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Survey of Energy Harvesting Technologies for Wireless Sensor Networks

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ABSTRACT Energy harvesting (EH) technologies could lead to self-sustaining wireless sensor networks (WSNs) which are set to be a key technology in Industry 4.0. There are numerous methods for small-scale EH but these methods differ greatly in their environmental applicability, energy conversion characteristics, and physical form which makes choosing a suitable EH method for a particular WSN application challenging due to the specific application-dependency. Furthermore, the choice of EH technology is intrinsically linked to non-trivial decisions on energy storage technologies and combinatorial architectures for a given WSN application. In this paper we survey the current state of EH technology for small-scale WSNs in terms of EH methods, energy storage technologies, and EH system architectures for combining methods and storage including multi-source and multi-storage architectures, as well as highlighting a number of other optimisation considerations. This work is intended to provide an introduction to EH technologies in terms of their general working principle, application potential, and other implementation considerations with the aim of accelerating the development of sustainable WSN applications in industry.

INDEX TERMS Energy harvesting, industry 4.0, wireless sensor networks.

I. INTRODUCTION

Along with other ambitions, Industry 4.0 promises that cyber-physical systems composed of cloud computing and Internet of Things (IoT) technologies will be used for environmental monitoring and enhancing decision-making capabilities. To realise this vision requires the deployment of self-powered wireless sensor networks (WSNs) [1].

WSNs may be used to monitor physical and environmental phenomena such as temperature, sound, pressure, and more and relay data to a centralised location for processing. Generally, a WSN is composed of a large number of static sensor nodes with limited processing and power capabilities that are deployed in a distributed manner and communicate over short-range radio links for cooperation [2].

To be useful, WSNs should be autonomous, operate with required perpetuity, and require little maintenance which can be costly and inconvenient depending on the number of nodes and the application itself which could necessitate nodes with limited accessibility [3]. However, providing energy to a WSN can be challenging due to their long lifetimes which may be over several years or decades depending on the application. And while the typical quiescent state power draw of wireless sensor applications is extremely low, transmission bursts when circuitry is powered up to take measurements and transmit data are power consuming [4].

Whilst the energy efficiency and expected lifetime of WSNs has increased over the last few years thanks in-part to sensor and software optimisations, lightweight communication protocols, and low-power radio transceivers, energy supply remains to be a major bottleneck [5], [6]. Solid-state batteries which are commonly used as an energy source in low power electronic devices require frequent and periodic maintenance in the form of recharging or replacement which limits network self-sustainability.

Making use of EH systems as alternative energy sources is seen as one of the most promising solutions for developing the next-generation of self-sustainable WSNs and reducing or eliminating battery lifetime limitations [1], [7], [8]. EH technology intends to convert various forms of ambient

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environmental energy such as heat, light, airflow, vibrations, electromagnetic waves and other phenomena to electrical energy in order to fully-or-partially supply a low-power electronics system. An energy harvester is considered to be an interface between one-or-more energy supplies (ambient energy sources) and one-or-more energy consumers or loads (systems that need powering). The challenge in designing EH systems is to provide a continuous and stable power supply to the load in spite of the adverse availability of an uneven or unpredictable energy source, whilst minimising the size and cost of the system itself [9].

As the demand for self-powered autonomous electronics with low power consumption has grown drastically in the electronics industry, EH techniques for capturing differing forms of ambient environmental energy have been studied more widely.

In this paper we survey the current state of EH technology in terms of existing EH methods, energy storage technologies, and EH system architectures with the aim of accelerating the development of sustainable WSN applications in industry. The paper is organised as follows: in section II we outline the range of ambient energy sources that are commonly exploited followed by a discussion of the existing methods for harvesting these sources that might be applicable to WSNs; in section III, we discuss commonly used energy storage mechanisms for microelectronics and their application to energy buffering in WSNs; and in section IV we describe and exemplify system architectures for combining EH technologies and energy storage devices effectively before outlining other design considerations when implementing an EH system in section V before some closing remarks in section VI.

Due to the breadth of EH techniques available and with new niche methods of energy recovery being regularly exploited frequently, this review will only consider the most widely applicable and developed methods of harvesting ambient *mechanical*, *radiant* (radio frequency and solar), *thermal*, *flow*, and *magnetic* sources of energy only and not lesser developed methods such as those in the biochemical domain e.g. biofluids (such as glucose) [10], biodegradable materials [11], tree trunks [12], human sweat [13], water droplets [14], and acoustic noise [15]. Similarly, our discussion of energy storage techniques is limited to battery and capacitor-related technologies and not other uncommon application storage mediums such as fuel cells [16].

II. SOURCES OF AMBIENT ENERGY AND HARVESTING METHODS

There are many sources of ambient energy that can be exploited with EH technology, some of which occur naturally whilst others are artificially generated by human activity and other technology. It is important to analyse the amount and time distribution of available sources in relation to a node's location to determine their reliability, feasibility, and overall suitability for inclusion in an EH system as the energy distribution may change which can cause problems for operation. It may change in known intervals such as daily or seasonally, be dependent on other occurring phenomena or actions, or change depending on a node's mobile location, and sometimes it may be predicted or controlled to suit needs [2], [6].

Many energy sources are exploitable by several methods but techniques used for large scale or industrial energy generation may be unsuitable for small-scale energy generation as many typical WSN applications require nodes to be small and lightweight. Notionally, *power density* defined as the power output per unit area in Wcm^{-2} or per unit volume Wcm^{-3}, is a widely-used metric for comparing different EH techniques [2] with the conversion efficiency of ambient energy to electrical energy also considered important, particularly when comparing differing techniques within a single EH method. Techniques often vary greatly in terms of their voltage and current characteristics so it is also important to consider this from an application point-of-view.

A. MECHANICAL VIBRATION HARVESTING

Vibration produces mechanical accelerations that cause the oscillation of mass components. This movement initiates opposing damping forces against the mass component that absorb the kinetic energy of the initial vibration and reduce the oscillation. This kinetic energy, which may be in the form of vibrations, pressure, or stress-strain, can be converted into electrical energy and harvested through use of a suitable Mechanical-to-Electrical Energy Generator (MEEG) [2], [17].

There are three transduction mechanisms mainly used in vibration-based power generation: ***electromagnetic***, ***electrostatic***, and ***piezoelectric***. *Electromagnetic transduction* is based on the relative motion of a magnet and coil, which induces an electric current. *Electrostatic transduction* is based on a variable capacitor where two plates move relative to each other and the capacitance changes. *Piezoelectric transduction* is based on piezoelectric materials, which develop a voltage difference when strained [18].

Natural and artificially generated vibrations are omnipresent with widely varying characteristics. Ambient vibrations contain a wide range of fundamental frequencies ([19] lists several commonly occurring vibrations with their typical accelerations and fundamental frequency) but some MEEGs including most piezoelectric generators have narrow operating ranges [17]. Therefore, it is important to first determine the characteristics of the ambient vibration source to better understand if the energy is exploitable.

While vibration EH is promising, a major challenge that needs to be addressed for efficient energy generation is to have the EH device in resonance with the source vibration frequency [20]. Any difference between these two frequencies can result in a significant decrease in generated power which is a fundamental limitation of resonant vibration generators and restricts their capability in real applications [21]. Whilst aligning this frequency is easy for consistent and constant vibrations such as industrial machinery, it is more difficult for ambient vibrations from differing sources. It is especially

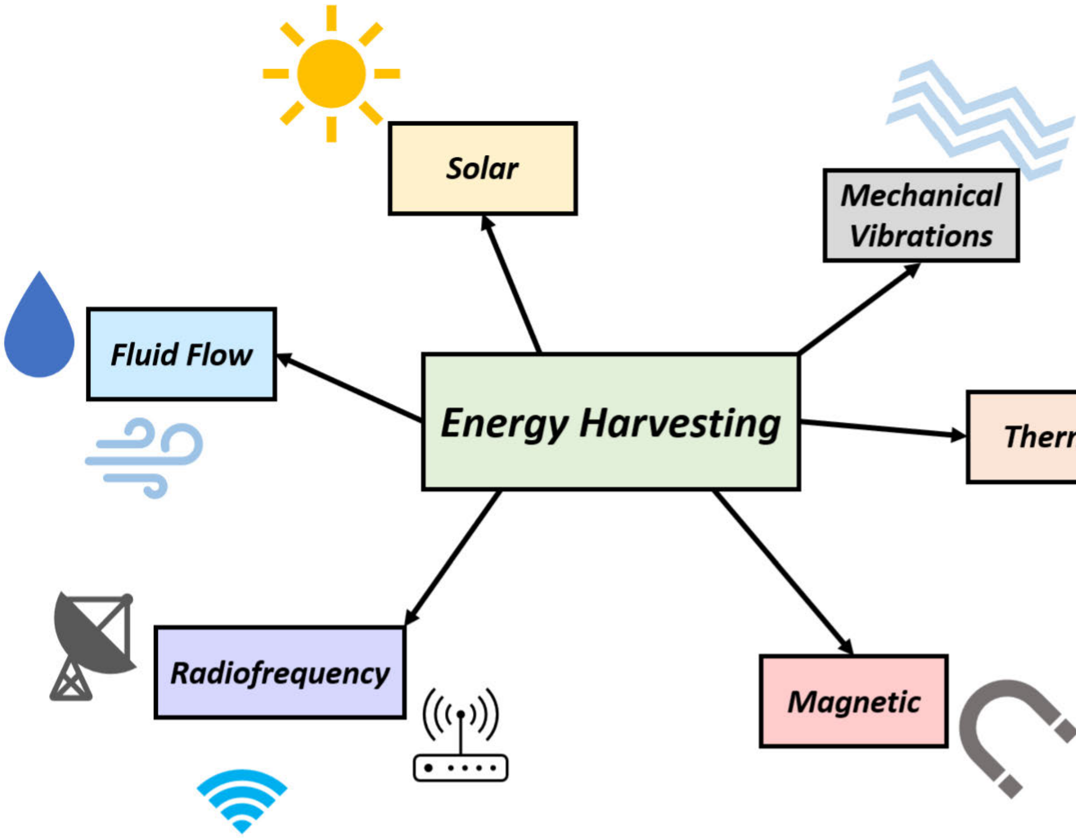

FIGURE 1. Sources of energy that can be harvested.

difficult to match the resonant frequency of small-scale vibration energy harvesters of millimetre-scale devices to the frequencies of common ambient vibrations because as size decreases, resonant frequency increases [18]. Overcoming this obstacle is usually done using either broad-bandwidth harvesting techniques to increase the range of frequencies at which energy can be harvested or active resonance frequency tuning to optimise energy generation at a single particular frequency [18], [21], [22].

It is also important to note that, unlike some other energy harvesters, all vibrational energy harvesters produce AC power but microelectronic devices and rechargeable batteries usually require a DC power supply, so proper power-conditioning circuitry must be incorporated into systems with vibrational EH [18] such as converting the alternating voltage output into a stable rectified voltage using an AC–DC converter and regulating the voltage output with a DC-DC converter [23]. Power conditioning circuits for vibrational EH are reviewed in greater detail by Hudak *et al.* [18].

As previously stated, input vibrations are often characterised by their (dominant) acceleration and frequency. This means that, unless the input energy is provided, that power density can be an insufficient parameter by which to compare different vibrational energy harvesters, despite being frequently used in the literature [23]. Additionally, the power output in vibrational energy systems scales with mass and not necessarily volume, but rough general comparisons can be made with power density [18]. With these points in mind, we discuss the characteristics of each vibrational EH method in greater detail.

1) ELECTROMAGNETIC

Electromagnetic transduction is based on the relative motion of a magnet and coil due to vibrations, inducing an alternating electric current [2], [18]

Electromagnetic generators have been effective for applications that require low power sources. Their main advantages are that they can work at low frequencies, require driving loads of very low impedance, are a reliable technology, and can be easily implemented at micro or macro scale. However, they have a very low voltage output [24].

Electromagnetic generators may also be difficult to integrate with microelectronics such as wireless sensor nodes as the strong magnetic field can interfere with the operation of the electronic components [18].

TABLE 1. Summary of energy harvesting methods.

