

Review

# A Review of Energy Harvesting Techniques for Low Power Wide Area Networks (LPWANs)

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**Abstract:** The emergence of Internet of Things (IoT) architectures and applications has been the driver for a rapid growth in wireless technologies for the Machine-to-Machine domain. In this context, a crucial role is being played by the so-called Low Power Wide Area Networks (LPWANs), a bunch of transmission technologies developed to satisfy three main system requirements: low cost, wide transmission range, and low power consumption. This last requirement is especially crucial as IoT infrastructures should operate for long periods on limited quantities of energy: to cope with this limitation, energy harvesting is being applied every day more frequently, and several different techniques are being tested for LPWAN systems. The aim of this survey paper is to provide a detailed overview of the existing LPWAN systems relying on energy harvesting for their powering. In this context, the different LPWAN technologies and protocols will be discussed and, for each technology, the applied energy harvesting techniques will be described as well as the architecture of the power management units when present.

**Keywords:** energy harvesting; LPWAN; IoT; LoRa; LoRaWAN; Sigfox; DASH7; NB-IoT

## 1. Introduction

The rapid growth of Internet of Things (IoT) applications and markets has been the main driver for the emergence of a wide range of innovative data transmission technologies, whose main objective is to satisfy a different set of requirements with respect to the ones typically targeted by human-centered personal communication devices. In this sense, while the key features for traditional Internet-based systems are low latency, large bandwidth, and high bit rates, for IoT-based architectures the crucial requirements turn to be low power, low cost, and large transmission ranges.

In order to fulfill these requirements, in the last years several novel technologies have been developed, leading to the definition of a novel category of data transmission technologies, the so-called Low Power Wide Area Networks (LPWANs). As the name suggests, all the technologies belonging to this family aim at targeting two of the features listed before, i.e., the low power consumption and the large transmission range; nevertheless, while the third requirement, the low cost, it is not explicitly cited in the denomination, it is still fulfilled by every LPWAN technology as, within the IoT vision, which foresees the presence of billions of interconnected objects all around the world, the low cost of the devices as well as of the connections is intrinsically mandatory to make these technologies actually employable.

LPWANs currently include proprietary and open platforms, cellular and non-cellular technologies, systems operating in the unlicensed Sub-GHz bands as well as in LTE licensed bands [1]. While the most widespread LPWAN technologies currently are Long Range (LoRa), SigFox, and Narrowband-IoT (NB-IoT), a plethora of other solutions can be found on the market, and it is foreseeable that a large number of novel technologies will emerge in the next years with the pervasive adoption of IoT systems

as well as with the emergence of novel cellular standards, not only within the upcoming 5G framework, but also with future sixth-generation technologies.

In general, as anticipated all LPWAN technologies fulfill the three requirements listed before, i.e., long range, low cost, and low power. Concerning long range, all LPWAN technologies are usually able to wirelessly transmit data from distances up to some kms in urban areas and some tens of kms in rural areas: these performances allow to set up large scale data acquisition infrastructures which are crucial in several application scenarios, as for example the Smart City and the Smart Industry ones. The term Smart City encompasses all those technological infrastructures that, thanks to the information and communication technologies, allow to optimize and make more efficient the daily processes that take place in urban environments, like, for example, traffic, waste management or public transport [2]. Data transmission in these contexts is usually required at a city scale, that means coverages that are in the order of the tens of square kms. As for an example, the Historic Centre of Rome has an approximate extension of 20 km<sup>2</sup>, making thus impossible to cover such a large area with more traditional transmission technologies like WiFi, Bluetooth or ZigBee. Conversely, tests proved that with LPWAN technology it is possible to cover the centre of a medium sized city with even a single access point [3].

Regarding the second requirement, i.e., low cost, LPWANs are seen as an alternative to traditional cellular networks due to the lack or to the limited presence of subscription costs: in any case, even when a fee is required, the cost is proportional to the small amount of data to be transferred. This means that it is by far lower than the rates applied by the mobile operators and becomes sustainable even when a large quantity of interconnected devices has to be deployed. Moreover, the cost of the radio modules is also very low, usually in the order of few euros for the transmitting devices and of few hundreds of euros for the gateways which are in charge of receiving and managing the transmitted messages for that technologies which are not provided with a proprietary infrastructure.

The third requirement, i.e., the low power, is probably the most significant one. Indeed, any kind of IoT infrastructure is based on the integration of a large number of interconnected devices that are in charge of acquiring data, often in remote places where the connection to an electrical grid is technically unfeasible. Moreover, in those cases where connections to the grid are available, as, for example, in Smart Home scenarios, the number of devices to be powered makes a wired connection practically unachievable. Only two alternatives are then viable: the use of batteries or the exploitation of any kind of renewable energy by means of harvesting solutions. Batteries can be a convenient option due to their low cost; nevertheless, they require to be replaced and, in case of non-rechargeable ones, they must be disposed after being used, with a not negligible environmental impact. Instead, energy harvesting represents an eco-friendly alternative, and as many sources of energy are constantly available, it allows to continuously power interconnected devices for long periods without requiring any human intervention. For these reasons, energy harvesting systems have always been applied to interconnected devices, in particular within Wireless Sensor Network (WSN) architectures, that can be seen as the forerunners of the more complex distributed IoT infrastructures based on LPWAN technologies. Regarding LPWANs, in the last years several energy harvesting based solutions have been proposed in literature, exploiting a wide range of different power sources. The aim of this paper is then to provide a structured survey of the existing solutions, focusing on the architectures of the proposed systems, as well as on the application scenarios, in order to point out the features of the harvesting techniques developed to power these kinds of interconnected devices. To this end, the literature was surveyed by resorting to appropriate keywords, as it will be explained later on, and by excluding works published more than five years ago. The outcome of this search were works describing energy harvesting systems along with their integration within the chosen network architecture. In so doing, several papers were taken into account and 44 of them will be analyzed in the core of this review paper. Besides these contributions, some others will be treated as well, as they deal with energy harvesting techniques by tackling the theme from a more general point of view.

Therefore, a comprehensive review of the existing energy harvesting solutions for the powering of LPWAN-based monitoring systems and architectures was drawn up.

The rest of the paper is structured as follows. Section 2 reports the research methodology that was followed in order to draw up this review. Section 3 provides a detailed overview of the most common LPWAN technologies, with a particular focus on the LoRa technology, and the associated LoRaWAN protocol, which currently represents the most widespread solution, and the one to which the most part of the works found in literature are related to. Section 4 provides an overview of the energy harvesting techniques developed for WSN architectures, and Section 5 is the core of the paper and surveys the existing harvesting solutions for LPWANs. Section 6 discusses the main topics that arose during the review, and Section 7 provides some conclusive remarks.

## 2. Research Methodology

The review of the state-of-the-art concerning energy harvesting techniques exploited in LPWAN-based applications was conducted consulting the most common tools for the research of scientific papers and contributions: *Elsevier Scopus*, *Google Scholar*, and *IEEEExplore*. In order to identify the suitable contributions, the research was conducted on the three tools using the following keywords; *LPWAN Energy Harvesting*, *LoRa Energy Harvesting*, *LoRaWAN Energy Harvesting*, *SigFox Energy Harvesting*, *Narrow Band IoT Energy Harvesting*, *NB-IoT Energy Harvesting*, *DASH7 Energy Harvesting*, *Weightless Energy Harvesting*, *IoT Energy Harvesting* and *Internet of Things Energy Harvesting*. For each of these keywords, at least 100 papers were examined. For the most significant ones (i.e., *LPWAN Energy Harvesting*, *LoRa Energy Harvesting*, *LoRaWAN Energy Harvesting*, *IoT Energy Harvesting* and *Internet of Things Energy Harvesting*) at least 200 papers were analyzed.

In order to be discussed in this work, only works describing the energy harvesting subsystem and its actual integration in a LPWA network architecture were chosen. Following this selection phase, a total number of 44 papers were discussed in Section 5: these contributions are to the best of our knowledge the only ones that satisfy the inclusion requirement. Apart from these papers, a few other contributions were found, integrating off-the-shelf solar panels in LoRa sensor nodes, without describing however the harvesting system architecture. We decided not to include them in the survey as solar-powered LoRa systems are the only ones that are relatively common and, at the level of description of those works, were reputed of few interest for what concerns the target of this survey.

