batteries

Review

Navigating Battery Choices in IoT: An Extensive Survey of Technologies and Their Applications

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Abstract: In recent years, there has been significant progress in IoT solutions for a variety of fields. The real-time functionality and remote deployment of IoT solutions are two crucial aspects that are necessary for their successful implementation. To achieve this, external batteries play a major role. While lithium–ion batteries are often the go-to choice for IoT devices, it is essential to recognise that different IoT applications have unique needs. Therefore, it is important to conduct a thorough examination of existing battery solutions and their suitability for various IoT applications. This paper presents an extensive survey of different battery technologies, accompanied by an assessment of their applicability in different IoT applications. The aim is to offer a clear and practical guide for researchers and professionals seeking the best battery solutions for their IoT applications.

Keywords: primary batteries; secondary batteries; battery evaluation

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1. Introduction

The Internet of Things (IoT) has ushered in an era of unparalleled connectivity, transforming everything from consumer gadgets to large-scale industrial systems [1]. In healthcare, for example, IoT-enabled medical devices monitor patient vitals in real time, potentially reducing hospitalisation rates [2–4]. In agriculture, IoT sensors track environmental conditions [5], optimising yield and conserving resources [6,7]. An overview of different possible IoT applications is illustrated in Figure 1. The key to the seamless operation of these diverse applications lies in their ability to deliver real-time functionality and to be remotely deployed—two factors that are pivotal for the successful implementation of any IoT system.

If IoT is the engine driving the next wave of technological innovation, then batteries can be considered as the fuel. Due to the range of application requirements, IoT sensors often need to be run remotely for an extended period, making the choice of battery a crucial decision in the IoT system setup.

While lithium–ion batteries are often heralded as the default option for IoT applications, this one-size-fits-all approach overlooks the unique energy needs of different IoT environments. Just as the power requirements of a smartwatch differ from an industrial sensor in a factory, so too do the best-suited battery technologies. Therefore, it is crucial to scrutinise existing battery solutions and assess their compatibility with various IoT applications. Without such an examination, we risk limiting the efficacy and potential impact of IoT technologies, prompting the necessity for comprehensive research in this domain.

Many surveys have been conducted on the suitability of different types of lithium–ion-based batteries for specific applications such as electric vehicles [8–11]. However, there is little or no review work available on the suitability of different types of battery technologies for a wide range of IoT-based applications.

In this paper, we address this shortcoming by critically reviewing the applicability of various types of battery technologies for a range of IoT applications such as the smart home and the smart city [12]. Two types of batteries are evaluated in this research work: Primary batteries, which are non-rechargeable, and secondary batteries, which are rechargeable. Lithium–ion batteries are an exception to this. They are available in both rechargeable and non-rechargeable form. The list and the classification of the battery technologies that will be evaluated are illustrated in Figure 2. Another type of energy source called supercapacitor is also included in the evaluation due to its recent promising results in the energy source domain [13]. Although there are many varieties of battery chemical compositions, for the sake of classification, in this paper we only consider eight distinct chemical composition of batteries.

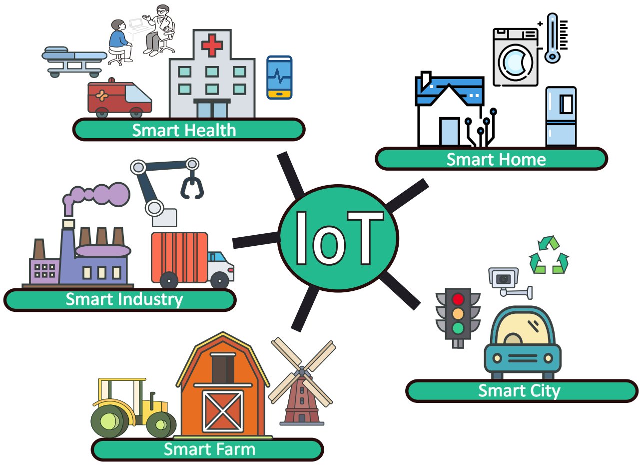


Figure 1. Different applications of Internet of Things.

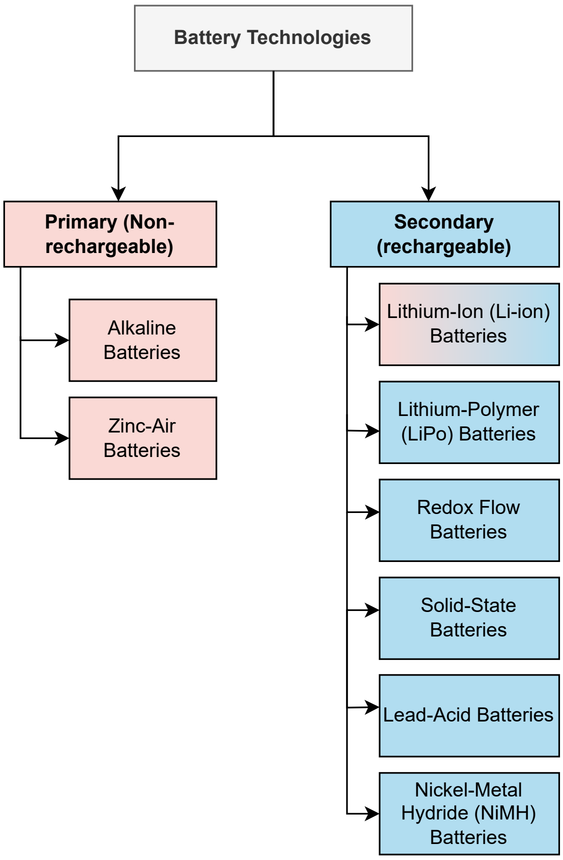


Figure 2. Classification of various types of batteries.

The contributions in this paper are as follows:

1. Analysis of a range of battery technologies for suitability in IoT applications.
2. Development of a battery–application compatibility matrix for data-driven critical analysis.

The rest of this paper is arranged as follows. Sections 2 and 3 present different IoT applications and an overview of different battery technologies, respectively. In Section 4, the battery technologies are evaluated according to several key characteristics. In Section 5, a suitability matrix of each battery technology in comparison to a range of IoT applications is established.

2. IoT Applications

IoT refers to a wide range of applications that use sensors, software, and network connectivity to collect and transmit data from everyday objects. This process improves operational efficiency and enhances user experience. IoT applications are becoming more diverse and widespread, and have established new possibilities for transformation in numerous fields. This work will focus on five IoT domains, namely healthcare, smart cities, smart homes, and farming and industrial automation.

2.1. Healthcare

The adoption of the Internet of Things (IoT), often known as the Internet of Medical Things (IoMT), has transformed the healthcare industry, allowing for more accurate diagnoses, personalised treatments, and better patient health outcomes. IoMT has assisted a diverse end-user group, including patients, healthcare providers, medical staff, and other closely related fields. The healthcare industry has improved by leveraging the application of IoT not just in patient-centric care to monitor patients remotely, provide personalised care, and optimise treatment plans but also in managing the hospital effectively, such as tracking inventory and equipment, monitoring patient safety, and managing hospital operations more efficiently and hence reducing healthcare costs [14]. Further analysis of the IoMT can be conducted in the sub-contexts of wearable and non-wearable applications.

Wearable

Wearable devices are a significant component of the IoMT ecosystem, particularly during health crises like the COVID-19 pandemic, where they played a crucial role in monitoring and managing health [15,16]. The smart, connected devices worn on the body, such as fitness trackers, smartwatches, and wearable monitors, gather information that is context-oriented and related to physical, behavioural, and psychological health [17–19]. These devices aid in the overall management of personal and community health, early detection of health issues, and timely intervention. However, with the increasing demand for wearable and implantable medical devices, there is an increasing need for reliable, safe, and long-lasting power sources.

Non-wearable IoT devices in healthcare are tools not worn on the body but which play a critical role in patient care. These devices, combined with the concept of IoT, offer efficient means for telehealth interventions, improving hospital efficiency, reducing human errors [20], and enhancing patient care. Examples include remote patient monitoring tools and medical dosage monitoring [20]. Hospital room automation, in-hospital contact tracing, medication management, patient safety, and more can be achieved through the integration of these non-wearable devices into the existing systems [21,22].

2.2. Smart Cities

In recent years, the concept of smart cities has gained significant traction owing to the advent of Internet of Things (IoT) solutions that aim to enhance the urban living experience and operational efficiency. IoT has enabled the development of various applications that can address urban challenges, such as real-time people counting and traffic monitoring systems to mitigate congestion and improve road safety [23]. Smart waste management systems can ensure timely trash collection and recycling, while IoT-enabled energy grids can optimize energy distribution and reduce wastage. Additionally, smart water systems can monitor and control water usage, aiding in the conservation of this vital resource. The immense potential of IoT in smart cities is evident, with each application contributing to a more sustainable and livable urban environment [24,25].

2.3. Smart Home

The domain of smart homes is centred around enhancing living comfort and security. Through IoT, homeowners can remotely control and monitor home appliances, security systems, lighting, heating, and cooling systems from anywhere. Applications like smart thermostats, automated locks, and voice-activated assistants have already found a place in many homes [26,27]. Furthermore, IoT can facilitate energy management through smart meters and appliances that operate during off-peak energy times to reduce electricity bills [28]. The development of more intuitive and integrated IoT applications continues to redefine the concept of home, making daily life more convenient and secure.

2.4. Smart Farm

The agriculture sector, too, stands to benefit significantly from IoT-powered smart farming. IoT applications in agriculture include precision farming, where sensors monitor soil conditions and crop health to provide actionable insights for farmers [29,30]. Automated irrigation systems can be developed to optimize water usage based on real-time data, while drone technology can aid in monitoring large farmlands and executing tasks like seeding or spraying pesticides [31]. Moreover, IoT can facilitate livestock monitoring through wearable devices that track the health and location of animals, ensuring their well-being and reducing losses [32].

