage the energy captured from harvesting sources, such as solar cells or other sources, and supply it to the load or store it in storage devices such as batteries or supercapacitors (figure 4). Their design typically includes several parts, impedance matching circuits, rectifiers, voltage multipliers, and DC-DC or AC-DC converters. These parts work synergistically to ensure that the harvested energy is converted and delivered to the load efficiently. Energy harvesting sources exhibit specific behaviors in terms of current and voltage, often characterized by variable energy profiles due to environmental conditions. For example, solar cells deliver different currents by their current-voltage characteristics and the light intensity to which they are exposed. To optimize the efficiency of the energy extracted from these sources it is essential to use DC-DC or AC-DC converters that adapt the source impedance to the impedance of the connected load. However, the design of such converters is challenging, as they must efficiently manage energy even at low power levels, minimizing losses due to rectification diodes and switching circuits [8].

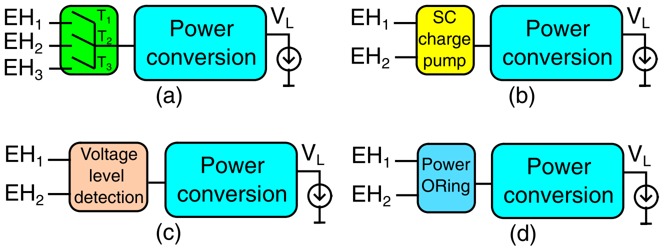

Figure 5. Overview of energy combining techniques. (a) Temporal multiplexing scheme [126]. (b) Use of a switched capacitor charge pump [128]. (c) Detection of the highest voltage level [129]. (d) Power ORing using diodes [127]. Reproduced from [128], with permission from Springer Nature.

Additionally, energy sources may change due to environmental conditions and ageing. Therefore, it is necessary to use a Maximum Power Point Tracker (MPPT) circuit to constantly monitor the source conditions and optimize the efficiency of energy extraction. MPPT can be implemented through a variety of control algorithms, including those based on fuzzy logic, neural networks and artificial intelligence algorithms. This component can be incorporated into both AC and DC converters and can adopt different techniques, such as resistive matching and conjugate impedance matching, depending on the input specifications of the power processing application [121, 122]. In addition to MPPT, there are other advanced techniques to maximize the efficiency of energy extraction in power harvesting scenarios. These include parallel synchronized switch harvesting on inductor (P-SSHI) and double synchronized switch harvesting (DSSH), which aim to synchronize voltage and current to optimize the level of energy captured.

This synchronization can be achieved by implementing peak detectors and other advanced electronic strategies [123].

Several authors report various circuit configurations proposed to optimize energy extraction from heterogeneous harvesting sources [124, 125]. These circuit topologies often combine linear regulators, which can adapt to the specific characteristics of each source to maximize the efficiency of the extracted energy. The process of extracting energy from the different hybrid sources initially involves rectifying each source separately based on its distinctive electrical characteristics. Subsequently, the resulting voltages from each source are combined with operational amplifier circuits. These circuits can be configured to add or multiply input voltages, depending on the specific needs of the application. In addition, the output of the op-amp is directly connected to a specially designed boost converter to increase the output voltage. The energy obtained from this process can then be used to recharge a battery and a supercapacitor, thus allowing excess energy to be stored for future use.

5.3. Energy combination techniques from multiple sources for energy harvesting systems

Several energy-combining techniques for multiple-source energy harvesting systems have been documented in the literature [126–131], as illustrated in figure 5. Figure 5(a) shows the use of a time-multiplexing system, where different intervals of time are assigned to each energy source to transfer its energy to the output load [126]. This approach shares the power conversion phase between all energy sources, reducing system costs. However, it requires that energy from all harvesting sources is always available, which may not be the case in many applications. In the event of the unavailability of one of the energy sources, the stored energy could flow back to the source, potentially leading to negative consequences on the output voltage and the efficiency of the system [127].

Another energy-combining technique, illustrated in figure 5(b), involves a switched capacitance charge pump to simulate a series of storage capacitors to sum their voltages. It is critical to ensure that the total voltage does not exceed the breakdown voltage of the transistor. Furthermore, this configuration requires careful management in case one of the harvesting sources is unavailable. Maintaining high efficiency over a wide range of input voltages and output loads can be challenging [127, 128]. Figure 5(c) presents a voltage-level sensing method for combining energy from different harvesting sources by simply selecting the source with the highest voltage. However, higher voltage does not necessarily imply higher power, leading to inefficient use of resources [129]. Figure 5(d) illustrates the power ORing technique for combining energy from different sources, which uses a diode for each source to transfer the energy to the output storage. This method represents the simplest form of a power combiner, but the voltage drop across the diodes may impact efficiency. Alternatively, active diodes can be used to improve efficiency [38].

