



Review article

Powering nodes of wireless sensor networks with energy harvesters for intelligent buildings: A review



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ABSTRACT

Intelligent buildings play a fundamental role in achieving efficient energy management in the building sector in many countries worldwide. Improving energy consumption within a building can represent significant financial savings and reduce carbon emissions. However, intelligent buildings may impose additional burdens and challenges in their energy use. Wireless sensor networks are essential for the control systems of most intelligent building systems. There are still opportunities to reduce the power supplied to their sensor nodes in these networks. These nodes require power levels that range from microwatts to milliwatts. Typically, primary non-rechargeable batteries provide power to the nodes. Replacing or replenishing these batteries could become an impractical activity with detrimental environmental impacts. Energy harvesters (EHs) appear as a potential solution to this problem, as they could complement the use of batteries while extending their lifetimes at the sensor nodes.

This paper provides a comprehensive review of the energy harvesting technologies currently under an experimental or development phase. Thus, one of the objectives here is to study if EHs can power by themselves or support current battery-powered sensor nodes at the building level. The environmental sources considered for harvester power extraction were mechanical motion, thermal, light, radio-frequency, and fluid flow. Also, the potential sites and building systems for extracting power through these harvesters are presented and reported. This paper includes the review of the challenges and opportunities for EHs depending on the mounting location and the particular characteristics of each EH technology. The research findings in this paper demonstrate that harvesters at the buildings can generate enough power to partially supply the power requirements for sensor nodes and even completely cover the power demands of specific operation modes.

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1. Introduction

Developing technology solutions to manage energy consumption in buildings efficiently is an area that has attracted much attention from researchers in recent years. In existing buildings, such technologies must be utilized without reducing the indoor comfort of the users (mainly visual and thermal comfort), which could be achieved via optimizing the operation and control systems of equipment such as heating–ventilation–air conditioning (HVAC), lighting, closed-circuit television (CCTV), access control, fire safety, security, and electric appliances. Addressing this issue is beneficial to society since buildings are among the largest energy-consuming systems worldwide (Litardo et al., 2021). According to the 2019 Global Status Report for Buildings and Construction Sector, about 30% of the global end-use energy consumption in 2018 was due to residential and non-residential buildings (International Energy Agency (IEA), 2019), which also generated about 28% of global energy-related CO₂ emissions. The electricity consumption of the building sector has been around 49% of the world’s total, with residential buildings consuming 27% and commercial and public buildings consuming 22% (Raturi, 2019).

HVAC systems consume the highest energy in buildings, with approximately 50% of the energy consumption in buildings in developed countries such as the US and UK (Tian et al., 2019; Jouhara and Yang, 2018). After HVAC systems, lighting systems are the second-largest electricity consumer in buildings with about 19% (Baloch et al., 2018; Doulos et al., 2019; Han others, 2019; Litardo et al., 2019a). Improving the energy efficiency in both types of systems in buildings would represent significant financial savings and reduction of CO₂ emissions. Therefore, it is vital to use innovative technologies that improve automated and intelligent control of all the systems that constitute a building.

The design and implementation of intelligent buildings is an alternative for reducing energy consumption, operating costs, and CO₂ emissions (Asadian et al., 2018). Typically, intelligent building control systems are reactive, compared to the predominant adaptive controls in smart buildings (Chang et al., 2020). Intelligent buildings can be seen as energy-generating entities that can perform load reduction, peak shaving, load shifting, load reduction during blackout and brownout events, grid stability, among other uses (Manic et al., 2016a). An exhaustive treatment of intelligent buildings is not within the scope of the present

work. Making a building “more intelligent” would start with the use of control systems that allow monitoring real-time operations and optimally control electrical loads, mainly lighting and HVAC (La et al., 2015). These functions could be achieved by building energy management systems (BEMSs) or building automation control systems (BACSs) based on controller networks. These controllers must be reliable, safe, scalable, and cost-effective since an inaccurate control or poor system management could significantly reduce the building performance and impact the economy and the environment (Hannan et al., 2018). Also, the continuous improvement of these components will allow a smoother integration of a building with utilities, other intelligent buildings, smart grids, and other electrical and technology systems (Manic et al., 2016b). Similarly, following the development of microgrids and smart grids, intelligent buildings can incorporate distributed energy resources (DERs), including distributed generation (DG) and distributed storage (DS) (La et al., 2015; Ouammi, 2016). The advancement of internet of things (IoT), machine learning, big data, cloud computing, and control algorithms are bringing intelligent buildings closer to becoming smart buildings (Zhang et al., 2019). In summary, all the required automation inside an intelligent building is governed by networks, communication protocols, control systems & equipment, operational data acquisition, data storage, and sensors.

Sensors are fundamental devices for the automation and control of intelligent buildings. For example, occupancy sensors can help control systems of buildings to achieve potential energy savings between 15% and 40% of total energy consumption (Kim and Srebric, 2017) and 56% on HVAC systems (Ekwevugbe et al., 2017). Furthermore, lighting control can achieve potential energy savings up to 75% (Chen et al., 2016). There are a variety of sensors available in the market which are used in buildings for measuring variables such as temperature, humidity, CO₂, volatile organic compounds, occupancy, proximity, pressure, flow, noise, vibration, and light intensity. The optimal location, appropriate deployment, and proper selection of these devices correctly monitor the above variables (Hidalgo-León et al., 2019).

A Wireless Sensor Network (WSN) is a technological infrastructure that enables numerous control and monitoring processes, which can be conducted remotely, in real-time, and with minimal human intervention (Pule et al., 2017). Wireless sensor nodes and a base station are the main components of a WSN. These sensor nodes allow the efficient support of intelligent building control systems without requiring traditional electrical

Nomenclature

WSN	Wireless sensor network	
EH	Energy harvester	
HVAC	Heating, ventilation, and air conditioning	
CCTV	Closed-circuit television	
IoT	Internet of things	
BEMS	Building energy management system	
BACS	Building automation control system	
RX	Received signal	
TX	Transmitted signal	
DER	Distributed energy resource	
DG	Distributed generation	
DS	Distributed storage	
Wi-Fi	Wireless fidelity	
RF	Radio frequency	
WLAN	Wireless local area network	
PEH	Piezoelectric energy harvester	
AC	Alternating current	
EEH	Electromagnetic energy harvester	
TEG	Thermoelectric generator	
DC	Direct current	
RC	Rectifying circuit	
LEH	Light energy harvester	
LED	Light-emitting diode	
GaAs	Gallium Arsenide	
GaNP	Gallium Indium Phosphide	
CFL	Compact fluorescent lamp	
LTE	Long Term Evolution	
GSM	Global System for Mobile Communications	
GPRS	General Packet Radio Service	
MAC	Medium Access Control	
DAP	Data access point	
EAP	Energy access point	
MEH	Microturbine-generator harvester	energy

wiring for communication and power supply for each of the traditional sensors (Minoli et al., 2017). Typically, a sensor node consists of a sensor, which detects the behavior of a variable to be measured. Then, this device sends electrical signals to an electronic data acquisition system for post-processing through a transmitting antenna. The data is then sent via RF to an RF gateway (sink node or base station). These sensor nodes provide high versatility as they can be installed in areas of difficult accessibility with relatively little effort, as minimal wiring is required. Also, a WSN can be configured, expanded, and updated at a low cost compared to wired sensor networks (Huang and Mao, 2017). A typical WSN can consist of dozens to thousands of nodes (Can and Sahingoz, 2015). Although WSNs still depend heavily on the intensity of the wireless connections, ultra-dense wireless networks are becoming a reality with recent technology developments.

A big concern for wireless sensor networks is the need for a power supply in each sensor node. As stated previously, the power consumption of a node can range from microwatts to milliwatts (Hayat others, 2019) in each of its operating modes. A sensor node could have four operating modes: (1) sleep, (2) idle, (3) receive, and (4) send. Also, the higher power storage

capacity of sensor nodes can extend the life of a WSN. The nodes are usually powered by non-rechargeable batteries, which have limited capabilities. They are an essential limiting constraint given the need to keep the nodes in operation for long periods of time (Nguyen and Nguyen, 2020). Table 1 shows some commercial wireless sensor nodes used in the building environment. As shown in the table, each device indicates the power extracted from its battery storage during wireless sensor operation mode. Also, the data was obtained and calculated from various manufacturer datasheets and user manuals, available online at the time of publication. Several standard small batteries are also listed, such as AA, AAA, CR, and E, whose lifespans always depend on the configuration of their wireless sensor nodes and environmental operating conditions (Hidalgo Leon, 2017). Also, the lifespan of these batteries can be several years, making the use of secondary (rechargeable) batteries unnecessary. Some researchers have reported that replacing batteries could become impractical due to various reasons, including human labor costs and the level of difficulty in performing these operations given the location of sensor nodes in the building (Nguyen and Nguyen, 2020; Wu and Yang, 2015; Rashid et al., 2018). Moreover, the massive use of wireless sensors could cause a significant environmental impact and severe health problems to living beings if the used batteries are improperly managed at the end of their lives. The reason is that batteries contain hazardous chemicals and heavy metals such as nickel (Ni), cobalt (Co), and lead (Pb) (May et al., 2018), which are considered carcinogenic and mutagenic materials (Zhang et al., 2018). This justifies new technological solutions that could complement the use of batteries while extending their lifetimes at the sensor nodes.

Energy harvesters appear as an option with much potential for the power supply to nodes of WSNs. EHs are electronic devices that capture small amounts of energy from their surrounding environment and convert them to low-power suitable for supplying electricity to electronic devices such as sensors, dataloggers, data-transmitters, IoT devices, wearable electronics, and health monitoring devices (Cioncolini et al., 2019; Goushcha et al., 2015; Hidalgo-Leon others, 2018). Commonly, EHs consist of an environmental energy-capturing device (transducer), a power conversion circuit (power converter, control system, and other electronic circuits), and an electrical load and battery. The electronic architecture developed in the power conversion circuit allows the power interface between the transducer and the load-battery. This circuit converts the transducer power to be suitable for the operation of the electrical load (sensor node) and energy storage in the battery. The latter happens when the transducer power is greater than the power required by the load. In addition, this circuit is used to match the impedance of the transducer to the load, thereby achieving the maximum power transfer from the transducer to the load (Chen et al., 2017; Cansiz et al., 2019). The power magnitudes delivered by a single EH range from a few microwatts to watts in small devices or prototypes. Fig. 1 shows the typical configuration of an EH in the context of the present work, considering a battery and a wireless sensor node as an electrical load.