2.5. Smart Industry

The transition of the industrial sector towards Industry 4.0 is largely driven by the adoption of IoT technologies. IoT applications in industries are vast and include the real-time monitoring of machinery to predict and prevent breakdowns, thus minimising downtime. Supply chain and inventory management can also be streamlined through IoT-enabled tracking systems. Additionally, smart safety gear can be developed to monitor the well-being of workers in hazardous environments, providing alerts in case of emergencies. These applications not only enhance operational efficiency but also contribute to creating safer and more sustainable industrial ecosystems.

3. Batteries for IoT Applications

3.1. Lead-Acid Batteries

Lead–acid batteries, invented in 1859, are still extensively used in the automotive industry [33]. The battery consists of acid and two lead electrodes, as seen in Figure 3. The lead–acid battery works by utilising a series of electrochemical reactions between its two primary electrodes which are a lead dioxide (PbO_2) positive plate and a sponge lead (Pb) negative plate, both immersed in an electrolyte solution that is composed of sulphuric acid (H_2SO_4) and water (H_2O). When the battery is discharged, the PbO_2 and Pb plates react with the sulphuric acid to produce lead sulphate ($PbSO_4$) and water. This reaction releases electrons, thereby providing electrical power. On the other hand, during the charging process, the lead sulphate and water are converted back into PbO_2, Pb, and sulphuric acid [34]. One of the challenges associated with this type of battery is sulphation. This happens when the battery remains discharged for an extended period, leading to the formation of larger, less reversible lead sulphate crystals. Lead–acid batteries are known for their cost-effectiveness and reliability, but their energy density is lower than many modern battery technologies.

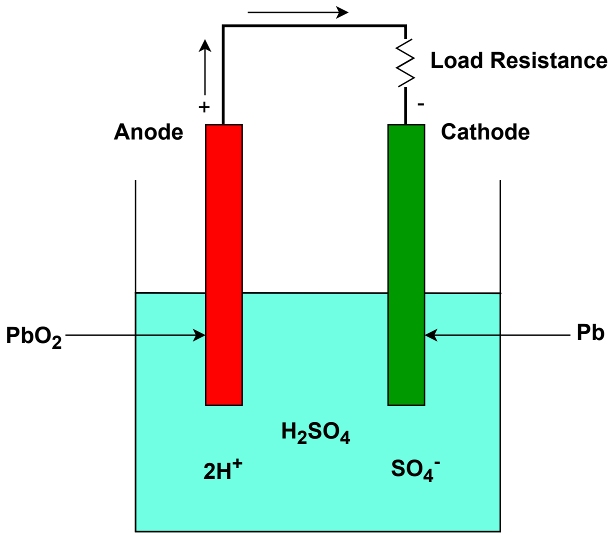


Figure 3. Operational setup of lead−acid battery.

3.2. Nickel–Metal Hydride (NiMH) Batteries

Developed in the 1980s as a successor to nickel–cadmium batteries, nickel–metal hydride (*NiMH*) batteries are commonly used for consumer electronics, power tools, and hybrid electric vehicles [35]. The electrochemical reactions (Figure 4) between the primary components of *NiMH* batteries, the positive electrode made of nickel hydroxide ($Ni(OH)_2$), and the negative electrode, a metal alloy capable of forming hydrides, enable their operation. During discharging, the nickel hydroxide at the cathode oxidises to nickel oxyhydroxide and releases electrons, while the metal alloy at the anode reacts with hydroxide ions to form a metal hydride. When charging, these reactions reverse. Compared to their predecessor, nickel–cadmium (*NiCd*) batteries, *NiMH* batteries have a higher energy density, a lower "memory effect" (wherein batteries lose capacity if not fully discharged), and a more environmentally friendly composition since they lack the toxic cadmium. While superior to *NiCd*, they exhibit a higher self-discharge rate and lower energy density than contemporary lithium–ion batteries. *NiMH* batteries are ideal for various applications due to their reliability, size versatility, and relatively lower cost than other types of batteries [36].

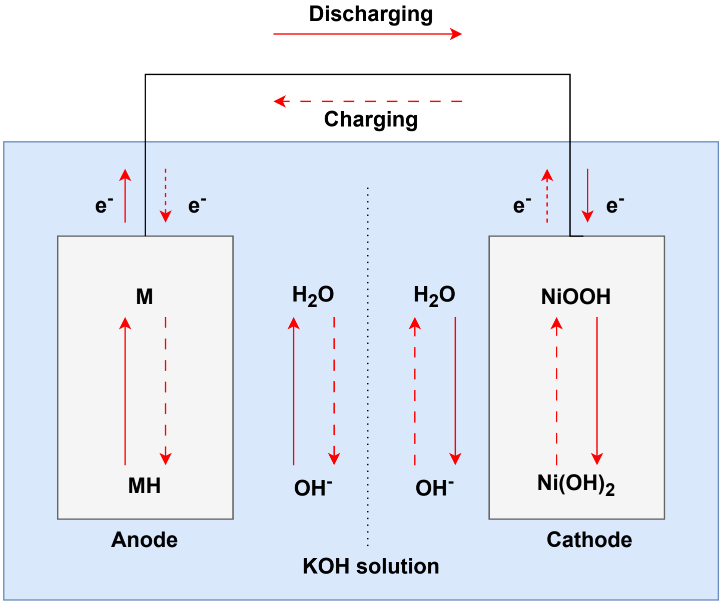


Figure 4. Operational setup of nickel−metal hydride battery.

3.3. Lithium–Ion (Li–Ion) Batteries

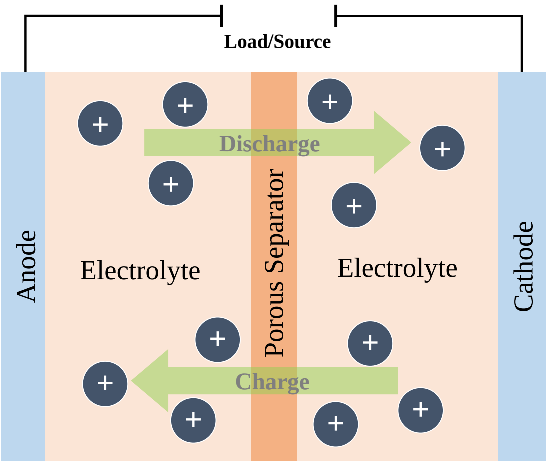
The lowest reduction potential and highest cell potential makes the element lithium a popular choice for batteries [37,38]. Lithium–ion batteries are a popular choice of battery over a wide range of applications ranging from portable electronics to electric vehicles. This is mainly due to their energy density, low self discharge, and low memory effect when compared to the other secondary (rechargeable) batteries.

In the 1970s, the development of lithium-based rechargeable batteries marked a significant milestone in the energy industry. In the following decade, the introduction of oxide cathodes further enhanced the performance of these batteries. The researchers later shifted their focus towards improving cell voltage and stabilisation, later leading to the commercialisation of rechargeable batteries by Sony in 1991. Since then, these batteries have become increasingly popular in the market and are widely used in various applications [39].

Lithium–ion cells are made up of three main components: a cathode composed of lithium metal oxide, an anode made from graphite, and an electrolyte that contains lithium ions. When the battery discharges, the lithium ions move from the anode to the cathode through the electrolyte, while electrons flow through the external circuit, providing power to the device. This process is reversed during charging [40].

Compared to traditional batteries, the unique structure of lithium–ion batteries provides an advantage due to their ability to generate electricity without dissolving the electrodes in the electrolyte. This is possible due to the presence of lithium in the cathode and its efficient storage capability in the carbon anode. This process helps prevent battery deterioration and increases the number of charge and discharge cycles the battery can undergo.

The lithium–ion batteries can be further divided into the following subcategories based on the cathode material and are summarised in Figure 5.



Composition of Lithium -Ion Batteries

Component	**Materials**
Cathode	Li_2CO_3
	$LiCoO_2$
	$LiMn_2O_4$
	$LiNiO_2$
	$LiFePO_4$
Anode	Graphite
	$Li_4Ti_5O_{12}$
Electrolyte	Ethylene carbonate
	Diethyl Carbonate
	$LiPF_6$
	$LiBF_4$
Separator	Polypropylene

Figure 5. Operational setup of lithium–ion battery.

3.3.1. Lithium Cobalt Oxide (LCO) Batteries

Lithium cobalt oxide ($LiCoO_2$) is a widely used cathode material in rechargeable lithium–ion batteries due to its high energy density. The material has a layered structure that is easy to synthesise and handle, making it a popular choice for commercial applications. However, cobalt is a scarce and expensive resource, which can limit the production of $LiCoO_2$ batteries. Additionally, $LiCoO_2$ batteries have a relatively short lifespan and can suffer from thermal instability, increasing safety concerns. Furthermore, the battery exhibits low specific power, which can limit its ability to deliver high power output. Despite these limitations, $LiCoO_2$ batteries remain popular for applications wherein high energy density is a primary concern, such as in consumer electronics and electric vehicles [41].

3.3.2. Lithium Manganese Oxide (LMO) Batteries

Lithium manganese oxide ($LiMn_2O_4$) with a three-dimensional spinel structure is used as a cathode. The spinel structure allows for high thermal stability and improves ion flow on the electrode. Manganese lithium–ion batteries can produce the same voltage as cobalt lithium–ion batteries and have the advantage that they can be made at a low cost.