Energy Source	Method	Application Environment	Energy Conversion Factors	Advantages	Disadvantages	References
Mechanical Vibration	Electromagnetic	Industrial machinery; transportation; Human activity; Roads and infrastructure;	Vibration frequency; Vibration acceleration;	Operate at low frequencies;	Requires resonant frequency matching; Moving parts; AC only; Low voltage; Interference with microelectronics;	[24]–[28]
	Electrostatic			No clear advantages	Requires resonant frequency matching; Moving parts; AC only; Requires input voltage to activate;	[24], [29]
	Piezoelectric			High voltage output; High power density;	Requires resonant frequency matching; Moving parts; AC only; Delicate materials; Not receptive at low frequencies;	[17], [24], [31]–[33]
Thermal	Thermoelectric	Industrial waste heat; Household water; Combustion engines; Domestic heaters; Body heat; Water vapour;	Spatial temperature gradient;	Long life due to stationary parts; High reliability;	Requires constant thermal gradient; Low conversion efficiency; Performs poorly on small gradients;	[36], [38]–[40]
	Pyroelectric		Temporal temperature gradient; Cycle frequency;	Room temperature operation; Wide spectral response; Piezoelectric properties; Flexible and thin form factor;	Requires cyclical temperature variation; AC only;	[34], [42], [43]
Solar	Photovoltatic	Natural light; Brightly lit indoor spaces;	Light intensity; Temperature gradient; Material properties;	Mature technology; Predictable; Scalable; Simple form factor; No moving parts;	Long periods of natural absence; Natural prediction limited;	[44]–[48], [50]–[52]
Flow	Aerodynamic	Outdoor environments; Ventilation ducts;	Flow speed; Turbine design;	Mature technology;	Difficult to apply form factor; Hostile application environments;	[53]–[55], [57]–[62]
	Hydrodynamic	Rivers / oceans; Water pipes;				[56], [58]
Magnetic		Power delivery infrastructure;	Magnetic field strength;	Predictable energy source;	Requires resonant frequency matching; Moving parts; Limited range; AC only;	[1], [64]–[66]
Radiofrequency		(Semi-)urban environments; Dedicated transmitter setup;	Source transmission power; Distance from source; Antenna gain; Antenna design;	Ambient or dedicated techniques; High conversion efficiency; Flexible form factor; No moving parts; AC or DC;	Requires tuning to frequency bands; Energy availability limited by safety; Inconsistency if non-dedicated;	[5], [67]–[77], [98]–[101]

Though not as widely used in WSNs as other methods, there are several examples of electromagnetic generators in the literature.

Ching *et al.* fabricated an electromagnetic generator of 1 cm^3 which was optimised to have a low resonant frequency. At a resonant frequency of 110 Hz and acceleration 96 ms^{-2}, the generator achieved a voltage and power output of up to 4.4 V and 830 μW respectively [25].

Beeby *et al.* developed an electromagnetic harvester that generated 46 μW and 0.15 V_{rms} at 52 Hz and 0.59 ms^{-2} at a device volume of only 0.15 cm^3 [26], thus providing useful power density and output voltage whilst operating at a frequency and acceleration in the range of those measured for ambient vibrations [18].

As one part of a multi-source EH system (see IV-C) for a wireless sensor node, Wang *et al.* implemented an electromagnetic vibration harvester for harvesting vibrations from industrial machinery, namely an air compressor, capable of generating 1.56 mW from machine vibrations at 25–48 *mg* acceleration and 49.3–49.7 Hz frequencies [27].

The efficiency of vibration-based harvesters is proportional to the excitation frequency, so Sari *et al.* proposed an electromagnetic generator capable of harvesting low-frequency environmental vibrations by converting them to higher frequency vibrations using a frequency up-conversion technique. Their generator effectively harvested energy from environmental vibrations of 70-150 Hz, generating 0.57 mV voltage and 0.25 nW power with a generator size of 0.15 cm^3. They also claimed that the power and voltage levels can be further multiplied by increasing the number of cantilevers or coil turns [28].

2) ELECTROSTATIC

Electrostatic transduction is based on variable capacitors where two plates move relative to each other and the capacitance changes, generating AC electricity. The capacitor can either be charge constrained, in which the voltage increases as capacitance decreases, or voltage constrained, in which charge flows from the plates as capacitance decreases [2], [18], [29].

Electrostatic methods are considered most appropriate for small scale energy harvesters. They have the advantage of high output voltage, easy adjustment of coupling coefficients, low complexity, and are easily integrated with other microelectronic devices because of their makeup. However, they also have a low capacitance and energy density [18], [24].

The main disadvantage of electrostatic transducers however is the need for two power sources to start the EH process. This is because the capacitor has to be charged with initial voltage. To activate an electrostatic generator, charge is injected into the capacitor at maximum capacitance and pulled off at minimum capacitance. The change of the gap between the electrode of the variable capacitor then generates an electrical output [29], [30]. As a result, passive electrostatic generators can only really be applied as an auxiliary power source to an external power supply and it is difficult to implement a maintenance-free sensor node. Although research has been carried out into designing various circuit structures that bypass the external power supply requirements, the low output power of these methods in the n-μW range means that electrostatic technology is unlikely to be used by itself to power WSNs [29].

3) PIEZOELECTRIC

Piezoelectric materials develop an electrical potential gradient when subjected to mechanical strain, producing an electric field that is proportional to the applied stress. This effect can be utilised as a transduction mechanism in vibration power generators by transforming the motion of vibration into an alternating current wave.

A conventional piezoelectric power harvester comprises a piezoelectric cantilever beam with a proof mass attached to the vibrating part of the device to lower the resonant frequency. In order to capture low frequency vibrations, a low stiffness cantilever is required. Similarly, bimorph arrangements with two layers of piezoelectric material are commonly used to improve harvester efficiency as it allows larger strain with lower resonant frequency than single layer structures.

Common piezoelectric materials in EH systems are lead zirconate titanate (PZT), barium titanate ($BaTiO_3$) and polyvinylidene fluoride (PVDF). Material performance is quantified by the piezoelectric strain constant, which is the ratio of the short circuit charge density to applied stress in C/N and describes the efficiency of energy conversion between mechanical and electrical forms. For this reason, PZT is the most commonly used piezoelectric material due to its high piezoelectric constant, however it is also extremely brittle and needs to be carefully handled to avoid damage when strained [17], [18].

Of the three vibrational transduction methods, piezoelectric methods have received the most attention due to their large power densities and ease of application. For instance, where the low voltage output of electromagnetic energy harvesters often requires multi-stage post-processing to be useful, usable voltage outputs are directly obtained from piezoelectric materials. And while electrostatic energy harvesters require an input voltage or charge to be applied to begin generating an alternating electrical output, the voltage output in piezoelectric EH emerges from the constitutive behaviour of the material, thus eliminating the requirement for external voltage input. Finally, piezoelectric devices can be fabricated both in macro-scale and micro-scale due to well-established thick-film and thin-film fabrication techniques unlike electromagnetic devices [23].

There has been a lot of work into capturing ambient energy using piezoelectric methods for WSNs and beyond:

Yoon *et al.* utilised a commercial off-the-shelf piezoelectric harvester, Volture V22BL and were able to generate 3.072 mW from a vibrational source of 53 Hz and 1 g acceleration, but faltered in ambient conditions as the unstable operational environment generally did not match the resonant frequency of the system, highlighting the need for resonance frequency tuning [17].

Yang *et al.* demonstrated a piezoelectric-based batteryless EH system that can supply a total energy of 160 μJ at 2.5V from a single button-pressing action to transmit a signal over a short distance to a transceiver [31].

Lee *et al.* developed a piezoelectric energy harvester to harvest energy from the acceleration of tires whilst driving. Their system generated 13.7 nW cm^{-3} across a 60 mm patch which was sufficient to power the developed node continuously despite the low power density [32].

Finally, Zhu *et al.* investigated the use of a piezoelectric energy harvester for harvesting road-induced vibrations from automobiles for powering on-board wireless sensors by conducting a survey of the vibration frequency distribution whilst driving on different roads and building an EH prototype. Their survey found a broad frequency distribution present in the vibrations measured, with different vehicles and roads possessing slightly different frequency spectrum due to their composition with the largest average amplitudes in the 12–30 Hz range and with high accelerations up to 1g with higher quality roads yielding less energy and lower frequency vibrations due to their smoothness. Based on this survey and their implemented EH device, they concluded that scavenging these ambient automotive vibrations yields enough useful energy to power a well-placed wireless sensor but to optimise the energy harvested required the resonant frequency of the cantilever beam to be designed according to the dominant vibration frequency, and a self-tuning technique for the resonant frequency should be employed to account for the broad band of frequencies [33].

Generally speaking, the implementation of mechanical energy harvesters is complicated due to the characteristics of each method, and these methods possess a more finite lifespan than some other EH methods due to mechanical deformation and abrasion caused by harvesting. In addition, vibrational energy is environmentally uncommon in large amounts unless harvesting directly from the source generating the vibration. Therefore, mechanical energy harvesters are generally only suitable as auxiliary power supplies [29].

B. THERMAL ENERGY HARVESTING

Thermal EH is a promising method for capturing freely available heat and converting it to a more usable form, such as mechanical or electrical energy. There is an abundant supply of wasted heat energy that remains untapped from both natural and artificial sources including geothermal, volcanic, and solar heat, to automotive internal combustion engines, industrial waste water, and household water. If this waste heat could be harvested and utilised, it would be a substantial energy source due to its ubiquity and environmental friendliness [34], [35].

Although, thermal energy harvesters possess low energy conversion efficiencies, typically around 1–10%, they can operate at low temperatures and are very reliable due to their being solid-state devices with no moving parts. These factors render thermal EH self-sustainable with very low maintenance costs and therefore suitable for WSN applications and providing power in remote or hard-to–reach areas having even been reliably used in spacecraft for decades of power supply [35].

Here, we focus on the most common forms of thermal EH for WSNs: *thermoelectric* and *pyroelectric*. For a more detailed and comprehensive review of all thermal EH methods, see the work of Kishore *et al.* which also elaborates on two other forms of thermal EH that are not commonly used for WSN harvesting; namely *thermomagnetic* which relies on the effect of temperature on magnetocaloric materials, and *thermoelastic* that utilises shape memory alloys and thermal strain to generate energy [35].

1) THERMOELECTRIC

Thermoelectric harvesters are the most popular thermal harvesting technology [35]. They are based on the Seebeck effect and generate direct current in response to thermal gradients (spatial temperature changes). They are composed of two plates separated by pairs of p-type and n-type semiconductor blocks ordered in parallel and connected electrically in series with one plate being the 'hot side' and another being the 'cold side'. The open circuit voltage of a thermoelectric element depends on the temperature difference between the hot and cold sides, and on material properties (Seebeck coefficients) [6], [35].

Generally, greater conversion efficiency can be attained the higher the temperature difference [2], [36]. Thermoelectric generators have poor performance at low temperature differences but for higher temperature differences power density is principally scales with the square of the difference in temperature [2]. A steady temperature gradient must be maintained in order to generate sustainable electricity and a constant voltage. But in an environment where temperature is spatially uniform without a gradient according to the principle of increased entropy, it is difficult to achieve a large temperature difference [34] and when placed in a stable heated environment, a thermoelectric system will stop generating power after a while when both plates achieve the same temperature [6].

Thermoelectric harvesters have a long life, stationary parts, and highly reliable characteristics [35] but their low efficiency yields low power densities and is a major hindrance to wider adoption. However, more recent thermoelectric materials and efficient modules have achieved more than 10% efficiency [2], [37].

Thermoelectric harvesters been used in a wide array of scenarios. Datta *et al.* created a 64 $\times$ 64 mm prototype device for harvesting thermoelectric energy from asphalt pavement roadways able to generate 10 mW of electrical power permanently over a period of 8 hours [38]. Lu *et al.* harvested thermal energy from room heaters to control a ZigBee-based node used for temperature monitoring of the room and achieved a power output of 150 mW at a gradient of approximately 34°C between 55-21°C [39]. Leonov *et al.* applied thermoelectric harvesters to harvesting human body heat and achieved a power density of $0.14\mu Wmm^{-2}$ for a 700 mm^2 device for small temperature differences of only 5°C [40]. Meanwhile Xiong *et al.* constructed a model of a two-stage thermoelectric harvester of blast furnace slag water waste heat with an average temperature gradient of 50°C and achieved a maximum conversion efficiency of around 2.66 % [36].

