

Review article

Innovations in energy harvesting: A survey of low-power technologies and their potential

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ABSTRACT

Nowadays low-power energy harvesting technologies represent the most sustainable and reliable alternative to traditional batteries that convert ambient energy from chemical reactions, vibrations, magnetic fields, and moisture into usable electrical energy for compact and self-sufficient electronic devices. However, a significant research gap into assessing the reliability, efficiency, and practical deployment of these technologies in various applications still exists. This article encompasses a comprehensive review of different types of electrochemical, kinetic, capacitive, inductive, piezoelectric, and moisture-based energy harvesting techniques. Each method is investigated with respect to their fundamental physical concepts. Thus, a critical discussion of the scientific evolution and functional mechanisms of each technology along with their applications and output characteristics is presented. Based on output characteristics, applications of these energy harvesting techniques in portable electronics, medical implants, wireless sensor networks, industrial monitoring systems, and smart infrastructure are examined in detail. Key challenges, including limited energy conversion efficiency, material constraints, and economic feasibility, are addressed to highlight current limitations. By identifying future research directions and emerging trends, this study highlights the potential of low-power energy harvesting technologies to provide sustainable and reliable energy solutions for several low-power electronics.

1. Introduction

Energy harvesting is the process of capturing and storing energy from various sources, such as sunlight and vibrations, to provide power to small electronic devices. These techniques have been useful among various sectors, such as the biomedical devices, wearable technologies, and Internet of Things (IoT's) (Shuvo et al., 2022). For example, the IoT's are typically set in places far away from cities or difficult to reach, wherein manual replacement of batteries would be time-consuming and costly (Gomathy et al., 2022). By harvesting energy from vibrations, light, heat, moisture or electromagnetic radiations, these devices can operate for several years without any maintenance (Kalyani et al., 2015). Recent investigations have indicated the dramatic increase of IoT deployments while identifying energy harvesting techniques as the key driving element behind such development, specifically within resource-constrained locations (Laturkar and Laturkar, 2024).

Nomenclature

IoT's Internet of Things KEH Kinetic energy harvesting

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EHS	Energy harvesters	AI	Artificial intelligence
ECEH	Electrochemical energy harvesting	EMEH	Electromagnetic energy harvesting
EBFCs	Enzymatic biofuel cells	MSEH	Magnetostriction energy harvesting
RFBS	Redox flow batteries	CEH	Capacitive energy harvesting
SOFCs	Solid oxide fuel cells	MEMS	Microelectromechanical system
DMFCs	Direct methanol fuel cells	TPMS	Tire pressure monitoring systems
EHS	Energy harvesters	WSNs	Wireless sensor networks
AMBFCs	Alkaline membrane-based fuel cells	IEH	Inductive energy harvesting
SOECs	Solid oxide electrolysis cells	PEEH	Piezoelectric energy harvesting
PEMS	Proton exchange membranes	PVDF	Polyvinylidene fluoride
MEAs	Membrane electrode assemblies	PZT	Lead zirconate titanate
MFCs	Microbial fuel cells	SPEEHs	Stacked piezoelectric energy harvesters

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TENGs	Triboelectric nanogenerators	CBEHs	Cantilever beam energy harvesters
ILs	ionic liquids	AHCs	Asymmetric hygroscopic configurations
IMDs	Implantable medical devices	MEGs	Moisture-based electric nanogenerators

In health sectors, the use of harvester technology has made it possible to introduce medical implants and wearable health devices like bio-sensors, pacemakers as well as drug delivery systems that can attain power from biochemical reactions, body heat and muscle and organ movements (Ghazizadeh et al., 2024; Sohail et al., 2024). The recent advances in nano-thermoelectric materials have paved the way for designing more efficient thermoelectric devices for medical implants (Baskaran and Rajasekar, 2024). Now, these devices have the possibility of using small temperature gradients to extract more power, thereby increasing the feasibility of using thermoelectric devices to power medical implants (Sohail et al., 2024). Furthermore, wearable electronic devices are increasingly adopted in health monitoring and fitness applications; hence, they require a constant power supply for real-time health tracking (Canali et al., 2022).

Energy harvesting makes wearable technology very effective, especially when there is an increased demand for light, small and easy-to-use devices (Ali et al., 2023). Energy collected from body movement or environmental sources can be used by fitness trackers, smartwatches, and even smart textiles, leading to reduced reliance on traditional batteries as well as an enhanced user-friendly experience (Henriksen et al., 2018). Shoe insoles, for instance, exploit piezoelectric materials to harvest energy from walking or running (Hou et al., 2013). This power can then be used in many electronic devices, such as smartwatches and heart rate monitors (Ahmed et al., 2023; Deng et al., 2023). The adoption of wearables continues to grow due to novel developments in flexible piezoelectric materials associated with them (Wu et al., 2021a). These adapt to different shapes and surfaces, therefore finding use across various applications (Das Mahapatra et al., 2021). Hence, these technological advancements, in addition to improving user convenience, enhance product life while also reducing e-waste production and energy harvesting is consistent with the broader commitment to sustainability by helping to reduce waste from disposable batteries and advocating green energy processes (Ahmed et al., 2024). Substantial numbers of sensors are used in monitoring the environment together with urban conditions in smart cities (Montori et al., 2018), and energy harvesting can be used to ensure that the sensors remain powered up without burdening the environment through the excessive use of batteries (Dziadak et al., 2023). There are significant cost savings and environmental benefits that can come as a result of using autonomous sensors in smart cities because of decreased maintenance needs and lack of battery replacement (Javed et al., 2022).

Furthermore, the combination of renewable energy sources and power harvesting systems within urban areas enhances the move towards more energy-efficient and sustainable cities (Salama and Al-Turjman, 2023). Energy harvesting is also crucial in industrial contexts. For instance, vibration energy harvesting from machines can be used to power condition-monitoring sensors, ensuring that industrial systems operate without regular human interventions for power management (Arshad Mehmood, 2023). These systems are especially useful in predictive maintenance applications where energy-self-sufficient sensors constantly monitor machine health and forecast breakdowns, thereby minimizing downtime and increasing productivity. Industrial systems contain multiple sources of energy like wasted heat, vibrations, and even fluid flow, which can be tapped to power self-sufficient sensor networks and thus enable Industry 4. objectives (Kalsoom et al., 2020). Continuous expansion of the potential applications of this technology has recently occurred by virtue of the development of energy-harvesting materials and techniques. For example, the efficiency of energy capture

from ambient sources like electromagnetic fields and vibrations has been improved through the utilization of nano-materials and meta-materials (Góra and Lopato, 2023). Also, in energy harvesters, materials based on graphene, known for excellent conduction and flexibility, are being researched; hence, there would be a significant enhancement in power density as well as durability (Li et al., 2022a). The hybrids form among energy harvesters that incorporate various kinds of energies, for instance, solar and thermal have started to gain popularity because they offer more constant output power even in varying atmospheric conditions (Mohammadnia et al., 2020). There are various potential uses of energy harvesting technologies, some of them are provided in Fig. 1.

Energy harvesters have potential for providing power to monitoring sensors; however, current studies require elevation in the real assessment of environmental, social and economic feasibility (Gudlaugsson et al., 2024). Energy harvesting methods can be vital for expanding the life of sensors and lowering maintenance costs in systems pertaining to the IoTs (Sanislav et al., 2021). The power management system (PMS) developed in (Srivastava et al., 2021) is capable of harvesting and storing such low powers from constructed wetland-microbial fuel cells and thereby making the technology highly efficient and self-sufficient in pollutant treatment processes. Low power energy harvesting methods such as electrochemical (e.g., microbial fuel cells), kinetic, capacitive, inductive, piezoelectric, and moisture-based techniques play a significant role in advancing several Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Electrochemical energy harvesting (ECEH), as demonstrated by constructed wetland-microbial fuel cells, enables self-sustaining water treatment processes, reducing reliance on external power sources and supporting environmental sustainability and resource efficiency, which are crucial for urban infrastructure and clean water management (Srivastava et al., 2021). Kinetic and inductive energy harvesting offer clean energy solutions for transportation, potentially reducing carbon emissions and supporting sustainable urban mobility (Gholikhani et al., 2019). These technologies collectively contribute to environmental protection by reducing greenhouse gas emissions and promoting the use of renewable resources, aligning with the broader objectives of SDG 13 and SDG 11 by mitigating harmful environmental occurrences in urban areas and fostering resilient infrastructure (Kazancoglu et al., 2023). Socio-economically, the adoption of these energy harvesting methods can drive economic prosperity by enabling new industries, reducing energy costs, and supporting technological innovation, though there may be disparities in benefits between developed and developing economies due to resource demands and trade dynamics (Peng et al., 2023). Thus, integrating these low power energy harvesting technologies into urban and industrial systems supports a transition to a low-carbon economy, enhances energy access, and promotes sustainable development across multiple SDGs (Kazancoglu et al., 2023; Peng et al., 2023; Srivastava et al., 2021; Gholikhani et al., 2019).

2. Literature review

2.1. Electrochemical energy harvesting

Electrochemical energy harvesting (ECEH) is a mechanism whereby the direct conversion of chemical energy into electric energy is carried out by means of electrochemical reactions, which are usually based on redox processes and this technique uses galvanic cells or fuel cells as its foundation, where oxidation-reduction reactions take place, leading to the generation of electrons that can actually serve as electrical power (Hasan et al., 2021a). Different types of ECEH are the types introduced using photovoltaic and other such effects, enzymatic biofuel cells (EBFCs), redox flow batteries (RFBs), microbial energy harvesting, self-charging batteries, Hydrogen-based electrochemical cells, thermo-galvanic cells, solid oxide fuel cells (SOFCs), and direct

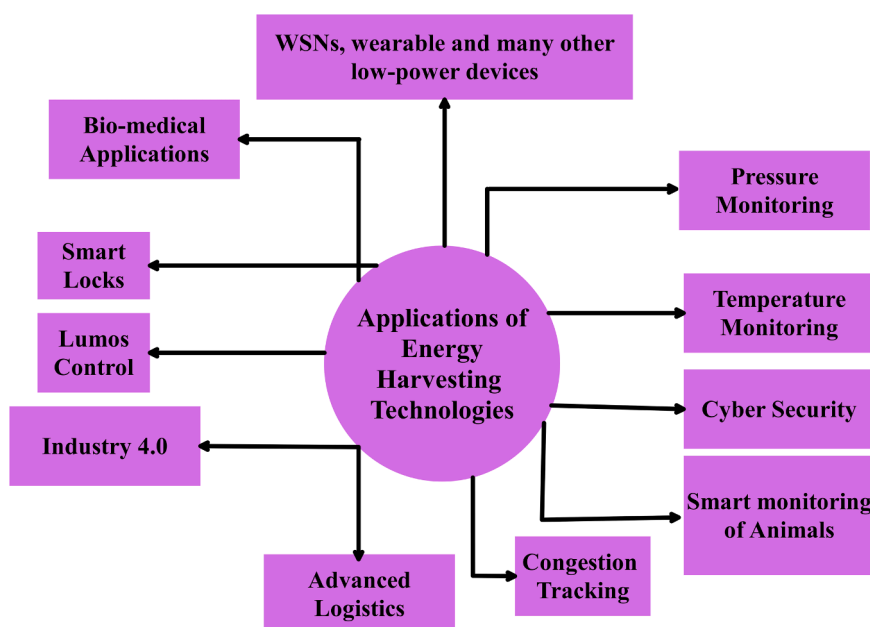


Fig. 1. Various potential uses for energy harvesting technologies.

methanol fuel cells (DMFCs), ionic liquid-based ECEHs and hybrid ones. The EBFCs are considered emerging energy harvesters (EHs) in the ECEH technology, which can generate electrical power from biological substrates by capturing biochemical energy. The two primary factors determining the efficiency of these cells are the number of electrons gained per fuel molecule and the efficiency of electron exchange between electrode and enzyme (Kabir et al., 2022). Since these EBFCs can produce electric power from lactate and glucose, therefore, they are highly adapted for providing power to implantable medical devices (IMDs) (Huang et al., 2022).