However, there is a disadvantage to using manganese in lithium–ion batteries. During charging and discharging, manganese may dissolve out into the electrolyte, which can shorten the battery life. Therefore, researchers and manufacturers are continually working to improve the stability of the cathode material to overcome this issue and make lithium manganese oxide a more reliable and long-lasting option for lithium–ion batteries [42].

3.3.3. Lithium Nickel Manganese Cobalt Oxide

Lithium Nickel Manganese Cobalt Oxide ($LiNiMnO_2$) is a type of cathode material that is a combination of nickel, manganese, and cobalt and combines the advantages of the earlier versions of cathode materials. This material has a high energy density and good stability, making it a popular choice for use in electric vehicles and other high-performance applications. Additionally, $LiNiMnO_2$ has a relatively low cost compared to other cathode materials, making it an attractive option for large-scale battery production [43,44].

3.3.4. Lithium Iron Phosphate ($LiFePO_4$) Batteries

Lithium iron phosphate (LFP) is a type of lithium–ion battery that uses lithium iron phosphate as the cathode material. The olivine structure of $LiFePO_4$ gives LFP batteries their distinct electrochemical properties. The one-dimensional channels in the olivine structure allow for the relatively easy migration of lithium ions during the electrochemical processes. However, these channels also limit the rate at which these processes can occur, resulting in lower power densities compared to other lithium–ion chemistries. One of the significant environmental benefits of LFP batteries is the absence of heavy metals like cobalt and nickel in their cathode material. This makes them more environmentally friendly compared to other lithium–ion chemistries. LFP batteries have a higher cycle life compared to other lithium–ion chemistries, making them suitable for applications wherein frequent charging and discharging are required. Additionally, the thermal stability of the $FePO_4$ cathode material reduces the risk of thermal runaway, making LFP batteries one of the safest lithium–ion chemistries available [45].

3.3.5. Lithium–Polymer (LiPo) Batteries

The ideation of a battery with the potential to eliminate liquid electrolytes and, consequently, minimise the risk of leakage and safety hazards, has led to the development of lithium–polymer (LiPo) batteries. LiPo batteries offer a flexible and lightweight alternative to conventional lithium–ion batteries, making them commercially viable. The polymer in the LiPo batteries can be either “dry” or “gel-like”, facilitating the movement of lithium ions between the cathode and anode [46,47].

3.4. Solid-State Batteries

The popularity of lithium batteries has increased significantly, but they come with significant challenges. The use of liquid electrolytes makes them highly volatile and flammable outside their operating temperature, which raises safety concerns. The limited ionic conductivity and electrochemical stability also limit the cells’ voltage and capacity, thereby decreasing the energy density of lithium–ion batteries. However, solid-state electrolytes (SEs) can be an effective alternative to liquid electrolytes and can achieve much higher energy density and safety, while also overcoming most of the drawbacks of Li–ion batteries (LIBs) [48]. The lithium ceramic batteries are a promising subset of solid-state batteries that have a ceramic electrolyte. This ceramic material can conduct lithium ions between the cathode and anode during the battery’s charge and discharge cycles [49,50].

3.5. Alkaline Batteries

The alkaline battery was introduced in the 1960s as a significant improvement over the zinc–carbon batteries that came before it. Its primary use is still in consumer electronics, such as remote controls, flashlights, toys, and digital cameras. Alkaline batteries have become popular due to their relatively high energy density, longer shelf life, and consistent voltage output compared to zinc–carbon batteries. They work by electrochemical reactions between the manganese dioxide (MnO_2) cathode and the zinc (Zn) anode, which are immersed in an alkaline electrolyte, typically potassium hydroxide (KOH) (Figure 6). When the battery discharges, zinc at the anode undergoes oxidation, releasing electrons and producing zinc oxide. At the same time, manganese dioxide at the cathode is reduced, consuming electrons. This flow of electrons from anode to cathode produces electrical power. Unlike other battery types, alkaline batteries are primary cells, which means they are not rechargeable; once the chemicals inside are exhausted, the battery is depleted. Alkaline batteries have potential for IoT applications that require infrequent battery replacement or wherein device simplicity and low cost are paramount. Due to their stable voltage output and long shelf life, alkaline batteries can be ideal for low-drain IoT sensors or devices that remain in a standby state for a long time and only transmit data from time to time. Moreover, their widespread availability and standardised sizes, such as AA and AAA, make them convenient for consumer-facing IoT products, allowing users to replace batteries quickly [51].

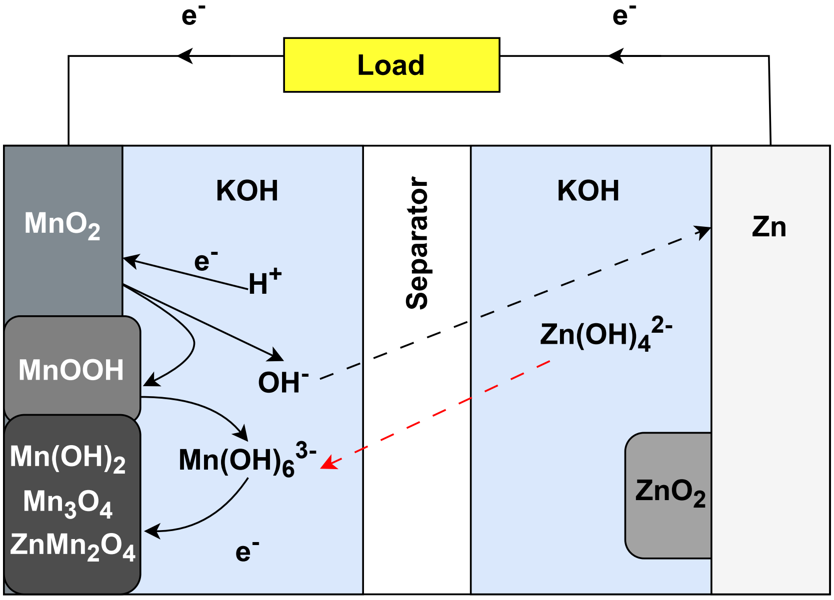


Figure 6. Operational setup of alkaline Zn−MnO_2 battery.

3.6. Zinc–Air Batteries

Designed initially as non-rechargeable batteries, zinc–air batteries gained popularity in the late 20th century due to their high energy density. It was an attractive choice for certain applications, particularly for small devices such as hearing aids. A zinc–air battery (Figure 7) comprises a zinc anode, an air (oxygen) cathode, and an alkaline electrolyte. The air cathode enables oxygen from the surrounding air to take part in the electrochemical reactions and helps in the electrons' movements. One key drawback of zinc–air is its short cycle life [52]. Zinc–air batteries are ideal for long-term low power and remote sensing applications as they can remain inactive for extended periods and provide power as required [53–55].

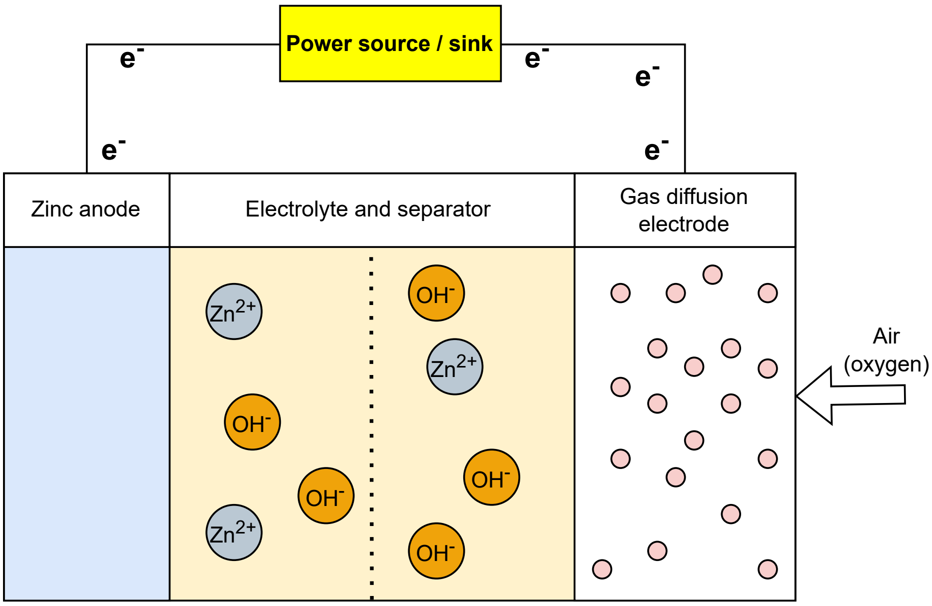


Figure 7. Operational setup of zinc−air battery.

3.7. Flow Batteries

Flow batteries, also known as redox flow batteries, were introduced in the 1970s, but their popularity as a solution for large-scale energy storage only became prominent in recent years. These batteries are primarily used in grid energy storage due to their ability to store vast amounts of energy for long periods. This makes them an ideal choice for integrating renewable energy sources such as solar and wind into the power grid as they can store excess energy generated during peak times and release it when the demand is high or generation is low. Flow batteries (Figure 8) work based on the electrochemical reactions of two liquid electrolyte solutions separated by a membrane. These electrolytes are stored in external tanks and are pumped through a cell stack, where they undergo redox reactions. In the cell stack, one electrolyte is oxidised at the negative electrode, releasing electrons, while the other is reduced at the positive electrode, accepting those electrons to generate electricity. One of the most significant advantages of flow batteries is their energy capacity, which is determined by the size of the electrolyte tanks. On the other hand, the size and design of the cell stack determine the power output, i.e., how quickly energy can be delivered, making them highly scalable and customisable based on specific requirements. While flow batteries are primarily designed for large-scale applications, they can also be used in IoT scenarios where long-duration, uninterrupted power is essential. For instance, in remote IoT sensor networks that monitor environmental parameters or infrastructure over extended areas, a flow battery system can ensure a consistent power supply, especially when combined with renewable energy sources. Flow batteries are also suitable for applications wherein maintenance or battery replacement is challenging due to their long cycle life and ability to undergo deep discharges without significant degradation. However, the requirement of external tanks for electrolytes and their complexity makes miniaturisation a challenge, making them less suitable for compact IoT devices [56].