2) PYROELECTRIC

Pyroelectric generators generate electricity based on the pyroelectric effect which occurs as a result of the interaction between polarisation and temperature change in some dielectric materials. Certain types of crystals are naturally electrically polarised and have non-zero spontaneous polarisation at room temperature. A change in temperature of the material causes a change in polarisation, which can be used to generate AC electricity [35].

Therefore, where thermoelectricity generates a constant voltage given a constant temperature difference between two spatially separated points on a device, pyroelectricity generates a temporary voltage when the device itself undertakes a temperature change over time [6].

Pyroelectric generators require cyclic variation in temperature in order to stimulate the energy conversion process. No charge is generated if the temperature remains constant [35], [41]. This can be achieved by methods such as oscillating the device between hot and cold fluids [34], or heating up with an external source and allowing natural cooling from the environment with convection currents [41].

Devices based on pyroelectric materials have many advantages, such as easy integration with on-chip circuitry, uncooled detection, room-temperature operation, high speed (121 ms [41]), low system cost, portability, and a wide spectral response with high sensitivity [34], [42]. Pyroelectric harvesters also have a form factor that can be very appealing with a simple structure that can be fabricated and applied relatively easily [42]. Many pyroelectric materials are also extremely thin [34], [43], flexible and formable which means a sensor can also be applied to curved surfaces with ease [41].

Interestingly, pyroelectric materials are also subclass of certain piezoelectric materials with non-centrosymmetric crystal structures and thus all pyroelectric materials are also piezoelectric which provides opportunities for multi-source harvesting with energy accumulated from both mechanical stress and temperature change [34], [41], [42].

Though pyroelectric generators can be applied to a broad range of temperatures, finding an environment where there is a sufficient heating/cooling cycle such that they can be deployed effectively can be challenging.

The most significant problem with pyroelectric harvesters is that the heat transfer rate between the device and operating environment limits the frequency of operation and the current generated, rendering pyroelectric generators to have a relatively low power density [6], [35] and so the maximum harvestable energy density, output voltage and current and efficiency are highly dependent on material selection and structure [42]. In order to improve the heat transfer rate and thus increases oscillating frequency, a few recent studies have proposed thin film based pyroelectric generators [35]. Yang *et al.* reported a PZT thin film (175 μm thickness) pyroelectric generator with a maximum power density of 215 μ W/cm^3 [43] and Leng *et al.* developed a pyroelectric generator based on polyvinylidene fluoride film [34].

Leng *et al.* were able to harvest heat energy from hot/cold water using a pyroelectric by alternately contacting a hot flow and cold flow to produce time-dependent temperature variations. The output voltage and current reached a maximum of 192 V and 12 μA, respectively, under a temperature change of 80°C with an output power density up to 14 μW cm or 1.08 W/cm^3 which was capable of driving 42 LEDS and charging a commercial 100 μF capacitor to 3.3 V in 90 seconds [34].

Sultan *et al.* also demonstrated the possibility of harvesting energy from water vapour, and human body heat and respiratory processes with a pyroelectric harvester with a commercial bendable piezo-composite patch transducer (that is also an active pyroelectric layer), between two conductive electrodes. They achieved an output voltage and current of 1.5 V and 1.5 μ A respectively with a power density of 34 nW/cm^2 under a temperature fluctuation from 37°C to 67°C [41].

C. PHOTOVOLTAIC ENERGY HARVESTING

Solar energy from both natural and artificial sources of light is the dominant form of radiant energy and it can be harvested with cells that take advantage of the photovoltaic effect. The photovoltaic effect can be observed when certain semiconductor materials, usually silicon-based, are exposed to sunlight and convert solar rays into DC power if struck with an appropriate amount of energy [2].

Photovoltaics are among the most mature EH technologies and are used heavily for large-scale renewable energy generation and increasingly in a number of smaller electronics due to their simple scalability with power proportional to the cell's surface area [2], [6]. The efficiency of a particular photovoltaic cell depends on the photovoltaic principle being followed (see [44]) and the type of material that the cell is made of, with mono-crystalline cells having an efficiency of 15–24%, polycrystalline an efficiency of 14–20.4%, and thin-film cells an efficiency of 8–13.2% [6]. Each material varies in cost and not all photovoltaic principles are yet commercialised [44].

The output power of photovoltaic cells depends mainly on light intensity and ambient device temperature [6]. Because of this, photovoltaic EH is most appropriate in outdoor environments where light intensity is greatest from direct sunlight but they can sometimes be effective in low light or with artificial light sources, particularly well-lit indoor environments such as hospitals, stadiums, and industrial buildings [2], [45]. Mathuna *et al.* reported on the efficiencies of different solar cells at various illumination levels. For a typical outdoor (bright and sunny day) illumination level of 500 Wm^2, conversion efficiency varied around 15% to 25% but for typical indoor illumination levels of 10 W/m^2, efficiencies varied around 2% to 10% [46]. Furthermore, while the typical power density of photovoltaics is 10-15 mW/cm^2 under direct sunlight of 100 mW/cm^2 in outdoor applications, it is only around 100 μW/cm^2 in low-level light of 10 W/cm^2 [47], [48].

The main difficulties with implementing photovoltaic harvesters is that in both artificial and particularly natural settings, light intensity and ambient temperature regularly vary which generates non-constant voltage and current [6]. Natural light harvesters are particularly susceptible to periods of energy absence such due to time-related variations of irradiance and during the night where no light is available. For this reason, most solar EH implementations employ a harvest-store-use architecture with additional storage capabilities [2], [49] (see III and IV). There are some mitigation techniques that can be used to provide stability and maximise useful power output. Firstly, the photovoltaic cell should be aligned with a light source in all possible to achieve the maximum possible energy efficiency, particularly in outdoor applications relying on natural solar energy [6]. To this end, adaptive solar trackers can be employed to automatically align cells to their optimum position even under changing alignment conditions [50]. Secondly, Maximum Power Point Tracking (MPPT) controllers should be employed in the system architecture to ensure that solar cells always operate around their maximum power point P_{max} under diverse irradiance and temperature conditions, and variable load characteristics [6] and an optimal MPPT algorithm should be employed [51]. Thirdly, prediction techniques for daily and seasonal patterns of light intensity can be used to inform a device's operation [2], [52].

D. FLUID FLOW ENERGY HARVESTING

Naturally or artificially generated air and water flow can be found everywhere from wind and rivers to ventilation ducts and water pipes. Though these fluid flows seemingly inhabit starkly different mediums, energy could be harvested from air and water flows using very similar methods using turbines and rotors that convert rotational energy to electrical energy using electromagnetic induction or piezoelectric methods [2], [3].

Exploitation of energy from solar and wind sources is at a mature level for large-scale applications and are widely used for industrial energy generation, but many of these methods are not compatible with miniature wireless sensor nodes [3] as the turbines are generally too bulky for what is required for WSNs [2]. However, there are several alternative methods for harvesting fluid flow for microelectronics including flapping wings based on the triboelectric effect [53], electromagnetic oscillating wings exploiting aerodynamic flutter [54], [55], piezoelectric methods [56], [57], and miniature turbines [58].

Azevedo *et al.* evaluated the use of different small-scale wind and hydro turbine designs for powering wireless sensor nodes at different flow characteristics. Turbines were varied according to application environment, geometric design, number of blades, blade length and other characteristics. Across the range of wind turbines, power density varied between 0.01 and 5.88 mW cm^{-3} depending on the particular turbine design and flow speed. Meanwhile their range of hydro turbines generated power densities varying between 0.63 and 70.14 mW cm^{-3}, again depending on turbine design and flow speed. The power conversion efficiency of each turbine varied depending on flow speed and efficiency did not necessarily increase as flow speed increased [58].

Similar to solar energy, flow speed can be unpredictable in its availability and thus variable in the amount of power produced. For this reason, techniques similar to those used in solar harvesting can be employed to ameliorate the potential performance impact. MPPT circuits can be integrated within the harvester system of wireless sensor node powered by a micro turbine generator to increase device reliability in a range of wind conditions [59] and prediction techniques that take into account phenomena such as weather forecasts, rainfall, tidal movements, or appliance usage statistics to plan energy use appropriately [60].

Although air flow harvesters are likely to be most applicable in outdoor environments such as agriculture [61] with potentially high (if variable) wind speeds, they have been shown to work at lower airflow speeds found in indoor environments, calm weather or based on simple human movements. For instance, Fei *et al.* presented a fluttering vibration-based EH system capable of charging a 1 F supercapacitor to 2 V under ventilation duct air flow speeds of less than 3 ms^{-1} [55], Chen *et al.* developed a triboelectric flutter harvester that could capture energy at wind velocities as low as 1.6 ms^{-1} and generate optimal power densities at 8 ms^{-1} with a power density of 52 nW cm^{-3} and a voltage and current of 175 V and 434 μA [53], and Rezaei-Hosseinabadi *et al.* showcased a wind EH design that combined a piezoelectric beam alongside a small wind turbine to harvest energy at low wind speeds on a cm-scale prototype achieving a power density of 0.59 mW cm^{-3} [62].

E. MAGNETIC ENERGY HARVESTING

Incidental magnetic fields arise from the plethora of power delivery infrastructure that occupy everyday life from electric power transmission cables, to electronic devices, transportation, manufacturing machines and more [63]. This ambient magnetic noise is typically 50/60 Hz with a weak magnetic field strength of less than 1 mT but is ubiquitous and found around any current-carrying wire, thus offering huge potential for EH [64], [65].

Traditional methods for capturing low-amplitude magnetic field based on Faraday's law of induction are not efficient for electrical power generation. Instead, more recently proposed magneto-mechano-electric (MME) EH methods composed of a resonating cantilever with piezoelectric layers, elastic metal beam, and a magnetic proof mass, have shown promising direct energy conversion from low amplitude, low frequency alternating magnetic field into an electrical field by utilising magneto-mechanical torque as a vibration source [65]. This method of EH is not as common as some of the others discussed as traditional electromagnetic generators have suffered from frequency, size, and efficiency related limitations [26], [66], however, these can be overcome with designs based on magneto-electric (ME) composite materials that generate electrical charge when stressed by even negligibly small magnetic fields [1], [64], [65]. When an MME generator is placed in an AC magnetic field the magnetostrictive layer in the ME composite responds by elongating or contracting (magneto-mechano coupling), thereby straining the piezoelectric layer which results in an output voltage across the electrical load through direct piezoelectric effect (mechano-electric coupling). Thus, the ME effect is the result of several energy transductions, from magnetic to mechanical and then finally electrical energy.

Several works demonstrate MME mechanisms with ME composites to reliably harvest low frequency environmental magnetic noise [1], [64], [65]. These methods achieved impressive power densities of 46 mW cm^{-3} Oe^{-2} under a weak magnetic field of 160 μT at 60 Hz [64], 3.22 mW cm^{-3} under a magnetic field of 700 μT [1], and ≈76 μW_{peak} cm^{-3} (≈38 μW_{avg} cm^{-3}) under 0.1 mT magnetic field, with ≈4.17 mW_{peak} cm^{-3} (2.08 mW_{avg} cm^{-3}) under 1 mT magnetic field [65] respectively. Annapureddy *et al.* also demonstrated an impressive range of applications including the construction of wireless sensor node for an IoT system. Their node comprised an MME generator, power-management circuit, supercapacitor storage, and an IoT wireless communication device with multiple sensors and the MME generator was able to supply sufficient energy to continuously drive the WSN module, which logged sensor data in real-time with low power usage before wirelessly transmitting information to a receiver in short 25s intervals [1].

Magnetic induction harvesting is extremely promising but less explored than other EH methods. The method relies on the presence of electrical wires which suggests power delivery infrastructure already in place which may make some deployment redundant and their technological implementation invokes moving parts which decreases device longevity and device efficiency depends on tuning to the correct vibrational resonance frequency [65].

F. RADIO FREQUENCY ENERGY HARVESTING

During radio frequency (RF)-based EH, transmitted radio waves are received by a device antenna and converted into a stable AC or DC power source to supply a sensor device. In this context, ''radio frequency'' refers to electromagnetic radiations with frequencies below 1011Hz, such as radio waves and microwaves, and where density is commonly quantified with electric field strength in Vm^{-1} [18].

