Review

Prospects of Wireless Energy-Aware Sensors for Smart Factories in the Industry 4.0 Era

Olfa Kanoun * , **Sabrine Khriji, Slim Naifar, Sonia Bradai, Ghada Bouattour, Ayda Bouhamed** ,
Dhouha El Houssaini and **Christian Viehweger**

Measurement and Sensor Technology, Technische Universität Chemnitz, Reichenhainer Straße 70,
09126 Chemnitz, Germany; sabrine.kheriji@etit.tu-chemnitz.de (S.K.); slim.naifar@etit.tu-chemnitz.de (S.N.);
sonia.bradai@etit.tu-chemnitz.de (S.B.); ghada.bouattour@etit.tu-chemnitz.de (G.B.);
ayda.bouhamed@etit.tu-chemnitz.de (A.B.); dhouha.el-houssaini@etit.tu-chemnitz.de (D.E.H.);
christian.viehweger@etit.tu-chemnitz.de (C.V.)
* Correspondence: Olfa.Kanoun@etit.tu-chemnitz.de

Abstract: Advanced sensors are becoming essential for modern factories, as they contribute by gathering comprehensive data about machines, processes, and human-machine interaction. They play an important role in improving manufacturing performance, in-factory logistics, predictive maintenance, supply chains, and digitalization in general. Wireless sensors and wireless sensor networks (WSNs) provide, in this context, significant advantages as they are flexible and easily deployable. They have reduced installation and maintenance costs and contributed by reducing cables and preinstalled infrastructure, leading to improved reliability. WSNs can be retrofitted in machines to provide direct information from inside the processes. Recent developments have revealed exciting possibilities to enhance energy harvesting (EH) and wireless energy transmission, enabling a reliable use of wireless sensors in smart factories. This review provides an overview of the potential of energy aware WSNs for industrial applications and shows relevant techniques for realizing a sustainable energy supply based on energy harvesting and energy transfer. The focus is on high-performance converter solutions and improvement of frequency, bandwidth, hybridization of the converters, and the newest trends towards flexible converters. We report on possibilities to reduce the energy consumption in wireless communication on the node level and on the network level, enabling boosting network efficiency and operability. Based on the existing technologies, energy aware WSNs can nowadays be realized for many applications in smart factories. It can be expected that they will play a great role in the future as an enabler for digitalization in this decisive economic sector.

Keywords: energy harvesting; vibration converters; energy saving; wireless power transfer; wireless communication; WSN

1. Introduction

Several trends of digitalization [1], Internet of Things (IoT), and 5G Networks address massive sensing and admit that wireless sensors deliver measurement data directly to a server or a cloud reliably and easily so that a big data basis can support decisions and several novel services can be realized. In industry 4.0, smart factories are supposed to build a linked and flexible production environment, with a comprehensive data stream through production at different levels, and easily adapt to changing demands, manufacturing processes, and manufacturing conditions [2]. Devices are needed to have seamless connectivity, interoperability, visualization, and high-performance capabilities. For the realization of this high intelligence level, factories should gather and process diverse data from physical, operational, and human resources to manage manufacturing systems' material supply, production, operations, and maintenance. Here, it comes the main role of sensors, which can automatically gather the necessary data in abundance. Sensors play a great role, as

they support the tracking of the entire manufacturing process and contribute to improving production performance, quality management, improving precision in production machinery, optimizing production tasks by the enhancement of automation and regulation, and detecting and identifying faults.

In smart factories, where a high level of system reliability and reactivity is demanded, the use of autonomous wireless sensors did not find a high acceptance initially because of general skepticism about reliable communication and energy supply, especially if they are battery driven. Energy supply becomes gradually essential, as flexible positioning and easy maintenance are critical features for accepting the massive use of wireless sensors [3]. Nevertheless, recent developments have revealed exciting possibilities to enhance energy harvesting (EH) efficiency by designing suitable converters, combining converters in hybrid solutions, and adopting opportunities for wireless energy transmission. Developments in microelectronics enable significant energy savings, making an energy supply from ambient sources increasingly practicable. Wake-up receivers switch unnecessary system parts entirely off and reduce energy consumption during sleeping phases [4,5]. Data aggregation techniques [1], clustering, and intelligent routing realized significant energy savings on the network level. The system design provides interesting chances to optimize EH-based solutions.

Recently, WSNs that use ambient energy for smart factories have attracted more attention from academia. The scientific publications on energy harvesting for industrial applications have been significantly increasing for 20 years now (see Figure 1). The distribution on ambient sources shows that most of the investigations were dedicated to vibration converters, as vibration is one of the essential ambient sources in machinery, from movements and shocks.
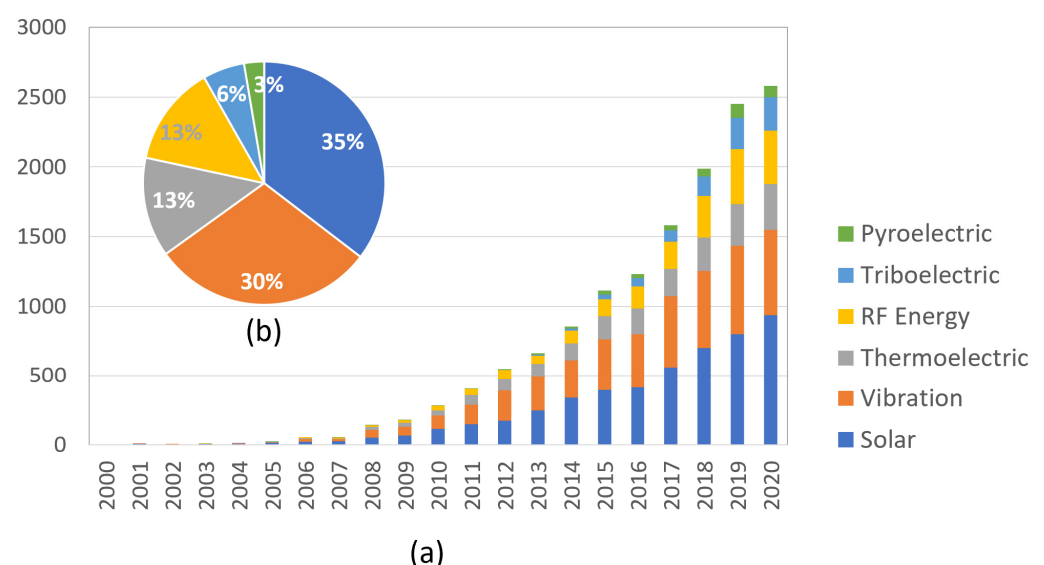
Figure 1. Development of publications on energy harvesting for industrial applications classified by dominant subfields since the year 2000: (**a**) number, (**b**) distribution on the different subfields.

Various valuable reviews have given insights into industrial wireless networks in the context of Industry 4.0 [6]. Some of them deal with energy harvesting technologies to supply wireless sensor nodes by using a certain type of ambient sources such as vibration [7], sound [8], and electromagnetic [9] and carbon nanocomposite-based energy generators [10]. Another type of review focused on the study of different energy harvesting sources to achieve self-power wireless sensor nodes for specific industrial applications, such as in machine condition monitoring [11], railway applications [12], and aeronautical industries [13].

This review reports on recent development trends that enable the practical use of wireless sensors in the industrial field. For this purpose, the crucial aspect is to increase

the energy income from ambient sources and reduce the energy consumption of the sensor node, especially for communication purposes. Therefore, we report possibilities for improving energy income at the node level and energy efficiency at the network level.

After an overview of the specific challenges for WSNs in industrial applications and the elaboration of the particular design requirements of WSNs in this field, we review supply strategies for energy-aware wireless sensor nodes from ambient energy in general that enables a long battery-free operation time in industrial environments. In the next part of the contribution, we focus on recent developments in key technologies that allow the applicability of WSNs in industrial settings, such as the use of hybrid conversion for increasing energy income and reliability. Then, we focus exemplarily on vibration energy harvesting as one of the primary ambient sources in industrial applications by introducing performance improvement techniques and novel trends in this field. Especially in industrial applications, wireless energy transfer is essential because of the possibility of coupling energy to moving parts and overcoming time intervals and conditions where usual ambient energy sources are not available. For this purpose, we focus, in Section 6, on wireless energy transfer and novel trends in this field. In the last part of the paper, we report on energy saving possibilities on the node and network levels, a key technology for enabling WSNs in the industry.

2. Chances and Challenges for WSNs in Smart Factories

Intelligent surveillance, condition monitoring, and predictive maintenance are tremendously important in smart factories. Several processes, such as tracking materials in transportation, logistics, and production, must be continuously monitored. The modern industry needs digitalization to improve adaptability, resource efficiency, and the integration of supply and demand processes (see Figure 2).

Figure 2. Power-aware wireless sensor networks in industrial environment.

Wireless sensor networks have significant advantages in this context, as they can be quickly and flexibly deployed and can optimize costs and reliability by reducing cables and preinstalled infrastructure. They can be easily installed and retrofitted in machines and utensils. Nevertheless, WSNs need to fulfil several requirements before their actual use in the industry, including communication security, real-time processes, reliability, longevity, and privacy controls. These requirements should be fulfilled even under dynamic operating conditions or by interferences due to electromagnetic fields or radio obstacles, such as metallic pipes and walls. A relatively high sending power may be needed in this case for communication, and energy consumption becomes critical.

The energy consumption of different WSNs depends on the application, associated hardware circuits, and network communication. The supply of the WSN can be principally cable-based [14], battery-based [15], energy harvesting-based or can use contactless supply circuits [16]. The battery-based system can be with primary batteries and rechargeable batteries that use wire-based chargers. In this field of applications, cables are not practical, especially in production chains. Batteries have a limited lifetime, limited capacity, need to be replaced, and are not environmentally friendly, making them not sustainable. As an alternative, energy harvesting [17] or contactless power transmission (CPT) [18] systems can overcome these challenges and ensure the network's autonomy for a long time. Table 1 shows potential applications for WSNs supplied by energy harvesting and energy transfer in smart factories. The appropriate energy harvesting solutions can be selected accordingly, depending on the sensor position, application, and prevailing environmental conditions. Nevertheless, harvesting energy from ambient sources has several challenges, including the limited power density and the instability of the generated energy, which depends on the ambient sources' characteristics.

Table 1. Use of energy harvesting in WSNs for smart factories.