The use of commercially available flat conductive polymers would potentially make enzyme immobilization-based EBFCs more durable and scalable, which in turn can improve their economic feasibility in commercial applications (Pelosi et al., 2022). In short, EBFCs can generate electric power from bio-catalytic reactions occurring naturally in the human body, making them suitable for several wearable devices and biosensors (Barelli et al., 2021). The RFBs present a promising alternative for electrochemical energy scavenging, mostly in the scope of grid-related energy storage and can be categorized into aqueous RFBs (Emmett and Roberts, 2021) and non-aqueous RFBs (Davis et al., 2023). The hydrogen-based electrochemical cells provide an efficient and sustainable way to generate and utilize hydrogen energy. The alkaline membrane-based fuel cells (AMBFCs), solid oxide electrolysis cells (SOECs) and photoelectrochemical cells are different types of hydrogen-based electrochemical cells. Thermo-galvanic cells involve the use of redox reactions taking place at electrodes of different temperatures, making them efficient in harnessing the waste heat. New techniques in this field, such as photo-catalytically boosted thermo-galvanic cells, have been designed, making it possible for them to convert heat into electricity as well as improve hydrogen production alongside electricity generation (Yu and Duan, 2023). Non-precious electrocatalysts can be used in the AMBFCs for redox reactions, but the alkaline media slows down the speed of hydrogen oxidation reaction, and further research is required to boost the durability and performance (Yang et al., 2022a). At intermediate temperatures, green hydrogen can be effectively produced using SOECs along with achieving faradaic efficiencies and high current densities (Kim et al., 2023).

Significant solar-to-hydrogen energy conversion efficiencies have been achieved by photoelectrochemical cells, and in order to increase charge separation and decrease recombination that results in effective

solar fuel production, these types of systems imitate the natural photosynthesis process (Ye et al., 2021). Membrane-less hydrogen peroxide (H_2O_2) fuel cells can efficiently generate green energy into electrical energy, water, and oxygen, and novel electrode designs make these cells an option for sustainable energy applications since they have simpler fabrication and quick reaction kinetics and enable these FCs to be commercially viable, it is necessary to have improvements in non-precious metal catalysts, simpler fabrication methods, and mechanisms for transferring charges effectively (Zhu et al., 2023). The advanced fabrication techniques (Zouridi et al., 2022) and new materials for cathode, anode and electrolyte for SOFCs are making them highly adaptable for portable devices (Zhang et al., 2022a). The chemical energy of methanol can be converted to electrical energy using DMFCs, but there are challenges related to performance and catalyst development; like the noble metal platinum (Pt) was being used as a catalyst in DMFCs, making these cells very expensive for commercial purpose, therefore, nowadays there is a focus on designing Pt-free or hybrid materials to minimize the cost and maintain excellent catalytic performance (de Sá et al., 2022). Therefore, non-noble elements like carbon-based catalysts are getting significant attraction for DMFCs (Yuda and Kumar, 2022). The DMFCs can be single-chamber DMFCs, micro-DMFCs, or active and passive DMFCs. The single chamber DMFCs use a membrane-less setup incorporating a Pt-free cathode and an electron acceptor and exhibit enhanced performance metrics compared to the conventional Pt-based DMFCs (Thimmappa et al., 2017). The micro-DMFCs consist of several key components like collectors, diffusion layers, catalytic layers, proton exchange membranes (PEMs), membrane electrode assemblies (MEAs) and microflow fluid plates and the performance and efficiency of these types of FCs are mainly influenced by all these components (Chen et al., 2017). The primary challenge in micro-DMFCs is swelling of the membrane and the issues of removing evolved CO_2 in the anode side and reducing water flooding in the cathode side of the micro-DMFCs, but these problems can be solved using the latest techniques of material fabrications and polymer modifications resulting in the enhanced performance (Sundarrajan et al., 2012). The primary challenges faced in passive DMFCs are in the reduction of methanol crossover and maximizing cathodic water removal for optimal performance (Abdelkareem et al., 2019).

Stress-voltage coupling in electrochemically alloyed electrodes can be utilized like lithium-alloyed Silicon electrodes-fabricated devices

producing electrical current by means of asymmetric stresses induced by bending, which are responsible for the lithium-ion flow between the electrodes (Kim et al., 2016; Xue et al., 2020). The piezo-electrochemical effect in Li-intercalated carbon fibers is able to convert the change of mechanical energy into electrical energy (Jacques et al., 2015). Thermo-cells can convert wasted and low-grade heat energy into electrical energy by employing surface alterations in these cells with carbon fiber electrodes, and potassium ferri-/ferrocyanide redox electrolytes help in achieving increased power output and enhanced efficiency (Artyukhov et al., 2021). Different effects, including photo-voltaic, flexoelectric, triboelectric, piezoelectric and pyroelectric effects, convert various forms of ambient energy into useful electrical energy using different electrochemical cells (Zhang et al., 2017). The most common application areas for ECEHs include microbial fuel cells (MFCs) that use natural processes to produce electricity from waste materials in soil, and this approach involves using microorganisms that can degrade organic matter, releasing their electrons for use as electrical power (Dziegielowski et al., 2021); hence, it becomes one method through which we can generate power out of garbage. In these systems, microorganisms consume organic sources, releasing electrons that are transferred to an electrode to generate electricity (Pandya et al., 2024), and it is possible to harvest from such systems at about microwatts and milliwatts per square meter of electrode area (Bijimol et al., 2022; Ghan-grekar and Shinde, 2007). Despite their power output, MFCs are highly advantageous because they convert waste materials into useful energy (Dupont et al., 2017) and can be used for wastewater treatment applications (Siddiqui et al., 2023). Thus, MFCs can be used for obtaining green energy and clean water (Guo et al., 2020; Malik et al., 2023). Mechanisms for charge generation like pyro-electric (temperature cycles), thermo-electric (temperature gradients), piezo-electric (strain), triboelectric (motion), flexo-electric (strain gradient) and photovoltaic (solar excitation) which are used in controlling electro-chemical

reactions and external devices are typically used with thermoelectric and triboelectric approaches, but pyroelectric, piezoelectric or photo-voltaic mechanisms can employ external devices as well as particulates directly interacting with electrolyte (Zhang et al., 2017); as demonstrated in Fig. 2.

Air self-charging like zinc-based batteries and light-assisted charging like triboelectric nanogenerators (TENGs) is also a promising technology in the ECEH and are suitable for applications demanding excellent reusability and high energy density and IoT applications, respectively (Liu et al., 2021a; Mi et al., 2022). At moderate temperatures ranging from 100°C to 200°C, ionic liquids (ILs) based ECEHs are suitable for energy harvesting because they have high thermal and electrochemical stability, non-flammability and non-volatility (Liu and Yu, 2019; Abraham et al., 2013). Although iono-gels are promising, they require improved mechanical strength and an understanding of their interface for possible use in sensor and energy harvesting technologies (Suen et al., 2022). Electrochemical capacitors are another importance of ECEH because they store energy electrostatic form, hence providing a quick charge-discharge cycle as well as high power density (Kumar et al., 2019). Applications that require wide temperature tolerance and bursts of energy, like backup power systems or regenerative braking systems of electric vehicles, are particularly well served by super-capacitors (Bu et al., 2020; Huang et al., 2019). Some of the commercial applications of ECEH are for small self-powered sensors and low-power portable electronic devices (Zhang et al., 2017; Bu et al., 2020), wearable devices (Kim et al., 2016), water desalination and splitting (Cao et al., 2016). Furthermore, IMDs utilize ECEH systems to obtain continuous power by converting energy from biochemical processes in the body (Mariello, 2022). A good example is when one considers that there are glucose fuel cells using glucose oxidation occurring within body fluids for energy production, hence serving adequately in low-energy biomedical implants (Jiang et al., 2020a; Rapoport et al.,

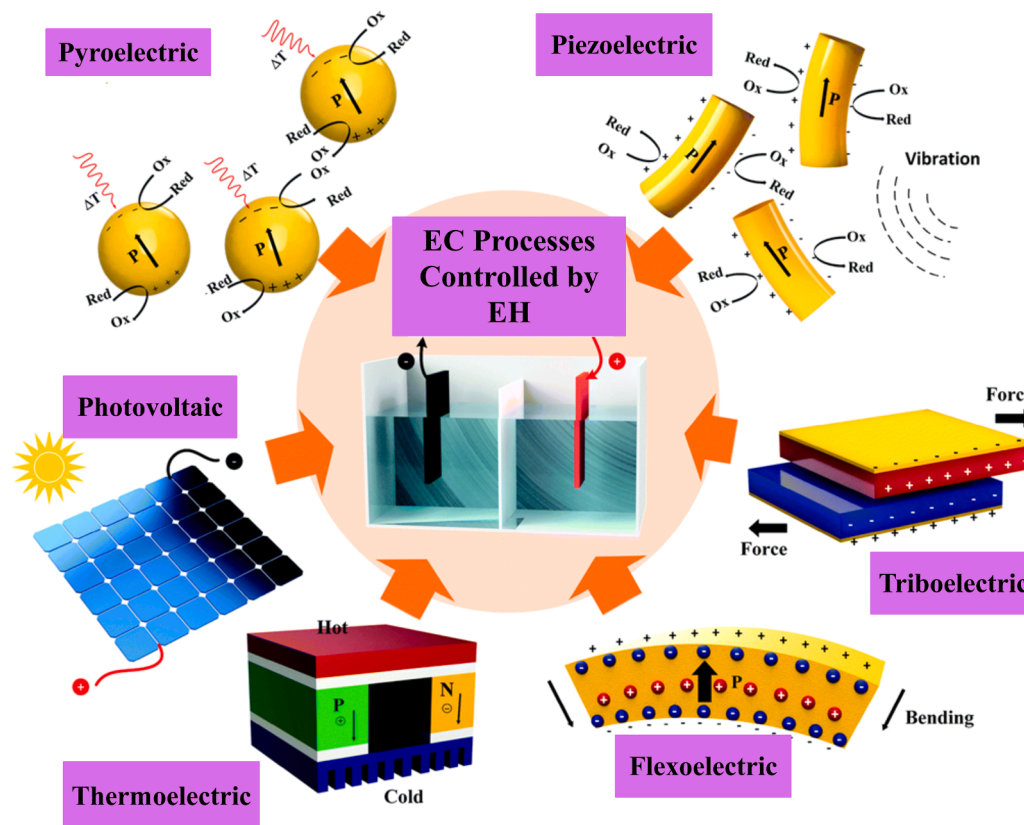


Fig. 2. Charge generation mechanisms for controlling electrochemical reactions in ECEH. Reproduced from Ref (Zhang et al., 2017). of the Royal Society of Chemistry under the Creative Commons Attribution 3.0 unported license.

2012).