The energy of radio frequency waves decreases with distance from the transmission source, therefore, the source transmission power, antenna gain, and distance between source and receiver are factors that affect how much energy can be harvested [2], [67]. RF methods can be compared according to their conversion efficiency of electric field strength to DC energy for which efficiency usually varies between 50-75% [2], but like other EH methods their power density is typically in the μW-mW range [49].

Sensor nodes that utilise RF energy harvesters follow two model designs that have either one or two radio transceivers respectively. In a dual radio model, one radio is used for energy harvesting while the other used for communication whereas in a single model one radio is responsible for both purposes. It is generally advantageous to have a single radio model to reduce size, physical complexity, costs and communication software complexity [2], [6] but multiple antennas may be advantageous to increase the amount of energy harvested [68].

There are two categories of RF energy source: *dedicated* and *ambient* [3], [8], [69]:

- *Dedicated Sources* are deployed by the application engineer to provide a predictable energy supply to specific devices. They are usually optimised to an effective transmission frequency and power to meet the requirements of the sensor device whilst complying with environmental regulations [8] and the application has complete control over the availability of power with the option to provide power continuously, on a scheduled basis, or on demand [2].
  Dedicated sources are not necessarily in a fixed location, neither are they always within range and able to provide power to a sensor node. RFID tags are one such instance where power is provided on-demand by an external reader which may or may not be portable [70]. Similarly, Zhou *et al.* and Fu *et al.* proposed automated and manual systems of mobile RF-based charging system to visit depleted sensors nodes and charge them wirelessly [5], [71] and Munir *et al.* designed an RF harvesting system for a mobile WSN spread over a large geographical area with fixed dedicated charging infrastructure so that nodes are only charged when within range of the infrastructure [67].
- *Ambient Sources* are anticipated sources of RF energy that are possible to harvest from unrelated transmission infrastructure in the environment that serve a purpose over a large geographic area [72], [73]. As they are unrelated to the WSN application, ambient sources are extremely variable in their nature and are not uniformly optimised for any given WSN application besides what they are designed for and as such their frequency and transmission power will vary [8].
  Some sources of ambient energy are static and reasonably predictable such as signals from cellular base stations, satellite transmitters, and broadcast TV and radio towers, but others are more dynamic and difficult to predict such as local Wi-Fi routers [74] and microwave radio links [8], [69]. Static sources can generally be relied upon to supply power in a consistent manner whereas dynamic sources require a more intelligent EH system to monitor for harvesting opportunities [8].

Dedicated sources can be useful in indoor environments and rural areas where ambient RF energy is less available [75]. Dedicated transmission sources also generally have much lower power usage as they are confined to operation in a small area and thus are relatively inexpensive to integrate into an environment [67]. However, the increasing penetration of wireless communication and broadcasting infrastructure means that the energy density of ambient RF is steadily increasing, especially in urban environments. Ambient RF energy density is usually highest in heavily urbanised areas and within proximity of power sources such as TV towers [76].

In fact, Ambient RF EH has been shown to be a credible method of powering WSNs in urban and semi-urban environments in the works of Piñuela *et al.* [77] and Muncuk *et al.* [75] who conducted RF surveys in the respective major cities of London, UK and Boston, U.S.A.

Piñuela *et al.* conducted a survey of the ambient energy levels across the range of the four largest communication frequency bands of the time, DTV, GSM900, GSM1800, and 3G, across all 270 tube stations on the London Underground and found that the power density of ambient RF energy at over 50% of the stations was enough to harvest energy in the μ/W range with the EH devices that the authors designed, with 45% of this provided by 3G frequencies [77]. It is notable that this survey was also completed in 2013 and yielded positive results before even the 4G network was active. It is now reported that 91% of the UK's landmass, 77% of homes and business, and 64% of UK motorways and A roads have 4G coverage, an increase across all measures on previous years and an indication of the general trend of development of communications infrastructure in the UK and elsewhere and the likelihood of the average available likely to increase year on year within safe government-permitted levels [78], particularly with the imminent roll out of 5G on the horizon.

While Piñuela stated that exploiting a single frequency band was most efficient for their particular implementation, they conceded that multi-band solutions may be more optimal without size or cost restraints [77]. In this vein, Muncuk *et al.*, while also conducting a RF survey of the city of Boston to demonstrate the practicality for EH, focussed on multi-band RF harvesting for continuous device operation and demonstrated an adjustable circuit for harvesting from LTE 700-MHz, GSM 850-MHz, and ISM 900-MHz bands with a single circuit and achieving 45% conversion efficiency [75].

Despite restrictions on its availability for safety, RF EH possesses several unique advantages. RF EH has the most potential for indoor applications as it can be found commonly, safely, and without reliance on highly specific infrastructure and does not suffer from large scale power level fluctuations or absences caused by time of day, weather, or associated activity that affect other energy sources [75] making it practical in outdoor environments too. Although some power level fluctuation is expected, RF energy has a more consistent and ubiquitous presence [78] than many other forms of ambient energy, thus RF EH is effective in any location with strong

RF signals such as urban environments [75] but even when strong RF signals are not available such as indoors or in rural areas, there is the flexibility to use a dedicated transmitter, or a range of hybrid ambient-dedicated approaches. The physical mechanism of RF harvesters is also desirable as it has a small form factor, cheap production costs, increased longevity due to no moving parts, and antennas can be designed to accommodate different user-friendly shapes [75].

However, the fact that RF transceivers are used for both communication and receiving power presents their most unique advantage. WSNs that use RF EH mechanisms can take advantage of 'one-to-many' wireless power distribution where one sensor node can transmit RF signals to power other receiving nodes in the surrounding area on a regular or sporadic basis. Though continuous power transmission is inefficient, the generally high conversion efficiency (50-75%) of RF EH means that this may be useful for well charged nodes lesser charged nodes and account for asynchronicity in power use and local absences of ambient energy [2]. Intelligent routing even can be applied to such systems by leveraging algorithms to predict link quality between nodes for communication purposes [79], [80], and predicting the amount of harvestable energy available for any given node in a WSN from other surrounding nodes [2] and creating an intelligent power supply network.

III. ENERGY STORAGE CONSIDERATION

An energy harvesting system should act as a buffer between the variable power consumption of the device and the wide dynamic range of the ambient sources. To be self-sustainable even in periods of energy absence, energy harvesting solutions require the utility of an energy storage mechanism to store captured energy when ambient energy is available and then to carefully use it to power when it is not [9], [49]. The alternative to energy storage is an autonomous system where harvested energy is used straight away. While this approach may have better life expectancy as it reduces the number of parts and is unconstrained by the storage medium's longevity, usually one of the major bottlenecks, it severely restricts the ability to operate perpetually and instead exclusively to when energy is available. While this may be suitable for certain 'on demand' applications such as piezoelectric buttons [31], it is undesirable for others.

Therefore, *Supercapacitors* and *Rechargeable Batteries* are commonly employed as energy storage devices for wireless sensor nodes to expand operational capacity [9]. When choosing an energy storage mechanism there are several competing factors that could be important to the designer depending on the application such as lifetime expectation, cycling efficiency, necessity of quick charging or discharging, and overall size (energy density) and weight dimensions (material density). From an application perspective, it is important to clearly specify operating conditions and choose appropriate battery devices to avoid operational problems [6].

A. BATTERIES AND RECHARGEABLE BATTERIES

Batteries can be primary (non-rechargeable) or secondary (rechargeable). Primary batteries have many advantages including higher capacity and temperature stability but their main disadvantage is the need for periodic maintenance and replacement at the end of life, whereas secondary batteries are rechargeable but are limited by their cycling capacity which dictates the number of charge/recharge cycles and means they will eventually need to be replaced when their capacity becomes too reduced for application [6].

Shaikh *et al.* recently speculated that, for the time being, WSN applications will continue to use disposable, long-lasting primary batteries instead of/in addition to rechargeable energy storage due to their higher energy densities over rechargeable battery and capacitor technology [2]. For instance, the energy density of non-rechargeable batteries typically varies between 1200-3780 J/cm^3 depending on the internal chemistry whereas rechargeable batteries can vary between 650-1080 J/cm^3 and capacitors have an even lower energy density with regular capacitors and supercapacitors having densities of 1-3 J/cm^3 and 10-100 J/cm^3 respectively [49].

The finite capacity of primary batteries does allow for better prediction and reasoning about the expected lifetime of the WSN and other relevant factors such as maintenance frequency but it also places a fixed limit on the amount of power that can be used across the device's lifetime and therefore will likely restrict the operation time or operating power etc., which is exacerbated by natural current leakage that consumes batteries (slowly) even when idle to reduce lifetime further. This suggests that systems employing disposable batteries are likely to be more costly in the long-run due to battery replacement and maintenance costs especially in applications where maintenance is difficult such as where nodes are located remotely, geographically sparse, or situated in areas with difficult access such as in medical [81], environmental [6], or structural monitoring domains [2]. Therefore, for applications requiring higher power over a node's lifetime, it is necessary to use a rechargeable storage medium such as a rechargeable battery or capacitor with a charging mechanism such as ambient EH.

1) RECHARGEABLE BATTERY CHARACTERISTICS

The characteristics of a battery are determined by its internal chemistry. It is important to be aware of the how internal chemistry affects different battery performance measures and how these measures can be best applied for efficient energy storage for a specific application [49]. Important battery specifications include storage medium, energy density, internal resistance, depth of discharge, self-discharge, and tolerance to overcharging [6]. An overview of different battery material characteristics are displayed in Table 2

The specific energy (Wh/kg) (energy density) indicates the maximum density of the stored energy in the battery per unit of mass, and differs for individual battery chemistries.

TABLE 2. Properties of different battery materials. Reproduced from Prauzek *et al.* [6].

Type	Rated Voltage (V)	Capacity (Ah)	Temperature Range (°C)	Cycling Capacity	Specific Energy (Wh/kg)
Lead-Acid	2	1.3	-20-60	500-1 000	30-50
MnO_2Li	3	0.03-5	-20-60	1000-2000	280
Li poly-carbon	3	0.025-5	-20-60	-	100-250
$LiSOCl_2$	3.6	0.025-40	-40-85	-	350
LiO_2S	3	0.025-40	-60-85	-	500-700
NiCd	1.2	1.1	-40-70	10 000-20 000	50-60
NiMH	1.2	2.5	-20-40	1 000-20 000	60-70
Li-ion	3.6	0.74	-30-45	1 000-100 000	75-200
MnO_2	1.65	0.617	-20-60	-	300-610

A battery's capacity is the amount of energy that can be stored in the cell at a full charge. The lifetime of most electrochemical batteries is in the order of hundreds to thousands of charging/discharging cycles (cycling capacity). During this time, capacity gradually decreases because of chemical corrosion of its electrodes [82]. Lifetime is greatly influenced by charging and discharging as frequent incomplete charge/discharge cycles can damage a battery's capacity over time [67], however specialised power management techniques can circumvent this problem by periodically performing a complete charge-discharge cycle to recover the battery after a high number of incomplete ones [61].

Battery capacity longevity is also influenced by ambient operating temperature [82]. A typical battery achieves nominal characteristics at temperatures around 20°C and any significant deviations from this temperature may result in shorter battery life and more frequent battery charges [83]. With the exception of lithium-ion, most batteries do not perform well in cold temperatures due to the increase of their internal resistance leading to a loss of capacity, whereas they perform well at elevated temperatures but at the cost of a significant shortening of their service life and risking of permanent damage [6].

Lead-Acid batteries are most commonly used for medium-sized devices. Their advantages include low cost, high reliability, and high efficiency. However, they have low cycling capacity and poor performance in extreme conditions. NiCd batteries have a long lifetime, fast charging, and vibration resistance but their main disadvantage is low capacity. NiMH batteries have better capacity and are less toxic which possibly makes them more suitable for environmental monitoring applications. Lithium-ion batteries have high efficiency, power density, and cell voltage. However, their high cost along with a tendency to cause fires when exposed to moisture limits their use. Alkaline MnO_2 batteries have the lowest self-discharge rate [6].