## 3. Low Power Wide Area Network Technologies

A dichotomous listing of LPWAN-enabling technologies could be the one amid cellular and non-cellular standards: the former ones are license-based while the latter ones are license-free. As a direct consequence, adopting cellular technologies entails pretty high running costs due to subscription to plans provided by telecom operators. Therefore, adopting these solutions may be hardly feasible whenever connectivity has to be provided to a large quantity of objects. However, the most favorable benefit that such technologies offer is that very wide coverages are ensured along with very little data losses and low latency, such that lack of connectivity does not turn out to be an issue any longer. On the other hand, license-free technologies are cheaper than cellular ones, at least most of the time. This is due to the fact that they exploit the spectrum belonging to Industrial, Scientific, and Medical (ISM) bands. Such frequencies are unlicensed though; therefore, they are intrinsically subject to interference that can hinder link quality. For the same reason, coverage of unlicensed technologies is relatively restricted and data losses could be only limited but not avoided. Another peculiarity characterizing license-free technologies is that their carrier frequencies are region depending. This means that hardware devices need to be carefully designed bearing in mind the place in which the network will be deployed. Conversely, cellular technologies are usually not affected by this issue. Hereinafter, some of the most important LPWAN enabling technologies are listed and briefly described while at the end of the Section they will be recapped in Table 1. A similar approach was followed in a review paper of few years ago [4] that performed a comparable contribution with respect to the one reported in this

Section and in this review in general. Therein, LPWAN technologies (either cellular and non-cellular, although the latter ones were treated more in detail) to be exploited within IoT contexts were reviewed by focusing on each specification peculiarity and suitability for different IoT paradigms so as to meet the relative requirements. In addition, design specifications of LPWANs were surveyed along with the fact that challenges, future insight and research directions were pointed out too.

### 3.1. LoRa

In 2012, The American company Semtech developed the Long Range (LoRa) modulation and since that moment it held the relative patent. LoRa is a robust technology allowing for quite wide coverage. Such features are allowed by the modulation fundamentals: indeed, LoRa is grounded on the Chirp Spreading Spectrum (CSS) modulation and adopts the Additive Links On-Line Hawaii Area (ALOHA) technique to access the communication channel (i.e., transmission may occur at any time). It is currently managed and controlled by the LoRa Alliance that is a consortium composed by more than 500 companies coping with hardware as well as software. This association periodically issues successive releases of the Long Range Wide Area Network (LoRaWAN) standard: a MAC layer communication protocol having LoRa modulation as physical layer. In contrast to the fact that LoRa is a proprietary modulation by which Semtech collects royalties from chip vendors embedding LoRa modules in their own boards, LoRaWAN standard is openly accessible. On the other hand, LoRaWAN is not the only standard built on top of LoRa technology, indeed Link Labs developed an alternative LoRa-based LPWAN. As it was previously mentioned, LoRa is a long range wireless technology allowing coverage extending from few kilometers in urban areas, up to tens kilometers in rural environments. Moreover, like other LPWAN standards, LoRa features single-hop communications within star topologies networks.

### 3.2. Sigfox

Sigfox is a French company having more than 10 years of activity during which Sigfox networks have been set up and run all around the world by operating on different sub-GHz ISM bands according to the region. Users exploiting the network are required to pay a subscription which varies depending on different plans. Sigfox is designed following the paradigm of star topology allowing for either uplinks and downlinks during which small size payloads (i.e., at most 12 B) can be transmitted. This turns out to be a major drawback along with a limited number of maximum transmitted packets per day in relation to the subscribed plan. On the other hand, a big benefit Sigfox provides is that it offers a full network infrastructure and a cloud service to collect, retrieve and analyze all the incoming data. Therefore, the only concern users have to deal with is the design and the realization of sensor nodes because all of the heavy lifting is accomplished by Sigfox itself. For what concerns bandwidth and data-rates, Sigfox requires extremely narrow band (i.e., 100 Hz) and it only allows for pretty slow data-rate (i.e., 100 bps). Finally, Sigfox makes use of the Binary Phase Shift Keying (BPSK) modulation and of the Random Frequency Time Division Multiple Access (RFTDMA) technique to access the channel.

### 3.3. DASH7

DASH7 is an open source protocol for LPWANs and, in general, for WSNs. It exploits three sub-GHz ISM bands (i.e., 433 MHz, 868 MHz, and 915 MHz) and its main features are extended battery lifetime due to limited consumption, quite large coverage range, low latency especially for moving nodes, and fairly high data-rate (i.e., up to 167 kbps). Moreover, DASH7 allows for bidirectional communications. DASH7 inherits its default parameters from the ISO 18000-7 standard and boosts the latter by defining a full communication stack starting from the physical layer up to the application one. DASH7 is also known as BLAST network technology due to the acronym of its principal attributes: Bursty (i.e., short and sporadic sequences of data are transmitted), Light (i.e., packet size is limited to 256 B), Asynchronous (i.e., there is no periodic synchronization within the network),

Stealth (i.e., the nodes only communicate towards pre-paired gateways) and Transitive (i.e., nodes may freely move within the environment and, at the same time, do not lose connectivity). Such a standard is managed and distributed by the DASH7 Alliance that is a nonprofit consortium made of either companies and universities. DASH7 exploits Gaussian Frequency Shift Keying (GFSK) modulation and provides for either a star, tree or node-to-node network topology. Concerning the MAC layer, DASH7 makes use of Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol.

#### 3.4. Ingenu

More than a decade ago, Ingenu was released and it was an innovative technology within the LPWAN framework as it exploits ISM bands having higher carrier frequencies than, for instance, Sigfox: Ingenu, indeed, runs at 2.4 GHz, thus sharing the same frequency of Bluetooth or WiFi. Such a feature entails pros and cons: this is an ISM band which is globally unlicensed thus developers do not have to think about the region their products will be employed; in addition, such a band allows for broader bandwidth in comparison with other sub-GHz ISM bands. On the other hand, though, within such a band link quality is worse than different sub-GHz frequencies due to the physics of the problem. Together with Differential Binary Phase Shift Keying (D-BPSK) modulation, the essence of Ingenu LPWAN is its proprietary and patented technology: the Random Phase Multiple Access (RPMA) that is either a physical and a Medium Access Control (MAC) layer. RPMA was specifically designed so as to meet the requirements of an LPWAN: long battery lifetime thanks to limited consumption, robustness towards interference, and wide coverage and high capacity of a single RPMA access point. Additionally, RPMA technology is also suitable to deal with bidirectional communication and broadcast transmission. Concerning the network infrastructure, Ingenu offers a full architecture likewise Sigfox does. Eventually, Ingenu also set up the first wireless machine network that is the largest IoT network worldwide which is especially dedicated to provide connectivity for machine. Sadly, though, such a facility was only established in few dozens of cities, the bulk of which are located in the US.

#### 3.5. Weightless

Weightless has been managed by the English Weightless Special Interest Group since 2012 and it encloses a set of wireless enabling technologies for LPWANs because, at its beginning, three standards were issued: Weightless-P, Weightless-N, and Weightless-W. However, as time goes by, two of those standards (i.e., Weightless-N and Weightless-W) were deprecated: Weightless-N only allowed for uplinks thus it was a monodirectional communication technology, while Weightless-W was devised to work within the unexploited frequencies belonging to the TV bands (i.e., 470 ÷ 790 MHz). Therefore, Weightless-P (or simply Weightless) is the only outlasting standard: it is a bidirectional standard requiring narrow band to run and occupying all of the frequencies belonging to the unlicensed ISM sub-GHz bands (i.e., 163 MHz, 433 MHz, 470 MHz, 780 MHz, 868 MHz, 915 MHz, and 923 MHz). Moreover, Weightless is also an open standard that adopts both the Gaussian Minimum Shift Keying (GMSK) and the Offset Quadrature Phase Shift Keying (OQPSK) modulations and the Time-Division Multiple Access (TDMA) scheme to access the communication channel.