Some environmental energy sources at the building level are present in artificial lighting, HVAC systems, floor panels, facades, water pipelines, exhaust systems, and Wi-Fi access points. Proper energy source selection for a specific EH could establish an ideal balance between the power supplied by the EH and the power consumed by the electric load (Pop-Vadean et al., 2017). For example, a sensor node could operate continuously as long as the EH generates enough power. Otherwise, a storage device (ultracapacitor or non-rechargeable battery) could be required to balance generation and consumption.

This paper provides a comprehensive review of energy harvesting technologies that use environmental energy sources in

Table 1
Some technical characteristics of commercial wireless sensor nodes and applications in the building environment.

Sensor	Battery number	Battery type	Electrical current during battery discharge mode	Operation voltage (V)	Power consumption	Building applications
Daylight	1	CR2450	7 μ A (nominal)	3	21 μ W	Any space
Airflow	1	CR2032	0.7 μ A (sleep) 2 mA (radio idle/ off) 2 mA (measurement) 25 mA (radio RX) 35 mA (radio TX)	3	2.1 μ W 6 mW 6 mW 75 mW 0.12 W	HVAC systems/ Environmental monitoring
Water	1	CR2032	0.7 μ A (sleep) 2 mA (radio idle/off) 2 mA (measurement) 25 mA (radio RX) 35 mA (radio TX)	3	2.1 μ W 6 mW 6 mW 75 mW 0.12 W	Reservoir level monitoring
Air velocity	2	AA	0.2 μ A (sleep) 0.7 μ A (RTC sleep) 570 μ A (MCU idle) 2.5 mA (MCU active) 5.5 mA (radio RX) 22.6 mA (radio TX)	3	0.6 μ W 2.2 μ W 1.72 mW 7.5 mW 16.5 mW 67.8 mW	Building/Room Pressure, computer rooms
Temperature	2	AA	0.2 μ A (nominal)	3	0.6 μ W	Chimney
Temperature and humidity	1	CR2477	33 mA (maximum)	3	99 mW	Any space
Motion detection	2	AA	1 μ A (Sleep) 570 μ A (MCU idle) 2.5 mA (MCU active) 5.5 mA (radio RX) 22.6 mA (radio TX)	3	3 μ W 1.72 mW 7.5 mW 16.5 mW 67.8 mW	Any space
Ambient light, temperature, humidity	3	AA	0.28 mA (normal) 0.44 mA (boost)	4.5	1.25 mW 2 mW	Any space
Light, presence and temperature	1	E	38 μ A (average) 26 mA (maximum)	9	0.34 μ W 0.23 mW	Rooms

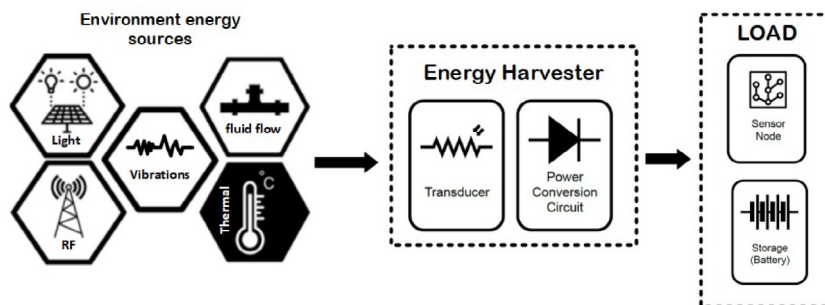


Fig. 1. Typical configuration of an EH, considering the environmental energy source, the EH technology, and a battery or the wireless sensor node as a load.

a building. This paper includes a review of the challenges and opportunities for EHs depending on the mounting location and the particular characteristics of each EH technology. Each section consists of an analysis and discussion on the technologies of EHs and how these could provide power for wireless sensor nodes.

The methodology for the current literature review prioritizes the selection of papers highlighting energy harvesting technologies that are currently in an experimental or development phase. This criterion was followed to review and compare only papers that described case studies and reported variables and indicators such as voltage and current requirements, power and energy consumption, and other relevant parameters. These indicators and variables are relevant as one of the contributions of this paper are to build a benchmark by which one can compare EH technologies to select the most appropriate one based on electrical requirements. The breakdown of each section of the present work was done according to the diagram in Fig. 2. The bottom part of this diagram shows the ambient energy sources commonly present in potential sites and building systems. These sources will be exploited using the energy harvesters (shown in blue boxes in

Fig. 2) reviewed in the present paper to supply power to the wireless sensor nodes. Each section will analyze an energy harvester technology from its corresponding environmental energy source.

This paper is organized as follows. Sections 2–4 are related to EHs that obtain their power from mechanical motion, which are: based on piezoelectric vibration, pendular oscillation, and electromagnetic induction, respectively. Next, Section 5 discusses EHs that use temperature differentials to generate power. Section 6 reviews EHs that use artificial lighting as a power source. Sections 7 and 8 review EHs that harvest energy from RF and water flow, respectively. Research findings are drawn in Section 9. Finally, we have Section 10 with the conclusions of this work.

2. Energy harvesters from piezoelectric vibration

Piezoelectric energy harvesting is the field of study of passively collecting energy from surrounding dynamic, thermal, and electrical activity by using devices with piezoelectric materials through the piezoelectric effect. The direct piezoelectric effect is the physical phenomenon that governs the piezoelectric energy

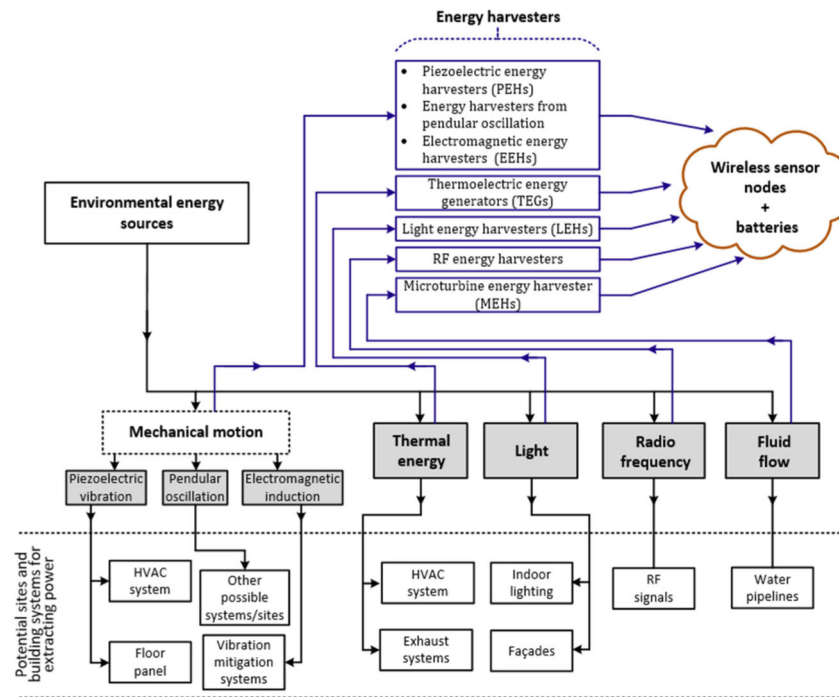


Fig. 2. Diagram of the present paper – Some ambient energy sources in buildings with their respective energy harvesters to supply power to the sensor nodes within the WSNs.

harvester (PEH) through the following constitutive equation that relates mechanical deformation with electrical generation:

$$\begin{bmatrix} \delta \\ D \end{bmatrix} = \begin{bmatrix} s^E & d \\ d & \epsilon^T \end{bmatrix} \begin{bmatrix} \sigma \\ E \end{bmatrix} \quad (1)$$

The first row of matrix Eq. (1) represents the mechanical domain equation where δ , s^E , d , and σ are the strain, compliance for a constant electrical field, transpose of the matrix of the piezoelectric effect, and stress, respectively. The second row represents the electric domain equation where D , d , ϵ^T , and E are the charge density, direct piezoelectric effect matrix, dielectric permittivity for constant stress, and electric field. It should be noted that the coupling term is the matrix of the piezoelectric effect (Yang et al., 2018).

Piezoelectric energy harvesting devices can be found in various shapes and configurations, like sheets, cymbal-shaped, cylindrical, and discs. Sheet-shaped devices are typically used in strain piezoelectric generation and are rated based upon their deflection level when loads are applied to them. Likewise, cymbal-shaped piezoelectric transducers generate power due to the deflection caused by the subjected pressure by external loads (like vehicle and human traffic). It is important to note that PEHs must be installed underneath the floor surface. The PEHs should operate without affecting the circulation of people.

Three main energy sources based on piezoelectric materials have recently gained increased attention: vibration, strain, and fluid flow (Liu et al., 2018). Vibration energy harvesting uses the concept of attaching a spring–mass–damper system as the secondary system to a primary oscillator, which can be any engineering system (for the purpose of the present study, a building). This system is usually comprised of a cantilevered beam with a mass on its tip and some configuration of piezoelectric material either on the mass or at the base of the beam. One possible configuration for implementing piezoelectric transducer-based EH technology is schematically portrayed in Fig. 3. This configuration uses a sheet-shaped piezoelectric transducer exposed to stress and deflection vibrations. Airflows can cause these vibrations over

the cantilever with tip mass. The transducer produces energy of an oscillating nature that must be processed by its power conversion stage, which is responsible for conditioning the signal to be compatible with the electrical load and battery.

Strain energy harvesting uses the concept of material deformation by directly coupling piezoelectric materials to surfaces subjected to elastic deformation (e.g., surfaces subjected to human or vehicle traffic). These systems have the advantage of not requiring tuning to any resonant frequency (Liu et al., 2018). Due to the high sensitivity of these devices to their resonant frequency, many applications using energy harvesters based on vibrations take advantage of nonlinear principles to widen the operational bandwidth of the devices, thus making them significantly more versatile (Yang et al., 2018).