Converters	Example for Applications
Solar cells	- Stationary nodes - Warehouse management and localization - Environments with few contaminations - Logistics
Vibration converters	- Monitoring and retrofitting of machines and tools - Monitoring of conveyor systems - Monitoring of transport systems - Predictive maintenance - Sensors attached to robot applications
Thermoelectric converters	- Heat dissipating machines and heat pipes - Monitoring on pipes and ducts in dark places - Industrial waste heat recovery - Thermoelectric conversion from solar energy - Wearable devices in human-machine interaction
Wireless power transfer	- Rotating and moving parts (e. g., conveyor systems) - Covered/sealed applications - Additional supply for interrupted sources - Systems with high power demand - Localization of tools and goods
Hybrid converters	- Systems with increased power demand - For systems needing a fallback option (e. g., security) - To support weak sources

In the next sections, we provide an overview of relevant energy harvesting solutions for industrial applications and smart factories, including solar and vibration energy harvesters as well as modern polymer composite-based flexible nanogenerators, which will play a big role in factories for gathering energy from manifold ambient sources, including movements, friction, chocks, and vibrations. Wireless energy transfer is also extremely interesting for coupling energy to moving objects and hard-to-contact components and elements. Overall, we focus on a selection of technologies with high potential and a realistic chance for use in smart factories. In particular, technologies that enable the development of energy-aware wireless sensor network are summarized in this paper. Figure 3 presents an overview of the energy effect on wireless sensor networks.
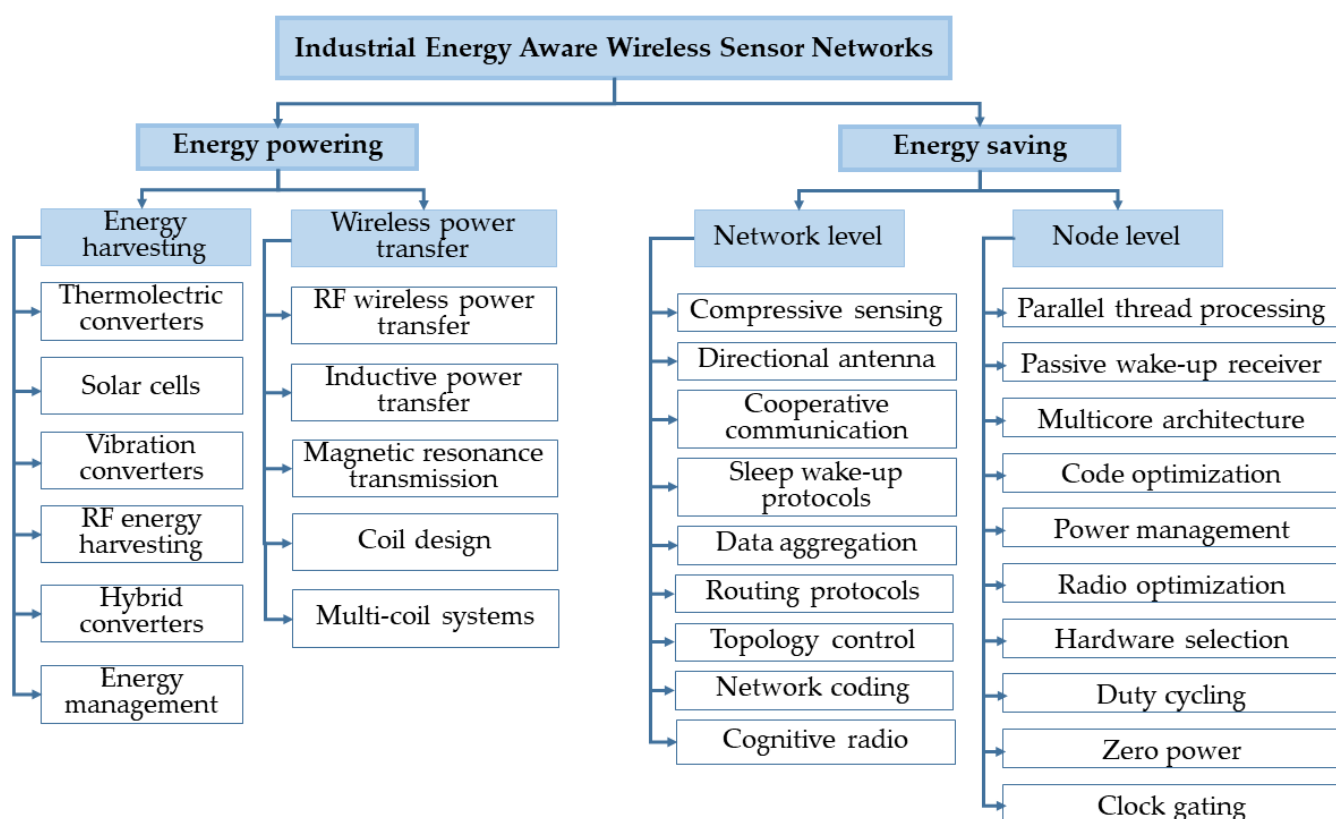
Figure 3. Taxonomy for industrial energy-aware wireless sensor networks.

### 3. Special Considerations for Solar Energy Harvesting

Solar energy harvesting is a well-known and developed power supply method for sensors in outdoor scenarios. The estimation of the power delivered for outdoor applications can be made by a characterization of the solar cell using standard test conditions (STC) with a reference spectrum (typically ASTM G-173-03 [19]). Afterwards, the required size of the solar cell can be estimated concerning the position, tilt angle, and estimated weather conditions.

For indoor scenarios, the situation is different, as the energy density and type of light can be diverse. Also, the risk of mechanical damage is always present, and the energy income is strongly dependent on environmental conditions, as well as shadows and dust exposure. Therefore, it may be necessary to protect the cell itself, as light sources are limited to energy-saving, LED, or fluorescent lamps. Classical light bulbs and halogen lamps are obsolete. The spectrum of these sources is very different from regular sunlight, with lower amplitude and narrower bandwidth. This relationship can be seen in Figure 4. It shows the measured output of the three different lamp types (LED/fluorescent/halogen) in comparison to the AM0 spectrum, which represents the sunlight without the influence of the atmosphere. Huge parts of the sunlight spectrum are missing in artificial light. For example, the fluorescent lamp shows only peaks. These peaks have a very high amplitude, but if the sensitivity of the solar cell in this part of the spectrum is weak, the output will be low anyway. This issue for artificial light is a general problem. Even if the total amount of illumination is similar, the spectral composition still is not. This limits the output and results in low-light conditions. STC for outdoor applications means 1000 W/m^2, and artificial light indoors usually means less than 10 W/m^2 [20].

Several strategies can be applied to overcome these challenges. The type of solar cell can be matched to the available light sources. If the spectral sensitivity reaches the peak(s) of the light source, then the output can be maximized. Cells that can better collect diffuse light are also more suitable, because depending on the building structure, there may be

more reflections. The positioning of the solar cells is also essential. The alignment is more critical than outdoors, as the total power is already low anyway. A wrong position or tilt angle can result in non-usable voltage and current values. This is also important for another aspect: electronics for energy management. In general, a DC/DC converter is required to reach a stable output voltage for the load. The main focus of this converter should not be efficiency, such as for outdoor applications, but the maximum range of operation. As the output of the solar cell can reach very low values, especially the voltage, the DC/DC converter should be suitable and able to use these voltages. It is better to have a conversion with bad efficiency than nothing at all. Therefore, a low minimum operating voltage is the target. Of course, losses should be minimized too.
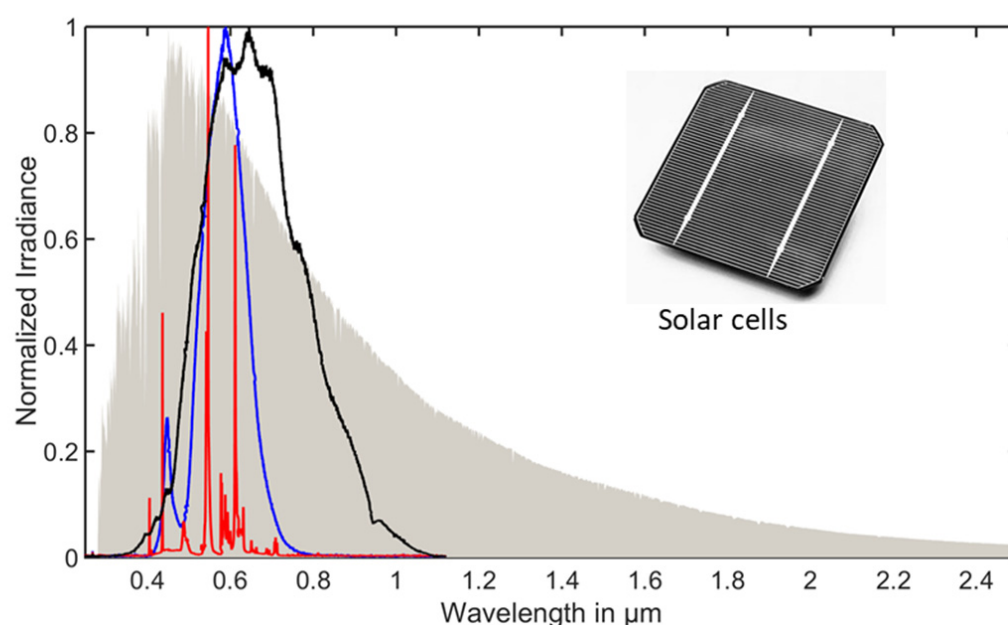
Figure 4. Normalized irradiance of a halogen lamp (black), an LED lamp (blue), and a fluorescent lamp (red) [21] compared to the AM0 spectrum (gray). (Note that the amplitude has been normalized for better visibility and spectral comparison).

In general, indoor light energy harvesting results in a strongly reduced output performance of the solar cells. In [22], this issue is shown for a cell with typical dimensions for IoT devices (1.9 cm × 5.0 cm). The power density for four different application positions varies in the range of 10–30 $\mu W/cm^2$ at the maximum power point. As soon as indirect solar illumination is present, this value increases by the factor of 20. This demonstrates the problem of the low light situation indoors. Common light bulbs with their broad-spectrum are not available anymore. Halogen lamps show a wide spectrum but are also outdated. In [23], a comparison of the output performance between STC and illumination with halogen lamps having a power density of 1000 W/m^2 was shown. The results clearly showed that, even with the same irradiation, the output performance with artificial light is worse due to the different spectral behavior of the source and the cell's sensitivity. Other research groups have worked on automated test setups to further characterize this issue. For example, Verbelen et al. demonstrated in [24] an automated test chamber with an array of different light sources for testing. Hamadani and Campanelli showed a test chamber in [25] for testing reference cells with varying spectra of the LED light. Both agree that even with similar irradiances, artificial light does not deliver the output performance of sunlight due to spectral dependence.

Therefore, selecting suitable cells is essential in designing energy harvesting solutions for indoor artificial light applications. Crystalline silicon cells show low efficiencies with artificial light; thin films (esp. CdTe) are better for weak and diffuse light [26]. Still, their efficiency indoors is worse compared to outdoors. The III-V-cells, especially GaAs, are

promising and can keep their good efficiencies for indoor use. Unfortunately, their high costs are a significant drawback [27]. Emerging technologies such as IPV and perovskite cells already show comparable results and might be a suitable solution in the future [28].

Fouling with dirt, dust, or other substances is a problem in general. It reduces the output power dramatically and brings the necessity of cleaning. In IoT applications, cleaning is not feasible, of course. Still, the problem exists and might be even worse in the industrial field, as various sources of pollution are available. In [29], the problem was described for 30 continuous days, showing the degradation due to dust. This reduces the output to 50%, which is a considerable decline that cannot be neglected. It is also possible to simulate the effect of shading due to dirt with reasonable accuracy, as shown in [30].

Without the option to clean small IoT devices, this effect cannot be avoided. Still, it is helpful to consider the possibility to tilt the cell during installation or switching to a safer place out of the reach of potential pollution sources.

The last aspect to consider is the available active time of the source(s), determined by potential light through windows and the ON-time of the artificial light, which is usually limited by the work time. If all aspects have been respected, a solar cell's necessary size and type can be determined, and a safe supply is possible.