Figure 6 illustrates the schematic block of an autonomous wireless sensor node designed for indoor monitoring and powered by a hybrid energy harvesting (HEH) system, which is based on a solar and a thermal

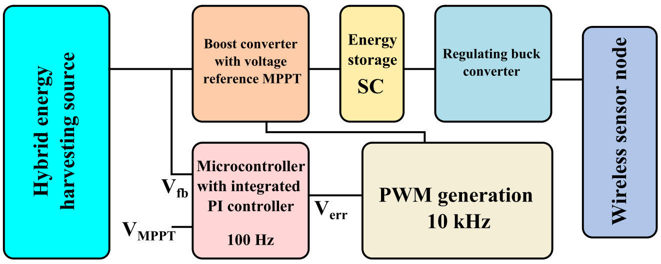

Figure 6. Functional block diagram of the HEH system. For further details, the reader can refer to [38].

source. The power management circuit is designed with an MPPT circuit that uses a fixed voltage reference. This system is composed of three main blocks [38]:

A boost converter equipped with an MPPT and a control circuit that generates pulse width modulation (PWM) to regulate the operating point of the HEH system. This mechanism is intended to maintain the harvesting power near the maximum power point (MPP).

An energy storage element, such as a supercapacitor, performs the function of accumulating energy from the sources and regulating its transfer between the source itself and the load.

A regulating buck converter is employed to provide a constant voltage to the wireless sensor node and other electronic circuits connected to the system.

The HEH system under consideration is designed to ensure the autonomous and sustainable operation of the sensor node, allowing the collection of energy from solar and thermal sources, the accumulation of this energy, and the distribution of a constant voltage to the associated electronic devices. The boost converter operates with a fixed voltage reference of 3.6 V. This value is compared to the feedback voltage signal, V_{fb}, from the output of the hybrid energy harvesting system. This signal also serves as the input to the MPPT-controlled boost converter. The resulting error, V_{err}, between the V_{MPPT} reference and the V_{fb} feedback, is processed by a proportional-integral (PI) controller integrated into a low-clock frequency microcontroller. This controller generates a low-frequency PWM signal, (100 Hz), to regulate the boost converter. The PI controller algorithm should be designed considering the dynamic performance and steady state of the system. It is characterized by a proportional gain calculated as the reciprocal of the integral gain [38].

By operating the microcontroller at a lower clock frequency, power consumption can be significantly reduced to microwatt levels [132]. However, to maintain the compact size of the HEH system by using small-sized passive components, it is necessary to increase the switching frequency of the PWM control signal generated by the low-frequency microcontroller to above 10 kHz. The low-frequency PWM signal (100 Hz) is subjected to filtering using a simple low-pass filter. The DC signal obtained is subsequently compared with a sawtooth wave to generate the duty cycle of the high frequency (10 kHz) PWM control signal destined for the boost converter.

In indoor environments, ambient energy resources, such as solar energy and thermal gradient, are not constantly available at constant power. Therefore, it is necessary to integrate an energy storage device, such as a supercapacitor, into the HEH system to collect excess energy coming from solar panels and/or thermal energy conversion devices. This allows the storage of such energy to provide power to the internal wireless sensor node when energy sources are not available [38]. Despite discrete standard capacitors, which have very small capacitance values, in the order of picofarads or microfarads, a supercapacitor is characterized by a significantly higher capacitance, measured in the order of farads. This makes the supercapacitor particularly suitable for energy storage. To complete the system, a switching voltage regulator has been introduced. This regulator is positioned after the supercapacitor and has the task of providing a constant operating voltage of 2.8 V to power both the wireless sensor node and the other electronic circuits. The efficiency of this voltage regulator, implemented as a buck converter, should be at least 80%–90% at the operating current level.

A device for combining energy from different harvesting sources is depicted in figure 7 within a complete energy harvesting system. This combiner is designed to overcome some limitations of the system shown in figure 6. In detail [127], the system can start operation from one of the passive sources without requiring the addition of additional components, taking advantage of the parasitic diode of the PMOS switch inside the combiner. This leads to a reduction in complexity and the use of additional space. The use of active diodes to transfer the collected energy to the storage capacitor eliminates the voltage drop associated with the use of