#### 3.6. LTE-M

Long Term Evolution (LTE) Machine Type Communication (LTE-M) operates, focusing on Machine-to-Machine (M2M) communication and IoT, by using the cellular LTE standard. Therefore, it is fully compatible with actual cellular networks. Indeed, telecom companies do not necessitate any additional device to be installed as they just have to update the firmware running on their base stations to the newer versions. Because of this, there exist some telecom providers that have already started activating such services making some experiments. In comparison with standard LTE, it offers optimized sleep modes from the point of view of consumption resulting in higher power budgets. Amid the cellular LPWAN technologies, LTE-M has the highest data-rate. However, it requires the

broader channel band. It exploits the 16 Quadrature Amplitude Modulation (16-QAM) and, for what concerns the channel access, it makes use of two methods stemming from the Frequency Division Multiple Access (FDMA): Single Carrier FDMA (SC-FDMA) for uplinks and Orthogonal FDMA (OFDMA) for downlinks.

### 3.7. NB-IoT

Notwithstanding that NB-IoT and LTE-M come from the same organization (i.e., the 3GPP), they differ for several aspects. First, NB-IoT has smaller data rate and narrower bandwidth than LTE-M. Second, NB-IoT does not necessarily work within LTE bands: it is designed to operate in a subset of LTE bands or even in the unexploited Global System for Mobile (GSM) bands. Even though it has lagged behind LTE-M, more and more telecom firms are investing on it at the moment. It has been notably used especially in Europe where it is finding its IoT alcove (e.g., asset tracking). NB-IoT standard specifications aver that it requires less power than LTE-M. This is a double-edged sword though: being thrifty from the point of view of consumption is always a good feature wherever sensor nodes relying on batteries are employed, but it also means having a worse penetration capability through obstacles. Regarding the physical layer, it may exploit both the Quadrature Phase-Shift Keying (QPSK) modulation and the Binary Phase-Shift Keying (BPSK) modulation. For what matters to the access to the channel methods, it shares all of them with LTE-M.

**Table 1.** LPWAN main enabling technology comparison.

	Type	Frequency Band [MHz]	Data-rate [kbps]	Channel Bandwidth [kHz]	Message Payload [B]	Coverage Range [km]
<b>LoRa</b>	Non-cellular	433 (CN) 868 (EU) 915 (US, AU)	0.3 ÷ 50	125 250 500	≤255	≈5 (urban) ≈15 (rural)
<b>Sigfox</b>	Non-cellular	868 (EU) 902 (US) 920 (AU)	100	100	≤12	≈40
<b>DASH7</b>	Non-cellular	433 (CN) 868 (EU) 915 (US)	9.6, 55.5 or 166.6	25 or 200	≤256	≈5
<b>Ingenu</b>	Non-cellular	2400	624 (uplink) 156 (downlink)	1000	≤10,000	≈45
<b>Weightless</b>	Non-cellular	Any sub-GHz ISM band	200 ÷ 100	12.5	≤48	≈2
<b>LTE-M</b>	Cellular	LTE bands	1024	1400	≤256	≈5
<b>NB-IoT</b>	Cellular	LTE subset bands	250	180	≤1600	≈1 (urban) ≈10 (rural)

## 4. Energy Harvesting Techniques for Wireless Sensor Networks

Sensor nodes belonging to LPWANs, or more generally to WSNs, typically rely on a limited source of power (e.g., batteries), which can act either as the only powering method or as a backup source. Nodes falling in the first case necessarily have to put into practice energy saving strategies (e.g., effectuating duty cycling or embedding low power components) in order to extend their lifetime. On the other hand, for nodes that are part of the second case it is fundamental to contrive energy harvesting techniques. Regardless of this distinction, equipping nodes with an energy harvesting system, whenever the deployment environment consents it, is always a serviceable method to extend their lifetime [5–7] as well as to reduce both human intervention for maintenance and environmental impact by decreasing the amount of batteries requiring disposal. However, the optimum would be to design self-powered sensor nodes [8] but this is extremely tough and, most of the time, it turns out to be challenging or even unfeasible.



In the case of outdoor operative scenarios, the most immediate renewable source of power is the solar one and a way to exploit it could be to provide nodes with photovoltaic cells. Such systems are grounded on a common structure: a rechargeable battery and a solar panel are simultaneously controlled by a Battery Management System (BMS) with the aim of correctly powering a device acting as load. In other words, the solar panel is exploited as a primary source of energy for either recharge the battery and power the load; whenever irradiation decreases (e.g., during nights or rainy and cloudy weather) the BMS disables solar panels and enables the battery (which, in the best cases should be fully charged) to power the load until favorable weather conditions occur once again. For instance, BMSs may be realized by employing circuits for Maximum Power Point Tracking (MPPT), that is, an algorithm guaranteeing that the load can utilize the almost peak power produced by the solar panel, thus obtaining an intelligent BMS carrying out its tasks thanks to hardware components rather than software instructions [9]; however, similar outcomes could be achieved by resorting to Pulse Width Modulation (PWM) in place of MPPT [10]. As a direct consequence, photovoltaic and solar panels should be thoroughly designed and identified. Indeed, sizes are not always directly proportional to performances as manufacturing processes and constructing materials play a key role [11]. Moreover, photovoltaic panels performances could be enhanced by supplying panels with cooling systems [12]. Without losing consistency, photovoltaic energy harvesting may be also employed within indoor environments provided that ad hoc systems are adopted [13,14]. Concluding, the literature has plenty of examples resorting to solar energy harvesting techniques to power WSN nodes due to the fact that it is straightforward. Instances range from simple and cheap solutions [15] to energy efficient and optimized alternatives [16] or systems aiming at maximizing sensor nodes lifetime [17].

One of the most instantaneous effects of sunlight is the occurring of heat and such a phenomenon may be exploited for energy harvesting too. Indeed, whenever a thermal gradient (i.e., a temperature difference) between two ends of a thermoelectric material is experienced, charges moving through the material due to heat generate a thermoelectric effect. Charges migrate from the hot junction towards the cold one causing a potential difference: this phenomenon is also known as Seebeck effect [18]. The interesting aspect of this technique is that it can be put into effect not only in situations in which heat is caused by sun rays, but whenever a thermal gradient arises due to the most disparate sources. For instance, in automotive applications, energy autonomous sensor nodes may be designed [19] exploiting the heat produced by the engine. Another idea could be that also heat dissipating by electronic devices could be harvested [20], or even exploiting thermal gradient within scenarios in which temperature monitoring is accomplished [21].

Another renewable source of energy available outdoor that can be exploited for energy harvesting purposes is wind. Aeolian harvesting systems commonly work exploiting windmills acting on DC motors: indeed, by resorting to reversibility, the latter ones behave as generators whenever the shaft is rotated by external torques. Ideally, due to such a property, a voltage at motor leads that is linearly dependent on the number of revolutions of the shaft is generated. However, such a phenomenon may also end up in a drawback: if wind speed would not be constant, as it could likely happen, voltage would not be constant too. Therefore, it would not be suitable for directly powering a DC sensor node. To this purpose, an optimized AC/DC buck-boost converter for aeolian energy harvesting was investigated [22]. Another shortcoming that is implicitly entailed by aeolian harvesting is that performances of such a technique is strongly depended on wind forecast, therefore a system that automatically copes with this issue may be useful [23] or, alternatively, setting up a method to predict power provided by wind could be a remedy as well [24].

Hydroelectric and aeolian harvesting share a similar scheme. Indeed, the main difference is that water flowing within pipes or conducts causes the production of energy rather than wind. Indeed, water pushing on mill blades causes mill rotation which is exploited to generate electricity by resorting to DC motor reversibility property as it happens in aeolian harvesting systems. The use cases may be various; however, this technique provides the best performances whenever it is exploited in scenarios in which water is forced to flow inside pipelines as it causes a pressure increase which directly

implies a greater amount of harvested energy. For instance, this strategy may be suitable for sensor nodes accomplishing the measurement of flow rates within pipes in domestic applications [25] or even for environmental monitoring issues inside underground Medieval aqueducts [26]. Concerning energy harvesting from sea waves, several studies proved its feasibility. Such a technique has a wide application within sensor nodes that are offshore deployed, either floating or underwater, as it is commonly inconvenient to reach such devices to perform maintenance procedures. Harvesting energy from sea waves is feasible as oscillations stemming from such a motion may be converted in electrical energy [27]. Moreover, that phenomenon may be enhanced by resorting to duck-shaped structures [28].