3.8. Supercapacitors

Supercapacitors have emerged as promising energy storage components in recent years. They are particularly useful in hybrid configurations where they are combined with other energy storage devices to improve overall performance. Supercapacitors are also called electric double-layer capacitors (EDLCs) or electrochemical capacitors (ECs), and they work by storing electrical energy in the double layer between the electrodes and the electrolyte. Supercapacitors offer higher specific energy than traditional capacitors and greater specific power than existing batteries. As a result, they are ideal for applications that require short charge–discharge cycles, ranging from a few seconds to several minutes [57,58].

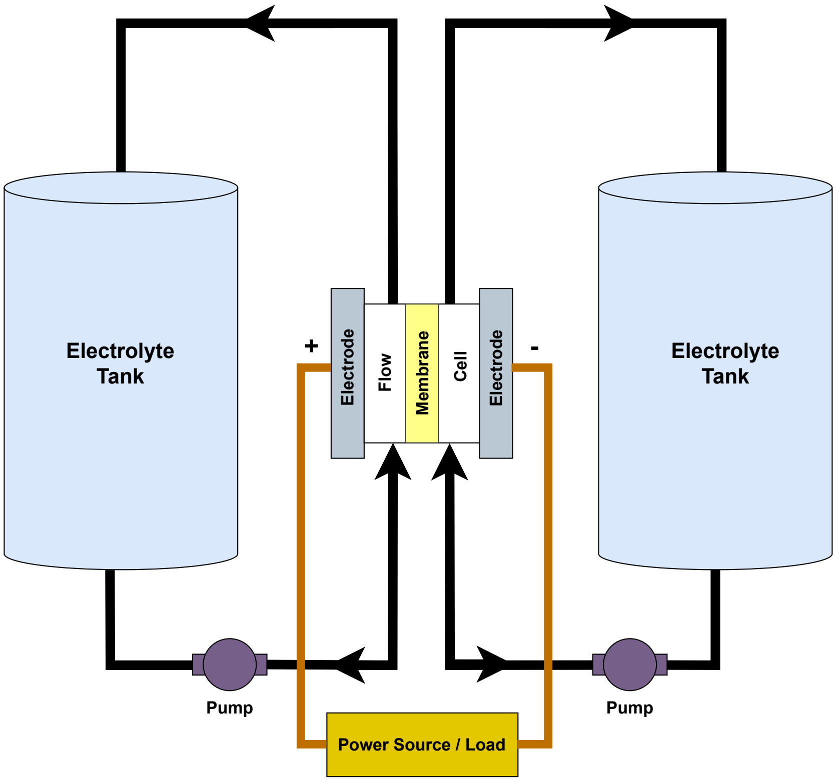


Figure 8. Operational setup of redox flow battery.

However, it is essential to acknowledge the current limitations in the technological maturity of supercapacitors in the domain of IoT applications. As of now, their integration as standalone energy storage solutions in IoT systems remains largely theoretical and requires further research and development.

4. Battery Evaluation

In this section, each of the different battery types will be evaluated according to their suitability for different IoT applications. There are many characteristics that can be used to classify the different battery technologies. The most critical parameters are listed below:

1. Energy density;
2. Temperature range;
3. Longevity;
4. Nominal cell voltage;
5. Safety;
6. Cost;
7. Energy efficiency.

It should be noted that, for most of the parameters, a range of values are reported in various sources. For this research work, the most common values found in the literature are used. Table 1 also summarises the various IoT-based applications in the literature and their choice of batteries.

Table 1. Literature summary of research articles utilising various battery types for each IoT applications. IoT Applications: A—Smart Health, B—Smart Home, C—Smart Cities, D—Smart Industry, E—Smart Farm. Battery Types: I—Lead Acid, II—NiMH, III—Li–ion, IV—LiPo, V—Solid State, VI—Alkaline, VII—Zinc–Air, VIII—Redox Flow, IX—Supercapacitor.

Research Article	**IoT Application**					**Battery Type**								
	A	**B**	**C**	**D**	**E**	**I**	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**
[59]			●				●							
[60]	●						●	●						
[61]				●			●							
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4.1. *Energy and Power Densities*

Energy density is a measure of how much energy a battery can store per unit volume or mass. There are two types of energy density, detailed below.

4.1.1. Gravimetric Energy Density

Gravimetric energy density, also known as specific energy, refers to the amount of energy stored per unit mass of the battery. It is commonly measured in watt-hours per kilogram (Wh/kg). Batteries with high gravimetric energy density are lightweight for their energy capacity, which is a significant advantage in mobile applications. However, a high gravimetric energy density does not necessarily mean that the battery is compact. Some lightweight batteries may occupy a larger volume, which could be a limitation in constrained spaces [81].

4.1.2. Volumetric Energy Density

Volumetric energy density measures how much energy a battery can store per unit volume, commonly expressed in watt-hours per litre (Wh/L). High volumetric energy density is crucial in applications where space is limited but weight is less of a concern, for example, for stationary energy storage systems such as smart grids. Figure 9 illustrates the gravimetric energy density (specific energy) and volumetric energy density, respectively [81,82].

Like energy density, power density is another essential consideration that refers to the rate at which stored energy can be delivered. Much like energy density, power density is categorised into two types: gravimetric and volumetric. Gravimetric power density is measured in watts per kilogram (W/kg), while volumetric power density is measured in watts per litre (W/L) [83,84].

Lead–acid batteries, for instance, offer an energy density of 40 Wh/kg [85], a relatively low figure, limiting their use in energy-intensive applications. They serve as a benchmark in the battery industry, often overshadowed by more advanced options in terms of energy retention capabilities. NiMH batteries exhibit a higher energy density than the lead–acid batteries often in the range of 40–110 Wh/kg [86]. In contrast, lithium–ion (Li–ion) batteries showcase a broader spectrum of performance, with a gravimetric energy density of around 180 Wh/kg [85,87].

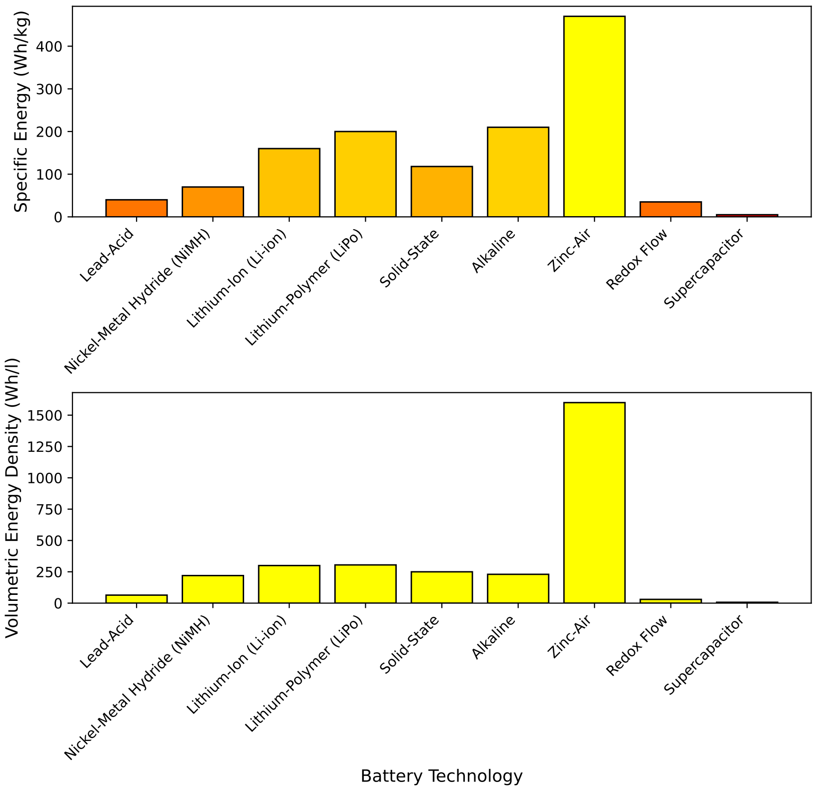


Figure 9. Average specific energy and volumetric energy density for different battery technologies. Average values obtained from articles.

The world of supercapacitors and flow batteries introduces additional considerations. Supercapacitors boast an incredibly high specific power (up to 10,000 W/kg) but fall short in specific energy, offering only 5 Wh/kg—significantly lower than Li–ion batteries [88]. They also have a linear discharge curve, which can be a disadvantage compared to the steady voltage delivery seen in electrochemical batteries. Flow batteries, mirroring the specific energy of lead–acid types (≈30 W/kg), find their niche in bulk energy storage, owing to their moderate power density and ramp-up speed, rather than in applications requiring swift power delivery [89,90].

Zinc–air batteries, with their high specific energy of around 500 Wh/kg [91], offer unique benefits and challenges. They are cost-effective, with a minimal self-discharge rate, making them suitable for specific low-power applications.

Lastly, the common alkaline batteries used in households underscore the trade-offs between performance and convenience. While they offer more or similar energy density to average Li–ion batteries under certain conditions [92], they do not match Li–ion batteries' performance under load. Their reliability lies in their very low self-discharge and greater leak resistance, marking their suitability for low-demand contexts.