The PEHs are amongst energy harvesters with the highest efficiency and lowest costs (Tao et al., 2017). These devices are not affected by environmental parameters such as temperature and humidity (Alluri et al., 2015) and can produce AC power within the range from μW (microwatts) up to mW (milliwatts) (Shim et al., 2015). A key consideration with piezoelectric transducer arrays inside modules or prototypes is that these can be connected in series or parallel to obtain higher voltage levels and current output.

Electrical and mechanical equipment operating inside a building has vibration levels that could potentially be used for energy harvesting. Examples include combustion engines, water pumps, compressors, electric motors, steam turbines, and fans. When these machines exceed certain vibration limits (which can result in possible damage), PEHs could also be set to produce warning signals without the need for wired sensors. These technologies are already being applied by several companies worldwide, such as Kinergizer and EnOcean (Lionel et al., 2018). For the rest of this section, we will review the applications of PEHs in a building environment, such as HVAC systems and floor panels.

2.1. HVAC systems

PEHs can harvest energy from the air flows inside the ducts of HVAC systems. These ductwork systems are used in most

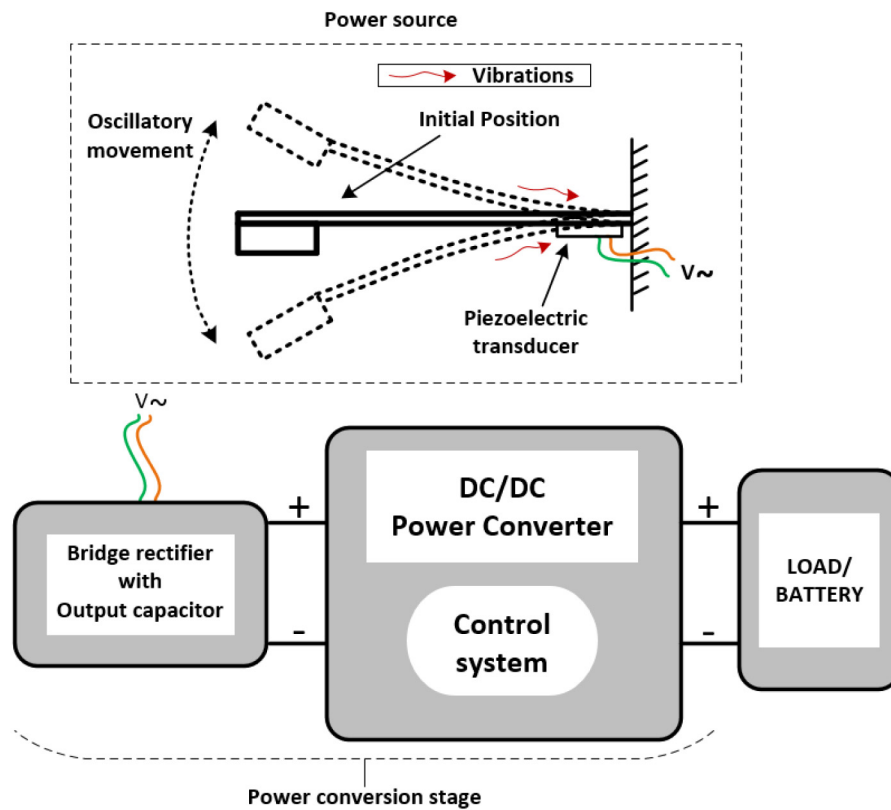


Fig. 3. Illustration demonstrating an energy harvester configuration that uses a sheet-shaped piezoelectric transducer to produce electrical power.

commercial, industrial, or residential buildings where harvesting opportunities can be widely exploited. Some researchers have reported using wind tunnels to simulate the conditions in ductwork systems, which are described in this section.

Three types of structures: cylindrical, rectangular, and T-shaped, were tested and analyzed in a wind tunnel (Gkoumas et al., 2017) with a PEH prototype based on a sheet-shaped piezoelectric transducer. The vibrations obtained from the T-shaped configuration generated a power supply of up to $400 \mu\text{W}$. A similar experiment conducted by Petrini and Gkoumas (2018) where cylindrical and T-shape structures were tested resulted in the generation of $200 \mu\text{W}$ and $400 \mu\text{W}$, respectively, with an airflow velocity of 3 m/s for both cases. The authors concluded that the T-shape structure exploits the galloping phenomenon (Piccardo et al., 2015) and provides optimal vibrations for a wide range of airspeeds. Some of the aerodynamic instability phenomena in ducts called “galloping and vortex shedding” start in residential applications between 2 m/s and 6 m/s (Gkoumas et al., 2017). Elvira-Hernández et al. (2019) showed that electromechanical modeling of PEH in air conditioning ventilation ducts for an office building could generate power levels of $37.45 \mu\text{W}$. This result was obtained under the following conditions: resonance frequency 60.3 Hz , maximum deflection of 2.485 mm , output voltage of 2.854 V , and load resistance of $217.5 \text{ k}\Omega$. The PEH prototypes inside the ductwork systems must be designed to not cause disturbances in the air flows, which could give rise to induced noises or the appearance of shedding effects. An inadequate installation could produce turbulent flows that may reduce the performance of the PEHs.

Furthermore, the rotational motion that occurs in some parts of HVAC systems can be used for power generation through PEHs. Guan and Liao (2016) experimented with two piezoelectric transducers mounted in a rotation system. Those devices obtained powers between $83.5 \mu\text{W}$ and $825 \mu\text{W}$ with rotation frequencies of 7 Hz and 13.5 Hz .

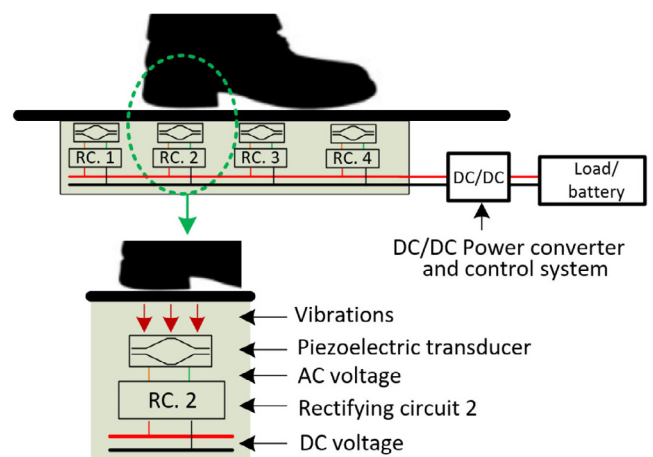


Fig. 4. Typical configuration of piezoelectric transducers inside floor panel to produce electrical power. The system includes the piezoelectric transducers, a rectifying circuits, power converter, and load.

2.2. Floor panels

Pedestrian traffic over surfaces made of PEHs can also generate electrical power for sensors and low-power devices such as cell phone charging stations. Fig. 4 shows a typical configuration of several piezoelectric transducers inside the floor panel, where first the current output of each transducer is rectified and then connected in parallel.

A function for calculating the power of a floor panel with PEHs is defined by Li and Strezov (2014) as:

$$P_{\text{PEH}} = MnER. \tag{2}$$

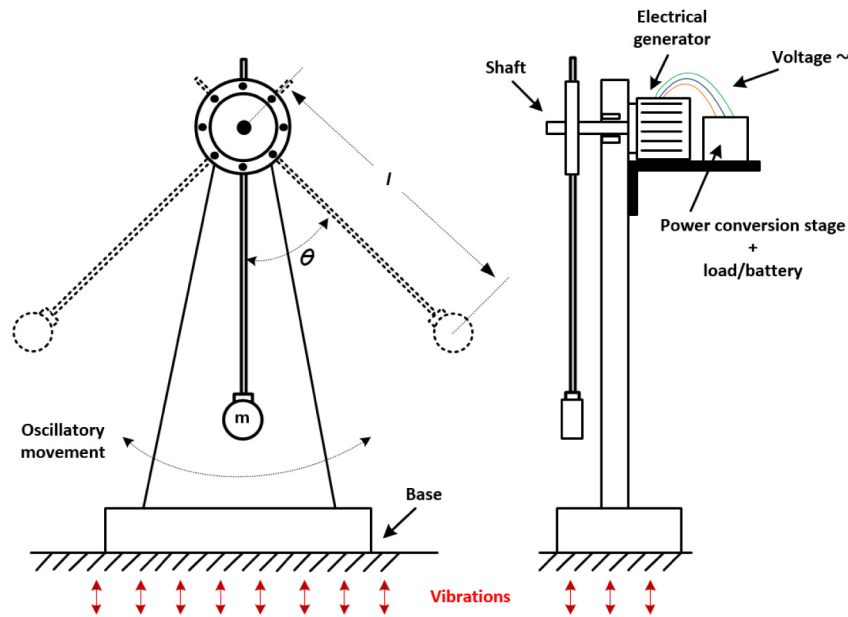


Fig. 5. Schematic diagram of a basic pendular oscillation mechanism with its main components for energy harvesting (side views).

where M is the number of pedestrians, n is the number of the activated floor panel, E is the electricity generated from a single footstep, and R is an enhancement rate related to impact effects on floor panels.

The analysis of the deformation of these transducers embedded in floor panels is the subject of considerable research. In Cascetta et al. (2018), the authors developed a prototype module consisting of 9 stacks of piezoelectric diaphragms (45 diaphragms in total). Each diaphragm is wired to a full bridge rectifier, and its output is connected in parallel in 44 additional similar configurations. The experimental tests of this work, taking into consideration a test resistance of 1 kΩ and the footstep of a man weighing about 85 kg, achieved power levels of around 66 μW with a load voltage between 30 V and 40 V. Expressions were used for the calculation of the maximum energy transferred to the load (E_{max}) and the total energy (E_{tot}) of the connection of N configurations were given by:

$$E_{max} = \frac{I_{p1} I_{p2} \Delta^2}{C_p (2 + \alpha)} \quad (3)$$

$$E_{tot} = \eta N V_{DC} I_{p1} \left[2\Delta - \frac{C_p V_{DC} (2 + \alpha)}{I_{p2}} \right] \quad (4)$$

where η is an efficiency factor, N is the number of piezoelectric transducers, V_{DC} is the DC voltage output of the rectifier bridge, I_{p1} and I_{p2} are the electrical currents related to the piezoelectric transducers, Δ is the time variation of when a current pulse occurs related to the piezoelectric transducer, C_p is the shunt capacitance of the piezoelectric transducer, and α is a loss factor.