4. High-Performance Vibration Converters

There are many moving, rotating, and reciprocating machines in industrial environments that produce enough vibration energy even after damping and strengthening, which can supply wireless sensor nodes in smart factories. For this, there are different types of transduction mechanisms, such as electromagnetic [31], piezoelectric [32], electrostatic [33], and magnetoelectric [34], as shown in 0So far, numerous vibration converters have been reported in the literature. A comparative analysis of these converters showed that electrostatic harvesters can be preferred for implantable microsystems since they are easy to integrate at MEMS level. Piezoelectric and electromagnetic converters are widely used for macro-scale devices, and several solutions are already commercialized in the market. On the other hand, although magnetoelectric converters have a high energy density, they are still far from commercial applications due to their cost. Two main properties, among others, must be considered to evaluate the performance of a vibration converter, and they are the conversion efficiency and the frequency bandwidth.

4.1. Efficient Converters

Even if an ambient source is adequate and available continuously, a suitable design remains challenging for a reliable solution. In this context, fundamental investigations are essential for developing a suitable converter design but are inadequate to use efficiently. Hence, deep studies of different constraints related to the application, such as the available ambient vibration, characteristics, converter position, and environment (size, material), are required to ensure a high working performance.

Therefore, the design of a vibration converter for a real application in smart factories cannot be based only on laboratory investigations under harmonic excitation [35]. All requirements and specifications of the aimed application must be fulfilled. First, the available applied vibration must be characterized by frequency and amplitude or acceleration [31]. This allows for the adjustment of the converter's design and operating frequency range, significantly increasing its output performance [34].

A key factor for the design of a vibration converter is the mechanical structure used to enable the relative movement between the converter elements in electromagnetic, electrostatic, or magnetoelectric converters or the method to apply a stress/strain on the piezoelectric element for the piezoelectric converters (see Figure 5). Specifically, the mechanical spring and cantilever beams are the most conventional structures used. However, magnetic springs, pendulum-based converters, and bi-stable and multi-stable configurations are interesting for designing highly efficient vibration converters. It must be indicated that an efficient design can be achieved by developing a model-based design of the con-

verter elements, taking into account the influence of external constraints. For instance, the designed converter in [31] is optimized to harvest available kinetic energy in a freight train. The field test results demonstrate that the energy harvester collects 4 mW. The study includes the investigation of the magnet and coil optimal configurations, their relative positions, and their housing properties.
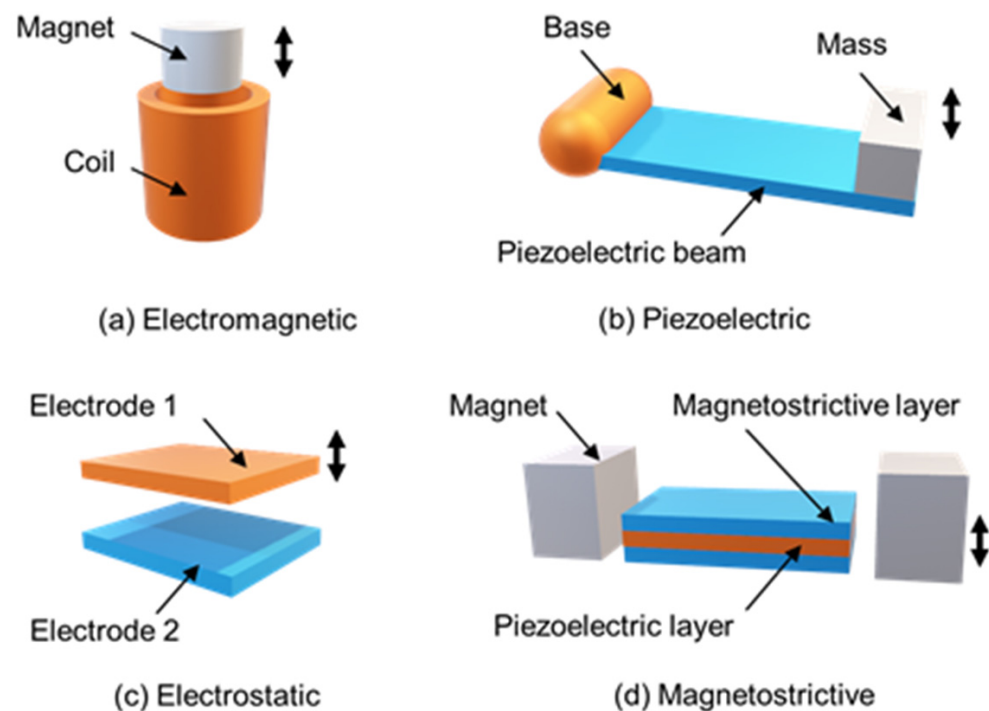
Figure 5. Schematic of the four main principles to convert mechanical to electrical energy. (**a**) Electromagnetic: based on Faraday-Neumann-Lenz, a time-variable magnetic flux and voltage are generated due to the relative motion between a coil and a permanent magnet. (**b**) Piezoelectric: piezoelectric materials are used to produce charge under applied stress/strain. (**c**) Electrostatic: a variable capacitor structure used to generate a charge. (**d**) Magnetoelectric: a combination of piezoelectric and magnetostrictive materials.

Similarly, in [36], a model-based design for a magnetoelectric converter is presented. Authors have studied the optimal magnetic field design acting on the magnetoelectric transducer, the influence of the bonding interface between the magnetoelectric and the piezoelectric layers, and the relative position between the two converter elements. Experimental investigations demonstrate that around one mW can be harvested from the vibration of a lawnmower.

4.2. Wide-Band Converters

Vibration sources in smart factories are not always harmonic. In this case, the converter efficiency can be increased by adjusting the resonance frequency of the designed transducer to the characteristic frequency range of the ambient source by mechanical [36] or electrical [37] tuning of the resonance frequency.

There are several possibilities to improve the converter bandwidth by introducing nonlinearity through several mechanisms, such as the use of a magnetic spring instead of a mechanical one [35] and the integration of smart materials that have a nonlinear behavior, such as piezoelectric [35] and magnetostrictive materials [34]. Another interesting approach is to use stoppers, as described in [38], where the frequency bandwidth could be increased by 140%.

A suitable strategy to increase the frequency bandwidth must consider the potential applications for the converter. For example, some converters that use the magnetic spring

principle are interesting and present an efficient solution to increase nonlinearity in a converter, enlarging its working frequency bandwidth. However, in terms of functionality, such a converter based on the magnetic spring principle or using a moving magnetic part is unsuitable for metallic environments, affecting its functionality. In conclusion, improving the frequency bandwidth by adjusting the proper structure presents an interesting solution. As an alternative, some researchers opted for the hybridization of vibration converters for better performance, which is detailed in Section 4.3.

4.3. Hybrid Vibration Converters

One of the interesting possibilities to extract more energy from ambient sources in smart factories is to design hybrid converters. Hybridization contributes to the improvement of the converter performance in terms of reliability, and it increases the harvested energy amount. Several combinations of energy harvesters have been proposed. They can be classified into main five combinations: piezoelectric–electromagnetic, piezoelectric–electrostatic, piezoelectric–triboelectric, electromagnetic–magnetostrictive, and electromagnetic–magnetoelectric converters. Few researchers opted to develop converters that combine even three principles: piezoelectric, electromagnetic, and triboelectric principles. In the following, the main architectures that consider the different combinations are detailed.

In [39], a combination of piezoelectric and electrostatic principles is proposed. The aim, thereby, is to develop a converter with a flexible structure that harvests from low-frequency human motions around 3 Hz and improves the energy density level of the converter. In this case, the average output power density is limited to the range of micro to nano-watts. Further, aiming to improve the performance of the piezoelectric part for a low frequency and high bandwidth, [40] proposed a hybrid converter that comprises multi cantilevers and a thermoelectric nanogenerator. The converter concept consists of a PVDF cantilever hitting the MNDS PDMS on the glass substrate due to external vibration, leading to energy conversion based on piezoelectric and triboelectric principles.

The magnetostrictive–electromagnetic combination is proposed by [41], where the main challenge was developing a converter in AA battery size. In this case, the improvement of the energy outcome is only at a level of microwatts by introducing the magnetostrictive material to the electromagnetic converter, without changing the volume.

For the piezoelectric–electromagnetic converters, the main aim of this hybridization is to improve the performance of the piezoelectric converter and adjust it for low frequencies by adding the electromagnetic principle as a tip mass [42]. The architecture combining these two principles is generally based on the cantilever beam structure, where the piezoelectric element is placed. The electromagnetic part is added as a tip mass, and its design always depends on the required working resonant frequency. In addition, other researchers focused on this combination to widen the operating frequency range of the converter [43]. This is achieved by introducing a nonlinear structure for the EM, leading to a nonlinear converter behavior, and enabling a wide frequency bandwidth.

The electromagnetic–magnetoelectric hybridization presents an interesting solution to improve the energy density of the converter as well as its reliability. Both converters harvest energy based on the variation level of the magnetic field, which enables the development of a converter where the energy density is improved compared to a single electromagnetic or magnetoelectric converter [44,45]. Due to the proposed design, energy can be harvested from both principles independently [45]. Recently, in [46], the combination of the three basic principles (electromagnetic, piezoelectric, and triboelectric) is proposed. Compared to the piezoelectric–electromagnetic version, the improvement is small due to the limited generated energy through the triboelectric principle.

The presented solutions above are challenging in terms of implementation due to the structural complexity. Nevertheless, the research on harvesting from ambient is still growing due to the progressive need for more advanced technologies responding to the application requirements, including flexibility and long-term exposure to the energy source.

5. Polymer Composite-Based Flexible Nanogenerators

Recently, the novel trend is developing miniaturized, flexible, and lightweight energy harvesters named nanogenerators, which can generate electrical energy from thermal and mechanical energy sources [47–49]. These sources are typically available with machinery, which offers an obvious supply option. Nanogenerators are attracting attention due to their conversion efficiency, easy fabrication process, low costs, and their possibility of fulfilling the demands of having a sustainable and self-powered source for operating novel flexible electronic systems [50]. They are relevant for smart factories, as they can easily be integrated into machines and elements and harvest energy following different principles.