Energy harvesting from sea waves inherits similar concepts that are adopted in systems harvesting energy from mechanical vibrations: indeed, both the sources of energy cause oscillations that are converted in electric power for running sensor nodes. Such a task is achieved by making use of piezoelectric crystals: they are materials characterized by the property that whenever they are subject to a mechanical deformation, a voltage is generated and vice versa. Therefore, this sort of harvesting could be exploited in a various number of scenarios presenting vibrating objects: vehicles [29], aircrafts [30], vibrating machineries [31], bridges [32], mainframe computers stacked in racks within data centers [33], or even in underwater environments [34]. Moreover, piezoelectric harvesting does not necessarily require either objects strongly vibrating [35] or bulky devices [36] thus making it widely suitable. In addition, piezoelectric materials stand at the base of acoustic energy harvesting [37,38] in which mechanical deformation is provoked by air waves generated by acoustic signals. However, acoustic harvesting may be also performed by falling back on Helmholtz resonators [39].

An alcove of WSN is the one related to wireless network whose nodes are attached to human body becoming wearable sensor nodes: the so called Wireless Body Area Networks (WBANs). Even in this context there exist harvesting techniques [40]. In particular, they exploit human body activities (e.g., movement [41,42], pace [43], and so on) in order to power sensor nodes. In other words, any of the methods that were developed for harvesting energy in a broad sense may be transplanted within the framework of WBANs.

Electromagnetic fields may be also harnessed for energy harvesting purposes. Such an idea is the basis on which wireless power transfer is grounded: nowadays this technique is massively adopted in docking stations that are capable of simultaneously charging several sorts of devices (e.g., smartphones, tablets, smartwatches, and so on). From a theoretical point of view, electromagnetic energy harvesting is ruled by Faraday law of induction stating that the variation of the flux of a magnetic field that is concatenated with an electrical circuit causes an induced electromotive force in the circuit itself generating a current opposing the flux variation gave rise to it. Therefore, multiple sources of dynamic electromagnetic field may be considered for energy harvesting: high voltage cables [44], power cables for smart grids [45], human body motions [46], antenna panels of satellites [47], and many more.

## 5. Energy Harvesting Techniques for LPWANs

In this section, we will discuss the existing literature focusing on energy harvesting solutions for LPWAN-based systems. While the research methodology was already presented in Section 2, before discussing the survey we would like to point out that the works were selected according to the principle that the presented results should be focused on the description of a working network architecture whose sensor nodes are powered by means of energy harvesting. For this reason, several works focusing only on the harvesting technique without contextualizing it within a specific LPWAN infrastructure were not taken into account. Similarly, we do not take into account works dealing with transmission technologies that fall within the IoT context but cannot be classified as LPWAN (e.g., Bluetooth Low Energy or WiFi).

This choice is justified by the fact that some surveys focusing on energy harvesting techniques for IoT in a broader sense have been already proposed. In particular, a preliminary analysis of energy harvesting techniques to be employed to power up wirelessly connected devices within the IoT framework is proposed in [48], while a deeper analysis of the state-of-the-art is faced in [49]. In this



review paper, all the possible harvesting techniques for IoT devices are analyzed in detail, focusing on a wide range of works that partially includes some LPWAN-based architectures.

As the focus of this review is not only on the harvesting techniques, but also on the transmission technologies, we decided to structure this section according to the different LPWAN standards. While a large part of the reviewed papers exploits the LoRa technology and the LoRaWAN protocol, the related subsection has been furthermore structured according to the harvesting principle. The other subsections focus on SigFox, DASH7, and cellular technologies. Regarding other LPWAN solutions, like Ingenu or Weightless, to the best of our knowledge the literature lacks of works dealing with energy harvesting solutions to power sensor nodes exploiting such communication technologies.

All of the energy harvesting sources that are reviewed in this section and the relative LPWAN enabling technologies for which instances were retrieved within the literature are schematized in Figure 1.

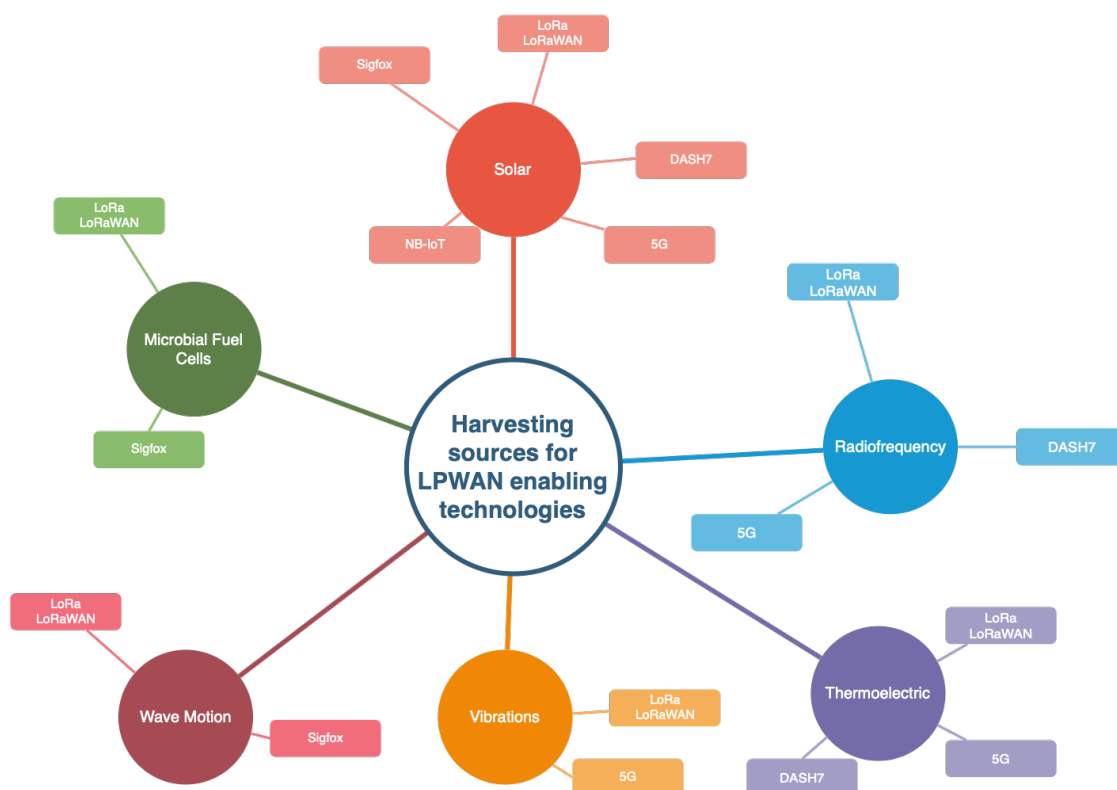


Figure 1. Harvesting sources for LPWAN enabling technologies.

### 5.1. LoRa and LoRaWAN

LoRa is currently the most employed LPWAN transmission technology for the realization of IoT architectures in a wide range of application scenarios. For this reason, together with several papers focusing on the description of systems exploiting a specific harvesting technique, some contributions were found in the literature dealing with specific architectures, not focused on a particular energy source. These contributions are precious for the design of the overall LoRaWAN systems and are then listed below. Papers dealing with systems powered by well-defined energy sources will be discussed then in the Sections 5.1.1–5.1.7, according to the specific harvesting principle.

Gleonec et al. [50] proposed one of the first works discussing the adoption of energy harvesting systems to power up LoRaWAN sensor nodes. While they do not adopt a specific harvesting technique, they focus on the management of multiple power sources, that are simulated by means of voltage generators. The proposed solution is validated by means of an experimental setup whose aim is to demonstrate the feasibility of a powering system multiplexing multiple energy sources. Such a multisource approach was also proposed in other works which will be discussed in Section 5.1.7.