4.2. Longevity

The longevity of batteries refers to the lifespan or duration over which a battery remains effective and capable of holding a charge and can be classified into shelf life and cycle life. Shelf life refers to the duration for which batteries can be stored without losing their charge or quality. A longer shelf life is beneficial for users, as it allows for more flexibility in stocking and deploying batteries [93]. Table 2 provides a summary of the estimated shelf life of batteries.

Table 2. Approximate shelf life of different battery technologies.

Battery Type	**Shelf Life (at Ideal Conditions)**
Lead–Acid	3–8 years
Nickel–Metal Hydride (NiMH)	4–6 years
Lithium–Ion (Li–ion) (Non-Rechargable)	5–10 years
Lithium–Ion (Li–ion) (Rechargable)	5 year
Lithium–Polymer (LiPo)	2–3 years
Solid-State	≈33 years
Alkaline	4–7 years
Zinc–Air	≈2 years
Redox Flow	≈20 years
Supercapacitor	Unlimited at discharged state

A primary factor that contributes to the shelf life is the self-discharge rate. It is the slow discharge over time even when the battery is not connected to any load [83,94]. Alkaline (2–3%), lead–acid (4–6%), lithium–ion (≈5%), and lithium polymer (>5%) batteries have a lower self-discharge rate per month compared to other battery types [81,95,96]. Zinc–air batteries follow them with ≈7% per month [97]. NiMH batteries and supercapacitors have the highest self-discharge rates. The NiMH battery has ≈5 to 20% of self-discharge in the first 24 h after a full charge [96].

For healthcare applications based on the Internet of Things (IoT), devices such as medical alert systems require a reliable battery life, and selecting batteries with minimal self-discharge is essential to ensure reliability. These devices are often used in critical life-saving situations and hence require a longer shelf life [14]. For smart home devices like smart thermostats and security cameras, a longer battery shelf life means less frequent replacements. This reduces maintenance costs and increases convenience for homeowners. On the other hand, for smart industry and city-related applications such as traffic management systems, public safety, and industrial automation, the scale is much larger. A longer shelf life will help address logistical challenges of frequent battery replacements in devices.

Proper storage conditions and choosing appropriate battery types can mitigate the self-discharge effect, ensuring that the batteries retain their charge for longer periods while in storage.

Cycle life refers to the number of complete charge and discharge cycles a storage device can undergo while still maintaining acceptable performance levels. It is a critical factor to consider, particularly when selecting rechargeable batteries, as it can directly affect the lifespan and usefulness of the device. A higher cycle life indicates a longer lifespan and greater value for the user.

To determine a battery's cycle life, multiple charge and discharge cycles are performed while monitoring the battery's capacity. It is essential to consider cycle life when selecting a storage device, particularly for IoT applications that require high performance and reliability over an extended period. Figure 10 compares an approximate cycle life time with different battery types.

However, it is worth noting that cycle life depends on various factors such as temperature [98], charge and discharge rate, cycle interval, and active material characteristics.

4.3. Nominal Cell Voltage

Nominal cell voltage is a standardised measure used to categorise and compare batteries of the same or similar chemistry. It refers to the average or rated voltage that a battery cell is designed to deliver during its discharge cycle. IoT devices often operate under constraints such as low power availability. Thus, understanding a battery's nominal voltage can help design energy-efficient circuits and systems. Selecting a battery with an appropriate nominal voltage for the IoT device's power needs can optimise its operational lifespan (Table 3).

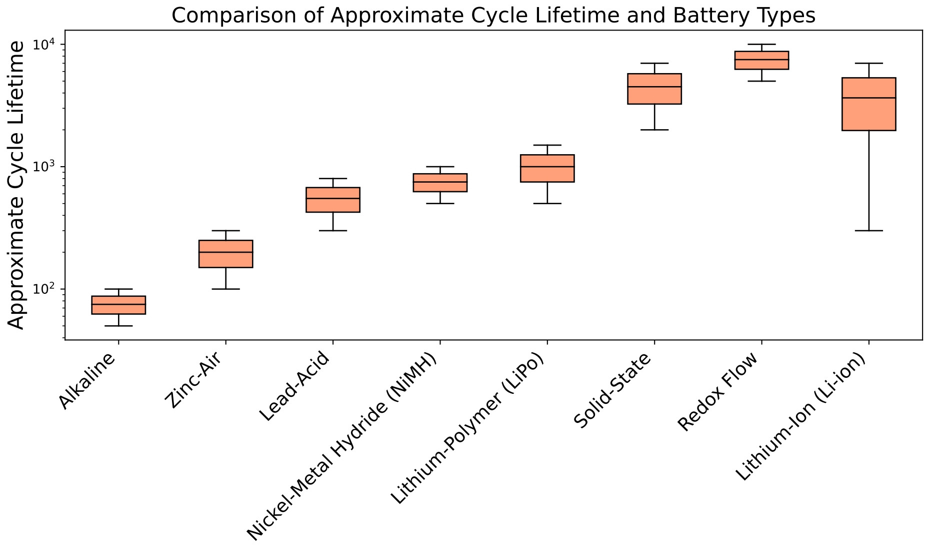


Figure 10. A comparison of approximate cycle life time and battery type.

Table 3. Nominal cell voltage of different battery types.

Battery Type	Nominal Cell Voltage (V)
Lead–Acid	2.1
Nickel–Metal Hydride (NiMH)	1.2
Lithium–Ion (Li–ion)	3.6
Lithium–Polymer (LiPo)	3.7
Solid-State	3.7
Alkaline	1.5
Zinc–Air	1.4
Redox Flow	1.4
Supercapacitor	2.7

4.4. Cost

It is essential to consider the cost of battery chemistry when selecting a battery for IoT applications. The primary factors determining the cost are the battery chemistry, materials, and manufacturing process. The choice of battery type depends on the specific requirements of the IoT application. For example, lead–acid batteries are a traditional choice due to their cost-effectiveness and reliability. However, their bulky nature may be a drawback, especially in wearable and portable healthcare devices. NiMH batteries are moderately priced and offer a decent energy density, making them suitable for non-wearable healthcare IoT and smart home applications. Li–ion and LiPo batteries have a slightly higher cost but are a popular choice in most IoT devices due to their high energy efficiency and compact nature. Supercapacitors can offer excellent performance; however, they have a high cost in the current market, which is expected to decrease as the technology matures in the future [99,100]. Table 4 summarises the cost of batteries per Wh in USD.

Another important factor to consider when evaluating batteries is their environmental disposal costs. Many studies analyse the environmental impact of battery disposal, including toxicity, material recovery, and recycling complexity.

Lead–acid batteries have a well-established recycling infrastructure, making them highly recyclable. However, they are environmentally toxic, particularly in freshwater and marine ecosystems, resulting in higher environmental costs [101].

Lithium–ion and lithium–polymer batteries have similar environmental costs as they rely on expensive materials such as lithium, manganese, and cobalt, which can lead to resource depletion. Although research is ongoing to improve their recyclability, their increasing demand necessitates careful consideration of their environmental impact [102].

Alkaline and zinc–air batteries have a lower environmental impact due to their use of more common materials. Solid-state batteries, an emerging technology, are still under study regarding their life cycle analysis [103,104].

Table 4. Approximate cost range of different battery types.

Battery Types	Approximate per Wh Cost Range (USD)
Lithium–Ion	0.9361
Lead–Acid	0.6975
Nickel Metal Hydride	0.8546
Alkaline	0.1
Lithium–Polymer	2.3095
Solid-State Battery	0.8
Zinc–Air	0.3095
Redox Flow	5.7
Supercapacitors	5

4.5. Operating Temperature

The temperature parameters have a significant impact on the battery's electrochemical properties, efficiency, capacity, aging mechanism, and safety. It is crucial to operate batteries within specific temperature limits (Figure 11) to ensure optimal performance. For instance, in lithium–ion batteries at lower temperatures, the plating of metallic lithium on the anode accelerates the ageing process. In contrast, at higher temperatures, the cathode degrades, causing an increase in the internal resistance and a decrease in capacity due to the growth of the solid electrolyte interface layer. Thermal stability is also crucial to ensure the battery remains safe to use under varying temperature conditions. A lack of thermal stability can cause dangerous situations such as thermal runaway, which may lead to a fire or explosion. Therefore, when selecting the right battery for an IoT application, it is vital to understand and consider temperature-related parameters to provide the desired performance and safety.

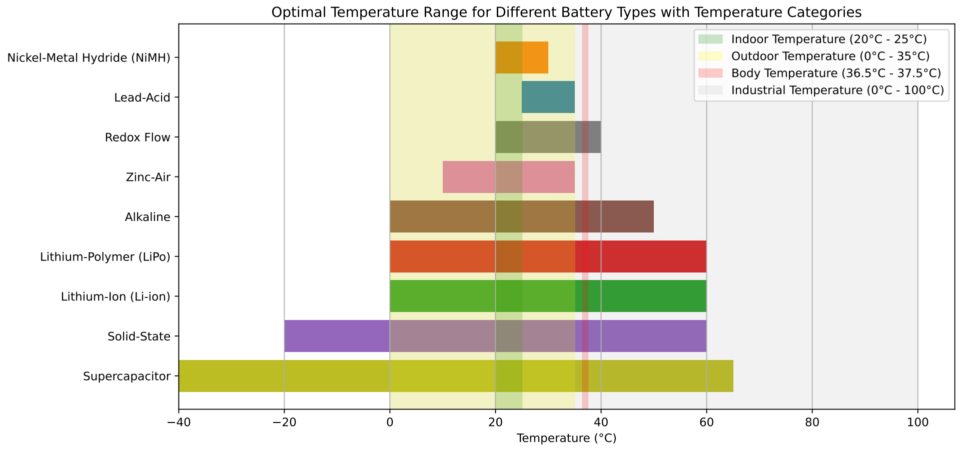


Figure 11. Temperature range for IoT applications and suitable battery types.