A floor tile was modeled, simulated, and implemented to generate power for a wireless occupancy sensor (with a storage capacitor) in Sharpes et al. (2016). The authors used five piezoelectric discs in the tile connected in parallel to a single rectifier circuit. The tests were carried out by having a 71 kg person walk over the tile to generate a voltage of 15 V at the maximum power operating point. Similarly, in Hwang et al. (2015), a tile was modified using springs and a tip mass for indirect energy transmission. Here, the authors reached an approximation between the vibration frequency of the tile and the resonance frequency of the piezoelectric module through the mechanical modifications mentioned above. Under this condition, with four modules using the same impedance of 15 kΩ, the power achieved ranged from

770 μW to 55 mW peak. The curved piezoelectric transducer was modeled and implemented inside a floor field (Kathpalia et al., 2017). The experimental results showed that with a vibrational frequency of 2 Hz, a 7 N force, and a 100 kΩ load impedance, the average generated power resulted in roughly 70 μW.

3. Energy harvesters from pendular oscillation

Pendular oscillation mechanisms have been extensively studied for their use in power generation applications. Firstly, a conventional pendulum mechanism is formed by a mass (m) suspended by a string attached to a pivot on a rigid frame, which is fixed to a rigid base. The period of oscillation (T) of the pendulum with a swing amplitude (θ), is given by:

$$T = 2\pi \sqrt{l/g}; \quad \theta \ll 1, \quad (5)$$

where l is the length of the pendulum and g is the acceleration of gravity.

Fig. 5 shows a schematic diagram of a basic pendular oscillation mechanism with its main components for energy harvesting. As can be seen in the figure, the oscillatory motion of the pendulum can be produced by the vibrations received at the base of this mechanism, which in the present case is vertical (y-axis). The oscillation of the pendulum produces a torque on the generator's shaft, which in turn will generate power. This power must be conditioned by a power conversion stage (similar to Fig. 3) to transform these signals to DC power. This section focuses on the use of this technology at the building level.

3.1. Other possible systems/sites

The movement on pendular mechanisms when placed in large volume reservoirs (swimming pools, water tanks, and water cisterns) or electrical/mechanical machines can be used for energy harvesting. The movement of waves is of a stochastic nature, while the movement produced by machine vibrations is of a harmonic type and can be easily predicted (Dotti et al., 2017). In the experimental tests from the available literature, the magnitude of the movements is simulated using electrodynamic shakers.

In Marszal et al. (2017), the mathematical model of a pendulum system was validated by experimental measurements made

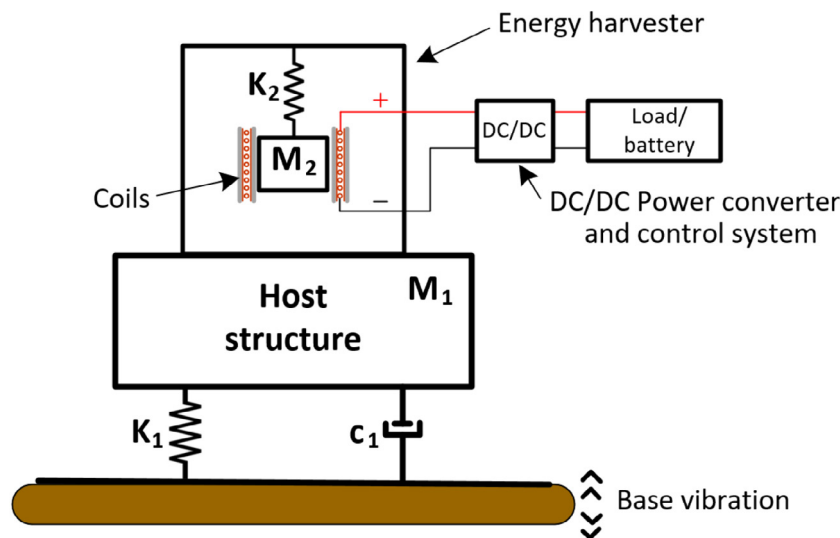


Fig. 6. Typical configuration of an energy harvesting setup from a vibration isolation system.

in an inflatable boat in a swimming pool. The experimental EH provided a power of around 0.4 W, with a pendulum length of 0.18 m, and an electrical load of 101 Ω. This research showed that the shorter the pendulum length, the more efficient the harvested energy. This system was represented mathematically by the governing equations:

$$I_1 \ddot{\theta} + c_1 \dot{\theta} + m\omega^2 A \cos(\omega t) \sin\theta + mg \sin\theta = 0, \tag{6}$$

$$I_2 \ddot{\delta} + c_2 \dot{\delta} + \text{sing}(\delta) M_f = 0$$

where θ is the angular displacement of the pendulum, δ is the angular displacement of the flywheel, I_1, I_2 are the moment of inertia of pendulum and reduced moment of inertia of the freewheel-gear box-shaft-electric generator system, respectively, m is the mass of the pendulum, l is the distance from center of gravity to the pivot axis, c_1, c_2 are the viscous angular damping coefficients, M_f is the friction torque, A is the amplitude of vertical excitation, ω is excitation frequency, and t is the time variable. In this expression and hereafter, overdots represent derivatives with respect to time.

A parametric pendulum mounted on a reciprocating mechanical vibrator was studied in Dotti et al. (2017), where the pendulum axis was mounted on ball bearings, which the authors claim to be an actual situation for energy harvesting to the use of a dry friction component. The modeling and experimental observations concluded that a crucial step for achieving acceptable energy harvesting results is to correctly estimate the zones of rotation for this type of EHs. The governing differential equation is:

$$ml^2 \theta'' + T_v + T_c + ml(y'' + g) \sin\theta = 0 \tag{7}$$

In this case, l is the distance between the center of gravity and the axis of the pendulum, y is the vertical displacement of the axis, θ is the angle measured from the equilibrium position, T_v is the viscous friction torque, and T_c is Coulomb's friction torque. In this expression, $(\cdot)'$ denotes the derivative $d(\cdot)/d\tau$, where τ is a dimensionless time variable where $\tau = \omega_0 t$ and ω_0 is the natural frequency of the pendulum.

A system consisting of two decoupled rolling pendulums was used to harvest energy at low frequencies in Punyakaew and Parinichkun (2020), where a cam was constructed to create a multi-frequency excitation. External excitation frequencies represented the common motion in an industrial vibrating machine and a sea wave motion. Experimental results showed that when the angular velocity of the cam changed from 1.149 Hz to 1.236 Hz, the electrical power outputs of pendulums one and two were 1 mW and 23.2 mW, respectively.

4. Energy harvesters from electromagnetic induction

Electromagnetic energy harvesters (EEHs) are based on Faraday's law of electromagnetic induction. These devices are also known as magnetic induction energy harvesters. All the reviewed literature in this section shows the technology at prototype stages, including documented realizations of pendulum mechanisms. The focus in this section is on vibration mitigation systems.

4.1. Vibration mitigation systems

Civil structures, particularly high-rise buildings, are prone to large dynamic responses due to wind loads and seismic events such as earthquakes (Chu et al., 2017; Xie et al., 2015). These types of motion could cause damage to the entire structure (Zheng et al., 2019). For this reason, some structures are protected through vibration mitigation systems, such as vibration absorbers and structural dampers. At the same time, these systems can be used for energy harvesting purposes by harnessing the dynamic energy in the other direction: that is to say, generating power in their dissipating mechanisms. Fig. 6 shows a typical configuration of an energy harvesting setup from a vibration isolation system, where M_1, K_1 and C_1 respectively represent the mass, stiffness and damping of the host structure, whose response is to be reduced by the addition of the attenuator of mass M_2 . Here, an additional electrical system is embedded in the device such that electromagnetically induced current can be collected and stored for future use.

In Kecik (2018), a system of an auto parametric pendulum vibration absorber and a Maglev harvester is presented. This EEH is based on the motion of a permanent magnet that induces a voltage across the terminals of an electric coil. The system is thus allowed to recover power while the pendulum is at rest and during swinging motion. The simulation results showed a collected power of 0.12 W with a load resistance of 1.2 kΩ and an excitation amplitude of 30 mm. In this type of application, the harvested power (P_{har}) is given by Rocha et al. (2019):

$$P_{har} = \left(\frac{\alpha}{R_{load} + R_{int}} \dot{x} \right)^2 R_{load} \tag{8}$$

where α is the electromechanical coupling coefficient, R_{load} is the resistance of the external load, R_{int} is the internal resistance of the coil, x is the displacement of the magnet, and the coefficient

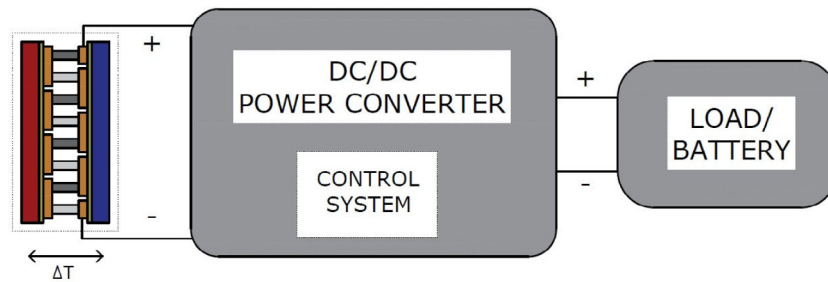


Fig. 7. TEG configuration with a DC/DC power converter and its connection with a load (sensor node) and battery.

$\alpha = NBl$, with N being the number of coil turns, B the average magnetic field strength, and l the coil length.