A general architecture focusing on the functioning of a battery-less LoRaWAN sensor node, powered by an undefined source of energy, is presented in [51]. The model proposed in this work is interesting for any system powered by any kind of renewable energy: indeed, the architecture is based on a capacitor for energy storage and operates according to functioning model that allows to guarantee the continuous operation of the system. While the model is effective, it is based on the assumption that a constant energy is provided to the harvesting system: nevertheless, this requirement cannot be satisfied by some of the most common energy sources such as the solar one. The same battery-less approach is presented in [52]: in this case, instead of focusing on the architecture of the LoRaWAN device, the paper tackles protocol issues related to packet collisions and minimum throughput maximization.

Finally, one last paper was identified focusing on the performances of LoRaWAN devices powered by an energy harvesting system that may fit with different power sources. Indeed, in [53], the impact deriving from the adoption of a renewable source of energy for LoRaWAN networks in industrial monitoring applications on the overall systems costs is analyzed: a comparison of the maintenance costs due to replacement of batteries in battery-powered devices with or without the use of harvesting solutions is provided, pointing out the benefits deriving from the adoption of these techniques in the proposed application context.

#### 5.1.1. Solar

As already underlined in Section 4, solar energy is the most common environmental power source for the realization of self-powered wireless systems. For what concerns the LoRa technology, a relatively large number of papers have been identified, dealing at different levels with the adoption of photovoltaic (PV) panels for the powering of either LoRa nodes [8,54–61] or LoRa Gateways [62,63]. In general, all those papers share the same configuration for what concerns the energy harvesting system: this includes the use a small scale PV panel, a BMS, and an energy storage system that may be whichever amid a battery or a supercapacitor.

Starting from the works describing End Nodes architectures, the majority of them propose an energy harvesting system to be employed for a specific application scenario; indeed, only one contribution was found dealing with a general purpose sensor node [54]. This paper provides an effective theoretical way to dimension the energy harvesting components of the node as well as the energy storage devices (i.e., batteries and supercapacitors) and the PV panels. The structure of a solar-powered sensor node is then described in detail: in this system, the charge process is managed by means of an SPV1050 low-power harvester by STMicroelectronics, implementing the MPPGT function. An INA226 power monitor by Texas Instruments is also introduced in the system to check the battery status. The energy consumption of the sensor node is carefully evaluated and field test results are provided for a fortnight operation period. This paper is especially interesting since the proposed architecture can be also used with other harvesting techniques (e.g., the adoption of Peltier modules instead of PV panels is suggested in the text), by simply replacing the harvesting component.

A first group of papers mainly focuses on the overall system architecture, without discussing in detail the energy harvesting solution: in these works, a basic structure employing commercial PV panels and supercapacitors or batteries for energy storage is presented, shifting the main focus on the application scenario. Polonelli et al. [55] present the architecture of an energy self-sufficient LoRaWAN sensor node to be employed for the measurement of the displacement of cracks in buildings within the frameworks of Structural Health Monitoring (SHM). The energy harvesting system presented in this work is based on the use of a solar panel connected to an SPV1040 step-up converter by STMicroelectronics. An L6924D battery charger (by STMicroelectronics too) is used to manage the charge of a 2 F supercapacitor. A similar, but less detailed architecture for what concerns the solar harvester, is presented in [56]; in this case, the proposed system is expected to be floating on the sea surface, while collecting data concerning water temperature and transmitting them ashore by means of LoRaWAN protocol. The harvesting unit encompasses a solar panel connected to two parallel

7.5 F supercapacitors, while no charge management electronic component is used. Another paper [57] focuses on earthquake detection and discusses the architecture of a LoRaWAN sensor node embedding accelerometers and other environmental sensors. In this case, the node is powered by a 2000 mAh LiPo battery whose charge is managed by a commercial Arduino-type Solar Charger Shield by Seeed Studio, connected to a 1.5 W off-the-shelf solar panel. Despite the simplicity of the technical solution, the paper also proposes a detailed analysis of the node power consumption which is useful to evaluate the sizing of the energy harvesting system. Matthews et al. [58] present an interesting platform integrating LoRa data transmission and UHF RFID contactless identification for vehicle recognition: the described platform is powered by means of a PV system which is not described in detail. Finally, a last paper [59] presents a simple architecture for environmental monitoring based on the off-the-shelf STMicroelectronics I-Nucleo-LRWAN1 multi-sensor shield: the system is powered by means of a 4 F supercapacitor charged by means of a PV panel, but no details are provided concerning the charge management system.

A second group of papers, while being related to a specific application scenario, discusses more in detail the implemented solar harvesting system. Rossi and Tosato [60] present a LoRa sensor node to be employed for environmental pollution monitoring, providing a detailed description of the energy harvesting solution. In this system, the charge management unit is composed of a BQ25570 harvester power management circuit from Texas Instruments, which is used to charge a lithium battery. As the sensor node has a large operating current absorption, an additional stage was added to supply it, which is composed of a TPS63000 Buck-Boost Converter from Texas Instruments, regulated by means of a Texas Instruments TPL5110 timer, periodically enabling the current drainage. Regarding the PV panel, in this paper three different solutions are tested, two custom-made and one off-the-shelf: the first two are, respectively, based on 50 Ixys cells arranged on an x-shaped matrix, and 12 Sanyo micro-PVs in parallel, while the commercial one is a 1 W panel from Seeed Studio. Following a set of system tests, the authors demonstrate that the best choice is represented by the Seeed Studio commercial PV panel which provides in general better performances with respect to the other solutions.

In [8], another interesting application scenario is faced: indeed, the paper presents a wearable LoRa sensor node, to be used for personal environmental data collection. One of the most challenging requirements that such a system has to fulfill concerns the energy harvesting system dimensions, as the monitoring device has to be worn by users. To overcome this limitation, the proposed solution is centered on a 3 cm radius circular PV panel that is arranged into a watch-shaped device integrating the whole sensor node components. The charge process is managed by an ADP5090 controller from Analog Devices, which regulates the charge of a 12.5 F supercapacitor. The overall power consumption of the node is evaluated in detail and field tested in order to identify a duty-cycling able to guarantee a continuous operation of system is assessed too. Finally, a last more recent contribution was identified providing a detailed description of a solar energy harvesting system for environmental sensor nodes [61]: the structure is similar to other contributions, being based on a LTC3105 DC/DC converter from Analog Devices on an AM-5412CAR amorphous silicon solar cell from Panasonic Eco Solutions, charging a Li-ion battery.

Regarding solar energy harvesting systems used to power LoRaWAN Gateways, only two contributions were identified. In this case, the power requirement is by far higher than for End Nodes, as Gateways are required to always listen to incoming packets from End Nodes, and then no duty-cycling policy can be applied. For this reason, in [62] the sizing of the PV plant to be used to power the Gateway is discussed in detail, proposing an algorithm to estimate the system power consumption. As the Gateway also has to forward the packets received by the End Nodes to the LoRaWAN Network Server, the energy requirement must include the powering of another data transmission technology too. As the system is expected to be cable-less, the consumption of 4 different technologies (i.e., LTE, WiMax, Satellite and Long-Range WiFi) is discussed as well as the analysis of carbon footprint. Then, the achievable CO<sub>2</sub> saving with the four different typologies of data transmission is investigated too. In [63], an edge computing paradigm within LPWAN framework is tackled. The proposed architecture

includes Gateways, that rely on harvested energy, receiving data from End Nodes. In contrast with traditional harvesting systems, the authors propose a stochastic model grounded on a Markov decision process to manage the scavenged energy. Finally, simulations proved the feasibility and the effectiveness of the system. In particular, Gateway cooperation is stochastically controlled, as it has just been mentioned, so to look for an optimum state allowing computation and data-forwarding tasks with the aim of cleverly managing the harvested energy. In so doing, a Gateway may offload a task to another one if such an action is believed to be the one minimizing the required energy. Concerning the harvesters, they are supposed to be systems scavenging energy from ambient light. In addition, harvesting is modeled as a stochastic process accounting for harvesting rate rather than harvesting volume of energy to be assessed within variable temporal slots.