Nanogenerators can be categorized according to the source of energy (see Figure 6). The first category uses mainly mechanical sources and is divided into two types, which are the triboelectric nanogenerators (TENGs) and the piezoelectric nanogenerators (PENGs) [51]. The working principle of the TENGs depends on a conjunction of triboelectrification and electrostatic induction between two contacted materials, as illustrated in 0In contrast, the piezoelectric nanogenerator mainly applies an external force to piezoelectric materials, leading to electric dipole moments between the two electrodes. The second category is based on converting thermal energy into electricity with a pyroelectric effect. Indeed, pyroelectric materials are a subclass of piezoelectric materials. However, not all piezoelectric materials have a pyroelectric effect. Pyroelectric materials exhibit a spontaneous polarization caused by temperature fluctuation [52].
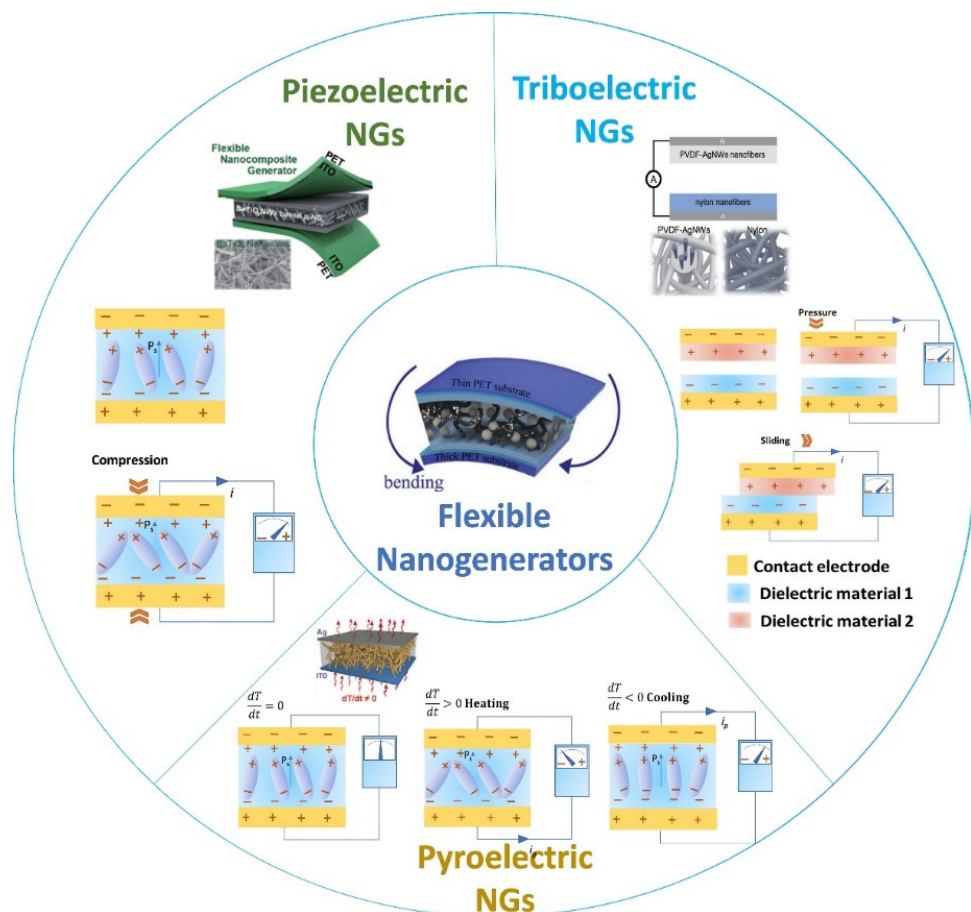
Figure 6. Overview of nanogenerators working principles.

In order to realize flexible nanogenerators, polymer materials are usually used because they can exhibit flexible properties, mechanical stabilities to withstand more significant deformation, as well as piezoelectric and ferroelectric properties. The most common piezoelectric polymers are Polyvinylidene fluoride (PVDF) [53], polyvinylidene fluoride-

trifluoro ethylene (PVDF-TrFE) [54], polyamides (PA) [55], and polylactic acids (PLA) [56], among which PVDF and their co-polymer have been extensively used due to their high piezoelectric properties. However, the performance of polymer nanogenerators can be improved by including piezoceramic particles [57], carbon nanomaterials [58], metallic nanoparticles [59], biomaterials, or hybrid materials [60].

5.1. Piezoelectric and Triboelectric Nanogenerators

Polymer composite-based piezoelectric nanogenerators have attracted extensive interest for the supply of electronics due to their enormous output, conversion efficiency, and flexibility. Usually, the functionality and performance of the flexible nanogenerator depend significantly on the chosen polymer and reinforcement. So far, various piezoelectric polymer composite materials have been developed to realize micro-scale and nano-scale generators. The most commonly used polymer composites are PVDF and co-polymer filled with piezoceramics nanoparticles, such as zinc oxide ZnO [61], lead zirconated titanate (PZT) [62], and Barium Titanite (BaTiO3) [63], owing to their excellent piezoelectric properties. Shin et al. [63] reported the fabrication of high-performance PENG based on BaTiO3-P (VDF-HFP) composite thin-film prepared with a solvent-assisted composite thin film formation process to attain optimal distribution of BaTiO3 within the polymer matrix. Using different solvent ratios, the optimal NG achieves a compressive force of ~0.23 MPa normal to the surface a high output voltage and current of 110 V and 22 µA, respectively.

Further studies focus on embedded piezoceramic particles in a highly stretchable and flexible polymer, such as polydimethylsiloxane (PDMS) [64,65]. The use of soft polymer matrices will offer nanogenerators unique advantages over other polymers, including the simplicity and scalability of the fabrication process and improved durability at high mechanical deformation. This kind of nanogenerator provides higher flexibility for industrial applications to harvest energy from movements. Park et al. [66] fabricated a high large-area NG based on lead zirconate titanate (PZT) embedded in PDMS using a simple, low-cost, and scalable bar-coating method. The NG exhibits up to ~100 V and ~10 µA, enough to power 12 light-emitting diodes (LEDs) without external energy-storage systems. Hybrid polymer composites have been developed by adding conductive nanoparticles such as carbon nanotubes or Ag nanoparticles to increase the performance and distribution of piezoceramic particles. The role of these conductive particles is to form a network within the polymer matrix to achieve a good distribution of the piezoceramic nanoparticles, as demonstrated by Park et al. [67], and enhance the dielectric property, leading to a better piezoelectric property. The use of conductive nanoparticles can eliminate the requirement of making poling process, which is very long and unsafe.

However, piezoelectric nanogenerators show a limited ability to harvest from weak energy sources. In this regard, many efforts have focused on developing nanogenerators based on triboelectric effects due to the possibility of tackling the above problem. As the working principle of these nanogenerators relies on contact-induced electrification between the different dielectric materials, other methods have been adopted to boost the performance, including surface patterning, chemical functionalization, and composite structure. Using chemical functionalization, the charge capturing capability of the triboelectric material will be enhanced. For example, Wang et al. [68] reported improving the output four times for TENG modified with amine as the head group. Many efforts have been devoted to modifying the surface of TENG by creating wrinkling or buckling within it. Sun et al. [69] reported about a soft NG, which is a self-healable, stretchable, and transparent thin film containing Ag nanowires/poly (3,4 ethylenedioxythiophene) composite electrode sandwiched with self-healable poly (dimethylsiloxane) (PDMS) elastomers. The characteristics of this TENG can be tuned according to the buckling wavelength of the electrode. The resulting TENG scavenges mechanical motion energy and reaches an open-circuit voltage of ~100 V and a maximum power density of 327 mW/m^2.

Others use high dielectric materials, such as BaTiO3, to enhance the charge-attracting or -trapping capability [70]. Compared to PENGs, TENGs provide higher output power that can reach the watt level, which can also help power electronic devices.

5.2. Pyroelectric Nanogenerators

Piezoelectric polymer composites have been effectively used to harvest small-scale mechanical energy. As either strain or temperature can create the piezo potential, several works have focused their study on harvest energy based on the pyroelectric effect, which is based on the spontaneous polarization of the piezoelectric materials due to temperature variation. For example, Yang et al. [71] reported flexible pyroelectric NGs fabricated to harvest energy from sunlight illumination using PDMS filled with lead-free KNbO3 nanowires grown by a simple hydrothermal method. The obtained nanowires have a single-crystalline structure with a growth direction of [011].

5.3. Hybrid Nanogenerators

Many studies have focused on optimizing the performance of nanogenerators to avoid the limitation of each kind of nanogenerator by hybridizing the energy harvesting system using dual or trial effects to improve the energy output and expand the application scope. Suo et al. [72] reported a novel hybrid nanogenerator formed with two nanogenerators using BaTiO3NP/PDMS composite film and two different working principles, which are piezoelectricity and triboelectricity. In this work, the two nanogenerators shared energy conversion. According to Suo et al. [72], the hybrid NG voltage possesses higher output performance than the triboelectric and piezoelectric harvesters' performance. Another option is using a hybrid nanogenerator based on different conversion principles to raise the overall power output. In [73], a fully stretchable hybrid nanogenerator working on a combination of piezoelectric and pyroelectric effects was developed. The nanogenerator comprises micro-patterned piezoelectric polymer P (VDF-TrFE) thin film, PDMS-CNT composite, and graphene. A prosperous and stable output voltage is obtained under both thermal and strain effects.

Energy harvesting systems present challenges in implementation, availability, and the generated amount of power, which cannot be offered in some applications. In this case, alternative wireless charging systems can be implemented. Section 6 is devoted to presenting an overview of the recent achieved development of wireless charging systems.

6. Wireless Charging

In general, as a high level of reliability is required in industrial applications, the necessary energy supply should be guaranteed along the operation time. Especially in smart factory systems, where the ambient energy cannot deliver sufficient energy supply, wireless charging provides an alternative for supplying sensors. This is important for WSN in various environments, such as machines, which can contain oils or water, chain conveyers, or even for tracking boxes transporting elements for the production process. Contactless power transfer offers many advantages, where cables and sockets can be removed, moving elements can be supplied, and the energy can be transferred on demand. In addition, it is possible to supply a WSN without additional storage elements [16], which decreases the size of a node, as the storage elements usually have large dimensions compared to integrated electronics. In this section, an overview of different wireless charging systems for the supply of WSN is presented.

Different concepts can be applied to power WSN devices wirelessly, such as radio frequency (RF) [72], magnetic resonance power transmission (MRPT) [74], and inductive power transmission (IPT) [16]. These techniques differ by their charging efficiency and range, frequency band, and the used wave field. Table 2 resumes the main characteristics of each system. These systems can supply the WSNs [16,75] or charge the associated batteries [74]. The main limitation for the IPT system is its charging range [16], which depends on the alignment between the charging circuit and the device. The MRPT systems

are usually defined as derivative systems of IPT systems, where the coils resonate with the internal capacitor [16].

Table 2. Characteristics of wireless power transmission systems.

Characteristics	Contactless Power Transmission Method		
	Radiofrequency	**Magnetic Resonance Power Transmission**	**Inductive Power Transmission**
Wave type	Electromagnetic field	Magnetic field	Magnetic field
Charging range	Medium to long (from m to km)	Short to medium (from cm to m)	Very short (from mm to cm)
Relative power	nW—mW	mW—few W	MW—kW
Working frequency range	MHz-GHz	MHz	kHz

6.1. Structure of CPT Systems

The general structure of the presented systems is based on transmitting and receiving sides [74]. The transmitter side is connected to the energy source. It consists of an oscillator circuit with a specific frequency and power level connected to a transmitter coil. In [76], the general structure of the receiving side CPT system is shown. The receiving coil is connected to an LC resonant circuit with associated capacitors and coils on both sides. In some scenarios, the receiving side load behavior on the system efficiency is considered during the resonance circuit development or by specific control circuits [77]. However, the connection of the resonance circuit affects the circuit bandwidth and the attitude of the output voltage and current [78].