The parameter (α) is the coefficient that couples the electrical and mechanical systems where its experimental identification was developed in [Mitura and Kecik \(2016\)](#). In this experiment, the EEH was subjected to dynamic and quasi-static tests, and a significant conclusion was that α depends strongly on the position of the magnets in the electric coil. The functional dependency of α is:

$$\alpha(x, \dot{x}) = \frac{L_{\text{coil}} \frac{di}{dt} + R_{\text{total}} i}{\frac{dx}{dt}}, \quad (9)$$

where x is the displacement of the magnet, i and L_{coil} are the currents through the coil and its inductance, respectively, R_{total} is the sum of the load and inductance (coil) resistors.

A new definition of the coupling coefficient of Eq. (9) is introduced in [Kecik et al. \(2017\)](#). The experimental results showed that α is a non-linear function of the magnet position and depends highly on the magnetic coordinate inside the electric coil, where the maximum power occurs at the coil terminals.

Certain modifications at the pendulum can improve the power recovery of mitigation systems. An EEH prototype based on a double pendulum subjected to base excitation using electric coils attached to the pendulum masses was reported in [Chunawala et al. \(2016\)](#). The mathematical modeling of this system predicted a generated power of up to 9 mW, with a vibration frequency of 2 Hz and an amplitude of 1 mm. The authors suggest that the power level obtained is sufficient to power a sensor. [Kecik and Mitura \(2020\)](#) demonstrated a Maglev-configuration-based EEH with the addition of an EH, placed in the electrical generator coupled to the pendulum shaft. The experimental results showed a power recovery of 100 mW, where approximately 64 mW came from the EH placed in the electric generator. Several research projects reported differences between modeled and experimental results attributed to the friction of magnets in motion inside the pendulum tubes. Furthermore, the induced voltage at the terminals of the electric coil and the motion of the magnets must maintain a correct relationship, which is of great relevance for the improvement of the power delivery of the EEH prototypes.

5. Energy harvesters from thermal energy

EHS that use thermal energy to generate power are known as thermoelectric energy harvesters, also known as thermoelectric energy generators (TEGs) ([Enescu, 2019](#)). These EHS are based on a combination of the Peltier, Seebeck, and Thomson effects ([Sun et al., 2020](#)), all of which allow the transformation of temperature gradients from the environment into electric voltage and vice-versa ([Fan et al., 2017](#)). In other words, a TEG transducer consists of two sides: one cold and one hot. Power is generated depending on the temperature differential to which these sides are exposed. A basic TEG configuration is shown in [Fig. 7](#).

HVAC systems and exhaust systems in buildings can be used as potential sources for this technology due to the temperature levels generated in their heating and cooling processes. These TEGs have a low thermal to electrical power conversion efficiency, which could reach from 1% to 20% ([Wu et al., 2018](#)). According to the power levels generated by the elements mentioned above, TEGs can be used to power sensors, mobile phone chargers, alarms, and other low-power appliances. Other advantages of the TEGs include the fact that they do not generate noise, have a long lifespan with high reliability due to their compact form, they do not require spare parts, have no operating costs, and their operation does not generate polluting gases ([Demir and Dincer, 2017](#); [Li others, 2017](#); [Kim et al., 2018](#)). The power generated by the TEGs reviewed in this section range from a few mW to about 25 W, due to the stacking capabilities of these transducers.

5.1. HVAC systems

Temperature differentials from a few degrees to over 100 °C can be found in multiple sections of the HVAC systems ([Ramadan et al., 2017](#)). In experiments conducted by [Milić et al. \(2017\)](#), one of the tests with TEGs in a sensor node produced approximately 500 μW and a current load of 12 mA with a temperature differential of 15 °C, taking into account that one of the sides of the transducer was at ambient temperature (30 °C). This result was similar to those obtained in the simulations conducted under the same conditions. In tests carried out for the self-powering of a sensor node during the sending of signals every 3 min, the lowest open-circuit voltage obtained by a TEG was 62 mV and a power of 84 μW with a temperature differential of 2.6 °C ([Guan et al., 2017](#)). It is essential to highlight the efficiency of a transducer (η_{TE}), which is given by [Favarel et al. \(2016\)](#):

$$\eta_{TE} = \frac{\Delta T}{T_H} \frac{\frac{m}{m+1}}{1 + \frac{m+1}{ZT_H} - \frac{\Delta T}{2T_H(m+1)}} \quad (10)$$

where $\Delta T = T_H - T_C$ is the temperature difference: T_H (hot side temperature), T_C (cold side temperature), Z is a merit factor of thermoelectric material, and m is the ratio between the electric load and the internal resistance of the transducer.

5.2. Exhaust systems

Waste heat from combustion processes in buildings is a potential source of power for sensors. For example, waste incineration plants at hospitals and chimneys could be optimal places for the research and implementation of TEG technology. In [Aranguren et al. \(2017\)](#), the authors developed a prototype made up of 16 TEG modules (for each level) applied on two levels along with the chimney of a combustion chamber. This prototype was validated using a previously developed computational model. The maximum power generated by the TEGs was 24.59 W with a maximum temperature of 560 °C. The relative error between the

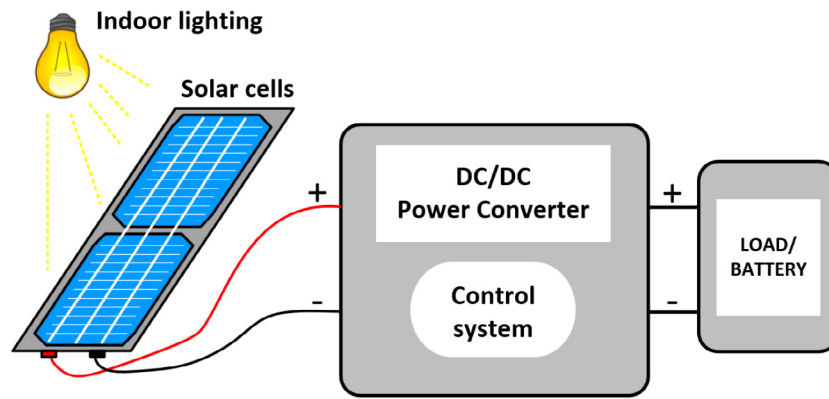


Fig. 8. Schematic diagram of solar cells for purposes of indoor light energy harvesting.

results of the model and the prototype was between $\pm 12\%$. Khalil and Hassan (2020) showed analyses of placing 3 TEGs with heat spreaders along with a chimney. In one of the cases analyzed, a total of about 220 mW was generated considering the length of the spreaders of 140 mm and a separation between them of 140 mm, the temperatures of hot gases of approximately 200 °C (hot sides) and 25 °C of ambient temperature (cold sides). A significant conclusion of this work establishes that the upper TEG has the lowest conversion efficiency and the lower TEG has the highest conversion efficiency.

6. Energy harvesters from light

Light energy harvesting is the process by which the available light in the environment is converted to electrical energy by using an EH device. Artificial lighting in buildings can be used in light energy harvesters (LEHs) for generating low power (Kim et al., 2019). The transducer of LEH is a cell or panel based on the photovoltaic effect. Fig. 8 shows a basic schematic diagram of solar cells for indoor light energy harvesting. These devices are considered among the technologies with the highest power density of all the EH transducers (Fröhlich et al., 2015). Nevertheless, the exposure of these transducers to conditions such as light intensity, duration, temperature variation, spatial positioning, and light technology (Fröhlich et al., 2015), need to be complemented with other EH technologies or with the use of batteries or capacitors (Takshi et al., 2015), to maintain a continuous supply of power to the load.

6.1. Indoor lighting

Artificial lighting technologies used for solar cell testing in this section include LEDs, fluorescent, and incandescent bulbs. The light intensity ranges for these technologies vary from 200 to 1000 lux. These intensities correspond to typical light bulbs found in schools, universities, hospitals, offices, hotels, restaurants, and other buildings (Richman, 2015). LEHs with batteries could be used to power nodes in WSNs.

In Li et al. (2015), four types of solar cells were exposed to different lighting sources and intensities inside a building. The types of lighting used were incandescent, fluorescent, and white light LEDs. The results showed that the amorphous-Si solar cells had a similar power output under three light sources, making these cells the most suitable for energy harvesting. Similarly, GaAs solar cells are studied in Mathews et al. (2015) with a GaInP solar cell being compared to commercial cells and exposed to light from light-emitting diode (LED) lamps and compact fluorescent lamps (CFLs). The lighting levels used were 200 lux and 1000 lux, where the GaAs cell had a higher power density

(92.2 μWcm^{-2}) than the GaInP cell (87.2 μWcm^{-2}) at 1000 lux. A higher power density was found using flexible dye solar cells, where said cells showed performances of 12.4% and 10% exposed to fluorescent and LED lighting, respectively (De Rossi et al., 2015). The light intensity level during testing was 200 lux. These percentages surpassed the performance of other cells in indoor tests such as polycrystalline and amorphous silicon cells. These cells have a low cost in the market, but studies are being carried out on their constitutive materials to improve cell efficiency and durability (Lee et al., 2017b). In Di Giacomo et al. (2016), three different perovskite solar cells were tested at outdoor and indoor lighting settings. With CFL lamps at 200 lux, the cell with a layer of plasma-enhanced atomic layer deposition showed a maximum power density of 15.4 μWcm^{-2} and maximum efficiency of 24%. Likewise, this type of cell showed the best performance with outdoor lighting during testing. Table 2 summarizes the results obtained from experiments with various solar cell technologies, some previously analyzed. It can be seen that the performance of cells mainly depends on their manufacturing materials.

6.2. Façades

During the last decade, research efforts have also focused on implementing solar systems on the façades of buildings. This includes building walls, windows, or any glazing elements, which are part of the building envelope (Litardo et al., 2019b). Vasiliev and Alameh (2019b) published a review that summarizes recent advancements in these technologies and provides examples of their performance on buildings around the world. Some of the solar panel arrays on façades reached performances of the order of watts per square meter of maximum power output generation. An interesting case is an experiment in Australia (Vasiliev and Alameh, 2019a), which was carried out to demonstrate the field performance characteristics and practical application potential of high-transparency, clear glass-based solar windows. Here, a group of 18 solar windows with monocrystalline silicon cells, placed in an atrium entrance, produced power magnitudes from a few watts to 200 W during tests carried out between May/2019 and June/2019. Also, the results showed that the north-facing windows with an area of approximately 1.3 m² were able to harvest about 0.1 kWh each on a sunny winter day.