Conventional battery technologies such as Nickel Metal Hydride and Nickel-Cadmium offer high energy densities and good discharge rates but suffer from short cycle lives and adverse memory effects [84], whereas modern battery technologies such as lithium-ion offer high energy densities, discharge rates, and cell voltages, and longer cycle life in addition to eliminating memory effects [49]. All battery technologies should however be used with care as their chemistry means they are associated with general environmental and waste disposal issues and susceptible to extreme weather conditions that may break down the battery and result in chemical leakage [2].

B. CAPACITORS AND SUPERCAPACITORS

Addressing shortcomings in rechargeable battery technology such as cycling capacity and lifetime limitations rests in a new class of battery-free nodes to enable applications that simply aren't possible because of the necessary battery replacement maintenance. Recently, supercapacitors have received growing interest in energy harvesting systems as replacements or additions to batteries to compensate for their limitations [2], [85].

Capacitors are passive two-terminal electrical components used to store energy electrostatically in an electric field. Conventional capacitors have long lifetimes in terms of their cycling efficiency and have a high power density and charge and discharge extremely quickly which makes them useful for providing short bursts of high power with low duty cycles [49] but they have significantly lower energy density in comparison to typical batteries.

On the other hand, supercapacitors have an electrochemical mechanism that leads them to have properties somewhere between rechargeable batteries and regular capacitors. They are able to quickly accommodate large amounts of energy as their energy density is significantly greater than capacitors but slightly less than rechargeable batteries, and they have a better charging efficiency than rechargeable batteries that yields much faster charging but which is less efficient than regular ceramic capacitors [86].

Supercapacitors are generally preferred to conventional capacitors for EH sensor nodes and possess several advantages over rechargeable batteries including extremely long life cycles of over one million recharge cycles, high charging and discharging efficiency, a wider range of operating temperatures, vastly slower ageing and degradation, and more eco-friendly material composition than batteries [6], [49], [85]. The energy density of supercapacitors has also reached a level that makes them practical as energy storage elements and comparable with rechargeable batteries.

However, supercapacitors cannot be used as drop-in replacements for batteries without first considering the charging and discharging characteristics of both [85].

TABLE 3. Comparison of supercapacitor and Li-ion battery properties. Reproduced from Libich *et al.* [86].

Attribute	Li-Ion	Supercapacitors		
		EDLC	Pseudo	Hybrid
Charge Time (s)	600	1-10	1-10	100
Cycle Life	500	1,000,000	100,000	500,000
Cell Voltage (v)	3.6	2.7	2.3-2.8	2.3-2.8
Specific Energy (Wh/kg)	250	3.5	10	180
Cost per kWh (USD)	140	10,000	10,000	-
Operating Temperature (°C)	-20-60	-40-65	-40-65	-40-65
Self-Discharge per Month (%)	4	60	60	-

Supercapacitors differ from batteries with their lower energy density and high self-discharge current, and once fully charged they discharge at a much higher rate than traditional batteries which may make them problematic for powering the load during extended periods of ambient energy shortages [9], [67]. Self-discharge rates can range from 60% per month [86] to 11% per day [87]. If not addressed, charge leakage can significantly decrease the operational time of powered devices. Also, given that the energy density of supercapacitors is lower than that of batteries, it may seem desirable to maximise the capacitance rating of a supercapacitor to store more energy. However, as the voltage is linearly proportional to the charge level, the larger the capacitance, the greater the unusable stored charge below the minimum usable voltage level for the target system [85]. Larger capacitors also suffer from cold-booting problems where the capacitor is empty and the voltage of the energy storage unit takes time charging to reach a minimum level to power the node, resulting in periods of inactivity which will need to be addressed with an appropriate system architecture (see section IV-B).

1) SUPERCAPACITOR TYPES

Superconductors can be further divided into three categories according to their energy storage principle: *Electric Double-Layer Capacitors* (EDLC), *Pseudo-Supercapacitors*, and *Hybrid Supercapacitors* [86], [88]. Each supercapacitor type can also be constructed from a range of materials that affect their properties. Summaries of these material types and their effect on specific capacitance as well as further information on each supercapacitor type can be found in the review by Muzaffar *et al.* [88].

EDLC supercapacitors are the most common form of supercapacitor and comprise the majority of the commercial market and as such have a much lower cost compared to the other supercapacitor types They possess good durability, energy density, and cycling stability in the range of millions of cycles [86], [88].

Pseudocapacitors (or Faradaic supercapacitors) have an operation principle that is said to be more comparable of batteries than capacitors due to the fast and reversible redox reactions that take place. They have a greater energy density and capacitance 10–100 times higher than normal EDLCs, but their operation principle brings forth several disadvantages including lower power density, cycling instability, lower charging efficiency, lower discharge rate, and faster degradation of components when compared with EDLCs [86], [88]–[90].

Hybrid supercapacitors are the most recent supercapacitor type and composed of components used in both EDLCs and pseudocapacitors to produce a greater energy density, power density, cycling efficiency, higher voltage, and the capability to provide high currents than other supercapacitor types. From a construction and operational point of view they resemble lithium-ion batteries but have higher power density and lower energy density whilst retaining the benefits and behaviours of capacitors in general [86], [88].

C. COMPARING RECHARGEABLE BATTERIES AND SUPERCAPACITORS

Rechargeable Batteries and *Supercapacitors* are the most commonly employed energy storage devices in WSNs [9] but have differing characteristics. Libich *et al.* produced a useful comparison of the different supercapacitor types and commonly used Li-ion batteries, shown in Fig. 3.

In particular, the differences between cycle lives of 100,000-500,000 versus 500 and monthly self-discharge rates of 60% versus 4% for supercapacitors and rechargeable batteries highlight the most significant differences between the two storage mediums, with noticeable differences in operating temperature ranges and charging times also present. However, it must again be stressed that the properties of both batteries and supercapacitors vary hugely depending on the material and design [6], [88].

IV. ENERGY HARVESTING ARCHITECTURES

Combining the aforementioned EH and energy storage techniques into an effective power supply system for a given application can be challenging with many design considerations to take into account including identifying appropriate sources of energy, and selecting and optimising the utility of appropriate harvesting methods and storage mediums. Some environments may offer more than one exploitable energy source. Likewise, it may be more efficient to use multiple energy storage mechanisms including of different types.

In this section, we describe generic EH system topologies with regards to the integration of energy storage elements and the performance characteristics of each. Then we describe methods for improving the energy efficiency of harvesting systems by increasing the number of storage elements and

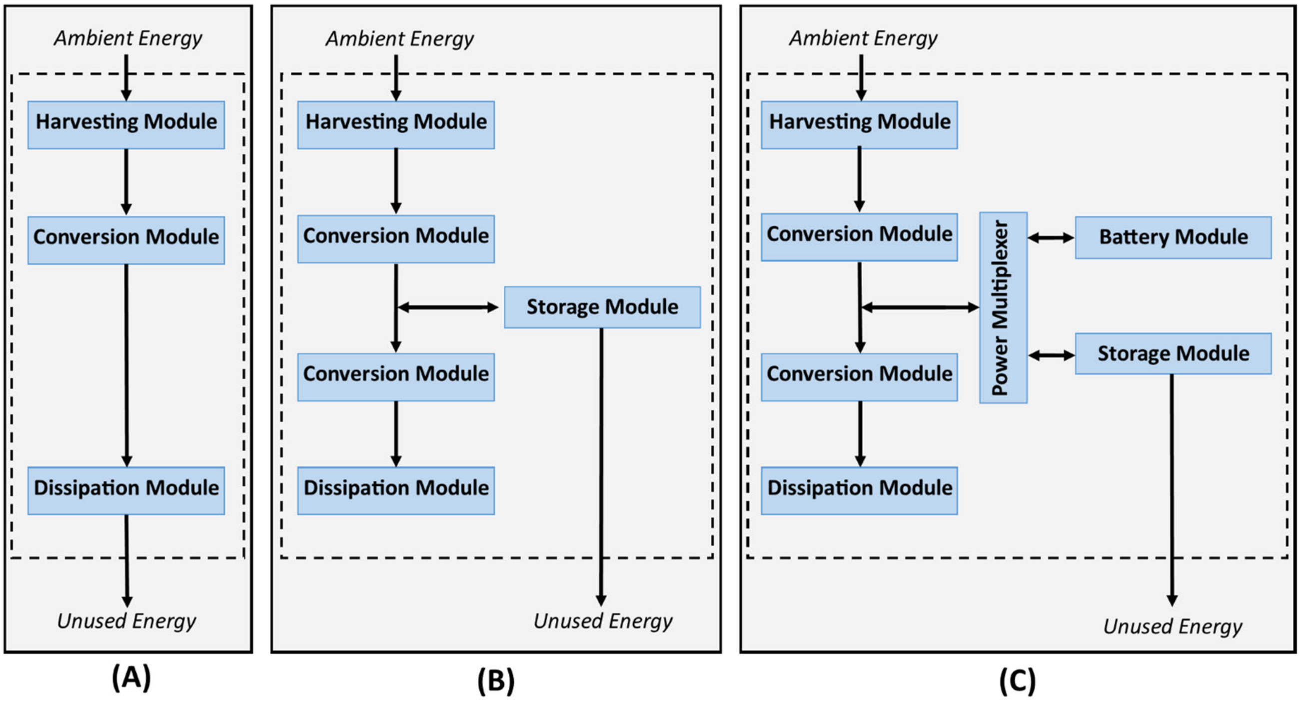

FIGURE 2. Power Management Topologies: A) Autonomous Harvesting System; B) Autonomous Hybrid Harvesting System; C) Battery-supplemented Harvesting System; Reproduced from Prauzek *et al.* [6].

specialising the way in which they are integrated before describing instances where multiple-EH techniques have been combined to power WSNs.

A. SYSTEM TOPOLOGIES

Prauzek *et al.* distinguished three generic topologies for EH systems: *Autonomous Harvesting Systems*, *Autonomous Hybrid Harvesting Systems*, and *Battery-supplemented Harvesting Systems* shown in Fig. 2) [6].

1) AUTONOMOUS HARVESTING SYSTEMS

Autonomous harvesting systems fully satisfy their energy needs from ambient sources without needing batteries, and thus only operate when an energy source is available. The design of these systems is governed by the *energy neutrality principle* where they can never consume more energy than the harvesting device can deliver which must be reflected by the power management system and it should be designed to perform at the maximum level supported by a given environment and its energy availability characteristics while meeting the application objectives. This is usually achieved by employing prediction algorithms to estimate future energy availability to manage resources effectively [2], [91].

The main advantage of this approach is simplicity and the circumvention of lifetime and performance bottlenecks achieved by foregoing storage elements. However, since there is no energy buffer and the harvesting module is the only source of energy in the system this means excess energy will be lost if the load consumes less energy than available from the environment while simultaneously placing restrictions on device operation to exclusively when an energy source is available which may be problematic for more variable sources [6]. Therefore, this approach is most suited to when power is required 'on-demand' in relation to the presence of an energy source.

2) AUTONOMOUS HYBRID HARVESTING SYSTEMS

Unlike autonomous harvesting systems, autonomous hybrid harvesting systems implement an energy reservoir such as a rechargeable battery or supercapacitor such that the harvesting device collects energy to power system operation and recharge a storage device. This architecture is said to be the most common type of EH system as it allows for more liberal adherence to the energy neutrality principal than systems without secondary storage as a hybrid system can sometimes consume more energy than the harvesting source provides (using stored reserves), as long as production and consumption rates are balanced over time. The battery and the EH device must be sized so that they satisfy the energy needs of the system but with proper energy management this topology can operate perpetually and vastly increase the operational lifetime of a system [6].

3) BATTERY-SUPPLEMENTED HARVESTING SYSTEMS

Battery-supplemented harvesting systems have a battery as the main source of energy and a harvesting device that plays an important, but secondary, role. The goal of energy management in such systems is to limit battery energy usage and increase the system's lifetime by making external recharging or replacement of batteries less frequent. These systems can use primary or secondary batteries and harvested energy can directly or indirectly power the load or its specific parts. This approach can greatly increase system reliability and allow for greater data acquisition, processing, and transfer. As long as the batteries have some useful charge left, a system such as this can continue to operate in situations when secondary storage is depleted and environmental energy is not available. Necessarily, it does have a lifetime limitation for when a replacement battery is needed, but this can be after a very long time [6].