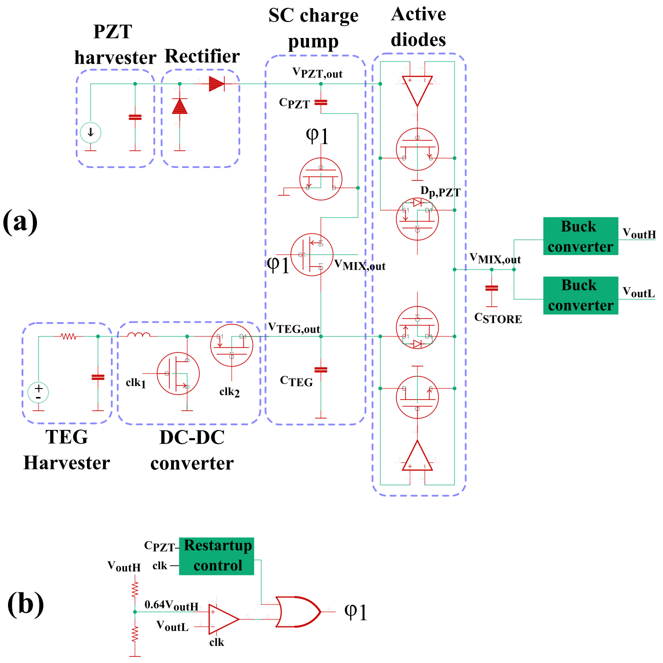

Figure 7. (a) Circuit diagram of an energy combiner with power ORing, charge pump and (b) restart prevention system [127]. Reproduced from [128], with permission from Springer Nature.

Schottky diodes. This implementation improves overall efficiency and ensures the availability of a greater amount of energy in the output storage. Two switches are employed to prevent the system from restarting, allowing the collection source voltages to be summed across their respective output capacitors. This process is based on monitoring the voltages regulated by voltage converters (buck converters). This approach maximizes the power generated by harvesting sources and prevents restart cycling. This allows the use of collection sources, even when the individual voltage of each of them may not be sufficient to operate the load. Power fluctuations and extremely low availability of ambient power can lead to a complete shutdown of a wireless sensor node. Most current wireless sensor nodes are not capable of automatically recovering from a depleted state in a so-called cold start. This is because power management requires a minimum level of energy to power a microcontroller-based system, which is not always available once the power reaches a certain voltage level. To ensure the recovery of the wireless sensor node in these cases, the so-called voltage supervisors, voltage detectors or reset ICs can be implemented such as buffer circuits, control circuits, start circuits, switching circuits and activation circuits [8, 127]. For further details, the reader can refer to [8].

As highlighted in figure 7, there are two energy harvesting sources: thermoelectric (TEG) and piezoelectric (PZT). Two DC-DC voltage converters (buck converters) are connected to the energy combiner, generating two regulated voltages, V_{outH} and V_{outL}, where V_{outH} exceeds V_{outL}. This configuration with two regulated voltages is common in wireless sensor nodes [133, 134].

Figure 7(a) presents a detailed energy combiner circuit within a complete energy harvesting system. As highlighted in the representation, each energy source is connected to an active diode. An active diode acts as a standard diode but eliminates the voltage drop problem associated with traditional diodes. This component includes a transmission gate, consisting of NMOS and PMOS switches, along with a synchronized comparator. Using the synchronized comparator reduces static current and minimizes power consumption compared to the continuous-time comparator. The comparator clock is synchronized with that of the DC-DC converter so that the evaluation of the comparator occurs during the charging phase of the DC-DC converter. The PMOS switch inside the transmit gate is connected so that its parasitic diode, $D_{p,PZT}$ connect the input with the output. This configuration is fundamental to the startup mechanism that exploits one of the energy harvesting sources. To prevent an unwanted restart of the system, a restart prevention technique is employed which involves connecting both capacitors in series using a control signal labeled as 'φ_1'. The φ_1 signal is activated only when the voltage coming from a single energy source is insufficient to power the output load. Figure 7(b) describes the φ_1 signal generator circuit, which includes a voltage comparator capable of monitoring the regulated output voltage, V_{outL}, along with a fractional (0.64) value of V_{outH}. Furthermore, figure 7(b) shows the restart control logic, which generates the φ_1 signal based on a predefined frequency [127].

Initially, each energy capacitor is uncharged. The startup action is triggered by one of the energy harvesting sources, in this case, a PZT harvester. This causes the C_{PZT} capacitor to charge. In addition, thanks to the connection