4.6. Energy Efficiency

Energy efficiency is the ratio of discharged energy to charged energy. Energy losses are converted into heat that must be dissipated to avoid battery overheating. Figure 12 illustrates the energy efficiency of different batteries.

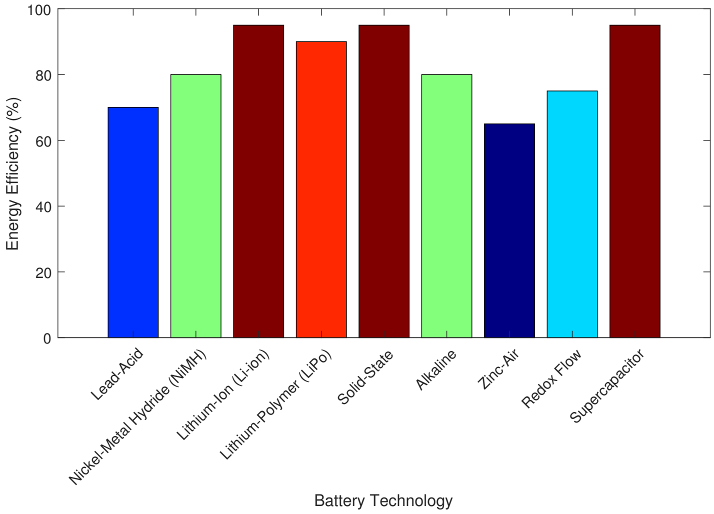


Figure 12. Average energy efficiency of different battery technologies.

4.7. Safety

The diverse nature of IoT applications, ranging from wearable healthcare gadgets to smart industrial setups, demands careful consideration regarding their safety, especially in the human body proximity devices such as wearables. In applications that require close and prolonged contact between wearable batteries and human skin, safety and medical compatibility are major concerns [105]. The primary issue involves tissue or skin allergy and toxicity. Lead–acid batteries pose more significant risks due to their toxic chemical compositions and operational requirements [85]. Hence, they are usually ranked lower in terms of safety. Lithium-based batteries (Li–ion and LiPo) are widely used battery chemistry in most IoT devices. However, there is a risk of thermal runaway if the device is poorly managed. Alkaline and zinc–Air batteries are safer when compared to the other battery types. These batteries are required to meet the standards set by IEC 60086-2 [106]. Table 5 shows the safety considerations for each type of battery.

Table 5. Safety considerations of different types of batteries.

Battery Type	Notes
Lead–Acid Batteries	Generally safe if maintained properly. Hazardous materials present.
Nickel–Metal Hydride (NiMH) Batteries	Known for good safety profile, but can experience thermal runaway if overcharged.
Lithium–Ion (Li–ion) Batteries	Known for potential safety risks such as fires and explosions, particularly in electric vehicles.
Lithium–Polymer (LiPo) Batteries	Similar safety concerns as Li–ion, with additional risk due to flexible casing.
Solid-State Batteries	Known for better safety due to solid electrolyte, reducing the risk of leakage and thermal runaway.
Alkaline Batteries	Generally safe, but may leak caustic potassium hydroxide if damaged or over-discharged.
Zinc–Air Batteries	Known for safety, but can suffer from drying out which can affect performance.
Flow Batteries	Known for good safety profile as they typically contain non-flammable electrolytes.
Supercapacitor	Generally safe, but may pose risks if subjected to over-voltage conditions.

5. Requirements for IoT Applications

When designing an IoT system that includes a wireless network, processing unit and end nodes, several crucial factors need to be examined in detail. One of the primary considerations is the energy density requirement of the system, which must be optimised to ensure efficient and effective operation. In addition, the power consumption needs to be carefully analysed to ensure that the system can carry out its intended functions without rapid battery depletion. It is important to ensure that the battery life is long to guarantee that the system can operate for an extended period before requiring a replacement. Finally, safety is crucial during the design phase to prevent any potential hazards to users or the environment.

Wireless networks like BLE (Bluetooth Low Energy), LoRaWAN, GSM, and Wi-Fi play crucial roles in the IoT system. The communication between devices and these networks is often the most power-intensive part of the system, and their battery requirements vary significantly due to their inherent design and operation. Several studies have compared the power consumption of these wireless networks for various applications (Table 6) [5,107]. BLE is known for its low power consumption, making it suitable for applications with crucial battery life. BLE's low power consumption is followed by LoRa, which is also designed for low power consumption but over longer ranges compared to BLE. On the other hand, while offering higher bandwidth, Wi-Fi tends to have higher power consumption than BLE and LoRa, which could lead to shorter battery life in IoT applications. IoT over cellular networks, such as EC-GSM-IoT and NB-IoT, is designed to be a low power wide area network (LPWAN) technology with long-range communication while conserving energy.

Table 6. IoT network overview.

Technology	Power Consumption	Energy Density Requirements	Range	Battery Life Expectancy	Typical Applications
BLE	Very Low	Low	Short (up to 10 m)	Medium	Wearables, Beacons
LoRaWAN	Low	Medium	Long	Long	Remote Sensors, Agriculture Monitoring
IoT over Cellular Network	Low	Medium	Long	Long	Smart Meters, Asset Trackers
WiFi	High	High	Short	Short	Smart Home, Industrial IoT

Sensor and end nodes in IoT systems are often designed to operate within a selected network for an extended period. The energy density requirement of a sensor node is typically inferred from the device's power consumption, size, and coverage range, which are crucial factors in the battery selection process. In healthcare IoT applications, such as wearable sensors, there is an emphasis on extended battery life, miniaturisation, safety, and minimal maintenance [108]. These applications often utilise the BLE network, which requires a smaller coverage range. Hence, the energy density requirements are medium.

For smart home applications, focusing on home automation systems and smart appliances, the predominant use of WiFi necessitates higher energy density. The need for continuous operation without frequent recharging, especially in compact devices like security cameras and smart locks, underscores the importance of high-energy-density batteries [109]. In smart city applications, the diverse functionalities—encompassing public safety, transportation, and environmental monitoring—require sensors that cover extensive areas and handle significant data transmission. These systems typically rely on Cellular-IoT and LoRa for long-range and city-wide coverage, necessitating higher energy density for reliability and longevity, particularly as these devices are not significantly size-constrained. Similarly, in smart industry, IoT devices can be larger, and the harsh operating environments, combined with the need for continuous, uninterrupted operation, justify a moderate-to-high energy density requirement.

Contrarily, smart agriculture systems often utilise IoT networks capable of longer ranges. These may not require miniaturization, exhibit a higher tolerance for maintenance, and have access to more robust power sources [110]. Therefore, energy density requirements in smart agriculture are lower compared to the aforementioned applications.

Longevity is another crucial parameter that needs to be considered while selecting batteries. For sensor nodes deployed in remote locations, smart waste management applications [111], or asset trackers, the primary constraints are the cost of replacing the batteries and the labour required for the replacement. Therefore, battery life should be able to last for several months up to more than ten years, meeting the high life expectancy demands for batteries.

To maximise life and provide an efficient energy solution, IoT devices are often used with energy harvesters, run optimised algorithms that schedule power-saving modes, and employ battery and power management circuits. Energy harvesting provides a sustainable way to power IoT devices by using renewable resources to generate electricity [112]. It utilises ambient energy from sources such as solar [112], tribo-electric [113], or mechanical vibrations [114] to power the IoT device, or stores the energy for future use. The energy storage can be a rechargeable battery, a supercapacitor, or a combination of both, each with its own advantages and limitations, which are outside the scope of this review. For example, the combination of the energy harvesting system and the micro energy storage unit in wearable devices enables the continuous power supply in different circumstances [115].

In the context of IoT applications across various domains, the importance of battery safety varies, reflecting the unique operational environments and the potential risks associated with each application. For smart city applications, which include public safety, traffic management, and environmental monitoring, the importance of battery safety is acknowledged with moderate importance. This is attributed to the robust safety protocols, emergency response systems, and redundancy features inherent in smart city infrastructures, effectively mitigating the impact of battery safety issues in densely populated urban settings.

In contrast, smart home and smart health IoT applications warrant a crucial emphasis on the safety property of the battery. Smart home devices, powering essential functions like security systems and smoke detectors, directly influence personal safety and property. The lack of comprehensive safety infrastructure akin to public spaces elevates the significance of battery safety in home environments. Similarly, in healthcare, battery safety is paramount. Given the life-critical nature of these devices and due to the fact that these batteries may often be in contact with the body, any failure due to battery issues poses a significant risk, making safety a top priority [116]. Conversely, smart industry and smart farming applications, involving automation and monitoring in manufacturing and agricultural environments, respectively, are assigned a lower safety rating. This is reflective of the stringent safety standards and protocols in industrial settings, coupled with the less densely populated nature of farms, which collectively reduce the direct human risk associated with battery malfunctions in these sectors. These varied rankings underscore the differential prioritisation of battery safety, shaped by the direct human risk, the operational context of the IoT applications, and the existing safety infrastructure and protocols within each domain.

The operating temperature range of a battery is a crucial consideration that varies significantly across different application contexts. In smart health applications, the importance of this factor is amplified due to the critical nature of medical devices. Thermal imbalances in batteries can pose serious safety risks and lead to device malfunctions. However, the emphasis lowers for applications predominantly exposed to outdoor and varied environments—such as in smart cities, industrial settings, and smart farms. In these scenarios, the ability to rely on a specific temperature operating range is limited by the broad temperature fluctuations these environments experience. Moreover, prioritization of other factors, such as longevity, energy density and cost, takes precedence over the battery's temperature operating range. In the context of smart home applications, extreme temperature tolerance is less critical due to generally more controlled indoor environments, but it remains a moderately important factor in ensuring the reliability and longevity of a wide array of home devices, from essential security systems to everyday appliances.