7. Energy harvesters from radio frequency

Radiofrequency (RF) waves, also called RF spectrum, can be exploited to supply power to low-power devices such as sensors inside buildings. These harvesters require input signals from the frequency spectrum radiating between 3 kHz and 300 kHz (Cansiz et al., 2019). RF spectrum is mainly used for communications

Table 2
Comparison of various solar cell technologies for energy harvesting.

Work	Type of solar cell	Efficiency (%)	Area (cm ²)	Source of lighting for delivered power	Maximum power (μWcm ⁻²)
Li et al. (2015)	Polycrystalline silicon	14	68.64	Incandescent,	570
	Amorphous silicon	13.4	20.28–25.2	RGB color-controllable LED light	75–113
	Dye-sensitized TiO ₂	11.4	30.5	Incandescent	24
Mathews et al. (2015)	Gallium Arsenide	20.6	8.5	LED lamp	16.6
	Gallium Indium Phosphide	10.4	29.7	LED lamp	17.6
De Rossi et al. (2015)	Flexible dye	12.4	0.25	Fluorescent	8
	Flexible dye	10	0.25	LED	6.6
Di Giacomo et al. (2016)	Perovskite with Glass ITO substrate	24	Not specified	Fluorescent	15.4
	Perovskite with Glass FTO substrate	22–35	Not specified	Fluorescent	0.3–5.9

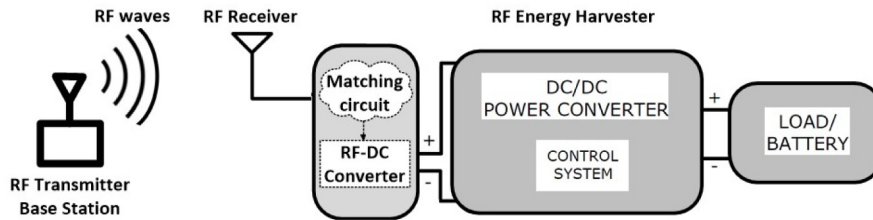


Fig. 9. System architecture of power transfer between the base station and RF energy harvester.

where base stations transmit and receive waves. Different services are broadcasted within this spectrum, such as AM/FM radio, TV, LTE, GSM, GPRS, and Wi-Fi (Wang et al., 2016). Signal propagation from a base station to a device (e.g., sensors) for power transfer depends on distance. However, the signal intensity loss can be minimized by using devices such as power beacons (Huang et al., 2015). Cansiz et al. (2019) showed that these RF harvesters could reach efficiencies that range between 15% and 84%. Although the power density of these devices is low, it is sufficient to power sensors.

7.1. RF signals

Wi-Fi devices can transmit signals inside buildings, which could be used to power sensor nodes, mainly in areas with power restrictions. Unlike other harvesting technologies reviewed, RF harvesters use antennas (transducers or RF receivers) to capture the RF waves. Furthermore, these harvesters have additional components such as impedance matching circuits, RF-to-DC rectifiers, voltage multipliers, and load (or energy storage) devices (Cansiz et al., 2019). Wireless sensors use small batteries for their operation; thus, the purpose of these RF harvesters is to extend the life or reduce the use of these batteries. The efficiency of an RF harvester (η_{RFh}) with all its components can be calculated as:

$$\eta_{RFh} = \eta_{ant} \eta_{rec} \eta_{mul} \eta_{load} \quad (11)$$

where η_{ant} is the efficiency of the antenna and matching circuit, η_{rec} is the efficiency of the RF-to-DC rectifier, η_{mul} is the efficiency of voltage multiplier, and η_{load} is the efficiency of the load (or energy storage device). A simple schematic for power transfer between wireless devices using a base station as a transmitter can be seen in Fig. 9. RF transducers require adequate impedance matching circuits to improve their power harvesting capabilities (Nechibvute et al., 2017).

Some authors indicate that energy harvesting from RF signals has significant challenges since the power supply at each sensor node is dynamic and stochastic (Park and Hong, 2014). In Shen et al. (2017), the authors presented an optimized triple-port pixel antenna and triple-port rectifier with a DC power converter, which improved the RF power harvesting inside a determined area. The authors reported that a GSM-1800 (1.8–1.88 GHz) band

was chosen for testing, and the efficiency achieved by the antenna system for the RF power harvesting application reached 9% with a maximum harvested power of 57 μW. The overall system efficiency was calculated by using the following expression:

$$\eta_M = \frac{P_{DC}}{P_{RF1} + P_{RF2} + P_{RF3}} \quad (12)$$

where P_{DC} is output DC power and P_{RF} is the power harvesting for each port.

An IoT system was designed in Hou et al. (2017) consisting of several Data Access Points (DAPs) for information collection and several Energy Access Points (EAPs). The EAPs can perform wireless power transfer through the use of RF energy harvesting. Here, the authors concluded that the performance of the IoT system depends on whether the EAPs allow for optimization of the power received by their sensors. In Taghadosi et al. (2017), a harvesting circuit, composed of two highly efficient RF-DC rectifiers for IoT sensor applications were tested with an operating frequency of 953 MHz. The power conversion efficiencies achieved in the experimental tests were 84.4% and 56% with power inputs of −12.5 dBm and −15 dBm, respectively. The power outputs achieved with these inputs were 46.5 μW and 17.76 μW, respectively. In the authors' opinion, this circuit can also operate in a frequency band around 2.4 GHz (Bluetooth/WLAN) with the appropriate impedance matching.

A significant limitation of energy transfer from RF signals is the interference with other frequency bands, where different applications (including other energy transfer devices) are operating. A potential solution to this problem was proposed in Lee et al. (2017a) through the Medium Access Control (MAC) protocol for IEEE 802.11 Wi-Fi stations. This protocol allows wireless power transfer to devices within a wireless-powered communication network by using power beacons. Likewise, studies are being conducted to establish optimized functions focused on data and energy transfers for powering mobile wireless devices through RF energy harvesting. This was analyzed in Khalfi et al. (2017), where results showed an increase in battery lifespan but a slight increase in base station power consumption.

8. Energy harvesters from fluid flow

Water flow in building pipelines could be another way to use EHs. Microturbines could use the potential energy (high water

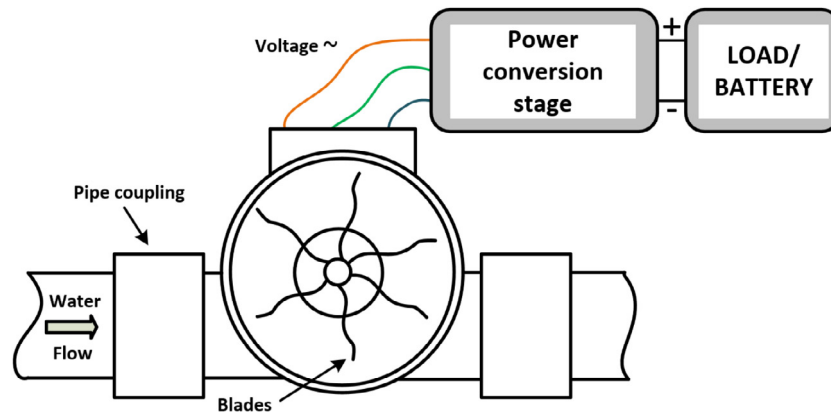


Fig. 10. Configuration of conventional MEH for small cross-sectional diameter water pipelines in buildings.

head), kinetic energy, and water pressure in water pipelines to produce power. The vertical water pipelines have great kinetic and pressure energy potential for energy harvesting (Hussein and Farouk). A microturbine energy harvester (MEH) mainly consists of a propeller (blades), an energy extraction circuit, and an AC alternator (Rödel et al., 2016). Fig. 10 shows a typical configuration of a MEH for small cross-sectional diameter water pipelines in buildings. The mini-hydro turbine generates AC voltage, which needs to be conditioned with a power conversion stage similar to the one in Fig. 3. This stage has to consider the electronics required to rectify the signal from an AC voltage. In the commercial market, some of these devices commonly produce DC voltages of 5 V and 12 V and power up to 10 W (Walmart, 2021).

The power supply rate of MEHs depends on the size of the microturbine and the pipeline diameter, which can deliver power in the range of a few mW to high power levels 24/7 (for public electric grid insertion or self-consumption power applications). For example, some companies such as SOAR Hydropower (Soar-Turbines, 2022) have been exploiting this technology on a large scale in urban water pipelines in cities where this process is reliable and 100% environmentally friendly without impacting the water delivery (Porkumaran et al., 2017).

In building applications, potential sites for the application of MEHs are tap water supply, drainage, and hot/cold water return pipes for large air conditioning systems (Casini, 2015). MEHs can be very useful for intelligent metering, data monitoring systems, and wireless sensors. New types of control valves for dissipating overpressure in water pipelines offer great potential for energy harvesting because these can recover the energy losses that occur in pressure reductions (Samora et al., 2016b).