### 5.1.2. Radio Frequency

Wireless power transfer by means of magnetic or inductive coupling is widely used in several contexts, from passive Radio Frequency Identification (RFID) systems to wireless chargers for mobile phones. While such a powering technique requires a limited distance between the Radio Frequency (RF) source and the device to be powered, thus contradicting the wide area operational principle of LPWANs, some LoRa-based systems powered by means of RF harvesting were found in literature. A first solution exploiting the wireless RF channel to power a LoRa node is presented in [64]. In this paper, the architecture of the harvesting circuit is described in detail, focusing on the antenna design as well as on the RF-DC circuit that is required to convert the Alternate Current (AC) signal generated by the receiver antenna to a DC one that can be used to power a sensor node. Following the description of the system, the realization of a wirelessly powered LoRa node is presented and its functioning is validated by means of field tests. While the wireless power transfer is achieved, the systems suffers from the short transmission range limitation pointed out before since the tested operational range is shorter than 2 m, and it is then in contrast with the wide area requirement.

While the short range is clearly a limitation for the adoption of this type of harvesting for LoRa systems, Peng et al. [65] propose the so-called PLoRa system, that aims at providing long range transmission from passive sensor nodes by means of backscatter transmission. Regarding the node powering, this exploits environmental RF signals from any possible source in the 900 MHz frequency band as well as solar energy when the former one is not available: the nodes are provided with a 0.33 F supercapacitor for energy storage. While the proposed system is able to achieve data transmission at distances up to some hundreds of meters, it cannot be fully considered as RF-powered as the presence of the solar panel is crucial to guarantee the long range operation.

Another interesting contribution regarding wireless power transfer for a LoRaWAN sensor node is presented in [66]. In this paper, a whole experimental setup is described in detail comparing the performances of the system according to the use of different typologies of electronic components. In particular, the performances of two different RF-DC converters are investigated, correlating a commercial P2110B converter from Powercast with a device realized ad-hoc. Similarly, the performances of different typologies of antennas were analyzed and compared. As in previous cases, while the system proved to be effective to power a LoRaWAN node, the actual operating distance was in general very short, below 3.5 m.

A final contribution is provided in [67]: this paper presents a theoretical discussion concerning wireless power transfer in general, and comparing different techniques: inductive coupling, ultra-dense millimetre-wave small cells and Magnetically Coupled Resonance (MCR). A solution based on this last technique (i.e., MCR), exploiting ferrite structures, is then presented and discussed, albeit a practical implementation of the system is not provided. Nevertheless, while the proposed system may be interesting, the lack of its actual implementation prevents from discussing its potential performances.

### 5.1.3. Thermoelectric

Thermoelectric energy is harvested by means of thermoelectric generators which exploit temperature gradients to supply electrical power, as it was previously mentioned in Section 4. In so doing, self-powered LoRa End Nodes to be employed for industrial monitoring issues may be designed and implemented as the work in [68] illustrates. Indeed, the authors propose a flexible thermoelectric generator to be wrapped around heat pipes reaching the temperature of 70 °C. Additionally, the sensor node is in charge of monitoring sundry parameters (e.g., pipe temperature, ambient temperature, humidity, CO<sub>2</sub> concentration, and organic compound concentration). Moreover, the authors point out that within indoor environment like an industrial one, thermoelectric generators are by far suitable for energy harvesting than, for instance, photovoltaic devices, as the former devices are able to constantly harvest energy regardless of the available amount of light as only a temperature gradient is needed. The developed sensor node has a common architecture which comprehends the harvester, a BMS, a rechargeable battery, a DC–DC converter, dedicated sensors, a microcontroller, and a transceiver enabled by LoRa modulation.

Continuing in the same vein of industrial monitoring, the authors of [69] propose a battery-less and maintenance-free LoRaWAN End Node harvesting energy from industrial cooling pipes at 80 °C. Such a device is exploited to monitor vibrations of machineries. Due to the fact that this study follows the footsteps of the previous one, the sensor node architectures of both the nodes resemble each other. However, the main dissimilarity amid the two prototypes concerns energy storage since [69] makes use of a 5 F supercapacitor rather than a rechargeable battery.

Thermoelectric generators are also able to fully operate even when they are employed for harvesting energy from trees [70]. Such a study is therefore interesting because the relative test campaigns, that were set up throughout several months across seasons, demonstrate the feasibility and the effectiveness of the system. In this setting, the thermoelectric generator makes use of the temperature gradient arising between the tree trunk and the ambient air: indeed, the inner temperature slowly varies while the outer one experiences more sudden changes due to sun rising and setting. Therefore, such an event takes place on a daily basis thus allowing a theoretically perpetual power supply for a LoRaWAN End Node.

Finally, the authors of [71] propose an autonomous LoRa End Node powered by a thermoelectric generator harvesting unused or wasted heat coming from disparate sources like hot water pipes or factory machineries. The device is employed for security and environmental monitoring issues. To achieve such tasks by only relying on the harvester, it embeds the same classes of components that were listed so far for comparable devices supplied by similar systems: besides the harvester there are a DC–DC step-up converter, a BMS, a storage element (i.e., in this case a supercapacitor), a voltage regulator, and the sensor node itself.

### 5.1.4. Vibrations

Mechanical systems as well as structures that are subject to stress, strain, or any other sort of external forcing term experience vibrations which can be promptly exploited for powering up sensors nodes by means of suitable harvesters. Such an idea is also exploited for supplying LoRa End Nodes too. Orfei et al. [72] developed a battery-less LoRa node for the monitoring of the asphalt of a bridge. Energy sufficiency is ensured by an electromagnetic energy harvester scavenging energy from bridge vibrations (which, for instance, are engaged by vehicles crossing it) that exploits Halbach array for permanent magnets arrangement so to increase the magnetic fields resulting in a miniaturization of the harvester still preserving its performances. The collected energy is firstly rectified and regulated and then stored within a supercapacitor. Overall, the node is capable of fulfilling its tasks (i.e., data sensing and data transmission) by leveraging on the energy harvested from bridge vibration occurring any time a vehicle passes through.

Harvested vibrations through electromagnetic devices are also the source of energy that is employed in [73] within industrial contexts. Indeed, it shows two sensors nodes that are supplied by



the vibrations generated by a standard industrial compressor: the former is a LoRaWAN End Node, while the latter exploits Bluetooth connectivity, and therefore it is neglected in this review as it falls outside the scope of LPWAN communication protocols. Similarly as before, the harvester requires a conditioning electronics achieving rectification and regulation, in a first stage, and a supercapacitor so to store the collected energy. Test results point out that the LoRaWAN node is able to reach the minimum sampling rate of 30 seconds which in most of the cases suffices monitoring requisites of slowly varying physical phenomena.

#### 5.1.5. Wave Motion

Energy harvesting lays its own foundation on energy conversion principles. Such a phenomenon gains a notable momentum whenever renewable sources of energy are exploited. Water waves intrinsically carry kinetic energy which is potentially boundless, therefore its harvesting could be a bold move. Chandrasekhar et al. [74] put into effect this idea so to power a LoRa position tracker hosted in a smart buoy for marine scopes. The harvesting system is enclosed within the buoy and it consists of a triboelectric nanogenerator and an electromagnetic generator for recovering kinetic energy of water waves. In addition to them, a solar cell is placed on top of the buoy just as a backup harvester whenever calm wave conditions are experienced. Despite the fact that heterogeneous energy sources are exploited, the work in [74] is not included within Section 5.1.7 because solar energy only plays a secondary role. The aforementioned generators are capable to efficiently convert kinetic energy into electrical energy that is stored either in a capacitor and in a Li-ion battery via a BMS. The triboelectric and the electromagnetic generators are simultaneously combined for pursuing the harvesting scope. Indeed, the former operates under contact and separation of triboelectric units that are especially manufactured. They are actuated by means of a cylindrical tube on which a coil is wounded along its outer surface while in its inner side a moving magnet is present thus forming the electromagnetic generator. This coupling allows to independently generate electrical power during the same mechanical motion due to waves.