The significance of energy efficiency in various IoT applications is uniformly important. This consistent prioritization reflects a universal recognition of the critical role that energy efficiency plays in the performance of IoT systems, irrespective of their specific application contexts. Similarly, cost is a crucial factor for all the domains.

Efficient solutions that use batteries require battery management circuits and algorithms. These monitor and manage the battery's performance by overseeing the charging and discharging processes. This ensures that the battery operates safely and efficiently. A battery management system (BMS) is essential to prolong the battery's life and maintain the performance of the device it powers. The key functionalities of a BMS include monitoring the state of charge (SoC), state of health (SoH), and the temperature of the battery. BMS ensures that batteries operate within safe parameters, which is critical to prevent any potential hazards, especially in healthcare and smart home applications [117].

From the discussion of different battery technologies described earlier, the performance of the batteries were quantified on a number scale of 1–5, with 1 representing poor performance and 5 representing excellent performance across different parameters. For instance, zinc–air batteries are awarded a top score of 5 for energy density to acknowledge their superior energy storage capabilities per unit mass. On the contrary, supercapacitors, which possess significantly lower energy density, receive the lowest score of 1 in this category. This scoring framework allows for a clear, quantifiable comparison of battery characteristics, facilitating the selection of the most appropriate technology for a given application based on performance metrics. The resultant ranking of each battery technology across different characteristics (e.g., longevity, energy efficiency) is illustrated in Figure 13.

Based on the discussion in the earlier sections, the significance of battery properties for different IoT applications is highlighted in Table 7. Employing a methodology similar to the one used for the radar chart in Figure 13, these metrics are quantitatively assessed on a scale from 1 to 5. Here, a score of 1 denotes "Least priority", 2 indicates "Low priority", 3 is "Moderate priority", 4 stands for "Important priority", and 5 signifies "Crucial priority".

Table 7. IoT application requirements.

	Energy Density	**Temperature Operating Range**	**Energy Efficiency**	**Longevity**	**Cost**	**Safety**
Smart City	Important	Low	Important	Important	Crucial	Moderate
Smart Home	Important	Moderate	Important	Moderate	Crucial	Crucial
Smart Health	Moderate	Important	Important	Important	Crucial	Crucial
Smart Industry	Moderate	Low	Important	Important	Crucial	Low
Smart Farm	Low	Low	Important	Important	Crucial	Low

The synergy between these two ranking systems was then analysed to identify the level of similarity, which resulted in the development of the battery–application compatibility matrix, illustrated in Figure 14. This matrix provides a visual representation and a quantitative measure of how well the performance attributes of various battery technologies correspond to the requirements of different IoT applications. This comparative analysis serves as a foundational tool for identifying the most compatible battery technology for each IoT application, ensuring optimised performance and efficiency. A higher matrix value indicates a more suitable battery–application match and vice-versa for a lower matrix value.

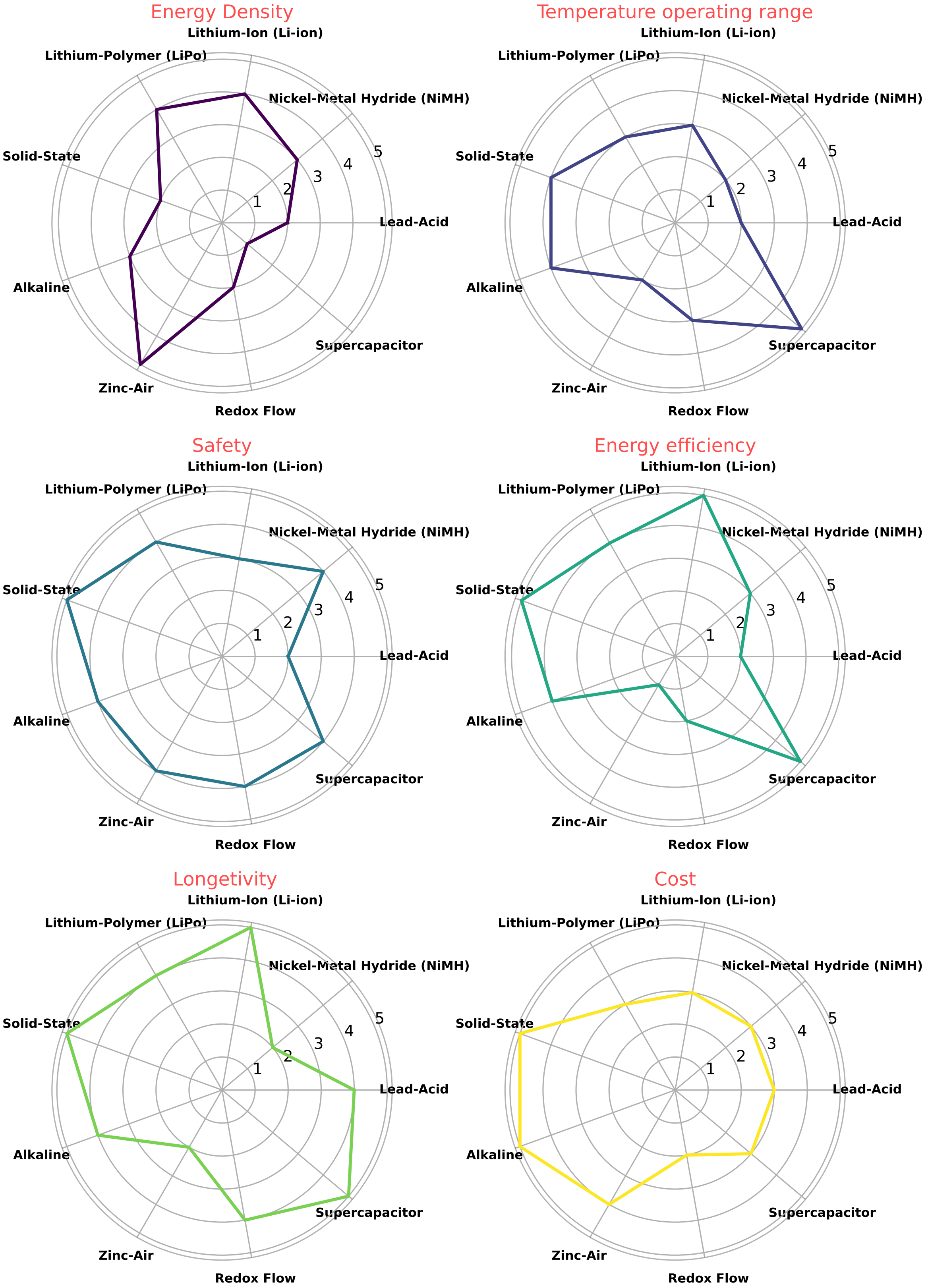
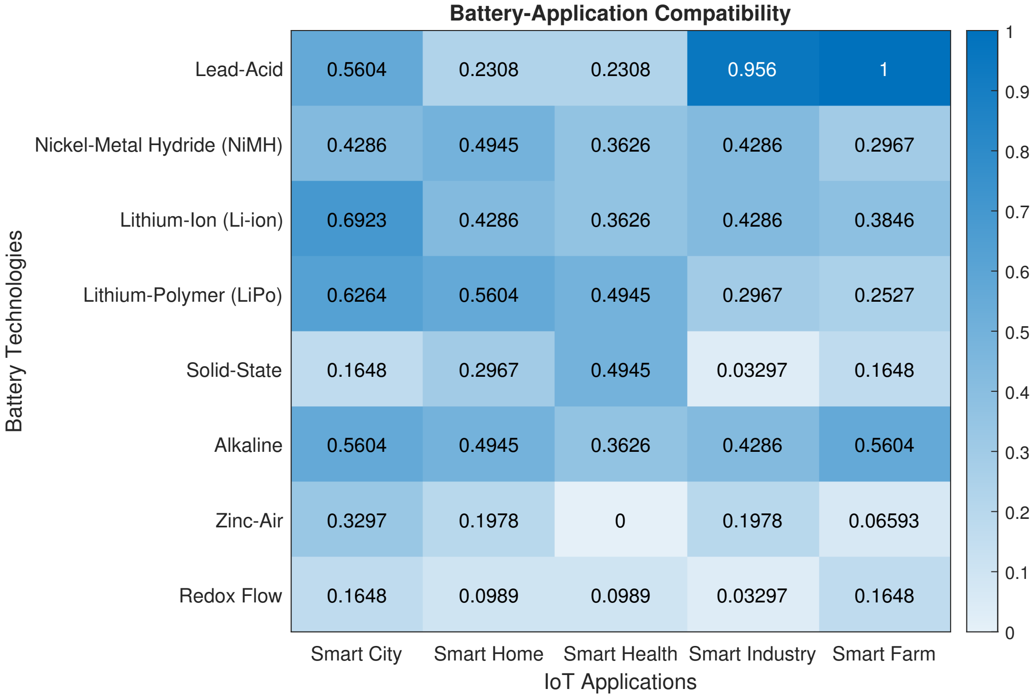


Figure 13. Comparison of battery technologies across different categories.



Battery Technologies	Smart City	Smart Home	Smart Health	Smart Industry	Smart Farm
Lead-Acid	0.5604	0.2308	0.2308	0.956	1
Nickel-Metal Hydride (NiMH)	0.4286	0.4945	0.3626	0.4286	0.2967
Lithium-Ion (Li-ion)	0.6923	0.4286	0.3626	0.4286	0.3846
Lithium-Polymer (LiPo)	0.6264	0.5604	0.4945	0.2967	0.2527
Solid-State	0.1648	0.2967	0.4945	0.03297	0.1648
Alkaline	0.5604	0.4945	0.3626	0.4286	0.5604
Zinc-Air	0.3297	0.1978	0	0.1978	0.06593
Redox Flow	0.1648	0.0989	0.0989	0.03297	0.1648

Figure 14. Battery–application compatibility matrix.