Recent progress in materials science advancements has increased the effectiveness and power of chemical energy generation systems from the electrochemical perspective. Much higher electrochemical reaction rates leading to higher energy outputs are seen in nanometer-sized materials like graphite clusters and carbon nano-tubes than in other materials due to their high surface areas (Hu et al., 2015; Zhang et al., 2016). Graphene's remarkable electrically conductive properties coupled with its huge surface area have made it facilitate quicker electron transfer, hence enhancing energy capture on the overall basis (Chen et al., 2019; Tang et al., 2015). There is much ongoing research to introduce bio-compatible materials that can be used for prolonged periods in human bodies, enabling an extended life of IMDs (Vijayakanth et al., 2023; Sobianin et al., 2022; Jeong, 2020). In addition, cost-effective forms of nano-catalysts, such as platinum particles, are being investigated to reduce costs while at the same time keeping high levels of catalytic activity (Lopez and Ustarroz, 2021). Despite these recent achievements, there are difficulties facing ECEH, including the low energy conversion efficiency and the high cost of electrode materials (Burmistrov et al., 2022; Liu et al., 2019; Cui et al., 2020). Currently, the focal point of research is not to rely on noble metals for electrode synthesis but on designing electrodes more efficiently, refining the design of electrochemical cells and discovering better procedures and techniques for electron transfer so as to optimize energy retrieval (Zamudio-García et al., 2023; Xu et al., 2016; Lee et al., 2019).

The sustainability and reliability of electrochemical energy harvesting techniques are linked with their efficiency, scalability, material choices and adaptability to real-world conditions. In some cases, electrochemical harvesters, especially those with two-phase immiscible liquid electrolytes have shown stable current output through multiple cycles and hence no short-term degradation provided the environment is kept controlled (Lee et al., 2024a). While innumerable advances have enabled the increase in the efficiency and durability of solar-to-fuel setups, further improvements in performances could be achieved through advanced electrochemical catalyst design and manufacturing technologies and by improving the overall design of these systems (Li et al., 2024a). For instance, Electrochemical impedance spectroscopy is a useful method of performance analysis of supercapacitors, assisting the development of enhanced energy harvesting and storage systems (Perdana et al., 2024). Triple-network hydrogels are advanced materials that increase ionic conductivity and mechanical stability to enable reliable and continuous energy conversion for low power devices. Under mechanical stress, flexible Na_xSb alloy-based electrochemical-mechanical strain energy harvesters provide tunable and repeatable voltage responses, which denotes their reliable operation under repeated use (Lei et al., 2024). The reliability of such energy harvesting techniques can be tested by novel techniques like Gaidai reliability method to ensure safer as well as reliable design of the device. This method can be used to predict failure/damage probabilities due to circumstances in the dynamic, high-dimensional energy-harvesting systems, even with only a limited set of measurements acquired from experiments (Gaidai et al., 2024).

The reliability of different types of capacitive energy harvesting techniques depends on their design, the materials used, and the specific application. The variable capacitance harvesters show effective performance even with miniaturized inductors and can also harvest energy from physical movements such as low-speed mechanical movement, which makes them suitable for implantable devices. Several green and abundant materials can be used in electrochemical energy harvesting, instead of relying on rare toxic and non-recyclable substances, and the use of these materials enables their massive scalability at low cost and easy manufacturability with the least of environmental risks (Chen et al., 2024a; Xuan et al., 2024; Jiao et al., 2024). Thus, electrochemical harvesting technology can change mechanical motion, low-grade waste heat, humidity, and solar energy into useable electrical energy supporting carbon neutrality (Seo et al., 2023; Heubner et al., 2022; Li et al.,

2024a).

The electrochemical energy harvester systems produce varied energy levels depending on the involved technology and application as summarized in Table 1.

3. Kinetic energy harvesting

The conversion of mechanical energy into electrical energy is termed kinetic energy harvesting (KEH), which refers to the production of electric power from motion and vibrations (Yang et al., 2024a). Various methods and strategies are used to improve the efficiency of KEH systems. Essentially, the KEH process mainly relies on transducers, which are used to convert kinetic movement into liable forms of electrical power through mechanisms like electromagnetic induction,

Table 1
Output characteristics and applications of ECEH techniques.

EH Techniques	Power output/ Energy density	Applications	References
Piezo-ECEH	1 $\mu\text{W/g}$	–	(Jacques et al., 2025)
Carbon nanotube aerogel-based thermo-ECEH	6.6 W m^{-2}	–	(Im et al., 2016)
Mechanical EHs in electrochemical cells	0.90–143.60 $\mu\text{W cm}^{-2}$	Low-frequency human activities	(Xue et al., 2020)
Surface-modified Carbon fiber-based thermo-electrochemical EHs	25.2 mW m^{-2}	Portable devices and energy storage	(Artyukhov et al., 2021)
Pt-free thermo-cells	12 W m^{-2}	–	(Zhang et al., 2017b)
Thermally regenerative electrochemically cycled flow cells	9 $\mu\text{W cm}^{-2}$	–	(Qian et al., 2021)
TENG with MXene-based micro-supercapacitors	7.8 $\mu\text{W cm}^{-2}$	Wearable devices	(Jiang et al., 2018)
CoNi_2S_4 micro-pseudocapacitors-based EHs	1163 mW cm^{-3}	–	(Kurra et al., 2015)
Bilayer Hydrogel Electricity Generator ECEH	72.2 mW m^{-2}	–	(Chen et al., 2024a)
Thermo-electrochemical cells-based EHs	140 mW m^{-2}	–	(Shpekina et al., 2019)
Energy harvesting based on EBFCs	1–1.3 mW cm^{-2}	–	(Zebda et al., 2011)
Textile supercapacitors for ECEH	18.9 $\mu\text{Wh cm}^{-2}$	Smart wearable devices	(Anon, 2025)
Biofuel cell-based EHs	9.64–53 $\mu\text{W cm}^{-2}$	Implantable self-powered devices	(Wan et al., 2020)
Energy harvesting based on EBFCs utilizing cogel electrodes	0.19 mW cm^{-2}	Bio-sensing	(Campbell et al., 2015)
Energy harvesting based on EBFCs	320 $\mu\text{W cm}^{-2}$	Biosensors and bioelectronics	(Li et al., 2021a)
Energy harvesting based on RFBS	129 mW cm^{-2}	Non-aqueous RFBS	(McGrath et al., 2024)
Energy harvesting based on RFBS	86.2 mW cm^{-2}	polysulfide/iodide RFBS	(Ma et al., 2019)
Supercapacitor based EHs	1922 $\mu\text{Wh cm}^{-2}$	Higher power densities	(Ojha et al., 2021)
Fuel cell-based ECEH	80 mW cm^{-2}	Hydrogen production	(Cai et al., 2018)
SOCs based ECEH	847 mW cm^{-2}	Higher power outputs	(Hou et al., 2021)
DMFCs based ECEH	11 mW cm^{-2}	Portable devices	(Shimizu et al., 2004)
DMFCs based ECEH	14.3 mW cm^{-2}	Portable electronic devices, MEMS	(Yen et al., 2003)
H_2O_2 fuel cells	2.84 mW cm^{-2}	Portable devices	(Kamboj et al., 2024)
TENGs based EHs	50 mW cm^{-2}	Wearable & biomedical devices	(Hasan et al., 2021b)

piezoelectric or electrostatic coupling (Hong et al., 2024; Mudiyanse-lage, 2024). The KEH functions differently, depending on the type of the transducer (Xia et al., 2024), and electromagnetic harvesters are especially helpful in such scenarios. If a magnet moves close or away from a wire coil, electromagnetic transducers operate on the rule of Faraday's law of electromagnetic induction, generating an electrical voltage across the wire coil (Lee et al., 2024b). This method is widely used in applications such as bicycle dynamos for lights and selected wearable devices that require continuous and assured movement (Zhao et al., 2018). Energy from systems of this kind usually amounts to milliwatts making them appropriate for LEDs and wireless sensors in terms of their power consumption (Toyabur Rahman et al., 2020).

When mechanical stress or strain is applied, then piezoelectric materials are commonly used for generating energy. Lead zirconate titanate and polyvinylidene fluoride (PVDF) are among the materials that are highly sensitive to vibrations, and they can produce electric charge from deformation due to mechanical forces (Das Mahapatra et al., 2021; Mutsuda et al., 2017; Maiwa, 2016). The piezoelectric energy harvesters are useful in transforming vibrational energy from machines and human activities, among many other dynamic environments, into electrical energy (Khan and Ali, 2019). These devices can embed piezoelectric transducers in their soles for harvesting the energy produced during walking or running, which may power wearable electronic devices like pedometers, and the energy produced can also be used to charge a small battery for storage (Xin et al., 2016; Kumar et al., 2020). It enables self-powered devices in the domain of wearable electronics, which do not require frequent recharging or changing of batteries (Mayer et al., 2021). The overview of KEH from human motion and its application is shown in Fig. 3.

Electromagnetic energy harvesting (EMEH) is best deployed when there is constant rotation or movement, as in machinery or automobiles. The approach presented in (POROBIC and GONTEAN, 2019) centers on linear magnetic generators made for deployment in high-amplitude, low-frequency vibratory environments. Triboelectric nanogenerators (TEGS) harvest electricity from wind, raindrops and human motion using the contact electrification and electrostatic induction phenomena, and TEGS are highly adopted for wearable devices because of their capability to obtain high-entropy kinetic energies (Gang et al., 2021). The wearable devices can use body movement's energy as their source of power, thus increasing operational life without traditional power source

needs (Xu et al., 2021; Wang et al., 2022b). Similarly, smart textiles are now integrating KEH devices that charge sensors or communication modules by the motion of the body, thus making advancements towards making wearable technologies more functional and independent, and the energy harvested can also be utilized for sensor networks (Gao et al., 2022). Mechanical modulation-based energy harvesting techniques increase the efficiency of energy harvesters using excitation-type, force/-motion amplification pathways or frequency up-conversion, and in turn, improving their effectiveness and lifespan (Zou et al., 2019). Bi-stable oscillators are capable of harvesting energy from broad-band and low-frequency vibrational environments (Fu and Yeatman, 2019).

Electrochemical KEH utilizes selective sweeping of ions in hybrid cells and is well-suited to low-frequency random kinetics like those caused by environmental movements and human activities (Jung et al., 2020). Magnetostriction energy harvesting (MSEH) is also an efficient and adaptable way of transforming ambient structural vibrations into electrical power (Liu et al., 2023; Deng and Dapino, 2017). MSEH uses finite element modelling (Backman et al., 2019) and pre-stress and biased magnetic field-based optimization techniques (Liu et al., 2023; Wang et al., 2024). Advances in nano-materials include nanowires and carbon nano-tubes; they give new hope for improving kinetic energy harvesters because they can convert mechanical power into electrical power much more efficiently (Chatterjee et al., 2020). Some researchers are working on hybrid systems where both piezoelectric and electromagnetic harvesters are combined in an effort to ensure constant generation of power over time (Wang et al., 2019; Zheng et al., 2022). For instance, piezoelectric-electronic hybrids can operate at much higher resonance than their mechanical vibration-driven counterparts selected by wind speed considerations (Gao et al., 2023). Different types of such hybrid systems could provide a solution for wearables and industrial applications due to their ability to adjust dynamically over broad ranges (He et al., 2018; Ren et al., 2020; Jung et al., 2020; Jiang et al., 2023).