To deliver the required power to the load, an AC-DC converter such as a single diode rectifier, full-bridge rectifier, and voltage multiplier can be used. The selection of the necessary converter depends on the required output voltage level and the working frequency. For low output voltage systems [74], voltage multiplier circuits are more suitable. Bridge rectifiers are used for high output voltage systems [79], such as IPT and MRPT. DC-DC converters can be merged with the circuit to regulate the acquired power according to the load specifications, generating a constant output voltage or current. Generally, for the MRPT and IPT systems, a coil with specific geometries and materials is used, such as copper and ferrites. The components of the structure can also be seen in Figure 7.
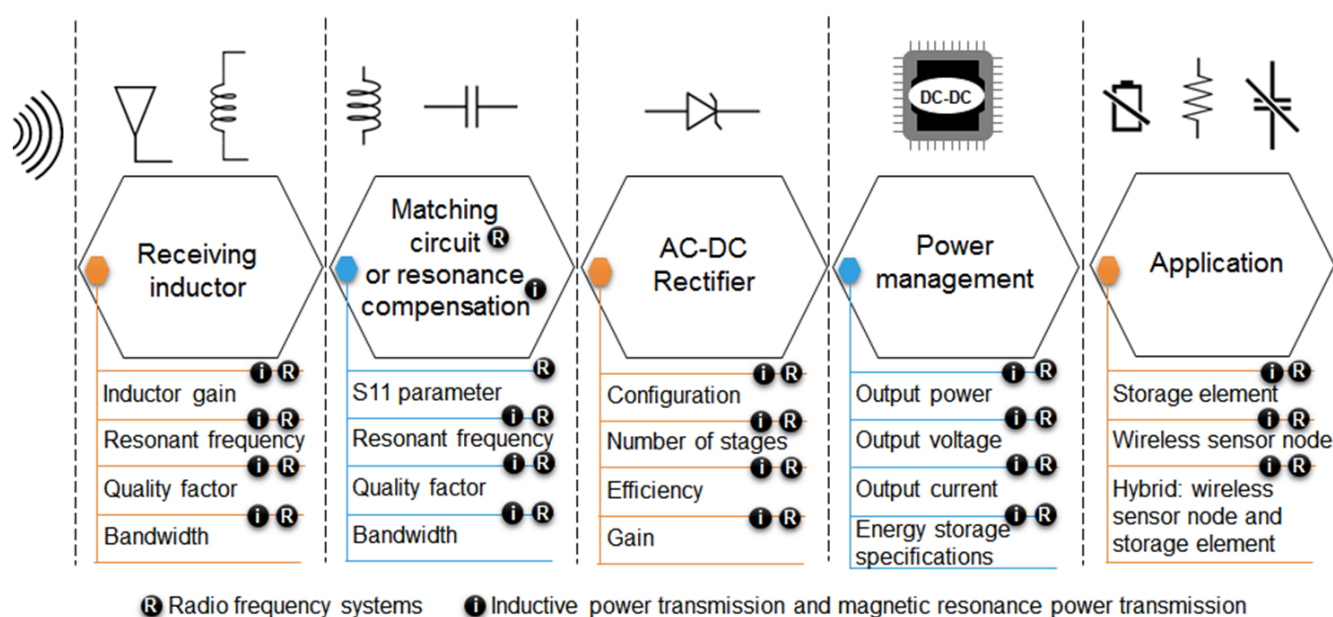

Figure 7. Structure of the receiving side in wireless charging systems.

6.2. CPT Coils

CPT design depends on various aspects such as the electronic circuit, the coil system, and the control architecture. The design of the CPT coils presents one of the research trends. CPT systems can be classified in mainly four possible architectures based on the number of transmitter and receiver coils, and they are singular input singular output (SISO) (see Figure 8a), singular input multiple output (SIMO) (see Figure 8b), multiple input singular output (MISO) (see Figure 8c), and multiple input multiple output (MIMO) (see Figure 8d). Multiple output systems increase the number of the receiver devices supported by the same transmitter circuit [76], where the multiple transmitter systems investigate the generated transmitter energy and the charging area. The multiple input systems can connect the coils in series [76] or parallel, generally activated by switches [16]. However, increasing the number of coils increases the complexity during implementation and the system cost, making them challenging.
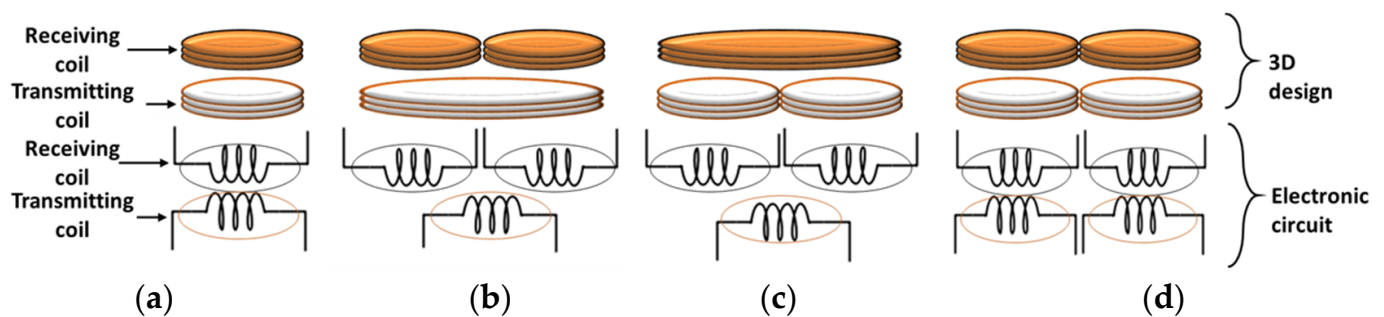
Figure 8. Wireless charging system architectures: (**a**) singular input singular output (SISO), (**b**) singular input multiple output (SIMO), (**c**) multiple input singular output (MISO), and (**d**) multiple input multiple output (MIMO).

In MRPT, the system can use additional intermediate coils to increase the charging distance range [18]. This intermediate coil is often resonating on the operating system frequency. Other challenges for improving the CPT system coils are considered in research, such as the design with the lowest thickness, weight, and robustness and tolerance to the environment, for temperature and humidity. For that, different geometries [79], materials [80], and technologies [81] are investigated.

Providing energy for a WSN, either through harvesting or wireless charging, is challenging. For that, many developments also focus on smart solutions that enable energy saving on the network level. This will be discussed in the following section.

7. Energy-Saving Techniques for WSNs

In addition to energy supply sources coming from ambient sources, it is important to reduce the power consumption of the wireless sensor node itself or when it is communicated to other nodes within the network. Some sensor nodes are equipped with non-rechargeable batteries, which are hard to replace, particularly in a large field or unreachable positions such as in railway monitoring [82]. In a smart factory and by the huge number of sensors needed, there is no acceptance for systems needing battery replacements often or risking a lack of reliability and longevity. This is why it is very important to realize an equilibrated system design reducing energy consumption and using a sufficient energy source, even for dynamic operation conditions.

Different energy-saving techniques have been introduced as enabling technologies to boost network efficiency and operability [83]. This section provides a panoramic view of the most relevant energy optimization techniques on the node and network levels (Figure 9).
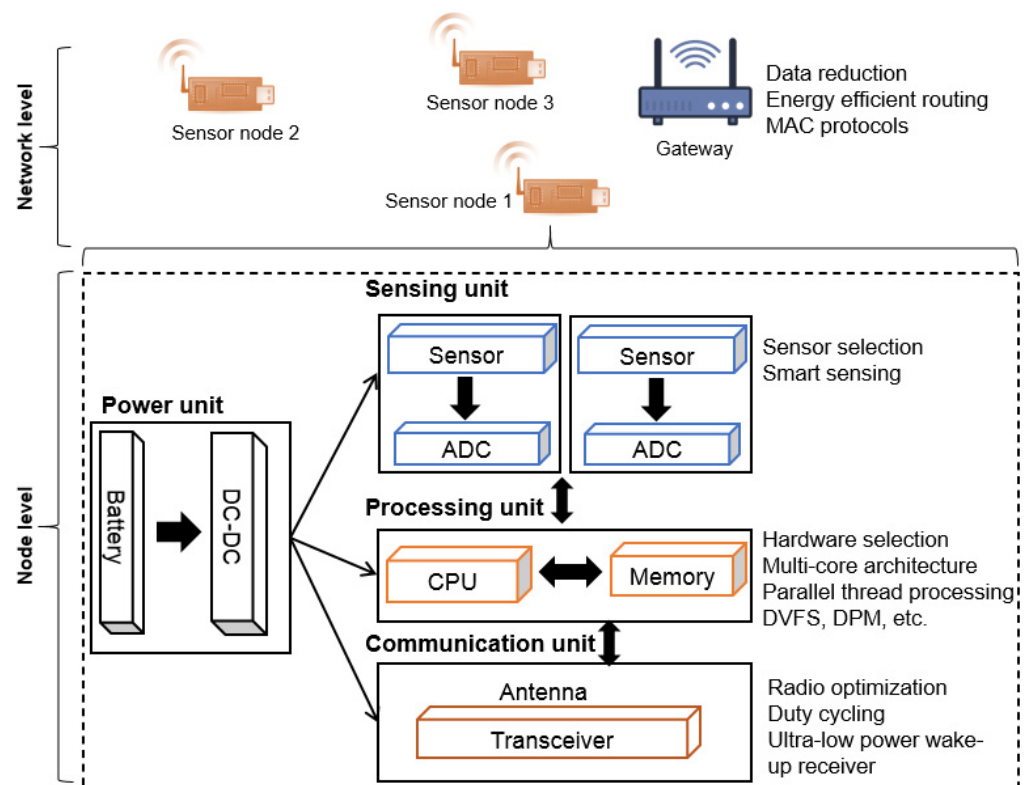
Figure 9. Energy-saving techniques in WSNs.

7.1. Node Level

The architecture of a sensor node has a significant impact on its energy consumption. Each node has a specific architecture [84]. The power consumption can be reduced at the node architectural level by choosing the hardware and software. Integrating the System on Chip (SoC) circuit into WSNs is a promising solution to reduce the power consumption by using HW/SW partitioning [85]. So, the most time-consuming function or complex algorithms such as video or image processing are performed with the hardware. However, SoC circuits are not flexible and are dedicated to a specific application.

For this reason, the field-programmable gate array (FPGA) is introduced. The clock gating presents one of the power reduction techniques used by the FPGA [86]. This unit can change the clock signal distribution and disables the hardware peripherals, which are not in use for this particular application. Despite this, the FPGA is known for its high-power consumption compared to other processors. That is why some works integrate hardware accelerators to reduce the processing and execution time, thus reducing the consumed power.

With the introduction of multi-core architectures, many developers use modern microcontrollers to optimize code performance by implementing separate instructions in separate microcontrollers. This is known as parallelism [87], where various cores execute programs in parallel, realizing more efficiency. Multi-core sensor nodes provide energy efficiency compared to traditional single-core nodes for two reasons. First, the energy spent on communication can be reduced by carrying out an in situ calculation of the detected data and transmitting only the processed information. Second, a multi-core node can distribute computations over multiple cores.

In contrast, each core operates at a lower voltage and processor frequency than a single-core node, resulting in significant power savings. The use of a single-core node for information processing in high-demanding processing applications needs the wireless node to operate at a high enough frequency and voltage to satisfy the application's delay demands, resulting in increased processor power loss. A multi-core sensor node decreases

overall memory access, instruction decoding, and clock speed, allowing better computing performance while consuming less power.

The consumed power of the microcontroller can also be reduced by changing the frequency considering the workload. For this, the dynamic voltage frequency scaling (DVFS) technique can be applied. The voltage and frequency are adjusted dynamically based on system performance requirements at a certain point of time [88]. Another energy-efficient solution is the dynamic power management (DPM) technique, where the power consumption level is tuned depending on the power mode. Indeed, the node is shut down automatically when it is in idle mode and activated in the active mode [89].

The consumed power of the sensing unit can be optimized by choosing a low power consumption sensor that has one or more low power modes, such as the shutdown state. The smart sensing method is introduced to achieve low power sensor consumption by using integrated digital logic in the sensor design, enabling sensors to carry out their internal self-power management. This method is applied to pressure sensors, magnetometers, and accelerometers [90].