B. MULTI-STORAGE SYSTEMS

An energy buffer integrated serially in an autonomous or autonomous-hybrid architecture where harvested energy directly charges a single energy storage device to subsequently power the load is known as a *single-path* architecture. Single-path architectures are susceptible to a 'cold booting' issue that occurs when the energy storage unit is completely empty and its voltage takes time to reach a minimum level from charging to enable it to power the node, resulting in a period of inactivity. This problem can be overcome with a *dual-path* architecture composition consisting of two (or more) energy storage units to buffer harvested energy [4].

Dual-path architectures have primary and secondary storage. When environmental energy is available, harvested energy will be prioritised to charge the primary storage device which should have a small capacity so that it may be quickly charged to a minimum voltage sufficient to activate the sensor node. When the primary storage is fully charged, excess energy can be driven into a secondary storage device with a larger capacity. Then, when environmental energy is insufficient, energy can be drawn from the secondary storage to the primary storage to ensure continuous operation. As the secondary storage has a larger capacity it can provide longer term operation during periods of energy absence and ensure more reliable and consistent performance [4].

Dual-path architectures can be implemented with different combinations of energy storage mechanisms to suit an application such as a capacitor and supercapacitor together [92], arrays of differing supercapacitors [4], [85], [93], or a supercapacitor and rechargeable battery in tandem [9].

For systems composed of multiple supercapcitors, another power management optimisation that was recently proposed is *Dynamic Capacitor Switching* (DCS) which improves the efficiency of systems comprised of multiple supercapacitors of differing capacitance and was found to be particularly useful for mobile WSNs (i.e. environments where the energy availability of different sources can vary over time in ways that may be difficult to predict).

Supercapacitor size is critical for mobile WSN performance but selecting an optimal capacitance value is difficult. Small capacitors charge quickly and enable the node to operate in low energy environments but cannot support intensive tasks such as communication whereas larger capacitors can support energy-intensive tasks but can prevent the node from booting at all if energy availability is low Munir *et al.* proposed using an adaptive learning algorithm to predict the amount of available ambient energy and dynamically switch between multiple capacitors of differing sizes depending on energy availability. The proposed hybrid platform is only powered by a single capacitor at any given time. When the node detects a high energy area it switches to a bigger capacitor to accumulate available energy and store for later use when the node is in a low energy area. Although they describe their dynamic switching algorithm as non-trivial since it requires tracking and predicting environmental energy, their method showed a 40% increase in the amount of energy harvested and an 80% improvement in sensor coverage compared to fixed capacitor approaches, thus helping to mitigate the trade-off between fast start-up time and the amount of stored energy [67].

C. MULTI-SOURCE ENERGY HARVESTING

Exploiting several ambient energy sources concurrently can improve a system's reliability by reducing dependence on the availability of a single energy source [9]. If a system's energy supply is more reliable, then it is sometimes feasible instigate a trade-off of reduced storage capacity in favour of additional EH capabilities where a system's size or complexity is of concern such as increasing the size of harvester components [4].

There is no fixed way to combine energy harvesters as combinations are application dependent. However, some sources are more naturally paired in certain environments, and some harvesters may be more intuitive to combine depending on their form.

Le *et al.* designed a modular plug-in EH system with commercial, off-the-shelf (COTS) components to support multiple sources simultaneously in a dual-path architecture with energy storage. Their system used a combination of solar and wind-based generators specifically, but their implementation demonstrated a modular approach to add complementary harvesters with ease through repetition of a generic circuit as long as the energy adapter connecting a harvester to the main circuit is designed carefully [4]. Carli *et al.* presented a similar modular approach for harvesting the same energy sources and a plug-in style modularity for adding additional power sources with energy buffering provided by supercapacitors and a rechargeable battery [9], while Baranov *et al.* exploited a hybrid solar/wind power supply to power a supercapacitor-based sensor node in urban areas and outdoor industrial facilities perpetually [94].

Morais *et al.* explored the use of a multi-source energy harvester for harvesting from natural solar, wind and water flow sources simultaneously for charging a NiMH battery pack with experimental results proving capability for near-perpetual operation of an agriculture-based WSN with the EH mechanisms doubling up as sensors to provide relevant data on solar radiation, water flow and wind speed respectively [61].

Bandyopadhyay implemented a multi-source, dual-path system architecture based on photovoltaic, thermoelectric, and piezoelectric generators with an architecture that used inductor-sharing to combine the energy harvested from the three generators to improve cost-effectiveness by reducing the number of components at a minor efficiency expense [95].

Meanwhile, Wang *et al.* introduced a similar supercapacitor-based EH system for structural health monitoring of industrial machinery that utilised photovoltaic, thermoelectric, and electromagnetic vibrational generators to supply power to a wireless sensor node [27].

Several researchers have also taken advantage of the interesting property that pyroelectric materials are also piezoelectric materials with several nano-generators reported with pyroelectric/piezoelectric materials [42]. For instance, Wang *et al.* demonstrated a hybrid nano-generator able to scavenge thermal and mechanical energies either individually or simultaneously using pyroelectric, piezoelectric, and triboelectric effects [96].

Although the use of multiple energy sources can increase the reliability of the system power supply, it also increases number of components and the overall complexity of the system architecture leading to increased costs. Yet, it has been shown that it is possible to combine a variety of different EH mechanisms to great effect even when individual generators produce characteristically different outputs of differing voltage and currents [95]. Like choosing single-source EH methods, deciding whether to implement multi-source EH requires thoughtful consideration of the operating environment to ensure there is a benefit to the increased complexity through a material increase to subsequent energy availability and system sustainability.

V. FURTHER DESIGN CONSIDERATIONS

Although this paper has focussed on the selection and composition of appropriate energy harvesting and storage technology which is of itself non-trivial, there are numerous other facets of design which contribute to the overall efficiency of an EH WSN which can make the difference between an approach being feasible or otherwise.

Prauzek *et al.* identified a methodical procedure for designing efficient EH WSNs within some arbitrary environment and listed a number of technical items to consider during development at both node and network level across hardware and software. As well as source identification, system topology, and storage mechanism, consideration must be given to communication requirements and technology, and the various optimisation and control algorithms employed at different system levels [6].

In terms of communication, the choice of hardware component will dictate important characteristics such as a device's effective range and its power consumption. If used in conjunction with RF harvesting technology, an assessment needs to be made as to whether a single or dual antenna model is necessary as this will impact a device's complexity and form. Furthermore, communication requirements should be scrupulously analysed in terms of the required data transfer, communication protocol, and communication frequency [6] as communication is often one of the most energy intensive tasks for a WSN [2].

In terms of control algorithm design, there are a myriad of optimisations that could be made at node and network level with many optimisations specific to the employed harvesting technique and system architecture.

Some such optimisations include: using prediction techniques to balance device operation between use of stored energy and the expectation of future energy [2], [6], [97]; node-level adaptive control such as MPPT for variable energy sources [6], [51]; parameter optimisation; data compression to reduce storage and communication overheads; separation of computational duties between node and cloud to minimise energy use [2], [6]; optimal allocation of resources for various tasks at the node [98], [99] and sink level [100]; optimisation of node locations and associated network/EH infrastructure [5], [71]; and complying with safety regulations while delivering optimal performance [101].

Furthermore, tasks should be interleaved and scheduled at the node level to achieve robust performance, minimise energy consumption, and exploit energy storage architecture efficiently in an efficient control algorithm by combining light tasks such as sensing and computation which may take place frequently, while separating energy-intensive tasks such as communication to take place less frequently [67], [97].

VI. CONCLUSION

In this paper we have described a range of contemporary EH approaches for WSNs and their application in detail including vibrational methods (electromagnetic, electrostatic, and piezoelectric), thermal methods (thermoelectric and pyroelectric), solar methods (photovoltaic), flow-based methods (hydrodynamic and aerodynamic), magnetic methods, and radiofrequency methods. We also described the most commonly used energy storage technologies for WSNs in rechargeable batteries and supercapacitors and highlighted their differing characteristics, respective advantages and disadvantages, and application potential, before discussing different contemporary EH system topologies for combining EH with energy storage appropriately to power a load including autonomous, autonomous-hybrid, and battery supplemented harvesting models. Finally, we highlighted a broader range of considerations that should be given to designing WSN EH systems.

EH systems for WSNs are non-trivial to design but their application can reap a range of logistical, environmental, and economic benefits and their deployment will only become more important and more common as we adapt towards Industry 4.0. EH systems have the ability to increase a device's operational lifetime, average energy consumption, or self-sustainability. However, as we have seen the most appropriate EH system for a given application is highly dependent on the application itself and the nature of the environment in which is resides. Therefore, great consideration must be given to identify an abundantly exploitable energy source that can be harvested within the constraints and limitations of the available methods while also remembering that the success of an EH-powered WSN depends on many other physical factors, technical decisions, and algorithmic optimisations outside of simply the selection and combination of the harvesting and storage methods.

REFERENCES

[1] V. Annapureddy, S.-M. Na, G.-T. Hwang, M. G. Kang, R. Sriramdas, H. Palneedi, W.-H. Yoon, B.-D. Hahn, J.-W. Kim, C.-W. Ahn, D.-S. Park, J.-J. Choi, D.-Y. Jeong, A. B. Flatau, M. Peddigari, S. Priya, K.-H. Kim, and J. Ryu, ''Exceeding milli-watt powering magneto-mechano-electric generator for standalone-powered electronics,'' *Energy Environ. Sci.*, vol. 11, no. 4, pp. 818–829, 2018.

[2] F. K. Shaikh and S. Zeadally, ''Energy harvesting in wireless sensor networks: A comprehensive review,'' *Renew. Sustain. Energy Rev.*, vol. 55, pp. 1041–1054, Mar. 2016.

[3] K. Z. Panatik, K. Kamardin, S. A. Shariff, S. S. Yuhaniz, N. A. Ahmad, O. M. Yusop, and S. Ismail, ''Energy harvesting in wireless sensor networks: A survey,'' in *Proc. IEEE Int. Symp. Telecommun. Technol.*, Nov. 2016, pp. 53–58.

[4] T. N. Le, T. P. Vo, and A. V. D. Duc, ''Plug-in multi-source energy harvesting for autonomous wireless sensor networks,'' in *Proc. Int. Conf. Adv. Comput. Appl. (ACOMP)*, Nov. 2017, pp. 105–108.

[5] P. Zhou, C. Wang, and Y. Yang, ''Self-sustainable sensor networks with multi-source energy harvesting and wireless charging,'' in *Proc. IEEE Conf. Comput. Commun. (IEEE INFOCOM)*, Apr. 2019, pp. 1828–1836.

[6] M. Prauzek, J. Konecny, M. Borova, K. Janosova, J. Hlavica, and P. Musilek, ''Energy harvesting sources, storage devices and system topologies for environmental wireless sensor networks: A review,'' *Sensors*, vol. 18, no. 8, p. 2446, Jul. 2018.

[7] S. Chamanian, S. Baghaee, H. Ulusan, Ö. Zorlu, H. Külah, and E. Uysal-Biyikoglu, ''Powering-up wireless sensor nodes utilizing rechargeable batteries and an electromagnetic vibration energy harvesting system,'' *Energies*, vol. 7, no. 10, pp. 6323–6339, Oct. 2014.

[8] P. Kamalinejad, C. Mahapatra, Z. Sheng, S. Mirabbasi, V. C. M. Leung, and Y. L. Guan, ''Wireless energy harvesting for the Internet of Things,'' *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 102–108, Jun. 2015.

[9] D. Carli, D. Brunelli, L. Benini, and M. Ruggeri, ''An effective multi-source energy harvester for low power applications,'' in *Proc. Design, Autom. Test Eur.*, Mar. 2011, pp. 1–6.

[10] B. J. Hansen, Y. Liu, R. Yang, and Z. L. Wang, ''Hybrid nanogenerator for concurrently harvesting biomechanical and biochemical energy,'' *ACS Nano*, vol. 4, no. 7, pp. 3647–3652, Jul. 2010.