The reliability of KEH systems is the main concern because varying input conditions and the durability of materials can affect their performance. Recent advancements, including the development of the adaptive kinetic energy reallocation (AKER) mechanism, have managed to address these challenges and provide a more stable output power across excitation frequencies, reducing the power fluctuation by an amount of almost 46 %, and increasing the operational bandwidth of such wearable harvesters (Xia et al., 2024). In railway and urban parking



Fig. 3. Outline of the human motion-based energy harvesting and WSN application. Reproduced from Ref (Wang et al., 2022a). with permissions from ACS Applied Energy Materials, vol. 5, no. 6, pp. 6601–6615, Jun. 2022. © 2022 American Chemical Society.

applications, KEH devices have been tested both through simulation and experimental, yielding high conversion efficiencies and practical levels of output, thus supporting their very viability as self-powered infrastructure (Li et al., 2022a; Wu et al., 2021b). In land transportation, several KEH systems are in place to recover the kinetic energy dissipated by trains, vehicles, and parking infrastructures. In these setups, speed bump modules, hybrid electromagnetic-piezoelectric conversion, and vibration rectification are used as mechanisms to potentially convert kinetic energy to electricity more efficiently, with a demonstrated efficiency of up to 68.41 % and enough power is generated for running sensors, displays, and illumination in real applications (Li et al., 2022a; Wu et al., 2021b; Tang et al., 2022; Pan et al., 2021).

KEH finds its niche in novel fields of energy harvesting, in which accurate heart-motion analyses have revealed major opportunities for powering implantable devices. The possibility of energy harvesting from cardiac motion depends on correct positioning and accurate movement patterns so that customized harvester designs should be developed to enhance energy output (Sokolov et al., 2020; Margielewicz et al., 2024). The development of nonlinear and actively synthesized KEH systems has widened the spectrum of explicable motions (Khazaei et al., 2024). Additionally, the development of nonlinear and actively synthesized KEH systems has expanded the range of usable motion types, making it possible to harvest energy from arbitrary and non-harmonic acceleration waveforms, such as those produced by human movement (Sokolov et al., 2020), (Margielewicz et al., 2024). Continued research is recommended to address these gaps and further enhance the reliability and potential of KEH systems for widespread adoption in self-powered applications (Pan et al., 2021). The KEHs produce varied energy levels depending on the

involved technology and application as summarized in Table 2.

4. Capacitive energy harvesting

In the capacitive energy harvesting (CEH) procedure, the mechanical power is converted into electrical power, and this is achieved through the use of variable capacitance theory. Typically, there are two plates in this process where one plate or both move due to an external force, which results in changed capacitance, thereby giving rise to electricity generation (Oh et al., 2022; Vallem et al., 2021) and is best achieved by capacitive harvesters that can exploit small and repetitive movements, thus presenting an excellent suitability for microelectromechanical systems (MEMS) as well as other devices that have low operation power (Bodduluri et al., 2022). CEH is as simple as not including magnetic materials, a characteristic that makes it so unique among other techniques, allowing for its miniaturization while integrating it into different electronic systems, especially those for which lightweight and compact power sources are needed (Li et al., 2020; Zhang et al., 2019). Using various configurations, like parallel-plate capacitors, interdigitated comb structures and variable capacitors with moving dielectric materials, can result in capacitive energy harvesting from electrostatic fields (Azizi et al., 2017). These configurations utilize the charge separation principle and mechanical movements necessary for affecting capacitance to function (Yu and Ma, 2020). In the parallel-plate configurations, one of its plates is stationary while another moves, changing their distance and hence altering capacity and generating electrical charges (Feng et al., 2018). The MEMS devices often employ interdigitated comb structures because they provide a way of achieving both larger relative displacements and enhanced changes in capacitance during operation, leading to more power output (Zhang and Seshia, 2023). This process is fairly simple to perform when compared to others because it can employ well-known semiconductor fabrication techniques as a result, are advantageous for use in conjunction with MEMS devices and other microelectronics systems (Lin et al., 2013). Moreover, the CEH also includes obtaining power from the surrounding electric fields of power lines without making a direct physical contact with them and it is achieved through capacitive coupling effect to create a capacitor between the power line and the energy harvester and the harvested power is then used for several applications including online monitoring devices (Srilaket et al., 2024; Zhou et al., 2022a; Gulati et al., 2018; Li et al., 2023). Different types of EHs can be used to harvest energy from power lines as described in Fig. 4.

In high electromagnetic noise environments like in industrial automation, CEHs have a potential for automotive systems where it is necessary to have reliable alternate power supplies (Jamil et al., 2023). These harvesters typically provide a power range between nanowatts and micro watts depending on the amount of mechanical excitation and device configuration (Bodduluri et al., 2022). They are widely used for supplying power to wearable electronic devices (Lv et al., 2021). CEHs can be integrated into fabrics so that they can produce energy-generating clothes that could feed the integrated electronic components such as temperature sensors or LEDs in movements alone (Cong et al., 2020; Chen et al., 2020). The automotive industry has adopted the use of CEH systems especially for tire pressure monitoring systems (TPMS) (Bowen and Arafa, 2015). The mechanical deformation on the tire is used in generating power for the sensors that monitor tire pressure in these systems (Germer et al., 2022). Advances in materials and fabrication processes have increased performance levels for CEHs (Hemant and Kandasubramanian, 2020). They have achieved higher energy densities as well as improved durability during repetitive mechanical stress via the utilization of advanced dielectric materials, including polymer composites, and such dielectric materials are typically incorporated with nanoparticles or other additives, thereby generating higher dielectric constants, leading to higher energy storage capacities and improved energy harvesting efficiencies (Guo et al., 2019). Also, microfabrication technologies have progressed so much in

Table 2
Output characteristics and applications of KEH techniques.

EH Techniques	Power density/ Mean power/ Energy density	Applications	References
Inertial EHs	454.82 $\mu\text{W}/\text{cm}^3$	Wearable devices	(Cai and Liao, 2021a)
Piezoelectric MEMS-EHs	33 $\mu\text{W}/\text{cm}^3$		(Liu et al., 2011)
Flexible KEHs	22 $\mu\text{W}/\text{cm}^3$	IMDs and wearable electronics	(Chiu et al., 2015)
KEHs	8.3 $\mu\text{W}/\text{cm}^2$	WSN	(Xu et al., 2023)
EM-KEHs	1.6 mW/cm^3	self-powered devices	(Peng et al., 2021)
Piezo-electromagnetic coupling based KEH	11.35 $\mu\text{W}/\text{cm}^3$		(Shi et al., 2020)
EM- EHs	346.61 $\mu\text{W}/\text{cm}^3$	Smartwatches, wristband	(Cai and Liao, 2021b)
CTLPH based KEH	17.31 μW	IMDs	(Ghodsi et al., 2023)
MCEEH-based KEH (Magnetically coupled electromagnetic EHs)	26 mW	Wristwatches, sensors, hearing aids	(Li et al., 2021b)
Hybrid EHs on KEH	8 $\mu\text{W cm}^{-3}$	Low-power wearable devices	(Halim et al., 2019)
KEHs	30–4200 μW at a wheel speed of 200–900 rpm	TPMS	(Wang et al., 2015)
KEH from floors	520 mW per footstep	WSNs, IoTs	(Jintanawan et al., 2020)
PEEH for rotational KEH	88.89 μW to 923 μW	Self-powered and real-time monitoring applications	(Abdulkhaliq et al., 2023)
EM-KEH	11.6 μW to 27.5 μW	–	(Wang et al., 2017)
Hydrokinetic-PEEH	570.3 $\mu\text{W}/\text{cm}^3$	–	(Zhao et al., 2021a)

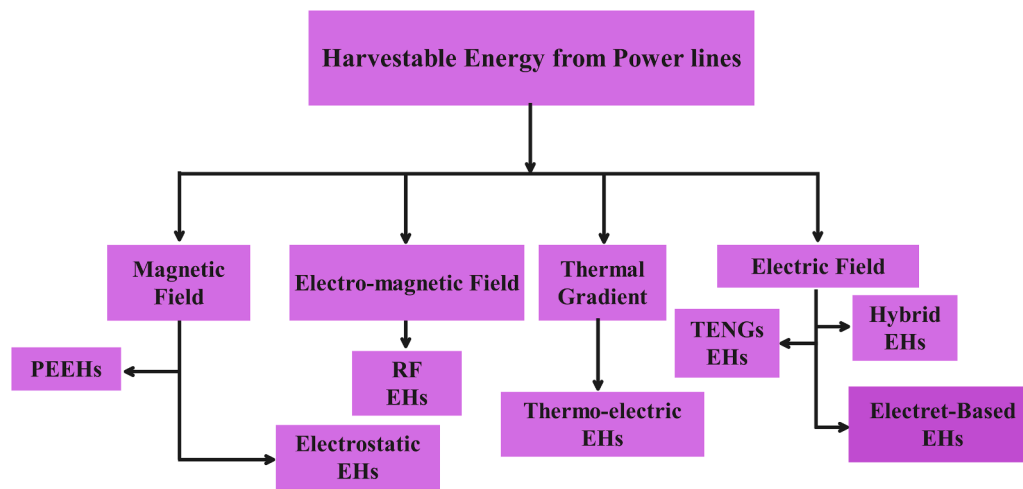


Fig. 4. Different Cutting-edge EHs for power lines.

the recent past that CEH devices could be developed to work effectively at small scales; hence making them ideal for applications in fields such as biomedical and other portable electronics (Hasan et al., 2021b). MEMS capacitive harvesters can transform micro-vibrations present in the human body or machines into electrical power—these might be used to power IMDs (Mahmud et al., 2022).

There are some constraints associated with carbon electrodes based CEHs (Ratajczak et al., 2019). The researchers are seeking ways to include artificial intelligence (AI) algorithms to these adaptive systems in order to make them better at always anticipating any possible changes brought about by surrounding environments, thus resulting in smarter and self-driving EHs (Siddhartha et al., 2023). One of these limitations is its comparatively low power output making it only suitable for ultra-low-power appliances like wireless sensor nodes (Riba et al., 2023). Also, this conversion mainly depends on amplitude and frequency of mechanical input, thus making capacitive harvesters most efficient under specific conditions where there is an unambiguous movement (Azizi et al., 2022). The efficiency of mechanical-to-electrical energy conversion is often limited by factors like leakage current flow (Ilin et al., 2020), high dielectric loss (Zhu et al., 2019), and non-ideal mechanical structures of capacitors (Huang et al., 2013). There are ongoing efforts to address these challenges through the development of adaptive systems that can optimize the energy conversion process, taking into consideration varied environmental conditions (Qi et al., 2022). It demands the development of advanced control algorithms together with AI methods for thus broadening their practical areas of application (Chu et al., 2019a, 2019b).

Various types of supercapacitors are providing an inexpensive yet sustainable charging resource alternative for battery cells in low-consumption electronic devices such as wireless sensor networks, IoTs, and wearable electronics (Subasinghage and Gunawardane, 2024). In various circuit designs, efficiency from 15 % to 50 % has been achieved by using variable capacitors, which is suitable for low power devices (Harerimana et al., 2020). Multi-in-plane capacitive transducers can be used to provide reliable harvested power from ambient vibrations for wireless sensing networks (WSNs) and other low-power electronic devices (Jamil et al., 2023). Electrostatic vibrations-related MEMS energy harvesting techniques offer low power supply and battery replacement services to WSNs, thus eliminating the need for battery replacement, which enhances space charge stability (Li et al., 2022b), but different types of vibration-based energy harvesting techniques still need further advancements (Hossain et al., 2023), and, to further improve the sustainability of these technologies, more research is needed on factors such as energy storage systems, power management, cost and environmental effects, so that these technologies can be effectively transferred from the

laboratory to real-world applications. The CEHs produce varied energy levels depending on the involved technology and application as summarized in Table 3.