The communication unit is the most energy-consuming component in a sensor node. Optimizing the transceiver parameters effectively reduces overpower consumption during wireless communication by optimizing the antenna direction, power transmission, and modulation [91]. Therefore, directional antennas aim to decrease the data retransmission and interference generated by omnidirectional antennas. When a node transfers data in a given direction, a neighboring node can also transfer simultaneously and with no interference, resulting in a considerable reduction in energy consumption. Setting the radio transmission parameters depending on specific link quality parameters, including the received signal strength indicator (RSSI) and link quality indicator (LQI) or according to certain network conditions is defined as transmission power control (TPC) method, which is used to save the radio power consumption [92]. At the same time, the modulation optimization methods are introduced to identify the optimal modulation parameters of the radio with the lowest power consumption. Over short distances, the circuit's power consumption is greater than the power consumed for the transmission, and the reverse is true for long distances. Consequently, the appropriate modulation parameters that compromise the transmission signal power and the distance between the nodes are crucial.

One of the most energy-efficient operations is switching the radio transceiver into standby mode when no communication is needed. The best way to do this is to turn off the radio when there is no data to be transmitted or received and turn it on again when a new data packet is available. Another approach to save the energy within the communication unit is to use a different, ultra-low-power wake-up receiver (WuRx) by turning off the rest of the system and providing a permanent on-demand communication feature, with low power consumption in the order of μW [93]. The wake-up receivers are used together with the main receiver, which is switched on only on request. Once a signal is received with a unique identifier, the main processor and the rest of the peripherals are immediately activated. The detection of wake-up packets can be achieved with appropriate circuits with ultra-low power consumption.

7.2. Network-Level

The communication between sensor nodes within the same network or the base station is one of the major sources of energy dissipation in WSNs. Thereby, different energy-efficient techniques can be used to reduce the network overall power consumption significantly. Data reduction approaches are introduced as key solutions for energy saving by transforming the data to be sensed, treated, and transmitted to the sink node into smaller units for decoding by the receiver node, thus reducing the network power consumption. They can be categorized into three schemes, namely data prediction, data compression, and in-network processing. Data prediction refers to the abstraction of the sensed data [94]. It forecasts the output values of the wireless sensor node with a specified error range and produces two instance patterns in the receiver node and the corresponding source node.

When the prediction pattern is correct, the receiver can handle any request made by the user while not communicating with the source node and having the correct value. If there is an inaccurate prediction pattern between the receiver and the sensor nodes, the used pattern requires updating. Therefore, using data prediction mechanisms can reduce the volume of messages transmitted from the source node to the receiver, thus reducing the energy required for communication. Data compression is intended to compress the data captured from the sensor node by this node itself or through an aggregator node [95]. Afterwards, only the necessary data is forwarded to the destination node.

Several methods can be applied when the receiving node decompresses incoming data, such as adaptive model selection, lossless compression, and Kalman filtering. Compressive sensing (CS) can be considered an energy-efficient data compression method by decreasing the volume transferred [96]. In this method, the original signal is converted into a new signal with reduced values, defined as sparsity. As the sampling rate is shortened, the power consumption is reduced. A significant characteristic of CS is its ability to rebuild a sparse signal from a reduced number of measurements, with no prior knowledge of the signal structure. The in-network processing scheme aggregates the data at the relay node, allowing the data from different nodes to be combined and transmitted to the receiver node in an individual packet. In this way, the amount of data is decreased, and the energy consumed is reduced.

To reduce the power consumption during data communication, routing is introduced, as one of the most energy-aware techniques, by aggregating data packets and selecting the energy-efficient paths between source and destination nodes. In this direction, clustering protocols present one of the most energy-efficient routing techniques by minimizing the number of transmitted packets and the distances between nodes simultaneously. It divides the network into groups called clusters, where a cluster head is selected to forward the received data from its cluster members and forward it to the base station or sink node. Several studies have been performed to save the energy within the network and have a longer network lifetime [97].

Another technique to save energy within the network is the efficient use of channel access. Therefore, the medium access control (MAC) schemes are introduced to arrange the communication from a sensor node to another node within the same network or between nodes from different networks by setting a sending time for every node [98]. Thus, the data collision problem is avoided, and the energy is saved. The most well-used in WSN is the time division multiple access (TDMA), which allows a strict synchronization between transmitter nodes and the sink node [99]. Each node has a specific time slot, and it is allowed to transmit only in the allocated time slot to avoid interference. Then, it goes into sleep mode when its time is finished. So, the energy consumption is significantly decreased to the minimum required for transmitting/receiving data, and the transmission is efficiently scheduled. TDMA is used in applications that need a high data rate and low delay, such as healthcare applications. Carrier sense multiple access (CSMA) or carrier sense multiple access/collision avoidance (CSMA/CA) are used by many applications such as WIFI, Zigbee, etc. [100]. So, nodes transmit their data only if the channel is free by implementing a carrier sense to check the channel state to avoid data collision. This protocol is not good for high data traffic because high traffic means high collisions. CSMA allows high flexible communication with low complexity.

8. Conclusions

Autonomous wireless sensor networks are gaining importance in industrial applications. They enable several indispensable functionalities and especially provide flexibility, as they can be easily installed and involve a low-maintenance effort. This review provides an overview of the potential of energy-aware power solutions for sensors in industrial applications. The contribution has shown a survey of relevant energy harvesting possibilities, including supply by energy harvesting from ambient sources and wireless energy transfer, each focusing on high performance and energy saving. Classical converters such as solar

cells or vibration transducers have advantages and disadvantages. For solar cells, the power output can be predicted. Vibration converters can be updated with new materials to improve the bandwidth. Furthermore, the potential of smart materials for nanogenerators has been discussed. These transducers enable new adaptive ways to convert power, tailored specifically to the energy sources.

Very important for all systems is the energy saving at the network level, which should be considered within the network design as well, as discussed in the last section of this review paper. The review of energy aware WSNs for smart factories shows that several solutions already exist and are well applicable to several applications in smart factories. These solutions make sensor systems independent from cable connections, making installation and maintenance easier and improving their acceptance. WSNs for industrial applications will become more important in the future. They represent an easy way to bring production to a new technological advanced level with high efficiency and manageable costs. With the continuous growth of automation and data technologies in industrial applications, the complexity of data collection, data processing, communication, and storage is significantly increasing. It results, in total, in a high demand for energy, even if the system elements may appear to use a small energy budget. Thereby, the developments in the direction of autonomous supply and energy efficiency support each other and constantly increase the feasibility, making them practical and useful for these developments. Supplying wireless nodes with energy coming from ambient sources and simultaneously implementing energy-saving techniques needs further exploration for better performance. Both aspects need to be considered together in a holly system design to elaborate optimized useful WSNs for this economically highly relevant sector of smart factories.

Author Contributions: O.K. contributed by conceptualization, methodology, original draft writing, visualization, editing, and funding acquisition. S.K., S.N., S.B., G.B., A.B., D.E.H. and C.V. contributed by writing of sections, reviewing, visualizing, and editing. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kanoun, O.; Keutel, T.; Viehweger, C.; Zhao, X.; Bradai, S.; Naifar, S.; Trigona, C.; Kallel, B.; Chaour, I.; Bouattour, G.; et al. Next generation wireless energy aware sensors for internet of things: A review. In Proceedings of the 2018 15th International Multi-Conference on Systems, Signals & Devices (SSD), Yasmine Hammamet, Tunisia, 19–22 March 2018; pp. 1–6. [CrossRef]
2. Kalsoom, T.; Ramzan, N.; Ahmed, S.; Ur-Rehman, M. Advances in sensor technologies in the era of smart factory and industry 4.0. *Sensors* **2020**, *20*, 6783. [CrossRef] [PubMed]
3. Kanoun, O.; Bradai, S.; Khriji, S.; Bouattour, G.; El Houssaini, D.; Ben Ammar, M.; Naifar, S.; Bouhamed, A.; Derbel, F.; Viehweger, C. Energy-aware system design for autonomous wireless sensor nodes: A comprehensive review. *Sensors* **2021**, *21*, 548. [CrossRef]
4. Bdiri, S.; Derbel, F.; Kanoun, O. An 868 MHz 7.5 µW wake-up receiver with-60 dBm sensitivity. *J. Sens. Sens. Syst.* **2016**, *5*, 433–446. [CrossRef]
5. Bdiri, S.; Derbel, F.; Kanoun, O. A tuned-RF duty-cycled wake-up receiver with −90 dBm sensitivity. *Sensors* **2018**, *18*, 86. [CrossRef]
6. Li, X.; Li, D.; Wan, J.; Vasilakos, A.V.; Lai, C.F.; Wang, S. A review of industrial wireless networks in the context of industry 4.0. *Wirel. Netw.* **2017**, *23*, 23–41. [CrossRef]
7. Abdelkareem, M.A.; Xu, L.; Ali, M.K.A.; Elagouz, A.; Mi, J.; Guo, S.; Liu, Y.; Zuo, L. Vibration energy harvesting in automotive suspension system: A detailed review. *App. Energy* **2018**, *229*, 672–699. [CrossRef]
8. Choi, J.; Jung, I.; Kang, C.Y. A brief review of sound energy harvesting. *Nano Energy* **2019**, *56*, 169–183. [CrossRef]

9. Sarker, M.R.; Saad, M.H.M.; Olazagoitia, J.L.; Vinolas, J. Review of power converter impact of electromagnetic energy harvesting circuits and devices for autonomous sensor applications. *Electronics* **2021**, *10*, 1108. [CrossRef]

10. Jeong, C.; Joung, C.; Lee, S.; Feng, M.Q.; Park, Y.B. Carbon nanocomposite based mechanical sensing and energy harvesting. *Int. J. Precis. Eng. Manuf.-Green Technol.* **2020**, *7*, 247–267. [CrossRef]

11. Tang, X.; Wang, X.; Cattley, R.; Gu, F.; Ball, A.D. Energy harvesting technologies for achieving self-powered wireless sensor networks in machine condition monitoring: A review. *Sensors* **2018**, *18*, 4113. [CrossRef]

12. Hosseinkhani, A.; Younesian, D.; Eghbali, P.; Moayedizadeh, A.; Fassih, A. Sound and vibration energy harvesting for railway applications: A review on linear and nonlinear techniques. *Energy Rep.* **2021**, *7*, 852–874. [CrossRef]

13. Le, M.Q.; Capsal, J.F.; Lallart, M.; Hebrard, Y.; Van Der Ham, A.; Reffe, N.; Geynet, L.; Cottinet, P.J. Review on energy harvesting for structural health monitoring in aeronautical applications. *Prog. Aerosp. Sci.* **2015**, *79*, 147–157. [CrossRef]

14. Nikhade, S.G. Wireless sensor network system using Raspberry Pi and zigbee for environmental monitoring applications. In Proceedings of the 2015 International Conference on Smart Technologies and Management for Computing, Communication, Controls, Energy and Materials (ICSTM), Avadi, India, 6–8 May 2015; pp. 376–381. [CrossRef]

15. Khriji, S.; Kallel, A.Y.; Reedy, S.; El Houssaini, D.; Kammoun, I.; Kanoun, O. Dynamic autonomous energy consumption measurement for a wireless sensor node. In Proceedings of the 2019 IEEE International Symposium on Measurements & Networking (M&N), Catania, Italy, 8–10 July 2019; pp. 1–5. [CrossRef]

16. Bouattour, G.; Elhawy, M.; Naifar, S.; Viehweger, C.; Ben Jmaa Derbel, H.; Kanoun, O. Multiplexed supply of a MISO wireless power transfer system for battery-free wireless sensors. *Energies* **2020**, *13*, 1244. [CrossRef]

17. Harb, A. Energy harvesting: State-of-the-art. *Renew. Energy* **2011**, *36*, 2641–2654. [CrossRef]

18. Cheah, W.; Watson, S.; Lennox, B. Limitations of wireless power transfer technologies for mobile robots. *Wirel. Power Transf.* **2019**, *6*, 175–189. [CrossRef]

19. Reference Air Mass 1.5 Spectra. Available online: https://www.nrel.gov/grid/solar-resource/spectra-am1.5.html (accessed on 21 July 2020).