#### 5.1.6. Microbial Fuel Cells

Aquatic environments that are characterized by favorable conditions (e.g., enough dissolved oxygen) are well suited as a developing habitat for floating microbial fuel cells. In spite of this, such bio-electrochemical systems proved to be able to operate even in anoxic conditions [75] and to power up LoRa End Nodes. The study finds out that especially designed microbial fuel cells are able to supply enough power for the LoRa node provided that a DC-DC converter is employed since a microbial fuel cell in itself would only scavenge an insufficient amount of energy. However, just very infrequent transmissions (i.e., twice a day) may be tolerated by such harvesting system though.

Microbial fuel cells may take place even in conjunction with plants, and the related harvested energy could suffice for enabling battery-less LoRa sensor node performing environmental monitoring within a smart cities framework [76]. Like comparable systems, such device is capable to generate a stable output voltage permitting the correct supplying of the node that embeds sensors, microcontroller, transceiver, and miscellaneous electronics (e.g., a DC-DC converter and a supercapacitor) employed for the harvester.

#### 5.1.7. Hybrid Techniques

A simultaneous exploitation of multiple sources of energy for harvesting purposes is advisable whenever the deployment scenario consents it. Indeed, premises for achieving zero impact sensor nodes from an energy point of view could be easily met. On the other hand, there exist studies comparing different sorts of harvesting techniques with the aim of finding out potential pros and cons. For instance, in the work in [77], solar, thermal, and piezoelectric harvesting techniques are investigated and correlated in order to design autonomous LoRa End Nodes. The latter has a standard architecture including the harvester, a BMS, a rechargeable battery, and the proper sensor node which



is in turn composed of sensors, microcontroller, transceiver, and so on. The principal results point out that solar harvester ensures enough chances to provide the node a self-sustaining state while the remainder two drastically decrease such probability. Unfortunately, though, all of those techniques have not been integrated yet within the aforesaid research work.

Solar and thermal energy harvesting are exploited in LoRa End Nodes so to obtain an energy-efficient device allowing for either short- or long-range communication [78]: indeed, besides standard LoRa transmissions enabling long range broadcast, also an energy aware wake-up radio is embedded in the system permitting to wirelessly trigger the node forcing data sampling and data sending tasks. In so doing, a twofold scope may be achieved: self-sustainability, due to harvesting and ultra-low-power building components selection, and transmission control, by exploiting the possibility to ping the sensor node via the wake-up radio.

The combination of solar and thermoelectric energy harvesting also drives the study put forth in [79]. Therein, an innovative floating device scavenging energy from both sun rays and thermal gradients is investigated. It makes use of LoRa modulation to convey data (i.e., samples of environmental parameters like temperature, humidity, and water pH) to the nearest Gateway. The mixture of the two energy harvesters allows for slightly less than 10 days of fully operation without sun light exposure. Therefore, such a floating LoRa End Node is able to harvest enough power to be completely autonomous.

At this stage it is crystal clear that solar energy harvesters are massively adopted as sunlight is the most immediate source of renewable energy, as it was stated earlier on in Section 4. Moreover, such a strategy usually plays a pivotal role in multiple sources harvesters. An additional instance is the one in [80] where it is in tandem with a radio frequency harvesting module to power up a LoRaWAN End Device for environmental monitoring scopes. Such a device is designed accomplishing energy self-sufficiency owing to the fact that an energy saving policy (i.e., duty-cycling between sleep and active mode) is actuated along with a backup rechargeable battery which does not need to be replaced and disposed thanks to the scavenging capabilities of the node.

## 5.2. Sigfox

Over the years, Sigfox has constantly gained approval amid the framework of IoT and LPWAN. Indeed, despite the fact that users have to subscribe and pay fees to exploit it, as the whole network infrastructure is in charge of Sigfox itself, such a technology proved to be quite plug-and-play because only sensor nodes need to be designed and implemented thus absolving users from concerns related to gateways and server side. Sigfox nodes share a common feature with others belonging to networks which are enabled by different communication standards: they are commonly designed to operate only relying on a limited source of power. Therefore, they still require to be thoroughly designed so to extend their lifetime by minimizing energy consumption. To this end, the authors of [81] put forth a study whose outcome is the derivation of a model, which is based on measurements on Sigfox hardware modules, so to assess hardware performances stemming from realistic usages. In particular, the authors claim that by exploiting a 2400 mAh battery an ideal lifetime spanning from 1.5 to 2.5 years while hourly transmitting six messages with a data rate ranging from 100 bit/s to 600 bit/s may be achieved. Moreover, an asymptotic lifetime of 14.6 years can be reached provided that message broadcasting rate is diminished. Some of the benchmarks that are accounted in the model are uplink physical layer data rate, payload size, unidirectional or bidirectional communication, and message losses. The overall result looks very promising and even satisfactory as it is. However, employing harvesting techniques could permit either to make use of smaller batteries so to reduce both node size and cost or to consent a bigger amount of transmitted data to fulfill application scenario requirements.

Likewise, different enabling technologies, solar energy harvesting is widely adopted in Sigfox sensor nodes. For instance, within water monitoring systems, self-sufficiency from the energy point of view could be achieved by making use of solar energy harvesting [82]. In particular, by keeping sensor node duty cycle below 0.4%, self-sufficiency is reached by resorting to a 720 mAh rechargeable battery,

an off-the-shelf solar shield acting as BMS and a 2 W solar panel delivering a maximum of 330 mA during favorable light states so to completely charge the battery in less than 3 h. Energy autonomy for Sigfox nodes employed within environmental monitoring was also investigated in [83]. Such a result stems from the fact that the node is powered by a solar cell, a 90 mAh coin cell battery both managed by an optimized BMS. In so doing, transmissions may take place every half an hour so to ensure 8 h of operation in full darkness that can be compared to the duration of nights during summer. Alternatively, such a duty cycle could be tuned thus resulting in a transmission every 5 min under overcast condition and still the autonomy is ensured.

The literature additionally presents works dealing with floating microbial fuel cells that are exploited to scavenge energy so to power up Sigfox nodes [84]. Floating microbial fuel cells may operate for more than a year as a sort of floating gardens which live within aquatic environments characterized by a large amount of dissolved oxygen. The energy harvesting system needs to be especially designed so to collect energy from a various number of the aforesaid cells that reside in the same water medium. In addition, since a maximum of 800 mV can be usually harvested from a single cell, DC–DC step-up converters are required to be embedded within the harvesting system. In particular, each microbial fuel cell is connected to its DC-DC converter, while the output storage element (i.e., a single capacitor) is in common with the aim of powering the load. In so doing, a maximum overall amount of 5 V can be reached which is largely suitable to power up sensor nodes. However, solely a very slow data transmission (i.e., once a day) can be ensured.

Kinetic energy of sea waves may be also harvested so to power Sigfox sensor nodes by exploiting oceanic undrogued drifters [85]. The harvester consists of a gymbal system, a gearing transmission capable of converting oscillations into rotations, a test mass, a flying wheel, and a micro-generator. Due to motion caused by sea waves, the harvester (that is enclosed within the drifter) rotates according to certain angles of roll, pitch, and yaw. Next, the test mass attempts to oppose such a motion in order to maintain a vertical position; therefore, it properly rotates owing to the gymbal structure. This phenomenon causes a torque that is transmitted through the gears to the flying wheel and, in turn, to the micro generator hosting a DC motor which transforms this rotation into DC current by exploiting the reversibility principle. Finally, such power is processed and managed by especially conceived devices so to provide up to 0.22 mW. Therefore, the whole system is not already suitable for being the main power supply and hence it is used as a backup power of a sensor node that is mounted on the drifter itself which communicates, by leveraging on Sigfox, for coastal communications.

### 5.3. DASH7

DASH7 networks are well suited for including either sensors and actuators owing to the intrinsic bidirectional capabilities of the protocol itself. Therefore, both sensors and actuators could be equipped with energy harvesters with the vision of being autonomous nodes. D'Elia et al. [86] put into practice this idea within the context of heat distribution systems in domestic buildings. Sensors and actuators communicate via DASH7: the former ones sample temperature and the latter ones drive motors for the tuning of radiators valves. Each class of nodes is provided with a dedicated harvester: the actuators scavenge energy from heat thus embedding a thermal energy generator, while the sensors are powered via photovoltaic cells. Likewise other systems previously described, the harvesters work along with DC–DC converters, BMSs, and rechargeable batteries.