5. Inductive energy harvesting

Inductive energy harvesting (IEH) is an effective and versatile method of utilizing Faraday's Law of electromagnetic induction in order to convert mechanical energy into electrical power. When a conductor such as a coil wire moves through or across a magnetic field, then an electromotive force is induced in it, thereby producing an electric current (Abidi et al., 2021). The IEH is widely employed in various fields that encompass rotating or vibrating movements, including wearable and IMDs (Dong et al., 2019) and automotive suspensions (Russo et al., 2021). This technique works like a system consisting of a coil and a magnet where alteration of their relative position results in the creation

Table 3
Output characteristics and applications of CEH techniques.

EH Techniques	Output characteristics	Applications	References
Triboelectric-EHs based CEH	0.48 W/m ²	Monitor human motions/activities	(Kim et al., 2017)
Electrostatic-CEH	0.6 μW	–	(Le and Halvorsen, 2009)
Rough surface electrodes based on CEH	3.18 μW/cm ²	Health monitoring sensors	(Adhikari et al., 2022)
Variable capacitance mechanism-based CEHs	16 μW/g	–	(Despesse et al., 2008)
Microporous electrostrictive EHs	0.38 W/m ³	Capacitive sensors	(Pruvost et al., 2018)
CEH from transmission lines of 10 kV	140.9 mW	–	(Zhou et al., 2024)
Electrostatic MEMS-based EHs	495 μW under sinusoidal vibration	Automotive applications	(Naito and Uenishi, 2019)
Electrostatic EHs	308 nW	–	(Kempitiya et al., 2013a)
Electrostatic EHs	1.688 μW	Communication transceivers and portable electronics	(Kempitiya et al., 2013b)
Compression-based CEH	0.58 μW/cm ²	Wearable devices	(Jiang et al., 2024)

of magnetic fields that bring about the production of electrical power (Kecik et al., 2017). The IEH can produce a relatively large amount of power compared with other forms of harvesting, and power output usually depends on features like magnetic flux density (Wright et al., 2023), coil design (Kiziroglou et al., 2019, 2020; Peng et al., 2021) and frequency for relative motion (Zhou et al., 2020; Liu et al., 2018a). Various configurations of coils, such as multi-turn coils (Yao et al., 2023), helical (Wang et al., 2016a), and spiral coils (Rodrigues et al., 2023), are usually employed in order to maximize magnetic flux linkage, thereby increasing energy generation efficiency. The block diagram for IEH technology is represented in Fig. 5.

The IEH is used widely within the automotive industry, especially in regenerative braking systems that are meant to recover energy when the vehicle decelerates. During this process, the kinetic energy produced by the motion of a car is changed into electricity based on inductive principles and used up for recharging vehicle batteries (Xie et al., 2023; Han et al., 2021). In the automotive sector, IEH is also used for harvesting energy from the vehicle's suspension system, such as using inductive generators to trap energy in vibrations originating from the road across the tires while causing them to move and deflect under normal loads and this energy is enough to provide power to different sensors and electronic controls fitted on-board in vehicles (Costanzo et al., 2021). The IEH also benefits wearable technologies, in particular those that are designed to use body movements for power generation. The inductive components integrated into the soles of shoes can convert mechanical energy produced during walking or running into electrical energy (Yili et al., 2015). The harvested energy can also be used to provide power to small wearable devices like healthcare monitors (Wu et al., 2021c), fitness trackers, multi-sensor bracelets and watches (Wang et al., 2016b; Chong et al., 2019) making them function autonomously from external power systems.

The IEH is incorporated into more hybrid systems that also include piezoelectric or capacitive ways of obtaining energy, and inductive hybrid systems combine advantages of various techniques (Shen et al., 2023), and these harvesters normally combine piezoelectric elements and electromagnetic components to harvest energy from vibrations and magnetic flux variations (Li et al., 2019). Similarly, an inductive-piezoelectric hybrid harvester taps magnetic flux changes as well as mechanical strain; hence, it operates under any type of movement and, in industrial settings and transport infrastructures, such hybrids have an advantage, especially when there is a mix of vibrational energy sources and magnetic ones (Shi et al., 2024). Although there are numerous advantages, inductive energy harvesting faces a series of challenges. One major limitation is that the magnetic source must be continuously moving relative to the coil, which is not always possible

(Wright et al., 2022). There are several factors influencing the efficiency of inductive energy harvesters, including electromagnetic interference presence (Xiao et al., 2022), magnetic coupling efficiency (Toluwalaju et al., 2022) and coil resistance (Kuang et al., 2021a; Bae and Kim, 2021).

The sustainability of low-power inductive energy harvesting technologies depends on their integration in performance, cost, environmental effects, and various applications. Recent research has shown that low-frequency based triboelectric and piezoelectric generators can be affordable and effective, even when used with low-cost circuits. Thus, biomechanical and structural vibrations can be also transformed to electrical power using ultra-low-frequency, hybrid energy harvesters, providing sustainable energy for portable and wearable low-power electronics (Wang et al., 2021). Therefore, the emergence of various mechanisms such as nanogenerators and MEMs facilitates to exploit ambient energies to collect power for the wireless sensor nodes in the 5 G and IoTs paradigm (Guo et al., 2021). The reliability of inductive energy harvesting technologies depends on various factors, such as design, circuit configuration, and materials used. Inductive electromagnetic harvesters, especially those that harvest energy from the magnetic field of power lines, have been experimentally proven to be able to provide stable and reliable power even from limited power sources, provided that magnetic core saturation and power conditioning are taken into account in their design (Martín Sánchez et al., 2020). Additionally, integrated power converters with inductor coils and low-profile autonomous circuits have further improved performance and reliability in energy harvesting scenarios, providing stability in power management and conversion (Çiftci et al., 2021; Tao et al., 2022). Thus, inductive energy harvesting technologies, when used with proper design and circuit optimization, can provide reliable and sustainable energy for low-power sensors and electronic devices. Although some challenges remain, such as low power output and compatibility for specific applications, research shows that these technologies have great potential to provide environmentally friendly, low-cost, and sustainable solutions for long-term use. These IEHs produce varied energy levels depending on the involved technology and application as summarized in Table 4.

6. Piezoelectric energy harvesting

Piezoelectric energy harvesting (PEEH) is a revolutionary technique that exploits the piezoelectric effect, in which certain types of materials generate an electrical charge when subjected to enforced mechanical stress and aim to change mechanical energy into electric energy for powering low-power devices. Piezoelectric materials, including

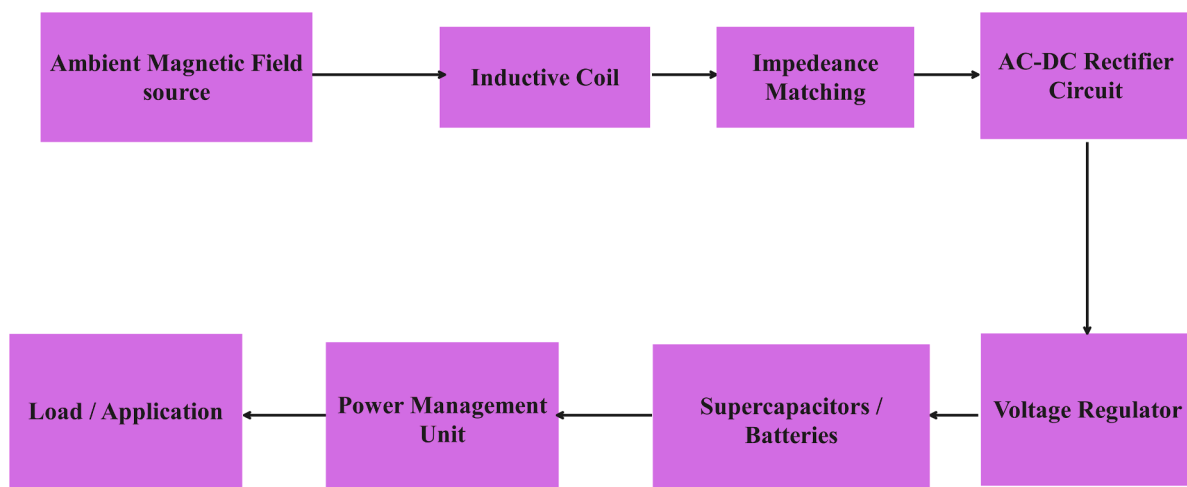


Fig. 5. Schematic for IEH System.

Table 4
Output characteristics and applications of IEH techniques.

EH Techniques	Output characteristics	Applications	References
Dual Halbach arrays based IEH	1.39 mW/cm ³	–	(Liu et al., 2015a)
Multi-directional IEHs	9.32 mW	–	(Qiu et al., 2017)
IEH from current carrying lines	103 μW/cm ³	–	(Wright et al., 2019)
Electromagnetic based IEH	4.84 mW	–	(Munaz et al., 2013)
IEH from vibration	2 mW	–	(Klein and Zuo, 2017)
IEH from proof mass and ferro-fluid	71.26 μW	–	(Chae et al., 2013)
Resonant electromagnetic vibration based IEH	50 mW	wireless sensor systems	(Qiu et al., 2015)
Magnetically ascended IEH during walking	5.35 μW	Wearable devices	(Pancharoen et al., 2016)
	103.55 μW	–	(Halim and Park, 2015)
IEH from electromagnetic MEMS	16.012 × 10 ⁻⁶ μW	–	(Liu et al., 2015b)
Nonlinear electromagnetic vibration based IEH	19.3 μW	–	(Podder et al., 2016)
Flux-guided magnet stacks based IEH	52 μWcm ⁻³	Wearable devices	(Halim et al., 2016)

polyvinylidene fluoride (PVDF), quartz, and lead zirconate titanate (PZT), are typically considered in EHs because of robust mechanical properties and high piezoelectric coefficients, and these characteristics position them at a high place for several types of applications (Das Mahapatra et al., 2021; Aabid et al., 2021). These materials can convert mechanical energy from human motion, vibrations, and other mechanical loads into electrical energy without any complex circuitry, which makes them useful in various applications, including wearables, medical implants and industrial applications (Liu et al., 2018b; Yang et al., 2018). The energy generated by piezoelectric energy harvesters is mainly influenced by various factors, including geometric properties of the device, material properties, frequency of implemented stress, and setup used to harvest energy (Lakshmi Prasanna et al., 2023). When humans move, for example, by walking or bending their joints, the generated energy is generally low, lying within the microwatt scale (Roudneshin et al., 2023). If piezoelectric harvesters undergo high-frequency vibrations from factory equipment, they can generate several milliwatts of power enough for the operation of industrial monitoring sensor networks wirelessly.