20. Long, Y.S.; Hsu, S.T.; Wu, T.C. Energy harvesting characteristics of emerging PV for indoor and outdoor. In Proceedings of the 2016 IEEE 43rd Photovoltaic Specialists Conference (PVSC), Portland, OR, USA, 5–10 June 2016; pp. 0796–0801. [CrossRef]

21. Viehweger, C.; Keutel, T.; Kasper, L.; Pfeifer, T.; Kanoun, O. System design and energy management for indoor solar energy harvesting under consideration of spectral characteristics of solar cells. *IJMTIE* **2013**, *3*, 1–15. [CrossRef]

22. Costa, M.S.; Manera, L.T.; Moreira, H.S. Study of the light energy harvesting capacity in indoor environments. In Proceedings of the 2019 4th International Symposium on Instrumentation Systems, Circuits and Transducers (INSCIT), Sao Paulo, Brazil, 26–30 August 2019; pp. 1–4. [CrossRef]

23. Sobczynski, D. Impact of light source spectrum in laboratory test of commercially available photovoltaic panels. In Proceedings of the 2018 Progress in Applied Electrical Engineering (PAEE), Koscielisko, Poland, 18–22 June 2018; pp. 1–5. [CrossRef]

24. Verbelen, Y.; Van Belle, D.; Blondeel, N.; De Winne, S.; Braeken, A.; Touhafi, A. Automated test chamber for indoor photo-voltaics. In Proceedings of the 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, UK, 20–23 November 2016; pp. 143–148. [CrossRef]

25. Hamadani, B.; Campanelli, M. Photovoltaic Characterization under artificial low irradiance conditions using reference solar cells. *IEEE J. Photovolt.* **2020**, *10*, 1119–1125. [CrossRef]

26. Mathews, I.; Kantareddy, S.; Buonassisi, T.; Peters, I. Technology and market perspective for indoor photovoltaic cells. *SSRN Electron. J.* **2019**, *3*, 1415–1426. [CrossRef]

27. Mathews, I.; King, P.; Stafford, F.; Frizzell, R. Performance of III–V solar cells as indoor light energy harvesters. *IEEE J. Photovolt.* **2016**, *6*, 230–235. [CrossRef]

28. Venkateswararao, A.; Ho, J.; So, S.; Liu, S.; Wong, K. Device characteristics and material developments of indoor photovoltaic devices. *Mater. Sci. Eng.* **2020**, *139*, 100517. [CrossRef]

29. Patil, T.G.; Asokan, S. Comparative analysis of calculation of solar panel efficiency degradation. In Proceedings of the 2017 Third International Conference on Science Technology Engineering & Management (ICONSTEM), Chennai, India, 23–24 March 2017; pp. 522–525. [CrossRef]

30. Kobayashi, S.I.; Aoyama, Y.; Kano, M.; Yachi, T. Simulation method for pv module power generation with dirt spots and reduction of output degradation. In Proceedings of the INTELEC 07–29th International Telecommunications Energy Conference, Rome, Italy, 30 September–4 October 2007; pp. 429–433. [CrossRef]

31. Bradai, S.; Naifar, S.; Viehweger, C.; Kanoun, O. Electromagnetic vibration energy harvesting for railway applications. In Proceedings of the International Conference on Engineering Vibration (ICoEV 2017), Sofia, Bulgaria, 4–7 September 2018; Volume 148, p. 12004. [CrossRef]

32. Kim, H.; Kim, J.; Kim, J. A review of piezoelectric energy harvesting based on vibration. *Int. J. Precis. Eng.* **2011**, *12*, 1129–1141. [CrossRef]

33. Dorzhiev, V.; Karami, A.; Basset, P.; Marty, F.; Dragunov, V.; Galayko, D. Electret-Free micromachined silicon electrostatic vibration energy harvester with the bennet's doubler as conditioning circuit. *IEEE Electron Device Lett.* **2015**, *36*, 183–185. [CrossRef]

34. Naifar, S.; Bradai, S.; Kanoun, O. A magnetoelectric vibration converter with tunable resonance frequency/Magnetoelektrischer Vibrationswandler mit einstellbarer Resonanzfrequenz. *tm—Tech. Mess.* **2019**, *86*, 97–101. [CrossRef]

35. Naifar, S.; Bradai, S.; Viehweger, C.; Kanoun, O. Survey of electromagnetic and magnetoelectric vibration energy harvesters for low frequency excitation. *Measurement* **2017**, *106*, 251–263. [CrossRef]

36. Naifar, S. *Model Based Design of a Magnetoelectric Vibration Converter from Weak Kinetic Sources, Scientific Reports on Measurement and Sensor Technology*, 9th ed.; Technische Universität Chemnitz: Chemnitz, Germany, 2019.

37. Cammarano, A.; Burrow, S.; Barton, D.; Carrella, A.; Clare, L. Tuning a resonant energy harvester using a generalized electrical load. *Smart Mat. Struct* **2010**, *19*, 055003. [CrossRef]

38. Gupta, R.; Shi, Q.; Dhakar, L.; Wang, T.; Heng, C.; Lee, C. Broadband energy harvester using nonlinear polymer spring and electromagnetic/triboelectric hybrid mechanism. *Sci. Rep.* **2017**, *7*, 41396. [CrossRef]

39. Eun, Y.; Kwon, D.; Kim, M.; Yoo, I.; Sim, J.; Ko, H.; Cho, K.; Kim, J. A flexible hybrid strain energy harvester using piezoelectric and electrostatic conversion. *Smart Mat. Struct.* **2014**, *23*, 045040. [CrossRef]

40. Han, M.; Zhang, X.; Liu, W.; Sun, X.; Peng, X.; Zhang, H. Low-frequency wide-band hybrid energy harvester based on piezoelectric and triboelectric mechanism. *Sci. China Technol. Sci.* **2013**, *56*, 1835–1841. [CrossRef]

41. Marin, A. Mechanical Energy Harvesting for Powering Distributed Sensors and Recharging Storage Systems. Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, 4 April 2013.

42. Sang, Y.; Huang, X.; Liu, H.; Jin, P. A vibration-based hybrid energy harvester for wireless sensor systems. *IEEE Trans. Magn.* **2012**, *48*, 4495–4498. [CrossRef]

43. Li, P.; Gao, S.; Cai, H.; Wu, L. Theoretical analysis and experimental study for nonlinear hybrid piezoelectric and electromagnetic energy harvester. *Microsyst. Technol.* **2015**, *22*, 727–739. [CrossRef]

44. Qiu, J.; Wen, Y.; Li, P.; Chen, H. Design and optimization of a tunable magnetoelectric and electromagnetic hybrid vibration-based generator for wireless sensor networks. *IEEE Trans. Magn.* **2015**, *51*, 1–4. [CrossRef]

45. Bradai, S.; Naifar, S.; Kanoun, O. Development of a hybrid vibration converter for real vibration source/Entwicklung eines Hybrid-Vibrationswandlers für eine echte Schwingungsquelle. *tm—Tech. Mess.* **2019**, *86*, 57–61. [CrossRef]

46. He, X.; Wen, Q.; Sun, Y.; Wen, Z. A low-frequency piezoelectric-electromagnetic-triboelectric hybrid broadband vibration energy harvester. *Nano Energy* **2017**, *40*, 300–307. [CrossRef]

47. Zhang, M.; Gao, T.; Wang, J.; Liao, J.; Qiu, Y.; Yang, Q.; Xue, H.; Shi, Z.; Zhao, Y.; Xiong, Z.; et al. A hybrid fibers based wearable fabric piezoelectric nanogenerator for energy harvesting application. *Nano Energy* **2015**, *13*, 298–305. [CrossRef]

48. Lee, S.; Bae, S.; Lin, L.; Yang, Y.; Park, C.; Kim, S.; Cha, S.; Kim, H.; Park, Y.; Wang, Z. Energy harvesting materials: Super-flexible nanogenerator for energy harvesting from gentle wind and as an active deformation sensor. *Adv. Funct. Mater.* **2013**, *23*, 2341. [CrossRef]

49. Hinchet, R.; Kim, S. Wearable and implantable mechanical energy harvesters for self-powered biomedical systems. *ACS Nano* **2015**, *9*, 7742–7745. [CrossRef] [PubMed]

50. Zheng, Q.; Shi, B.; Li, Z.; Wang, Z. Recent progress on piezoelectric and triboelectric energy harvesters in biomedical systems. *Adv. Sci.* **2017**, *4*, 1700029. [CrossRef]

51. Chandrasekaran, S.; Bowen, C.; Roscow, J.; Zhang, Y.; Dang, D.; Kim, E.; Misra, R.; Deng, L.; Chung, J.; Hur, S. Micro-scale to nano-scale generators for energy harvesting: Self powered piezoelectric, triboelectric and hybrid devices. *Phys. Rep.* **2019**, *792*, 1–33. [CrossRef]

52. He, H.; Lu, X.; Hanc, E.; Chen, C.; Zhang, H.; Lu, L. Advances in lead-free pyroelectric materials: A comprehensive review. *J. Mater. Chem C* **2020**, *8*, 1494–1516. [CrossRef]

53. Pusty, M.; Sinha, L.; Shirage, P. A flexible self-poled piezoelectric nanogenerator based on a rGO–Ag/PVDF nanocomposite. *New J. Chem.* **2019**, *43*, 284–294. [CrossRef]

54. Lee, J.; Yoon, H.; Kim, T.; Gupta, M.; Lee, J.; Seung, W.; Ryu, H.; Kim, S. Micropatterned P(VDF-TrFE) film-based piezoelectric nanogenerators for highly sensitive self-powered pressure sensors. *Adv. Funct. Mater.* **2015**, *25*, 3203–3209. [CrossRef]

55. Gong, S.; Zhang, B.; Zhang, J.; Wang, Z.; Ren, K. Biocompatible Poly(lactic acid)-Based hybrid piezoelectric and electret nanogenerator for electronic skin applications. *Adv. Funct. Mater.* **2020**, *30*, 1908724. [CrossRef]

56. Mathur, S.; Scheinbeim, J.; Newman, B. Piezoelectric properties and ferroelectric hysteresis effects in uniaxially stretched nylon-11 films. *Int. J. Appl. Phys.* **1984**, *56*, 2419–2425. [CrossRef]

57. Ponnamma, D.; Al Ali Al-Maadeed, M. Influence of BaTiO3/white graphene filler synergy on the energy harvesting performance of a piezoelectric polymer nanocomposite. *Sustain. Energy Fuels* **2019**, *3*, 774–785. [CrossRef]

58. Bhavanasi, V.; Kumar, V.; Parida, K.; Wang, J.; Lee, P. Enhanced piezoelectric energy harvesting performance of flexible PVDF-TrFE bilayer films with graphene oxide. *ACS Appl. Mater. Interfaces* **2015**, *8*, 521–529. [CrossRef]