Autonomous DASH7 nodes could be also realized by resorting to radio frequency harvesting, and specifically battery-less self-sustained nodes are shown in [87]. This task is solved by employing a tailor-made rectenna (i.e., the bulk of radio frequency harvesters) connected to a DC-DC converter along with a buffer capacitors and control circuits so to correctly power the sensor node. Of course, all of the building blocks are ultra-low-power components so to overcome to the little amount of harvestable energy coming from environmental radio frequency signals. Despite it, the prototype is capable to operate by intercepting signals within a radius of 17 m.

Energy harvesting could be the key for achieving completely autonomous sensors especially when such devices are designed to operate along with a wake-up radio triggering their functioning only when a wake-up packet is received as it is presented in [88]. Therein, the same prototype that was beforehand illustrated in [86] is equipped with wake-up radios and the relative impact on the nodes lifetime extension is discussed. In so doing, autonomy is elongated as the required energy to be harvested from the environment to correctly power the nodes drastically decreases. Of course, the wake-up radio definitely needs to be meticulously designed so to be as low power as possible in order to not significantly undermine the energy balance resulting from the harvesters. For instance, the wake-up radio that is adopted in [88] only draws up to 1  $\mu$ A.

#### 5.4. Cellular Technologies

Energy harvesting techniques are still scarcely adopted in systems based on cellular technologies. Indeed, the literature is not plenty of works dealing with this theme. A reasonable motivation could be that such communication standards generally require a vaster amount of energy in comparison with non-cellular technologies due to the fact that the former ones customarily offer higher performances with respect to the latter ones. However, some instances of harvesters for nodes communicating embracing cellular technologies are presented in [89], concerning NB-IoT, and in [90], regarding 5G.

Challenges and opportunities for energy harvesting to be used in NB-IoT sensor nodes with the aim of extending battery lifetime are listed within [89]. Precisely, energy harvesting for NB-IoT nodes is investigated in a smart home scenario where ambient light, either indoor and outdoor, can be scavenged. For what concerns indoor settings, window sills and books shelves are taken into account. The results from this study point out a predictable outcome: outdoor settings by far outperform indoor ones but still all of them provide a significant lifetime lengthening. Specifically, and on a yearly basis, indoor harvested ambient light can provide slightly less than 3000 additional messages of 50 B and 200 B length that only need a good signal coverage to be broadcast, while those figures decrease to few more than 250 whenever a deep coverage is necessary. On the other hand, additional messages that can be sent by exploiting outdoor ambient light roughly double up, respectively, for each of the aforementioned conditions.

Energy harvesting for the brand new 5G technology are summarized in [90]. Therein it is claimed that radio frequency energy harvesting is a favorable method for an alternative energy supply in order to be exploited within 5G communication systems. Along with radio frequency harvesting, also other renewable sources of energy (e.g., thermal energy, sun, light, and mechanical energy) are surveyed. Moreover, the paper additionally points out constraints related to energy harvesting such as causality: when some energy is harvested at the moment, it would be only available in the future. Due to this issue and the remainder that are listed, radio frequency harvesting seems to be a reliable and predictable energy source 5G networks may rely on.

## 6. Discussion

The just surveyed papers remark potentialities, efficiency, as well as effectiveness of energy harvesting techniques to be exploited within LPWAN contexts. Therefore, such methods will definitely have a booming and flourishing future as it is highly expected that the need of designing sensor nodes able to run relying on the aforesaid strategies will be more and more increasing for multiple reasons. First, if the number of fully autonomous sensor nodes (i.e., the ones which do not require batteries due to the fact that the energy they scavenge is sufficient) would blow up, then no more batteries will have to be substituted and disposed thus contributing to the reduction of pollution embracing a greener perspective. Second, for such nodes that do not reach an utter self-sufficiency, a notable reduction of human interventions for maintenance will be experienced resulting in an overall simplification of upkeep procedures. Additionally, even though harvesters may be more expensive than batteries, the overall node costs will be amortized throughout the whole lifetime since it experiences

a remarkable lengthening. Therefore, there exist all the conditions for considering them as full-fledged forms of investment.

As it was stated earlier on (see Section 4), the most immediate renewable source of power is the solar one. As a consequence, such a form of energy is also massively exploited for harvesting; indeed, this fact is confirmed by the conspicuous number of the reviewed studies dealing with it. Moreover, thermoelectric harvesters are also indirectly affected by solar energy since heat is the outcome of sun rays impacting on objects. However, albeit other sources of energy are not as mainstream as the solar one, some solutions exploiting them were cited as well as they proved to be as reliable and efficient as solar energy.

Regardless of the source of energy that is scavenged, sensor nodes relying on harvesters are pooled by a common architecture: the harvester itself is controlled by a BMS deciding whether to directly exploit the scavenged energy to power the node or to store it within rechargeable batteries or supercapacitors. In addition, whenever the source of energy is not constant, further electronics (e.g., AC–DC converters) is needed so to correctly supply the node: aeolian harvesters or systems exploiting mechanical vibrations usually suffer from such a matter. On the other hand, hydroelectric generators working within pipes do not ordinarily necessitate of those additional systems especially whenever the inner water flux is constant. Another discriminant dictating the energy harvesting technique to adopt is the application scenario. While outdoor solar is massively employed, indoor other strategies should be considered. For instance, within industrial environments thermal harvesting (e.g., from cooling systems) or mechanical vibrations harvesting (e.g., from vibrating machineries) are widely put into effect. For what concerns aquatic environments, microbial fuel cells are often taken into account provided that the aquatic context is suitable for cells living, while sensor nodes deployed overboard may take advantage of sea waves motion although the harvester needs of a thorougher design.

Apart from the exploited energy harvesting technique, the bulk of the reviewed papers deals with LPWANs to be employed for environmental or industrial monitoring. However, such facilities may be of precious aid in order to face and manage delicate issues like the one lashed out the entire world during 2020: pandemics. Indeed, the globe was stroke by what was named as Corona Virus Disease 2019 (COVID-19). Albeit a recovery phase was gradually started after some months from the outbreak, subsequent waves (the first of which presumably could occur for late 2020) were predicted. Therefore, as it is also suggested in [91], IoT infrastructures could play the role of crucial supporters to such a fight: for instance, a city-scaled pervasive monitoring network for the measurement of body temperature by leveraging on thermal cameras to be installed at the entrance of public places (e.g., schools, bars, shops, and so on) whose data could be retrieved and analysed by a central core (e.g., hospitals) so to cope with the spread of contagion could be a solution. However, the same concept could be applied to other disease monitoring scenarios too. Another subtle point arising whenever data flows through networks like LPWANs and IoT systems is the one of cyber risk that has to be intended in a broad sense: from personal information leakage to data transfer especially when sensible information is involved like in the case of the aforesaid example coping with COVID-19. On the concerns associated with the communication technologies introduced earlier on and with IoT in general, [92] gives a deep outlook in standardisation of IoT cyber risks as well as future perspectives by identifying IoT cyber risk vectors (i.e., IoT attack vectors from particular approach used so to mine into big data vulnerabilities) and by integrating them in models aiming at determining cyber risks impact. Therefore, we deem that besides the future development of energy harvesting techniques for LPWANs, also countermeasures for risks (which naturally emerge in this context) will experience a notable spike.

## 7. Conclusions

The aim of this paper was to provide a comprehensive review of the existing energy harvesting solutions for the powering of LPWAN-based monitoring systems and architectures. The literature was carefully reviewed and, at the best of our knowledge, all the most significant contributions dealing

with the proposed topic have been included in this survey. While the total number of reviewed papers may appear to be low (i.e., a total number of 44 contributions was discussed) we would like to point out that all the works were published in the last five years, since LPWAN technologies are relatively new in the context of IoT.

As LPWAN-based IoT systems are spreading very fast, the emergence of energy harvesting techniques is expected in the next few years. In this sense, we would like to point out that some renewable power sources, that are widely exploited in several technological contexts, like wind or water flow, were never applied to LPWAN systems. We believe that, at least for these two energy sources and hopefully for others, the appearance of prototypes and working systems over the next few years will be seen.

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