8.1. Water pipelines

In Hoffmann et al. (2013), a water flow meter was modified to harvest energy in domestic pipelines. The modified harvester was based on a flow-driven impeller wheel and an electromagnetic energy converter incorporating a three-phase coil circuit and a three-phase rectifier. The results showed that up to 720 mW could be obtained in a 20 liters/min flow. Also, the experimental measurements had a low error compared to the simulations. Similarly, in Du et al. (2017), a centrifugal water pump was used as a turbine in a prototype within a pipeline network built by Hong Kong Polytechnic University researchers. This prototype was made to be expanded into a typical high-rise building. The results showed that the pump under 10 m³/h with a pressure drop of 48 psi delivered a maximum output power of 110 W. The hydraulics laboratory of Politecnico di Milano used its patented turbine (called GreenValve) inside an 80 mm ball valve to control

pressure and harvest energy at the same time (Malavasi et al., 2018). The authors found that the maximum efficiency of the valve is given at intermediate flow rates, which generally occur in buildings. A turbine/generator prototype was installed in a DN250 water pipeline, consisting of a hydroelectric generator: an efficient water turbine with an energy storage system (Ma et al., 2018). The experimental results showed that at a flow speed of 0.8 m/s the maximum output power was 24 W with a water pressure drop of approximately 7 psi. A new shape of the turbine type was presented in Samora et al. (2016a), which the Instituto Superior Tecnico of Portugal developed. This turbine was placed in an 85 mm water pipeline where the maximum power obtained was 328 W, in conditions such as 1500 rpm turbine rotation speed, 48.15 m³/h, a pressure drop of 6.77 psi, and 51.45% efficiency. The relationship between the flow and efficiency, the hydraulic power (P_h), the mechanical power (P_{mec}), and the efficiency (η_h) are given by:

$$P_h = \rho g Q H \quad (13)$$

$$P_{mec} = \frac{2\pi N}{60} T_{mec} \quad (14)$$

$$\eta_h = \frac{P_{mec}}{P_h} \quad (15)$$

where ρ is the water density, g is the acceleration of gravity, Q is flowrate, H is the water head (pressure drop), N is rotation speed and T_{mec} is the mechanical torque.

A 135 mm turbine was used in the water pipelines of a 15 m building for energy harvesting. This device was then connected to a 12 Vdc generator (MMSRS et al., 2016). The authors recommended that the selected turbines should be of the Turgo or Pelton type for high-rise buildings. The maximum output power obtained in this experiment was 1.54 W. In Rödel et al. (2016), a MEH prototype generated up to 65 mW with a water velocity of 1.6 m/s inside a water pipeline, which had 80 mm in diameter and 2 m long. The efficiency achieved by this prototype was 0.55%.

9. Research findings

9.1. Benchmark and comparison of EH technologies

The EHs reviewed in this paper focused on supplying low-power devices such as wireless sensor nodes at the building level. However, there is a wide variation in the reported results of the power levels delivered by these devices due to factors such as the number of transducers, the combination of transducers of different harvesting technologies, shapes and dimensions of modules and prototypes, the intensity of radio frequency signals,

Table 3

Environmental energy sources and building potential sites/ building systems – reported power magnitudes from harvesters and their references.

Environmental energy sources Building potential sites/ building systems	Unit	Power magnitudes and references
Mechanical motion: Piezoelectric vibration		
HVAC systems	μW	37.45 (Elvira-Hernández et al., 2019), 83.5 (Guan and Liao, 2016), 200 (Petrini and Gkoumas, 2018), 400 (Gkoumas et al., 2017), 400 (Petrini and Gkoumas, 2018), 825 (Guan and Liao, 2016)
Floor panel	μW mW	66 (Cascetta et al., 2018), 70 (Kathalia et al., 2017), 770 (Hwang et al., 2015) 55 (Hwang et al., 2015)
Mechanical motion: Pendular oscillation		
Other possible systems/sites	mW W	1 (Punyakaew and Parnichkun, 2020), 23.2 (Punyakaew and Parnichkun, 2020) 0.4 (Marszal et al., 2017)
Mechanical motion: Electromagnetic induction		
Vibration mitigation systems	mW W	9 (Chunawala et al., 2016), 100 (Kecik and Mitura, 2020) 0.12 (Kecik, 2018)
Thermal Energy		
HVAC systems	μW	84 (Guan et al., 2017), 500 (Milić et al., 2017)
Exhaust systems	mW W	220 (Khalil and Hassan, 2020) 24.59 (Aranguren et al., 2017)
Light		
Indoor lighting	$\mu\text{W}/\text{cm}^2$	0.3 (Di Giacomo et al., 2016), 5.9 (Di Giacomo et al., 2016), 6.6 (De Rossi et al., 2015), 8 (De Rossi et al., 2015), 15.4 (Di Giacomo et al., 2016), 16.6 (Mathews et al., 2015), 17.6 (Mathews et al., 2015), 24 (Li et al., 2015), 75 (Li et al., 2015), 113 (Li et al., 2015), 570 (Li et al., 2015)
Facades	W	200 (Vasiliev and Alameh, 2019a)
Radio frequency		
RF signals	μW	17.76 (Taghadosi et al., 2017), 46.5 (Taghadosi et al., 2017), 57 (Shen et al., 2017)
Fluid flow		
Water pipelines	mW W	65 (Rödel et al., 2016), 720 (Hoffmann et al., 2013) 1.54 (MMSRS et al., 2016), 24 (Ma et al., 2018), 110 (Du et al., 2017), 328 (Samora et al., 2016a)

water pipeline sizes, and flow intensity, vibration, and lighting levels.

In recent years, wireless sensor networks have been expanding to buildings and other types of infrastructures, and even in urban areas. Also, the operation of sensor nodes in WSNs is becoming more efficient energy-consumption-wise. This will allow current EH developments to supply the necessary power to such nodes and possibly extend their batteries' lifetime.

This paper has identified and discussed both the modeling and experimental testing of EH prototypes for different potential power sources in buildings. We have focused on the experimental results in each EH studied. Table 3 shows some of the power magnitudes found in each of the potential sites and building systems by the harvesters in the present work. The information presented here would allow the reader to benchmark different EH technologies by the amount of power they can potentially generate under their specified operating conditions. The power magnitudes have been ordered in units of power such as μW , mW, and W. In the case of harvesters based on pendular oscillation, the column "Other possible systems/sites" has been identified. This is because the prototypes presented in Section 3 were designed and tested to take advantage of the vibrations that occur in places such as water reservoirs, swimming pools, water tanks, and electrical machines. It should be mentioned that the power magnitudes shown in the table are given according to the conditions established in their respective sections. Also, the power magnitudes have been ordered from lowest to highest in the column "Power magnitudes and references" in each application.

The harvesters reviewed in Table 3 can fulfill the purpose of supplying power by exploiting their respective environmental energy source, particularly when installed in sites within intelligent and smart building systems. Among all these technologies, the main differences are in the operating principles of the harvesters'

transducers and energy harvesting mechanisms. While no one solution or technology is applicable for all sites, the intent here is to show a variety of technologies that could be used in different scenarios or locations. In the rest of this section, some examples of EH technologies will be presented in descending order of potential power generation.

The highest power magnitudes were harvested in water pipelines and exhausted systems. Experimental tests on water pipelines reached magnitudes between 65 mW and 328 mW. These harvested powers depend mainly on the pipeline diameter and the size/power of the transducer used (electric turbine). On the other hand, TEGs show high potential for power harvesting in building exhaust systems. The magnitudes of power extracted in these systems were 220 mW, and 24.59 W. These results show that the stacking of these transducers plays a crucial role in improving the power supply to the sensor nodes.

In their power harvesting applications from pendulum oscillation and electromagnetic induction, harvesters are still in a current state of development. Few works in these fields were found in the literature within the scope of this work. The power ranges achieved with these technologies were from milliwatts to a few watts. The transducers of these revised harvester technologies consisted mainly of pendulum mechanisms exposed to vibrations. One pendulum system achieved a power of 0.4 W, considering changes in the distance between the shaft and the pendulum mass. Similarly, performing mechanical modifications on a pendulum system, the powers achieved were 1 mW and 23.2 mW. On the other hand, pendulum mechanisms with electromechanical induction devices reached higher power levels than the pendulum mechanisms previously mentioned. Here, the magnitudes achieved ranged from 9 mW to 0.12 W.

Much of the studies reviewed have been conducted on HVAC systems. In HVAC systems, the maximum power magnitudes

obtained were in the order of microwatts. The maximum power reached with TEGs was 500 μW while in PEHs it was 825 μW . The latter value was reached in the rotational mechanisms of these systems.

Similarly, other indoor areas such as the floor show the feasibility of generating power magnitudes with the harvesters reaching levels up to milliwatts. The power magnitudes harvested by the PEHs in their floor panel application were between 66 and 770 μW . Only one prototype reached a power of 55 mW due to four piezoelectric modules, including an indirect power transmission system. On the other hand, an RF harvester delivered a maximum power of 57 μW using the GSM-1800 radio frequency band. Other magnitudes achieved were 17.76 μW and 16.5 μW .

Also, the power density range obtained with indoor lighting was between 0.3 and 570 $\mu\text{W}/\text{cm}^2$. This last density was obtained with incandescent lighting; however, LED lighting is predominant in indoor environments. With this type of lighting, the densities achieved were 6.6 to 17.6 $\mu\text{W}/\text{cm}^2$. It is worth noting that building façades exposed to artificial and natural lighting, the solar cells would be able to generate higher power densities. However, compared to the other EH technologies, the focus has been on indoor lighting.

9.2. Potential of EHs for their use in WSNs

The results in Table 3 also show how some harvester technologies could fully cover the power requirements of some of the operating modes of the sensors in Table 1. For example, the air velocity sensor in Table 1 has a power consumption of 0.6 μW and 2.2 μW in its operating modes sleep and idle, respectively. PEHs installed in HVAC systems would instantly cover the power of this sensor because the reported power levels range from 37.45 μW to 55 mW. The harvester that supplies 55 mW could even cover the power requirement when the sensor is in RX mode. In the case of TX mode, the sensor node consumes 67.8 mW so it should draw power from the harvester and the battery. Here, we can see the reduction in battery usage, which would extend the battery lifespan. Likewise, all other harvester technologies could also fully cover the power of the sleep and idle modes of the air velocity sensor. The frequency of harvester power collection from the ambient power source is vital to meet the power requirements of the WSN nodes.

One of the challenges in some EH technologies is their constraint depending on the location where the WSN and sensor nodes would be installed. While the focus of this work is not on optimizing the location or selecting the most appropriate EH for each area, it is a constraint that needs to be addressed in the design stage of the WSN. For example, among the technologies reviewed that should have more precautions for their installations are MEHs. A MEH should preferably be installed with a bypass circuit to avoid disturbances in the water flow of the main water pipe. Furthermore, this setup is a safety measure if this device does not function properly. Likewise, floor panels with PEHs should be designed not to disturb the original floor. In the case of HVAC systems, PEHs must be installed without affecting the airflow in the ductwork such that there is minimum or no noise generation from fluid turbulence phenomena. These brief considerations are also vital for the correct operation of the harvester at each of their target sensor nodes.