Several types of Piezoelectric energy harvesting exist based on the application, structure, or mechanism used to harness mechanical or vibrational energy. If piezoelectric energy harvesters are exposed to vibrations from industrial machinery at high frequencies, the energy generated can reach some milliwatts, which is enough for wireless sensor networks employed in industrial monitoring (Kuang et al., 2021b). The primary types of PEEHs include stacked piezoelectric energy harvesters (SPEEHs), cantilever beam energy harvesters (CBEHs), cymbal transducers-based EHs, membrane-based EHs, bridge-type EHs, impact-based EHs, flexible films EHs, rotational EHs, and hybrid piezoelectric EHs. Diverse designs and mechanisms characterize CBEHs, allowing for optimized energy conversion from mechanical vibrations, leading to improvements in utilizing them in different environments due to adaptive control, multi-stage configurations, and internal resonance (Lu et al., 2022; Eshthardiha et al., 2021; Masara et al., 2021). The SPEEHs are best suited for installations with tight spaces and there is a need for superior energy conversion like in railway systems (Cao et al., 2022). The SPEEHs are generally maintenance-free and are widely

adopted in oceanic sensors (Kargar and Hao, 2022). The membrane-based Polyvinylidene difluoride (PVDF) PEEHs are highly sensitive to acoustoelectric changes even at lower sound frequencies and are highly efficient in transforming them to electrical energy (Zhang et al., 2022a). For WSNs in transformer stations, cymbal transducers-based PEEHs are used to provide reliable and stable power (Jiang et al., 2021). The rotational PEEHs exhibit high capability and strong durability in supporting the self-sustainable operation of wireless sensors incorporated within rotating machinery (Farias et al., 2022). These harvesters can be used to observe the condition and faults of bearings of the rotating machines (Zhang et al., 2022a) and are also useful to provide power to scientific calculators and identify faults in the rotor systems; hence they are employed for the long-term surveillance of rotating machinery (Zhang et al., 2022b). Furthermore, combining several piezoelectric elements into an array configuration can dramatically boost power generation, hence appears quite feasible for applications that need more energy (Long et al., 2021a). For example, it is evidenced in that compared to the classic full-bridge circuits, the self-powered three-channel arrays increased output power by 4.8 times (Long et al., 2022). An overview of different areas concerning PEEHs is presented in the Fig. 6.

Similarly, by arraying piezoelectric sheets on cantilever beams, these energy harvesters assist in increasing energy conversion efficiency as well as widening the frequency band (Zou et al., 2021). The piezoelectric response has been notably increased by the advent of nanostructured piezoelectric materials like nanocomposites, nanofibers and nanowires, hence increasing energy conversion efficiency (Bhadwal et al., 2023). The capability of micro-patterned piezoelectric harvesters to capture mechanical energy from the environment is effectively boosted by the improved design and efficiency brought about by state-of-the-art fabrication techniques like 3D printing (Yang et al., 2021a) and electrospinning (Beigh and Mallick, 2021). Flexible piezoelectric films-based hybrid-PEEHs are getting significant attraction nowadays because of high current densities and output voltages; for example, lead-free films based PEEHs show better flexibility and high breakdown electric fields (Y.-Y.-S. Cheng et al., 2021), and quantum dot hybridization-based PEEHs exhibit improved electrical performance (Fu et al., 2022). The hybrid EHs combine multiple energy conversion mechanisms to harvest energy from multi-directional vibrations and low-frequency environments and are well suited for providing power to low-power electronic devices with improved power density (Shi et al., 2024).

Using piezoelectric sensors energy can be harvested from vibrations, especially in the industrial WSNs and IOTs, where the efficiency and regulation of energy harvesting circuits are crucial for continuous and reliable operation (Rigo et al., 2024; Yang et al., 2025). Similarly, ultra-low power piezoelectric harvesting circuits designed for medical devices incorporate advanced circuits of DC-DC converters and maximum power point tracking to improve power management, energy stability, and system reliability (Rigo et al., 2024). Nanocomposite piezoelectric materials exhibit optimal performance for mechanical energy harvesting applications, empowering reliable lithography (Beigh and Mallick, 2021). In addition, it is possible to increase performance and reliability at even lower frequencies by combining mechanisms such as triboelectric and piezoelectric. In addition, it is possible to increase performance and reliability at even lower frequencies by combining triboelectric and piezoelectric mechanisms (Xiahou et al., 2023). The reliability of piezoelectric energy harvesting technologies depends on the materials used, the structure of the device, and the application environment. Piezoelectric materials can be single crystal, composite, and polymeric types. Single crystal materials have high piezoelectric properties and stability, but they are expensive and fragile. Composite materials combine ceramics and polymers, which achieve flexibility and low cost. Polymeric materials are lightweight, flexible, and biocompatible, making them suitable for wearable and implantable devices (Clementi et al., 2022; Sukumaran et al., 2021; Dowarah et al., 2024; Bhatnagar et al., 2025). Nowadays, piezoelectric polymers and

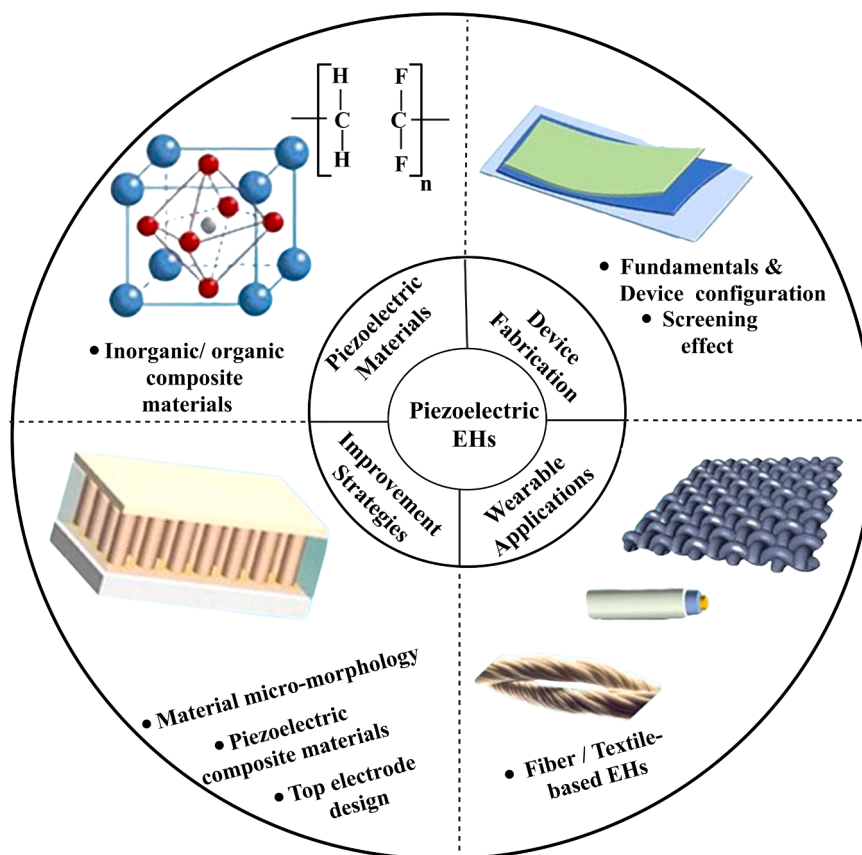


Fig. 6. Overview of synthesis, mechanisms, and multifunctional Applications of PEEHs, Reproduced, using licensed under CC BY 4.0 from Ref (He and Briscoe, 2024). Copyright © 2024, Q. He and J. Briscoe. Published by American Chemical Society.

biomaterials are striving to harvest energy from human activities and surroundings to power future flexible electronic devices (Dowarah et al., 2024). MEMS-based piezoelectric harvesters provide a sustainable solution for small-sized and low-power devices, especially when they are used to harvest energy from physical motion or the surrounding environment. Although their power output is limited, their small size and low maintenance requirements make them suitable for long-term and several autonomous applications (Hossain et al., 2023; Chen et al., 2024b; Zheng et al., 2023). With recent developments in processing methods, materials synthesis, and filler loading, PVDF-based piezoelectric materials are promising solutions to provide sustainable power to low power electronic devices (Sukumaran et al., 2021). The features and usage scenarios of PEEH techniques are listed in Table 5.

Table 5
Output characteristics and applications of PEEH techniques.

EH Technique	Output characteristics	Applications	References
Bidirectional PEEHs	16.85 μW , 15.9 $4 \mu\text{W}$	Portable devices and wireless sensors	(Čeponis et al., 2019)
Piezoelectric nanogenerators EHs	55.34 mW/cm^3	Portable electronics devices	(Hoque et al., 2017)
Lead-free PEEHs	0.819 mW/cm^3		(Xi et al., 2023)
Flexible PEEHs	27.4 $\mu\text{W}/\text{cm}^3$	Wearable and port devices	(Fu et al., 2018)
Bio-inspired PEEHs	9.3 mW/cm^3	Bio-medical applications	(Karan et al., 2019)
Barbell-shaped PEEHs	39.7 mW/cm^3	Self-powered WSNs	(Liu et al., 2021a)
PVDF-based PEEHs	8.61 mW/cm^3	–	(Song et al., 2017)

7. Moisture-based energy harvesting

In moisture-induced energy generation, the conversion of atmospheric humidity into electrical power is achieved through the interaction of moisture with functionalized materials and innovative designs (Tan et al., 2024). This procedure occurs when water molecules are adsorbed, leading to charge separation and thus producing electric current. The diffusion of water molecules can cause moisture-based electrical potential oscillations in some polymers, providing an opportunity to harvest electrical power (Long et al., 2021b). The interactions between water and solid surfaces and the principles of generating electricity from moisture are based on natural scientific processes. The transfer of protons through hydrogen bonds in water molecules can enable the movement of electric charge, which plays a key role in the process of generating electricity. The basic mechanisms of generating electricity from moisture are explained in Fig. 7.

Various materials like bio-fibers, graphene, carbon nanoparticles, and metal oxides have been investigated for their capability to harness energy from atmospheric moisture (Shen et al., 2020). There have been recent breakthroughs in introducing protein nanowires obtained from *Geobacter sulfurreducens* that rely on a moisture gradient in an attached film layer for reliable electric power generation (Liu et al., 2020a). The energy conversion efficiency can be further enhanced using key processes like photoexcited carrier migration and moisture-induced charge separation (Bai et al., 2022). Some other innovative materials comprise MXene-based composites and moisture-responsive crystalline materials with a potential for multifunctional capabilities along with high power density (Yang et al., 2021b; Li et al., 2021c). To increase moisture absorption and retain stable electrical power output, innovative designs like asymmetric hygroscopic configurations (AHCs) and Janus hetero-junctions have been developed (Wu et al., 2022; Zhang et al.,