59. Dudem, B.; Kim, D.; Bharat, L.; Yu, J. Highly-flexible piezoelectric nanogenerators with silver nanowires and barium titanate embedded composite films for mechanical energy harvesting. *Appl. Energy* **2018**, *230*, 865–874. [CrossRef]

60. Alam, M.; Mandal, D. Native cellulose microfiber-based hybrid piezoelectric generator for mechanical energy harvesting utility. *ACS Appl. Mater. Interfaces* **2016**, *8*, 1555–1558. [CrossRef]

61. Dodds, J.; Meyers, F.; Loh, K. Piezoelectric characterization of PVDF-TrFE thin films enhanced with ZnO nanoparticles. *IEEE Sens. J.* **2012**, *12*, 1889–1890. [CrossRef]

62. Bera, B.; Sarkar, M. Piezoelectricity in PVDF and PVDF based piezoelectric nanogenerator: A concept. *IOSR-JAP* **2017**, *9*, 95–99. [CrossRef]

63. Shin, S.; Kim, Y.; Jung, J.; Hyung Lee, M.; Nah, J. Solvent-assisted optimal BaTiO₃ nanoparticles-polymer composite cluster formation for high performance piezoelectric nanogenerators. *J. Nanotechnol.* **2014**, *25*, 485401. [CrossRef]

64. Ren, X.; Fan, H.; Zhao, Y.; Liu, Z. Flexible lead-Free BiFeO3/PDMS-Based nanogenerator as piezoelectric energy harvester. *ACS Appl. Mater. Interfaces* **2016**, *8*, 26190–26197. [CrossRef] [PubMed]

65. Lee, E.; Kim, T.; Kim, S.; Jeong, S.; Choi, Y.; Lee, S. High-performance piezoelectric nanogenerators based on chemically-reinforced composites. *Energy Environ. Sci.* **2018**, *11*, 1425–1430. [CrossRef]

66. Park, K.; Jeong, C.; Ryu, J.; Hwang, G.; Lee, K. Flexible and large-area nanocomposite generators based on lead zirconate titanate particles and carbon nanotubes. *Adv. Energy Mater.* **2013**, *3*, 1539–1544. [CrossRef]

67. Park, K.; Lee, M.; Liu, Y.; Moon, S.; Hwang, G.; Zhu, G.; Kim, J.; Kim, S.; Kim, D.; Wang, Z.; et al. Flexible nanocomposite generator made of BaTiO3 nanoparticles and graphitic carbons. *J. Adv. Mater.* **2012**, *24*, 2999–3004. [CrossRef]

68. Wang, S.; Zi, Y.; Zhou, Y.; Li, S.; Fan, F.; Lin, L.; Wang, Z. Molecular surface functionalization to enhance the power output of triboelectric nanogenerators. *J. Mater. Chem. A* **2016**, *4*, 3728–3734. [CrossRef]

69. Sun, J.; Pu, X.; Liu, M.; Yu, A.; Du, C.; Zhai, J.; Hu, W.; Wang, Z. Self-Healable, stretchable, transparent triboelectric nanogenerators as soft power sources. *ACS Nano* **2018**, *12*, 6147–6155. [CrossRef] [PubMed]

70. Jang, S.; Oh, J. Rapid Fabrication of Microporous BaTiO3/PDMS Nanocomposites for triboelectric nanogenerators through one-step microwave irradiation. *Sci. Rep.* **2018**, *8*, 14287. [CrossRef] [PubMed]

71. Yang, Y.; Jung, J.; Yun, B.; Zhang, F.; Pradel, K.; Guo, W.; Wang, Z. Flexible pyroelectric nanogenerators using a composite structure of lead-free KNbO3 nanowires. *J. Adv. Mater.* **2012**, *24*, 5357–5362. [CrossRef]

72. Suo, G.; Yu, Y.; Zhang, Z.; Wang, S.; Zhao, P.; Li, J.; Wang, X. Piezoelectric and triboelectric dual effects in mechanical-energy harvesting using BaTiO3/Polydimethylsiloxane composite film. *ACS Appl. Mater. Interfaces* **2016**, *8*, 34335–34341. [CrossRef]

73. You, M.; Wang, X.; Yan, X.; Zhang, J.; Song, W.; Yu, M.; Fan, Z.; Ramakrishna, S.; Long, Y. A self-powered flexible hybrid piezoelectric–pyroelectric nanogenerator based on non-woven nanofiber membranes. *J. Mater. Chem. A* **2018**, *6*, 3500–3509. [CrossRef]

74. Jonah, O.; Georgakopoulos, S. Wireless power transfer in concrete via strongly coupled magnetic resonance. *IEEE Trans. Antennas Propag.* **2013**, *61*, 1378–1384. [CrossRef]

75. Chaour, I.; Fakhfakh, A.; Kanoun, O. Enhanced passive RF-DC converter circuit efficiency for low RF energy harvesting. *Sensors* **2017**, *17*, 546. [CrossRef]

76. Mohan, S.; del Mar Hershenson, M.; Boyd, S.; Lee, T. Simple accurate expressions for planar spiral inductances. *IEEE J. Solid-State Circuits* **1999**, *34*, 1419–1424. [CrossRef]

77. Guidi, G.; Suul, J. Minimizing converter requirements of inductive power transfer systems with constant voltage load and variable coupling conditions. *IEEE Trans. Ind. Electron.* **2016**, *63*, 6835–6844. [CrossRef]

78. Tran, L.; Cha, H.; Park, W. RF power harvesting: A review on designing methodologies and applications. *Micro Nanosyst. Lett.* **2017**, *5*, 14. [CrossRef]

79. Lu, X.; Wang, P.; Niyato, D.; Kim, D.; Han, Z. Wireless charging technologies: Fundamentals, standards, and network applications. *IEEE Commun. Surv. Tutor.* **2016**, *18*, 1413–1452. [CrossRef]

80. Bissannagari, M.; Kim, T.; Yook, J.; Kim, J. All inkjet-printed flexible wireless power transfer module: PI/Ag hybrid spiral coil built into 3D NiZn-ferrite trench structure with a resonance capacitor. *Nano Energy* **2019**, *62*, 645–652. [CrossRef]

81. Jeong, S.; Kim, D.; Song, J.; Kim, H.; Lee, S.; Song, C.; Lee, J.; Song, J.; Kim, J. Smartwatch strap wireless power transfer system with flexible PCB coil and shielding material. *IEEE Trans. Ind. Electron.* **2019**, *66*, 4054–4064. [CrossRef]

82. Alawad, H.; Kaewunruen, S. Wireless sensor networks: Toward smarter railway stations. *Infrastructures* **2018**, *3*, 24. [CrossRef]

83. Khriji, S.; El Houssaini, D.; Kammoun, I.; Kanoun, O. Energy-efficient techniques in wireless sensor networks. In *Energy Harvesting for Wireless Sensor Networks*; De Gruyter Oldenbourg: Berlin, Germany, 2018; pp. 287–304. [CrossRef]

84. Götz, M.; Khriji, S.; Chéour, R.; Arief, W.; Kanoun, O. Benchmarking-Based investigation on energy efficiency of low-power microcontrollers. *IEEE Trans Instrum Meas* **2020**, *69*, 7505–7512. [CrossRef]

85. Sciancalepore, S.; Oligeri, G.; Di Pietro, R. Strength of crowd (SOC)—Defeating a reactive jammer in IoT with decoy messages. *Sensors* **2018**, *18*, 3492. [CrossRef] [PubMed]

86. Chéour, R.; Khriji, S.; El Houssaini, D.; Baklouti, M.; Abid, M.; Kanoun, O. Recent trends of FPGA used for low-power wireless sensor network. *IEEE Aerosp. Electron. Syst. Mag.* **2019**, *34*, 28–38. [CrossRef]

87. Liu, X.; Hou, K.M.; De Vaulx, C.; Shi, H.; Gholami, K.E. MIROS: A hybrid real-time energy-efficient operating system for the resource-constrained wireless sensor nodes. *Sensors* **2014**, *14*, 17621–17654. [CrossRef] [PubMed]

88. Chéour, R.; Khriji, S.; Götz, M.; Abid, M.; Kanoun, O. Accurate dynamic voltage and frequency scaling measurement for low-power microcontrollors in wireless sensor networks. *Microelectron. J.* **2020**, *105*, 104874. [CrossRef]

89. Tian, R.; Wang, L.; Zhou, X.; Xu, H.; Lin, J.; Zhang, L. An integrated energy-efficient wireless sensor node for the microtremor survey method. *Sensors* **2019**, *19*, 544. [CrossRef]

90. Kim, W.; Jung, I. Smart sensing period for efficient energy consumption in IoT network. *Sensors* **2019**, *19*, 4915. [CrossRef]

91. Yan, Q.; Peng, W.; Zhang, G. Optimal energy consumption tasks scheduling strategy for multi-radio WSNs. *Sensors* **2020**, *20*, 881. [CrossRef]

92. El Houssaini, D.; Mohamed, Z.; Khriji, S.; Besbes, K.; Kanoun, O. A filtered rssi model based on hardware characteristic for localization algorithm in wireless sensor networks. In Proceedings of the 2018 32nd International Conference on Advanced Information Networking and Applications Workshops (WAINA), Krakow, Poland, 16–18 May 2018; pp. 118–123. [CrossRef]

93. Bdiri, S.; Derbel, F. An ultra-low power wake-up receiver for realtime constrained wireless sensor networks. In Proceedings of the AMA Conferences 2015, Nuremberg, Germany, 19–21 May 2015; pp. 612–617. [CrossRef]

94. Khriji, S.; Raventos, G.V.; Kammoun, I.; Kanoun, O. Redundancy elimination for data aggregation in wireless sensor networks. In Proceedings of the 2018 15th International Multi-Conference on Systems, Signals & Devices (SSD), Yasmine Hammamet, Tunisia, 19–22 March 2018; pp. 28–33. [CrossRef]

95. Chiang, J.; Ward, R.K. Energy-efficient data reduction techniques for wireless seizure detection systems. *Sensors* **2014**, *14*, 2036–2051. [CrossRef]

96. Sun, J.; Yu, Y.; Wen, J. Compressed-sensing reconstruction based on block sparse Bayesian learning in bearing-condition monitoring. *Sensors* **2017**, *17*, 1454. [CrossRef]

97. Khriji, S.; El Houssaini, D.; Kammoun, I.; Kanoun, O. A fuzzy based energy aware unequal clustering for wireless sensor networks. In *Ad-hoc, Mobile, and Wireless Networks*; Montavont, N., Papadopoulos, G., Eds.; Springer: Cham, Switzerland, 2018; pp. 126–131. [CrossRef]

98. Lata, A.A.; Kang, M. A Survey on the evolution of opportunistic routing with asynchronous duty-cycled MAC in wireless sensor networks. *Sensors* **2020**, *20*, 4112. [CrossRef]

99. Ye, Y.; Zhang, X.; Xie, L.; Qin, K. A dynamic TDMA scheduling strategy for MANETs based on service priority. *Sensors* **2020**, *20*, 7218. [CrossRef] [PubMed]

100. Song, Y.; Qi, W.; Zhao, W.; Cheng, W. Full-duplex MAC protocol for CSMA/CA-based single-hop wireless networks. *Sensors* **2019**, *19*, 2413. [CrossRef] [PubMed]