9.3. Economic analysis

The literature reviewed showed no information regarding the economic analysis of the implementation of each harvester prototype. The authors of these papers indicated that some of the

harvester technologies such as PEH, MEH, TEG, LEH, and RF harvester demand low design and implementation costs for their application in buildings. However, they did not estimate or calculate these values or mention installation costs. Also, no maintenance costs were mentioned in technologies that have moving parts such as MEH and EEH. The prices of these technologies are a limitation that has also been presented in the literature (Gholikhani et al., 2020).

The motivation for these harvester technologies is to generate power using low-cost transducers and simple prototype electronic circuits. However, the implementation costs of a sensor node will rise with the use of a harvester. For example, compared to a conventional (battery-powered only) sensor node in a WSN, we can assure that the harvester and battery-powered node will register an increase in the initial investment costs for implementation in its WSN. This is because the new transducer and electronic circuit, which will work in parallel with the sensor node battery, will demand additional costs related to its purchase and assembly. In addition, stacking transducers to improve the power supply to the sensor node is another consideration that can raise installation costs.

9.4. Challenges and opportunities

9.4.1. Piezoelectric energy harvesters

Future studies of PEH applications in ductwork systems should focus on understanding the effects of airflow dynamics on these devices in different configurations (prototypes). Likewise, the use of rotational energy in some parts of these systems and other building machinery is a potential place for using these types of solutions. The performance of PEHs according to the rotation speeds of these systems is also a topic that should be studied in future research. On the other hand, the assembly and housing of these harvesters in HVAC systems still presents issues that must be solved in the future.

The assembly and encapsulation of PEHs inside floor panels still present issues that should be addressed in the future. In addition, the power generated from floor panels dramatically fluctuates depending on the location and walking patterns of people throughout the building, limiting the potential to power sensors continuously. The development of new studies related to the mechanical effects of vibrations caused by footsteps on floor panels and their power generation is essential for advancing this technology.

9.4.2. Electromagnetic energy harvesters

The prototypes EEHs applied to vibration control systems show the largest dimensions compared to the prototypes of the other technologies. Therefore, it is possible to obtain higher powers from these systems. However, the large sizes required for these types of systems invalidate their use for powering WSNs, as the location of the sensor nodes will likely be constrained in space. Nonetheless, EEH can still be used for powering other systems inside buildings. Additional improvements such as adding pendulums with EEH can help mitigate vibrations and produce low power. Also, the estimation of the coupling coefficient is a factor of vital importance in the performance of these systems. This coefficient is assumed to be fixed in many studies, leading to inaccurate results (Kecik et al., 2017). Therefore, researchers should identify functions to appropriately choose the coupling coefficient according to the magnet's position (or velocity).

The improvement of EHs from pendular oscillation depends greatly upon high-performance electrical generators. Further research efforts should improve the mechanical coupling between the pendulum mechanism and the electric generator to minimize potential losses caused by the reciprocating system. Likewise, gaining more insight into the dynamics of the entire mechanism of the pendulum (crank rotation plus pendulum oscillation) could significantly improve the power recovery from the system.

9.4.3. Thermoelectric energy generators

The main challenge facing TEGs for WSN is the nominal temperature and temperature differential required for power generation, which may affect the operation of a sensor node is located near this ambient source. In addition, the assembly and clamping of the hot and cold sides of each TEG (or module) on the pipes of the HVAC systems present issues that still need to be improved to achieve higher temperature differentials. The advancement of these technologies in their various applications depends on enhancing their manufacturing materials.

Developing larger prototypes with TEGs can produce higher power densities in HVAC systems. Because of this, this technology is a convenient choice for effectively using waste heat in such scenarios. This allows TEGs to be a promising EH application for powering different energy systems in buildings. Further experimental studies and modeling should be conducted for the TEG application, mainly focusing on understanding the interaction between flue gas parameters (temperatures, gas flow rates) and these devices from the base to the exit of the chambers.

9.4.4. Light energy harvesters

Light energy harvesters combined with batteries have a great potential to be used to power nodes in WSNs. The availability of indoor artificial light throughout most of the building environment during most of the workday (and sometimes even at night) might allow the continuous operation of sensor nodes. One challenge would be to ensure the solar cell is not obstructed from direct ambient lighting. This configuration must also consider replacing the battery at the end of its life, increasing implementation costs. Furthermore, solar systems in buildings' façades are a well-established technology that can supply a significant percentage of the building's load, provided sufficient solar radiation is available throughout the year. Currently, considerable research efforts seek to improve the materials for solar cells to achieve higher power densities. Amorphous silicon and dye-sensitized cells are of particular interest for indoor applications due to considerations such as flexibility, weight, pricing, and environmentally friendly manufacturing materials (Kim et al., 2019).

9.4.5. RF harvesters

RF harvesting technology is considered fundamental for improving power supply in sensor nodes and low-power devices in the field of IoT. Further research efforts in this technology field could enable the development of RF harvesters to supply long-term small amounts of power without incurring health and safety risks from electromagnetic exposure of living beings. The optimization of the components of this harvester is fundamental to obtain maximum efficiency while also considering other factors such as the magnitude of the transmitted powers, antenna gains, transmission distances, and operating frequencies. Also, the study of RF harvesters with several antennas for extracting energy from various bands in the RF spectrum will improve the power delivered to sensors.

9.4.6. Microturbine energy harvester

While MEHs have proven to be useful for various applications in buildings, one of their main constraints for their application in WSNs is their restriction to work in locations where water flow is present. This may limit the operation of these EHs in some sensor node locations. In addition, the output power of MEHs could be determined by the intermittent and unexpected water flow behavior. To compensate for the variability in generation, a battery or storage device may be used.

The suitable selection of the microturbine is essential for collecting water flow in the building water pipelines. The energy

harvesting of water flow in domestic pipelines should include bypass circuits to avoid disturbance of the main water flow or the risk of these harvesters falling into the main pipeline, mainly because these pipelines are generally small in diameter. Similarly, the development of new types of propellers will improve the rotation speed of the microturbine, which will increase the performance of the MEH. Since these harvesters are intrusive, they will provoke a pressure drop as any other fitting does on a piping system. Therefore, the installation of these devices on buildings should be in strategic places where the collected energy is larger than the additional pumping energy required for the proper operation of the piping system, or on large piping systems where the pressure loss would be relatively small, or on places where there is constant overpressure.

10. Conclusions

The EHs reviewed in this paper have strengths, but still, these technologies suffer from the intermittency of their environmental power sources. From the literature review, the authors of this paper have not found a single harvester technology that can completely replace the use of batteries. Therefore, harvesters still need to be coupled with batteries to provide power to the sensor node continuously and stably. Also, Section 9 demonstrates that the energy harvested by these devices in the building environment and building systems can supply power to the sensor nodes. Even these could completely cover the power required in their operating modes, such as sleep and idle in Table 1, verified by the results shown in Table 3. Similarly, EHs could increase their power harvesting levels by stacking transducers of the same technology or developing electronic harvester circuits that use two or more transducers of different physical operating principles.

The possibilities of extending the lifetime of sensor node batteries are a reality. Through further research in the field, EH technologies could be developed in the future as harvesters that could ultimately replace batteries. This latter is of vital importance since extending the use of a battery in a sensor node, or any electronic application will reduce the risk of contamination if this device is not handled/disposed of correctly. The pollution generated by disposing of batteries in landfills is harmful to all living things. Also, reducing the frequency of battery changes in the location of the sensor nodes will reduce costs. Therefore, it is critical to develop science and technology focused on improving the performance of harvesters.

The sections of this paper have given some guidance on where studies should be focused to improve harvester performance. The presented works analyzed harvester configurations applied in the building environment. Here, the research findings determined the magnitudes of power harvested by these devices. Still, we can easily intuit that much of the improvement of these technologies will depend on the development of advanced materials of construction and shapes of transducers and their assemblies and encapsulations, such is the case of technologies based on PEH, TEG, LEH and MEH. Similarly, in harvesters based on oscillation mechanisms exposed to vibrations, the development of electromechanical couplings will allow a more efficient power transfer during their operations. The same happens with the EEH, where functions should be sought to appropriately choose the coupling coefficients according to the movement of their magnets. In summary, the improvement of these devices will allow sensor nodes to permanently monitor building systems and their different areas of coverage, which is the fundamental basis for improving the energy efficiency of buildings.

According to the present study results, we believe that one of the technologies that could achieve this purpose in the future is RF-based technology, which still needs to be extensively

studied. These studies should be mainly focused on the fact that these devices do not increase the power consumption of RF transmitters and that the massification of these harvesters does not incur health and safety risks from electromagnetic exposure of living beings. This is because everyday Wi-Fi coverage in buildings improves with electronic devices such as the so-called “Wi-Fi repeaters”. RF harvesters could harvest energy even in the farthest places of facilities where other technologies based on piezoelectric, thermoelectric, photoelectric, and other transducers could not be applied.

The trend in building design nowadays points toward becoming more intelligent. This will be achieved through more efficient real-time monitoring and advanced control of each of the processes at the building level. Here, wireless sensor nodes play an essential role in intelligent buildings. Likewise, the expansion of these sensor networks will depend upon advancements in intelligent buildings, the internet of things, smart grids, and smart cities. However, a well-known limitation in WSNs is the power supply at the sensor nodes. Still, EHs will help increase the lifespan of these networks not only in the building environment but also in other types of infrastructure and even in urban areas.

The reviewed works do not show a detailed analysis of the implementation costs of each harvester technology. These works were focused on providing a technical analysis of the power harvesting magnitudes of the EHs under certain operating conditions.

Even though we have attempted to produce a comprehensive survey, many issues on EHs in buildings have not been fully covered due to the broad scope and topics, such as additional types of EHs and other environmental energy sources, applications in different sites and systems of the building, improvement of transducer materials, outdoor applications, development of other experimental prototypes, improved control systems for EHs, and hybrid EHs.

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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