[11] H. Wang, J.-D. Park, and Z. Ren, ''Active energy harvesting from microbial fuel cells at the maximum power point without using resistors,'' *Environ. Sci. Technol.*, vol. 46, no. 9, pp. 5247–5252, May 2012.

[12] C. P. Souza, F. B. S. Carvalho, F. A. N. Silva, H. A. Andrade, N. D. V. Silva, O. Baiocchi, and I. Müller, ''On harvesting energy from tree trunks for environmental monitoring,'' *Int. J. Distrib. Sensor Netw.*, vol. 12, Jun. 2016, Art. no. 9383765.

[13] J. Lv, I. Jeerapan, F. Tehrani, L. Yin, C. A. Silva-Lopez, J.-H. Jang, D. Joshuia, R. Shah, Y. Liang, L. Xie, F. Soto, C. Chen, E. Karshalev, C. Kong, Z. Yang, and J. Wang, ''Sweat-based wearable energy harvesting-storage hybrid textile devices,'' *Energy Environ. Sci.*, vol. 11, no. 12, pp. 3431–3442, Dec. 2018.

[14] W. Xu, H. Zheng, Y. Liu, X. Zhou, C. Zhang, Y. Song, X. Deng, M. Leung, Z. Yang, R. X. Xu, Z. L. Wang, X. C. Zeng, and Z. Wang, ''A droplet-based electricity generator with high instantaneous power density,'' *Nature*, vol. 578, no. 7795, pp. 392–396, Feb. 2020.

[15] M. Yuan, Z. Cao, J. Luo, and X. Chou, ''Recent developments of acoustic energy harvesting: A review,'' *Micromachines*, vol. 10, no. 1, p. 48, Jan. 2019.

[16] F. Chraim and S. Karaki, ''Fuel cell applications in wireless sensor networks,'' in *Proc. IEEE Instrum. Meas. Technol. Conf.*, May 2010, pp. 1320–1325.

[17] Y.-J. Yoon, W.-T. Park, K. H. H. Li, Y. Q. Ng, and Y. Song, ''A study of piezoelectric harvesters for low-level vibrations in wireless sensor networks,'' *Int. J. Precis. Eng. Manuf.*, vol. 14, no. 7, pp. 1257–1262, Jul. 2013.

[18] N. S. Hudak and G. G. Amatucci, ''Small-scale energy harvesting through thermoelectric, vibration, and radiofrequency power conversion,'' *J. Appl. Phys.*, vol. 103, no. 10, May 2008, Art. no. 101301.

[19] S. Roundy, P. K. Wright, and J. Rabaey, ''A study of low level vibrations as a power source for wireless sensor nodes,'' *Comput. Commun.*, vol. 26, no. 11, pp. 1131–1144, Jul. 2003.

[20] V. R. Challa, M. G. Prasad, and F. T. Fisher, ''Towards an autonomous self-tuning vibration energy harvesting device for wireless sensor network applications,'' *Smart Mater. Struct.*, vol. 20, Jan. 2011, Art. no. 025004.

[21] D. Zhu, M. J. Tudor, and S. P. Beeby, ''Strategies for increasing the operating frequency range of vibration energy harvesters: A review,'' *Meas. Sci. Technol.*, vol. 21, no. 2, Dec. 2009, Art. no. 022001.

[22] Y.-H. Shin, J. Choi, S. J. Kim, S. Kim, D. Maurya, T.-H. Sung, S. Priya, C.-Y. Kang, and H.-C. Song, ''Automatic resonance tuning mechanism for ultra-wide bandwidth mechanical energy harvesting,'' *Nano Energy*, vol. 77, Nov. 2020, Art. no. 104986.

[23] A. Erturk and D. J. Inman, ''Introduction to piezoelectric energy harvesting,'' in *Piezoelectric Energy Harvesting*. Hoboken, NJ, USA: Wiley, 2011, pp. 1–18.

[24] A.-R. El-Sayed, K. Tai, M. Biglarbegian, and S. Mahmud, ''A survey on recent energy harvesting mechanisms,'' in *Proc. IEEE Can. Conf. Electr. Comput. Eng. (CCECE)*, May 2016, pp. 1–5.

[25] N. N. H. Ching, H. Y. Wong, W. J. Li, P. H. W. Leong, and Z. Wen, ''A laser-micromachined multi-modal resonating power transducer for wireless sensing systems,'' *Sens. Actuators A, Phys.*, vols. 97–98, pp. 685–690, Apr. 2002.

[26] S. P. Beeby, R. N. Torah, M. J. Tudor, P. Glynne-Jones, T. O. Donnell, C. R. Saha, and S. Roy, ''A micro electromagnetic generator for vibration energy harvesting,'' *J. Micromech. Microeng.*, vol. 17, no. 7, pp. 1257–1265, Jun./Oct. 2007.

[27] W. Wang, A. Vinco, N. Pavlov, N. Wang, M. Hayes, and C. O'Mathuna, ''A rotating machine acoustic emission monitoring system powered by multi-source energy harvester,'' in *Proc. 1st Int. Workshop Energy Neutral Sens. Syst. (ENSSys)*, New York, NY, USA, 2013, pp. 5:1–5:6.

[28] I. Sari, T. Balkan, and H. Külah, ''An electromagnetic micro power generator for low-frequency environmental vibrations based on the frequency upconversion technique,'' *J. Microelectromech. Syst.*, vol. 19, no. 1, pp. 14–27, Feb. 2010.

[29] X. Tang, X. Wang, R. Cattley, F. Gu, and A. Ball, ''Energy harvesting technologies for achieving self-powered wireless sensor networks in machine condition monitoring: A review,'' *Sensors*, vol. 18, no. 12, p. 4113, Nov. 2018.

[30] R. Gherca and R. Olaru, ''Harvesting vibration energy by electromagnetic induction,'' *Ann. Univ. Craiova*, vol. 35, p. 6, 2011.

[31] J. Yang, M. Lee, M.-J. Park, S.-Y. Jung, and J. Kim, ''A 2.5-V, 160-μJ-output piezoelectric energy harvester and power management IC for batteryless wireless switch (BWS) applications,'' in *Proc. Symp. VLSI Circuits (VLSI Circuits)*, Jun. 2015, pp. C282–C283.

[32] J. Lee and B. Choi, ''Development of a piezoelectric energy harvesting system for implementing wireless sensors on the tires,'' *Energy Convers. Manage.*, vol. 78, pp. 32–38, Feb. 2014.

[33] Q. Zhu, M. Guan, and Y. He, ''Vibration energy harvesting in automobiles to power wireless sensors,'' in *Proc. IEEE Int. Conf. Inf. Autom.*, Jun. 2012, pp. 349–354.

[34] Q. Leng, L. Chen, H. Guo, J. Liu, G. Liu, C. Hu, and Y. Xi, ''Harvesting heat energy from hot/cold water with a pyroelectric generator,'' *J. Mater. Chem. A*, vol. 2, no. 30, pp. 11940–11947, Jul. 2014.

[35] R. Kishore and S. Priya, ''A review on low-grade thermal energy harvesting: Materials, methods and devices,'' *Materials*, vol. 11, no. 8, p. 1433, Aug. 2018.

[36] B. Xiong, L. Chen, F. Meng, and F. Sun, ''Modeling and performance analysis of a two-stage thermoelectric energy harvesting system from blast furnace slag water waste heat,'' *Energy*, vol. 77, pp. 562–569, Dec. 2014.

[37] N. Satyala, P. Norouzzadeh, and D. Vashaee, ''Nano bulk thermoelectrics: Concepts, techniques, and modeling,'' in *Nanoscale Thermoelectrics* (Lecture Notes in Nanoscale Science and Technology), X. Wang and Z. M. Wang, Eds. Cham, Switzerland: Springer, 2014, pp. 141–183.

[38] U. Datta, S. Dessouky, and A. T. Papagiannakis, ''Harvesting thermoelectric energy from asphalt pavements,'' *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2628, no. 1, pp. 12–22, Jan. 2017.

[39] X. Lu and S.-H. Yang, ''Thermal energy harvesting for WSNs,'' in *Proc. IEEE Int. Conf. Syst., Man Cybern.*, Oct. 2010, pp. 3045–3052.

[40] V. Leonov, T. Torfs, P. Fiorini, and C. Van Hoof, ''Thermoelectric converters of human warmth for self-powered wireless sensor nodes,'' *IEEE Sensors J.*, vol. 7, no. 5, pp. 650–657, May 2007.