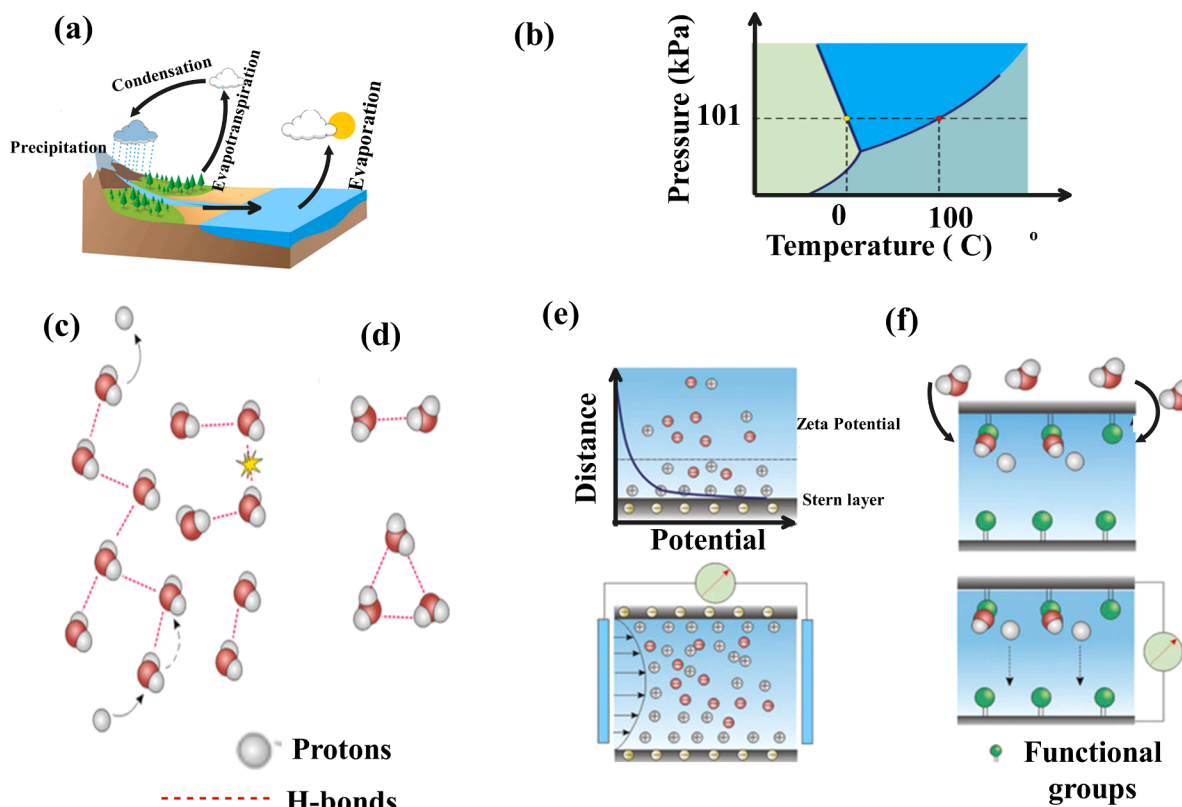


Fig. 7. (a) Ultimate principles of water–solid interactions and MEGs (b) The water cycle in Earth (c) Phase chart of water (d) Illustration of the proton transport through the hydrogen-bonded wires in liquid water, displaying the dynamic equilibrium between the formation as well as dissociation of hydrogen bonds (H-bonds). (e, f) H-bonding in the water dimer (upper) and water trimer (lower). (e) Conceptual realization of the streaming current-based electricity generation (f) Diffusion based on Ion gradients. Reproduced from Ref. with permissions (Shen et al., 2020).

2022c). The moisture-based energy harvesters like moisture-based electric generators (MEGs) are promising solutions for remote locations and off-grid areas. Self-healable MEGs based on Vanadium pentoxide (V_2O_5) have nanosheet membranes with high negative surface charges. They are capable of generating electricity from atmospheric moisture. These MEGs can be connected in a parallel and series fashion and can be used to provide power to humidity meters and calculators (Saha and Sonkusale, 2024). Likewise, wood-derived MEGs employ aligned ion nanochannels to harvest power from atmospheric moisture (Cai et al., 2022). The MEGs that are made from biodegradable materials are cost-effective, and their eco-friendly nature makes them suitable for wearable devices (Gao et al., 2024).

In addition to this, the MEGs are also used in harsh environments for applications like wireless communication systems and optical alarms (Li et al., 2024b). Moisture-based-electric nanogenerators (MENGs) are also used to harvest energy for providing power to wearable and portable electronics (Chen et al., 2023; Yang et al., 2024b). The MENGs work through the interaction of hydrophilic materials and water molecules, generating electric charges and producing electrical power (Guan et al., 2022). In MENGs, it is possible to reduce resistance and improve ion concentration gradients through different types of materials like nanostructured silicon and reduced oxides of graphene, enhancing power generation (Chen et al., 2023), and silicon nanotubes and polyelectrolytes can be utilized to facilitate moisture absorption and charge transport (Wu et al., 2022). Some smart crystalline materials are able to change their structure when exposed to moisture, thereby providing a way for converting humidity gradients into mechanical work as well as, finally, electricity, and it involves using actuators reactive to moistness in connection with a piezoelectric transducer (Yang et al., 2021b). Similarly, the combination of moisture-based energy harvesters with triboelectric energy harvesters results in improved electrical power

output (Li et al., 2024b). The moisture-driven energy harvesters with an ionic diode as well as ionic hydrogel are capable of producing power efficiently in the range of -20°C to 60°C and moisture range of 15–93 % while being freeze-resistant as well (Fang et al., 2024). Recent research shows that some innovative designs such as bilayer polymers and ion-selective aerogels can provide stable voltages (over 1.1 volts for 500 min) even at low humidity (20 %), indicating reliable performance even in dry environments (Guo et al., 2024; Zhao et al., 2024). Additionally, designs combined with cationic gels with varying salt concentrations and photocatalysis have shown the potential for long-term and continuous power generation, such as continuous current output of over 600 h (Duan et al., 2025; Kim et al., 2025). The output characteristics and applications of MEGs are listed in Table 6.

8. Challenges and future directions

The performance of practical applications of energy harvesting technologies face challenges because of limited conversion efficiencies and low power output (Mahmud et al., 2022; Zahari et al., 2024; Zhao et al., 2023). Recent developments in wireless power transfer and energy harvesting technologies based on radio frequency present the prospect of delivering power wirelessly in the future (Ullah et al., 2022). The advent of mechanical intelligence in energy harvesting can change the energy-harvesting technologies scope to help addressing environmental adaptability, low-reliability concerns and poor electrical output; hence making way for their use in artificial IoTs (Zhao et al., 2023). The integration of AI techniques in energy harvesting techniques is growing rapidly because it promises to improve sustainability and efficiency of the system. The primary challenge in integrating AI in ECEH is ensuring scalability of AI models, transparent models and high-quality data because The effectiveness of AI models like GANs as well as

Table 6
Output characteristics and applications of MEGs.

Energy harvesting method	Output characteristics	Applications	References
Evaporation-driven Water Flow	6 $\mu\text{W}/\text{cm}^2$	Humidity sensors	(Qin et al., 2020)
Sunlight-synchronized MEGs	1.426 mW/cm^2	–	(Bai et al., 2022)
Heterojunction moisture based EHs	2.2 $\mu\text{W}/\text{cm}^2$	–	(Wu et al., 2022)
Protein-based MEGs	5.5 $\mu\text{W}/\text{cm}^2$	Humidity sensors & healthcare applications	(Mandal et al., 2020)
Protein wires based EHs	8.5 $\mu\text{W}/\text{cm}^2$	–	(Liu et al., 2020a)
Surface potential oscillations-based Moisture EHs	1.12 $\mu\text{W}/\text{cm}^2$	–	(Long et al., 2021b)
Organic acid gradient-based MEGs	2.1 $\mu\text{W cm}^{-2}$	–	(Yang et al., 2022b)
Ionic hydrogel-based MEGs	71.5 $\mu\text{W cm}^{-2}$	Remote aquatic communications & marine IoTs	(Shen et al., 2024)
Solar-enabled water evaporation based EHs	2.1 $\mu\text{W cm}^{-2}$	–	(Xiao et al., 2020)
MEGs based on water-evaporation	150 nW	–	(Xue et al., 2017)
Synergistic coupling of tribo-voltaic & moisture based EHs	45.39 mWm^{-2}	–	(Sohn et al., 2024)
Evaporation-driven EHs	8.1 $\mu\text{W cm}^{-3}$	Self-powered devices	(Ding et al., 2017)
Moist-electric film generator based EHs	7.9 $\mu\text{W cm}^{-2}$	Flexible wearable, & self-healing electronics	(Wang et al., 2020)
Transpiration-driven EHs	16.65 μW	Low-power IoTs	(Bae et al., 2020)
Paper-based MEGs	2.5 nW/cm^2	Portable devices	(Gao et al., 2019)
Graphene oxide film under Moisture	4.2 mW m^{-2}	Sensor applications	(Zhao et al., 2015)

autoencoders highly depends upon the quality of the input data and the transparency of these models for optimization and prediction (Li and You, 2024). The Fig. 8 shows the schematic of energy harvesters based on intelligent systems, data processing, network processing steps, and

their output.

The electrostatic kinetic energy harvesters face challenges in designing optimal systems, involving the sophisticated management of discharging and charging electrical flows and further research into developing optimal design (Mahmud et al., 2022). In some systems, where CEH is associated with other capacitive devices, for example, capacitance-to-digital converters, the overall capacitance needs to be maintained within a certain range for appropriate operation of measurement systems and energy harvesting (Moser et al., 2011). To achieve technically sound solutions, energy harvesting systems based on the IEH technology, detailed design considerations are needed which might not be cost effective (Martín Sánchez et al., 2020). Thus, AI-based optimization techniques can be used for optimizing the design of electromagnetic EHs, providing reduced costs and improved efficiency in energy harvesting systems (Hadas et al., 2012).

Deep learning tasks should be carried out more efficiently in the presence of intermittent power supply in energy-harvesting IoTs and without the backup power, these devices may frequently experience power shortages, which complicates running AI tasks (Lv and Xu, 2022), but the AI-aided models can serve to optimize mechanical-to-electrical performance, surpassing present limitations related to the design and discovery of materials used for energy harvesting technologies (Jiao, 2021). AI development is expected to enable self-sustainable systems for these changes, EHs with data transmission units, and can play a vital role with the actual system in future deployments of 5 G or IoT applications (Guo et al., 2021). Federated learning uses energy harvesting for distributed training that does not involve the exchange of raw data. Such mechanism further deals with transmission of high-dimensional data and power constraints to enhance learning performance through device scheduling and efficient energy allocation (An et al., 2024). Adaptive security mechanisms based on AI can assist with the optimization of energy use through dynamically varying threats and security levels as per current energy availability, but the implementation of such mechanisms involves advanced algorithms along with real-time data processing (Mao et al., 2020). The challenges and potential solutions for AI-based EHs are summarized in Fig. 9.

Despite advances in low-power energy harvesting technologies, there are still significant research gaps in the existing literature for different kind of energy harvesting techniques, which are summarized in Table 7.

In addition, the evolution and mass acceptance of energy harvesting for sensor networks and IoT applications, standardizing and creating

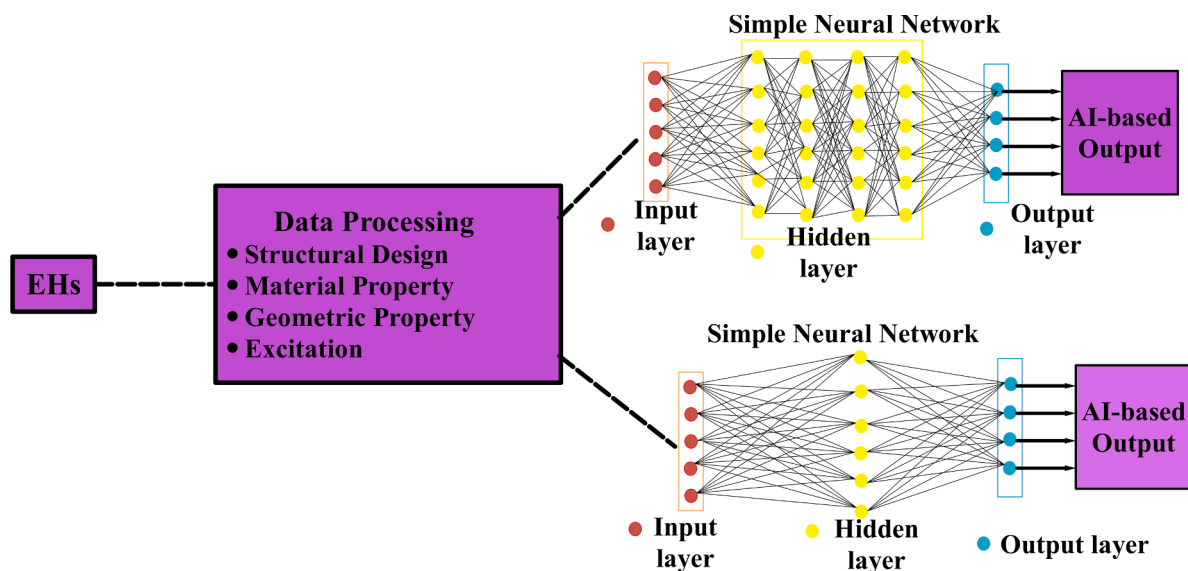


Fig. 8. Schematic overview of energy harvesters based on intelligent systems, data processing, steps of network processing and its output, reproduced from Ref (Divya et al., 2023). with permissions.