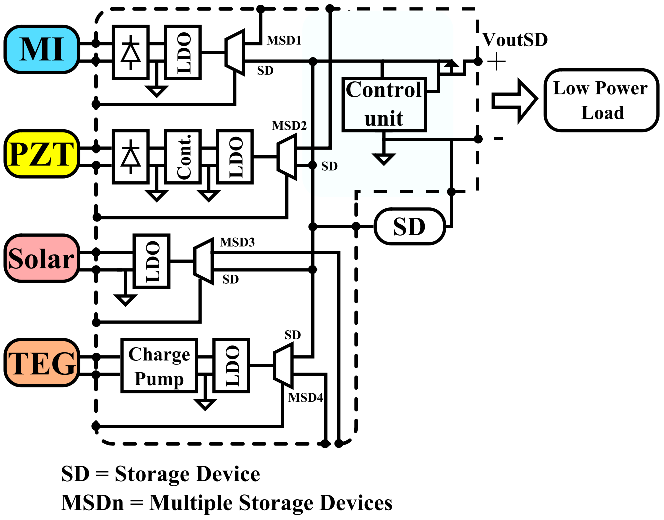

Figure 8. Schematic of a multiple energy harvesting system with 4 ambient energy sources. The architecture can collect and manage energy from different sources, such as electromagnetic induction (MI) at low power, vibration (low voltage PZT generators), sunlight (indoor environment), and thermoelectric (TEG) [125]. LDO is a low drop-out regulator to provides stable voltage to the load.

of the PMOS in the active diode and its parasitic diode $D_{p,PZT}$, the charges are transferred towards the main storage element C_{STORE}. Meanwhile, C_{STORE} accumulates charges until it generates enough voltage to power the buck converters and generate the voltages V_{outH} and V_{outL}. These two voltages are used to provide energy to the load and the internal clock needed to power the DC-DC converter, synchronized comparators, and control circuits [127].

During normal operation, active diodes allow the passage of voltages generated by energy sources, provided that these voltages exceed $V_{MIX,out}$. As a result, $V_{MIX,out}$ reaches a high enough level to generate both V_{outH} and V_{outL}. Therefore, the φ_1 signal is set to logic 1, thus separating the C_{PZT} and C_{TEG} capacitors from the switches. In case $V_{MIX,out}$ drops below V_{outH}, but remains higher than V_{outL}, the synchronized comparator shown in figure 7(b) is triggered. This indicates that the voltage generated by a single power source is not sufficient to produce the regulated voltage V_{outH}. As a result, the φ_1 signal begins to oscillate between 0 and 1. During the logic 0 state, the two capacitors C_{PZT} and C_{TEG} are connected in series, with both voltages contributing to $V_{PZT,out}$, becoming $V_{PZT,out} + V_{TEG,out}$. In this way, the upper active diode is activated to transfer the charge to the C_{STORE} storage capacitor. Once the charge transfer is complete, the top active diode is turned off and the restart control forces φ_1 back to logic 1, allowing the C_{PZT} and C_{TEG} capacitors to be separated again to be recharged by their respective harvesting sources until the corresponding voltages are reached. Therefore, φ_1 continues to oscillate between 1 and 0 until $V_{MIX,out}$ reaches again a high enough level to generate V_{outH} again. It should be underlined that the system uses the charge pump for a certain period to bring the output voltage back to the desired levels. The system ensures that the voltage generated by the charge pump does not exceed the rated voltage of the transistor through the control logic described in figure 7(b) [127].

In figure 8(a) block diagram of a multiple energy harvesting system (with 4 inputs) with a total quiescent power consumption of 160 μW is shown. The energy harvesting system can collect and manage energy from different energy sources, such as electromagnetic induction (MI) operating with a carrier frequency of regulated band of 13.56 MHz, vibrations (low voltage PZT generators), sunlight (indoor environment), and TEG. The maximum total power harvested with the addition of the three energy harvesting sources is approximately 6.4 mW, for the operating conditions defined by a PZT generator at 7 m s^{-2} and 80 Hz, 1500 lux for laboratory lighting and 200 mW emitted from a base transmitter at 25 mm coil spacing [125].

6. Conclusions

In conclusion, this review focuses on energy harvesting boards including an analysis of the state-of-the-art and commercial solutions in this field, along with a discussion on the identification of relevant environmental parameters in buildings. Successively, it examines real indoor energy sources for harvesting and addresses energy management within harvesting boards, with particular attention to the central role of energy conversion systems and storage in batteries and supercapacitors. Furthermore, the topologies of energy harvesting systems have been discussed. Moreover, the review continues by exploring hardware architectures and strategies for low-power operation, including microcontrollers, RF transceivers, memory and various impedance-matching circuits, rectifiers, voltage multipliers, and DC-DC or AC-DC converters. Also, the techniques for combining energy from multiple sources for energy harvesting systems have been dealt with. This study contributes to existing literature by giving insights into the complexities of energy harvesting devices. The main findings and insights collected in this comprehensive review could offer valuable guidance to various stakeholders (such as scholars, policymakers, and industry), supporting decision-making and strategic interventions. Moreover, a better understanding of energy harvesting challenges could benefit from this study, helping the definition of future targeted policies.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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