[41] A. Sultana, M. M. Alam, T. R. Middya, and D. Mandal, "A pyroelectric generator as a self-powered temperature sensor for sustainable thermal energy harvesting from waste heat and human body heat," *Appl. Energy*, vol. 221, pp. 299–307, Jul. 2018.
[42] A. Thakre, A. Kumar, H.-C. Song, D.-Y. Jeong, and J. Ryu, "Pyroelectric energy conversion and its applications—Flexible energy harvesters and sensors," *Sensors*, vol. 19, no. 9, p. 2170, May 2019.
[43] Y. Yang, S. Wang, Y. Zhang, and Z. L. Wang, "Pyroelectric nanogenerators for driving wireless sensors," *Nano Lett.*, vol. 12, no. 12, pp. 6408–6413, Dec. 2012.
[44] V. A. Milichko, A. S. Shalin, I. S. Mukhin, A. E. Kovrov, A. A. Krasilin, A. V. Vinogradov, P. A. Belov, and C. R. Simovski, "Solar photovoltaics: Current state and trends," *Physics-Uspekhi*, vol. 59, p. 727, Aug. 2016.
[45] H. Yu and Q. Yue, "Indoor light energy harvesting system for energy-aware wireless sensor node," *Energy Procedia*, vol. 16, pp. 1027–1032, Jan. 2012.
[46] C. Ó. Mathúna, T. O'Donnell, R. V. Martinez-Catala, J. Rohan, and B. O'Flynn, "Energy scavenging for long-term deployable wireless sensor networks," *Talanta*, vol. 75, no. 3, pp. 613–623, May 2008.
[47] Z. G. Wan, Y. K. Tan, and C. Yuen, "Review on energy harvesting and energy management for sustainable wireless sensor networks," in *Proc. IEEE 13th Int. Conf. Commun. Technol.*, Sep. 2011, pp. 362–367.
[48] V. Raghunathan, A. Kansal, J. Hsu, J. Friedman, and M. Srivastava, "Design considerations for solar energy harvesting wireless embedded systems," in *Proc. 4th Int. Symp. Inf. Process. Sensor Netw.*, Apr. 2005, pp. 457–462.
[49] G. Tuna and V. C. Gungor, "Energy harvesting and battery technologies for powering wireless sensor networks," in *Industrial Wireless Sensor Networks* (Series in Electronic and Optical Materials), R. Budampati and S. Kolavennu, Eds., Sawston, U.K.: Woodhead, Jan. 2016, pp. 25–38.
[50] K. Williams and A. Qouneh, "Internet of Things: Solar array tracker," in *Proc. IEEE 60th Int. Midwest Symp. Circuits Syst. (MWSCAS)*, Aug. 2017, pp. 1057–1060.
[51] S. Saravanan and N. R. Babu, "Maximum power point tracking algorithms for photovoltaic system—A review," *Renew. Sustain. Energy Rev.*, vol. 57, pp. 192–204, May 2016.
[52] S. M. Mousavi, E. S. Mostafavi, and P. Jiao, "Next generation prediction model for daily solar radiation on horizontal surface using a hybrid neural network and simulated annealing method," *Energy Convers. Manage.*, vol. 153, pp. 671–682, Dec. 2017.
[53] X. Chen, X. Ma, W. Ren, L. Gao, S. Lu, D. Tong, F. Wang, Y. Chen, Y. Huang, H. He, B. Tang, J. Zhang, X. Zhang, X. Mu, and Y. Yang, "A triboelectric nanogenerator exploiting the Bernoulli effect for scavenging wind energy," *Cell Rep. Phys. Sci.*, vol. 1, no. 9, Sep. 2020, Art. no. 100207.
[54] F. Fei, J. D. Mai, and W. J. Li, "A wind-flutter energy converter for powering wireless sensors," *Sens. Actuators A, Phys.*, vol. 173, no. 1, pp. 163–171, Jan. 2012.
[55] F. Fei, S. Zhou, J. Mai, and W. Li, "Development of an indoor airflow energy harvesting system for building environment monitoring," *Energies*, vol. 7, no. 5, pp. 2985–3003, May 2014.
[56] R. Song, X. Shan, F. Lv, and T. Xie, "A study of vortex-induced energy harvesting from water using PZT piezoelectric cantilever with cylindrical extension," *Ceram. Int.*, vol. 41, pp. S768–S773, Jul. 2015.
[57] S. Priya, "Modeling of electric energy harvesting using piezoelectric windmill," *Appl. Phys. Lett.*, vol. 87, no. 18, Oct. 2005, Art. no. 184101.
[58] J. A. R. Azevedo and F. E. S. Santos, "Energy harvesting from wind and water for autonomous wireless sensor nodes," *IET Circuits, Devices Syst.*, vol. 6, no. 6, pp. 413–420, Nov. 2012.
[59] Y. Wu, W. Liu, and Y. Zhu, "Design of a wind energy harvesting wireless sensor node," in *Proc. IEEE 3rd Int. Conf. Inf. Sci. Technol. (ICIST)*, Mar. 2013, pp. 1494–1497.
[60] A. Jushi, A. Pegatoquet, and T. N. Le, "Wind energy harvesting for autonomous wireless sensor networks," in *Proc. Euromicro Conf. Digit. Syst. Design (DSD)*, Aug. 2016, pp. 301–308.
[61] R. Morais, S. G. Matos, M. A. Fernandes, A. L. G. Valente, S. F. S. P. Soares, P. J. S. G. Ferreira, and M. J. C. S. Reis, "Sun, wind and water flow as energy supply for small stationary data acquisition platforms," *Comput. Electron. Agricult.*, vol. 64, no. 2, pp. 120–132, Dec. 2008.
[62] N. Rezaei-Hosseinabadi, A. Tabesh, and R. Dehghani, "A topology and design optimization method for wideband piezoelectric wind energy harvesters," *IEEE Trans. Ind. Electron.*, vol. 63, no. 4, pp. 2165–2173, Apr. 2016.
[63] World Health Organisation, "Static fields environmental health criteria monograph No.232," in *Natural Background and Human-Made Sources*. Geneva, Switzerland: World Health Organisation, 2006, ch. 3.
[64] J. Ryu, J.-E. Kang, Y. Zhou, S.-Y. Choi, W.-H. Yoon, D.-S. Park, J.-J. Choi, B.-D. Hahn, C.-W. Ahn, J.-W. Kim, Y.-D. Kim, S. Priya, S. Y. Lee, S. Jeong, and D.-Y. Jeong, "Ubiquitous magneto-mechano-electric generator," *Energy Environ. Sci.*, vol. 8, no. 8, pp. 2402–2408, 2015.
[65] M. G. Kang, R. Sriramdas, H. Lee, J. Chun, D. Maurya, G. T. Hwang, J. Ryu, and S. Priya, "High power magnetic field energy harvesting through amplified magneto-mechanical vibration," *Adv. Energy Mater.*, vol. 8, no. 16, Jun. 2018, Art. no. 1703313.
[66] G. Liu, P. Ci, and S. Dong, "Energy harvesting from ambient low-frequency magnetic field using magneto-mechano-electric composite cantilever," *Appl. Phys. Lett.*, vol. 104, no. 3, Jan. 2014, Art. no. 032908.
[67] B. Munir and V. Dyo, "On the impact of mobility on battery-less RF energy harvesting system performance," *Sensors*, vol. 18, no. 11, p. 3597, Oct. 2018.
[68] P. Nintanavongsa, U. Muncuk, D. R. Lewis, and K. R. Chowdhury, "Design optimization and implementation for RF energy harvesting circuits," *IEEE J. Emerg. Sel. Topics Circuits Syst.*, vol. 2, no. 1, pp. 24–33, Mar. 2012.
[69] G. Charalampidis, A. Papadakis, and M. Samarakou, "Power estimation of RF energy harvesters," *Energy Procedia*, vol. 157, pp. 892–900, Jan. 2019.
[70] R. Want, "An introduction to RFID technology," *IEEE Pervasive Comput.*, vol. 5, no. 1, pp. 25–33, Jan. 2006.
[71] L. Fu, P. Cheng, Y. Gu, J. Chen, and T. He, "Optimal charging in wireless rechargeable sensor networks," *IEEE Trans. Veh. Technol.*, vol. 65, no. 1, pp. 278–291, Jan. 2016.
[72] V. Dyo, T. Ajmal, B. Allen, D. Jazani, and I. Ivanov, "Design of a ferrite rod antenna for harvesting energy from medium wave broadcast signals," *J. Eng.*, vol. 2013, no. 12, pp. 89–96, Dec. 2013.
[73] T. Ajmal, V. Dyo, B. Allen, D. Jazani, and I. Ivanov, "Design and optimisation of compact RF energy harvesting device for smart applications," *Electron. Lett.*, vol. 50, no. 2, pp. 111–113, Jan. 2014.
[74] U. Olgun, J. L. Volakis, and C.-C. Chen, "Design of an efficient ambient WiFi energy harvesting system," *IET Microw., Antennas Propag.*, vol. 6, no. 11, pp. 1200–1206, Aug. 2012.
[75] U. Muncuk, K. Alemdar, J. D. Sarode, and K. R. Chowdhury, "Multiband ambient RF energy harvesting circuit design for enabling batteryless sensors and IoT," *IEEE Internet Things J.*, vol. 5, no. 4, pp. 2700–2714, Aug. 2018.
[76] S. Kim, R. Vyas, J. Bito, K. Niotaki, A. Collado, A. Georgiadis, and M. M. Tentzeris, "Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms," *Proc. IEEE*, vol. 102, no. 11, pp. 1649–1666, Nov. 2014.
[77] M. Pinuela, P. D. Mitcheson, and S. Lucyszyn, "Ambient RF energy harvesting in urban and semi-urban environments," *IEEE Trans. Microw. Theory Techn.*, vol. 61, no. 7, pp. 2715–2726, Jul. 2013.
[78] Ofcom, "Connected nations 2018 UK report," Ofcom, London, U.K., Dec. 2018.
[79] G. M. D. Araújo, A. R. Pinto, J. Kaiser, and L. B. Becker, "Genetic machine learning approach for link quality prediction in mobile wireless sensor networks," in *Cooperative Robots and Sensor Networks* (Studies in Computational Intelligence), A. Koubâa and A. Khelil, Eds. Berlin, Germany: Springer, 2014, pp. 1–18.
[80] T. Liu and A. E. Cerpa, "Data-driven link quality prediction using link features," *ACM Trans. Sensor Netw.*, vol. 10, no. 2, pp. 37:1–37:34, Jan. 2014.
[81] M. D and S. K, "Battery less thermo electric energy harvesting generator for implantable medical electronic devices," *Biomed. Res.*, vol. 27, pp. S150–S155, Jun. 2018.
[82] J. Sullivan and L. Gaines, "A review of battery life-cycle analysis: State of knowledge and critical needs," Argonne Nat. Lab., Tech. Rep. ANL/ESD/10-7, 2010.
[83] M. Aneke and M. Wang, "Energy storage technologies and real life applications—A state of the art review," *Appl. Energy*, vol. 179, pp. 350–377, Oct. 2016.
[84] C. Knight, J. Davidson, and S. Behrens, "Energy options for wireless sensor nodes," *Sensors*, vol. 8, no. 12, pp. 8037–8066, Dec. 2008.
[85] S. Kim and P. H. Chou, "Energy harvesting by sweeping voltage-escalated charging of a reconfigurable supercapacitor array," in *Proc. 17th IEEE/ACM Int. Symp. Low Power Electron. Design (ISLPED)*. Piscataway, NJ, USA: IEEE Press, Aug. 2011, pp. 235–240.

[86] J. Libich, J. Máca, J. Vondrák, O.Čech, and M. edlaříková, "Supercapacitors: Properties and applications," *J. Energy Storage*, vol. 17, pp. 224–227, Jun. 2018.
[87] C. Renner, J. Jessen, and V. Turau, "Lifetime prediction for supercapacitor-powered wireless sensor nodes," in *Proc. GI/ITG Fachgespräch Sensornetze (FGSN)*, Humburg, Germany, Aug. 2009, p. 4.
[88] A. Muzaffar, M. B. Ahamed, K. Deshmukh, and J. Thirumalai, "A review on recent advances in hybrid supercapacitors: Design, fabrication and applications," *Renew. Sustain. Energy Rev.*, vol. 101, pp. 123–145, Mar. 2019.
[89] B. Viswanathan, "Supercapacitors," in *Energy Sources*, B. Viswanathan, Ed. Amsterdam, The Netherlands: Elsevier, Jan. 2017, ch. 13, pp. 315–328.
[90] L. Zhou, C. Li, X. Liu, Y. Zhu, Y. Wu, and T. van Ree, "Metal oxides in supercapacitors," in *Metal Oxides in Energy Technologies*, Y. Wu, Ed. Amsterdam, The Netherlands: Elsevier, Jan. 2018, ch. 7, pp. 169–203.
[91] C. Bergonzini, D. Brunelli, and L. Benini, "Algorithms for harvested energy prediction in batteryless wireless sensor networks," in *Proc. 3rd Int. Workshop Adv. sensors Interfaces*, Jun. 2009, pp. 144–149.
[92] T. N. Le, A. Pegatoquet, O. Berder, O. Sentieys, and A. Carer, "Energy-neutral design framework for supercapacitor-based autonomous wireless sensor networks," *ACM J. Emerg. Technol. Comput. Syst.*, vol. 12, no. 2, pp. 1–21, Sep. 2015.
[93] C.-Y. Chen and P. H. Chou, "DuraCap: A supercapacitor-based, power-bootstrapping, maximum power point tracking energy-harvesting system," in *Proc. 16th ACM/IEEE Int. Symp. Low power Electron. Design (ISLPED)*, Austin, TX, USA. ACM, 2010, p. 313.
[94] A. Baranov, D. Spirjakin, S. Akbari, A. Somov, and R. Passerone, "POCO: 'Perpetual' operation of CO wireless sensor node with hybrid power supply," *Sens. Actuators A, Phys.*, vol. 238, pp. 112–121, Feb. 2016.
[95] S. Bandyopadhyay and A. P. Chandrakasan, "Platform architecture for solar, thermal, and vibration energy combining with MPPT and single inductor," *IEEE J. Solid-State Circuits*, vol. 47, no. 9, pp. 2199–2215, Sep. 2012.
[96] S. Wang, Z. L. Wang, and Y. Yang, "A one-structure-based hybridized nanogenerator for scavenging mechanical and thermal energies by triboelectric–piezoelectric–pyroelectric effects," *Adv. Mater.*, vol. 28, no. 15, pp. 2881–2887, Apr. 2016.
[97] P.-V. Mekikis, A. Antonopoulos, E. Kartsakli, L. Alonso, and C. Verikoukis, "Connectivity analysis in wireless-powered sensor networks with battery-less devices," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, Dec. 2016, pp. 1–6.
[98] K. Chi, Z. Chen, K. Zheng, Y.-H. Zhu, and J. Liu, "Energy provision minimization in wireless powered communication networks with network throughput demand: TDMA or NOMA?" *IEEE Trans. Commun.*, vol. 67, no. 9, pp. 6401–6414, Sep. 2019.
[99] X. Gao, D. Niyato, P. Wang, K. Yang, and J. An, "Contract design for time resource assignment and pricing in backscatter-assisted RF-powered networks," *IEEE Wireless Commun. Lett.*, vol. 9, no. 1, pp. 42–46, Jan. 2020.
[100] Z. Yu, K. Chi, P. Hu, Y.-H. Zhu, and X. Liu, "Energy provision minimization in wireless powered communication networks with node throughput requirement," *IEEE Trans. Veh. Technol.*, vol. 68, no. 7, pp. 7057–7070, Jul. 2019.
[101] H. Dai, Y. Liu, G. Chen, X. Wu, T. He, A. X. Liu, and Y. Zhao, "SCAPE: Safe charging with adjustable power," *IEEE/ACM Trans. Netw.*, vol. 26, no. 1, pp. 520–533, Feb. 2018.

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