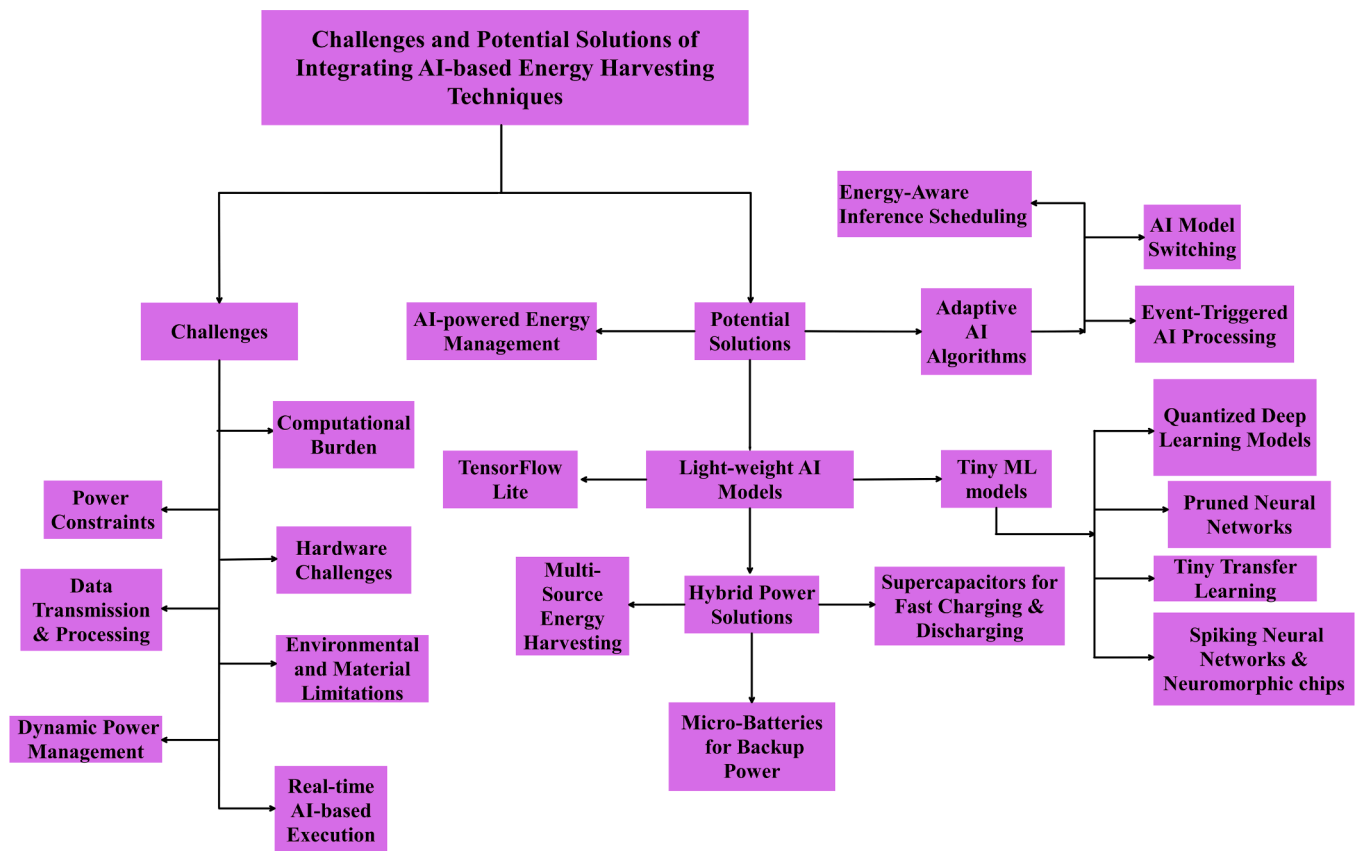


Fig. 9. Challenges and potential solutions of integrating AI-based EHs.

regulatory frameworks have become necessary for these devices. Since, energy harvesting enables distributed sensors to be operated without batteries and maintenance. Thus, interoperable and reliable standards need to be set for safety across these widely different devices and environmental conditions (Ibrahim et al., 2020; Ma et al., 2020). Standardized communication protocols and testing help confirm that energy harvesting devices from different manufacturers can communicate with one another, thereby upholding their reliable performance. Regulatory frameworks can impose safety requirements on medical implants and wearable devices (Chong et al., 2019; Ibrahim et al., 2020). These regulations are an essential requirement in health and environmental monitoring sensors and industrial automation, where the safety of the device and integrity of data must be prioritized (Liu et al., 2021b; Chong et al., 2019). For instance, biomedical and wearable devices are subjected to regulatory standards that do not allow any kind of interference from the energy harvesting component with patient safety and efficiency of the device (Chong et al., 2019). Modular and scalable system design are facilitated by the standardization of energy harvesting methods into wireless sensor networks and IoT systems (Ma et al., 2020; Liu et al., 2021b; Ibrahim et al., 2020). Thus, lack of universal standards can prevent the increasing acceptance of energy harvesting technologies, resulting in a situation that would present incompatibility issues and engineering costs for device manufacturers (Ibrahim et al., 2020; Ma et al., 2020). At the same time, diverse application areas of energy harvesting technologies may involve customized standards to accommodate their unique energy profiles and operational environments (Bairagi et al., 2023; Liu et al., 2021b; Chong et al., 2019). With consistent regulations and standards, more investors and consumers gain confidence in emerging technologies, and, in fact, those standards and regulations of data reporting protocols encourage their widespread adoption. Standardization and regulatory frameworks can have a positive effect on innovations as they tend to set clear standards for

performance and safety (Hassanpour Amiri et al., 2023). However, overly strict regulations may inhibit the evolution of novel energy harvesting mechanisms and adaptive systems (Zhao et al., 2023; Ma et al., 2020).

9. Conclusions

This review paper underlines the rising prominence of low-power energy harvesting techniques in addressing the expanding need for autonomous and sustainable energy sources. Through in-depth consideration of different types of electrochemical, kinetic, capacitive, inductive, piezoelectric, and moisture-based techniques, the study highlights different physical mechanisms and application areas of these techniques. Despite rapid technological developments, the literature shows a clear research gap and unanswered questions in systematically evaluating these energy harvesting techniques from the perspective of scalability, environmental adaptability, prolonged reliability and large-scale implementations. Some more challenges like material degradation, inadequate energy storage capabilities, high implementation costs and lower efficiencies also obstruct their widespread adoption. Thus, these issues present critical opportunities for further research. Future studies can be based on hybrid energy harvesting systems using multiple sources and techniques to overcome the limitations of individual technologies. There is also a need to develop novel materials with properties of nanostructured composites and biodegradable materials to improve performance and sustainability. In addition, incorporating advanced data-driven optimization AI-based energy management will significantly improve the adaptability and efficiency of these energy harvesting techniques under dynamic conditions. Future advancements in low-power energy harvesting technologies can play a transformative role in enabling innovative and self-sufficient autonomous systems in fields ranging from biomedical devices and environmental sensing to

Table 7
Research gaps / un-answered questions in energy harvesting techniques.

Techniques/ Technologies	Research gaps	References
Electrochemical	Integration, user comfort, biocompatibility, miniaturization, continuous operation	(Parrilla and De Wael, 2021; Zohair et al., 2020; Jiao et al., 2024)
TENGs-based Electrochemical systems	power management, hybridization, Low-frequency performance	(Xuan et al., 2024), (Xiahou et al., 2023)
Biofuel/ Microbial	Scalability, mechanistic understanding, integration with other systems	(Shukla et al., 2023; Jiao et al., 2024)
Thermo-electrochemical	Efficiency, commercial viability, stability	(Burmistrov et al., 2022)
Electromagnetic	Demand for improved efficiency integration with LPEDs	(Zhao et al., 2021b; Tang et al., 2022; Hadas et al., 2022)
Kinetic energy harvesting	Need for universal designs, sensitivity to environmental factors, device configuration, limited by material choice	(Zhang et al., 2021; Zong et al., 2025; Jiang et al., 2020a)
Kinetic energy harvesting	Output power stability and enhancing bandwidth	(Xia et al., 2024)
Capacitive Transducers-based	Complete assessment of performance under low-vibrating conditions with the integration of wireless sensor networks.	(Jamil et al., 2023)
Ultrasound-Induced Capacitive Systems	Long term stability, miniaturization and effective wireless power transfer	(Jiang et al., 2020b)
Parallel-Plate MEMS Capacitors	Further efficiency improvement and the adaptation in real-world settings	(Üstün and Üstün, 2024)
Pyroelectric capacitive energy harvesters	Need for scalability and efficient solutions	(Lheritier et al., 2022)
Inductive Electromagnetic Harvesters	Detailed design strategizing is needed to optimize technical and economic performance; limited energy availability from weak sources	(Sánchez et al., 2020)
Inductive Harvesting from Current-Carrying Structures	Optimization of materials and shapes of core for the highest conceivable power density	(Wright et al., 2019)
Inductive energy harvesting from power lines	Challenges regarding repeatable installations and performance uncertainty due to detachable interfaces	(Wright et al., 2022)
Vibration based general Piezoelectric	Ineffective efficiency, durability, and scalability	(Zhou et al., 2022b)
Energy harvesting-based on Piezoelectric materials	Device optimization	(Pan et al., 2024)
Energy harvesting from Piezoelectric tiles	Challenges regarding economic feasibility, large-scale integration & durability	(Sharma et al., 2022)
Moisture-based energy harvesting	Unresolved issues in optimization of operating devices, conversion efficiency & new material development.	(Shen et al., 2020)
Radiative cooling-assisted moisture-based energy harvesting	A thorough evaluation of the environmental impacts on the output characteristics as well as further enhancement of energy conversion efficiency.	(Guo et al., 2024)
Protein nanowire-based energy harvesting	Demand for sustained, location-independent and scalable energy conversion mechanisms	(Liu et al., 2020b)
Moisture-induced energy harvesting devices with	Further improvement in device performance and	(Das et al., 2024)

Table 7 (continued)

Techniques/ Technologies	Research gaps	References
biocompatible Albumin-MXene composites	finding new biocompatible, biodegradable materials for clean power generation	(Tan et al., 2024)
Hydro-voltaic electricity generation	A deeper understanding of mechanisms is needed, along with novel materials and smart system designs, to have an operation for long periods with sustained performance.	

industrial monitoring and next-generation IoT applications by addressing these research gaps. Thus, this review paper also serves as a foundational reference for researchers and practitioners seeking to advance the reliability, scalability, and sustainability of energy harvesting solutions.

CRedit authorship contribution statement

Qudrat Ullah: Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Conceptualization. **Jussi Keskkuru:** Writing – review & editing. **Tuomas Rauta:** Writing – review & editing. **Joel Haverinen:** Writing – review & editing. **Pekka Ruuskanen:** Writing – review & editing, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of Competing Interest

On the behalf of all authors, corresponding author declares that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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