As this paper discusses both primary and secondary batteries, rechargeability is an important factor to consider. All the IoT applications discussed have a preference for rechargeable batteries. For example, rechargeable batteries are highly valued in smart home applications as they power various devices that require frequent use, such as smart thermostats, security cameras, and home automation controllers. The ability to recharge reduces the inconvenience and expense of replacing batteries and is consistent with the consumer expectation for low-maintenance and cost-effective home technology solutions.

Therefore, the impact of primary battery sources was weighted to a factor of 0.75 (which indicates that, although rechargeability is of considerable importance, it does not singularly dictate a battery’s appropriateness for an IoT application).

Lithium–ion (Li–ion) batteries exhibit a high compatibility score of 0.6923 in smart city applications, which underscores their suitability for urban technological infrastructure. Their high energy density, longevity, and lightweight nature make them ideal for various energy-intensive smart city applications such as street lighting and traffic monitoring. Conversely, lead–acid batteries, with a compatibility score of 0.5604, present a moderate fit, likely favoured for their reliability and cost-efficiency in backup power solutions.

For smart home environments, lithium–polymer (LiPo) batteries show strong compatibility with a score of 0.5604, reflecting their growing presence in household electronics. Alkaline batteries also register a high compatibility score of 0.5604, aligning with their widespread use in consumer devices. Notably, while innovative, solid-state batteries have a lower compatibility score of 0.2967, suggesting that their current application in domestic settings may be limited.

In the domain of smart health, alkaline batteries stand out with a high compatibility score, indicating their prevalent use in medical devices due to their reliability and safety profile. The similar scores of NiMH, LiPo, and solid-state batteries, all around the 0.4945 mark, suggest their applicability in various health monitoring technologies despite their current less dominant position than alkaline batteries in this sector. Interestingly, zinc–air batteries, which are widely used in wearable applications due to their high energy density and compactness, have a lower score in almost all applications. This is primarily due to the cost and lifespan considerations of the compatibility matrix. Furthermore, zinc–air batteries possess a very low capacity for the high-current requirement that occurs when wireless transmission is active [118].

Turning to the smart industry, lead–acid batteries again score highly with 0.956, likely due to their robustness and capacity to provide backup power in industrial operations. This starkly contrasts the solid-state batteries, which score a mere 0.03297, indicating that, while they may offer benefits in other applications, they are not yet a mainstay in industrial settings.

In agricultural settings, characterised here as smart farm systems, lead–acid batteries also dominate with the highest compatibility score of 1, which reflects their reliability and cost-effectiveness for operations in remote or demanding environments. Meanwhile, zinc–air and Redox Flow batteries, with the lowest scores of 0.06593 and 0.1648, respectively, suggest that they may not be currently optimised for the heavy-duty and varied power demands of smart farming technologies.

6. Conclusions

In this paper, a systematic, critical evaluation of different battery technologies was presented for suitability of use in different types of IoT-based applications. Despite the prevalence of lithium–ion batteries, it was seen that there are other viable alternatives that may be more compatible for certain applications. In the realm of smart city applications, lithium–ion (Li–ion) batteries are considered the most suitable, followed by lithium–polymer, alkaline, and lead–acid batteries, which are also compatible with various applications. For smart homes, lithium–polymer, NiMH, and alkaline batteries are preferred. On the other hand, for smart health, lithium–polymer and solid-state batteries show potential. In smart industry and smart farm systems, lead–acid batteries emerge as the top choice due to their durability and cost-effectiveness. The battery–application compatibility matrix provided in this paper is a novel visualisation tool which provides a quantitative evaluation of the alignment between the performance characteristics of diverse battery technologies and the demands of various IoT applications. This work can serve as a reference point for researchers looking for suitable battery technology for their prospective IoT application.

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References

1. Lohiya, R.; Thakkar, A. Application Domains, Evaluation Data Sets, and Research Challenges of IoT: A Systematic Review. *IEEE Internet Things J.* **2021**, *8*, 8774–8798. [CrossRef]
2. Al-kahtani, M.S.; Khan, F.; Taekeun, W. Application of Internet of Things and Sensors in Healthcare. *Sensors* **2022**, *22*, 5738. [CrossRef] [PubMed]
3. Ma, Y.; Wang, Y.; Yang, J.; Miao, Y.; Li, W. Big Health Application System based on Health Internet of Things and Big Data. *IEEE Access* **2017**, *5*, 7885–7897. [CrossRef]
4. Baker, S.B.; Xiang, W.; Atkinson, I. Internet of Things for Smart Healthcare: Technologies, Challenges, and Opportunities. *IEEE Access* **2017**, *5*, 26521–26544. [CrossRef]
5. Wu, F.; Rüdiger, C.; Redouté, J.M.; Yuce, M.R. WE-Safe: A wearable IoT sensor node for safety applications via LoRa. In Proceedings of the 2018 IEEE 4th World Forum on Internet of Things (WF-IoT), Singapore, 5–8 February 2018; pp. 144–148. [CrossRef]
6. Xu, J.; Gu, B.; Tian, G. Review of agricultural IoT technology. *Artif. Intell. Agric.* **2022**, *6*, 10–22. 10.1016/j.aiia.2022.01.001 [CrossRef]
7. Dhanaraju, M.; Chenniappan, P.; Ramalingam, K.; Pazhanivelan, S.; Kaliaperumal, R. Smart Farming: Internet of Things (IoT)-Based Sustainable Agriculture. *Agriculture* **2022**, *12*, 1745. [CrossRef]
8. Miao, Y.; Hynan, P.; von Jouanne, A.; Yokochi, A. Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements. *Energies* **2019**, *12*, 1074. [CrossRef]
9. Rangarajan, S.S.; Sunddararaj, S.P.; Sudhakar, A.; Shiva, C.K.; Subramaniam, U.; Collins, E.R.; Senjyu, T. Lithium-Ion Batteries—The Crux of Electric Vehicles with Opportunities and Challenges. *Clean Technol.* **2022**, *4*, 908–930. [CrossRef]
10. Chen, W.; Liang, J.; Yang, Z.; Li, G. A Review of Lithium-Ion Battery for Electric Vehicle Applications and Beyond. *Energy Procedia* **2019**, *158*, 4363–4368. [CrossRef]
11. Armenta-Déu, C.; Boucheix, B. Evaluation of Lithium-Ion Battery Performance under Variable Climatic Conditions: Influence on the Driving Range of Electric Vehicles. *Future Transp.* **2023**, *3*, 535–551. [CrossRef]

12. Homssi, B.A.; Al-Hourani, A.; Magowe, K.; Delaney, J.; Tom, N.; Ying, J.; Wolf, H.; Maselli, S.; Kandeepan, S.; Wang, K.; et al. A Framework for the Design and Deployment of Large-Scale LPWAN Networks for Smart Cities Applications. *IEEE Internet Things Mag.* **2021**, *4*, 53–59. [CrossRef]
13. Winter, M.; Brodd, R.J. What Are Batteries, Fuel Cells, and Supercapacitors? *Chem. Rev.* **2004**, *104*, 4245–4270. [CrossRef]
14. Abdulmalek, S.; Nasir, A.; Jabbar, W.A.; Almuhaya, M.A.M.; Bairagi, A.K.; Khan, M.A.M.; Kee, S.H. IoT-Based Healthcare-Monitoring System towards Improving Quality of Life: A Review. *Healthcare* **2022**, *10*, 1993. [CrossRef]
15. Singh, R.P.; Javaid, M.; Haleem, A.; Suman, R. Internet of things (IoT) applications to fight against COVID-19 pandemic. *Diabetes Metab. Syndr. Clin. Res. Rev.* **2020**, *14*, 521–524. [CrossRef]
16. Wu, T.; Wu, F.; Qiu, C.; Redouté, J.M.; Yuce, M.R. A Rigid-Flex Wearable Health Monitoring Sensor Patch for IoT-Connected Healthcare Applications. *IEEE Internet Things J.* **2020**, *7*, 6932–6945. [CrossRef]
17. Farrokhi, A.; Farahbakhsh, R.; Rezazadeh, J.; Minerva, R. Application of Internet of Things and artificial intelligence for smart fitness: A survey. *Comput. Netw.* **2021**, *189*, 107859. [CrossRef]
18. Passos, J.; Lopes, S.I.; Clemente, F.M.; Moreira, P.M.; Rico-González, M.; Bezerra, P.; Rodrigues, L.P. Wearables and Internet of Things (IoT) technologies for fitness assessment: A systematic review. *Sensors* **2021**, *21*, 5418. [CrossRef]
19. Lingg, E.; Leone, G.; Spaulding, K.; B'Far, R. Cardea: Cloud based employee health and wellness integrated wellness application with a wearable device and the HCM data store. In Proceedings of the 2014 IEEE World Forum on Internet of Things (WF-IoT), Seoul, Republic of Korea, 6–8 March 2014; pp. 265–270. [CrossRef]
20. Nagaraj, P.; Muneeswaran, V.; Sudar, K.M.; Ali, R.S.; Someshwara, A.L.; Kumar, T.S. Internet of Things Based Smart Hospital Saline Monitoring System. In Proceedings of the 2021 5th International Conference on Computer, Communication and Signal Processing (ICCCSP), Chennai, India, 24–25 May 2021; pp. 53–58. [CrossRef]
21. Rathnayaka, A.; Gendy, M.E.G.; Wu, F.; Mamun, M.A.A.; Curtis, S.J.; Bingham, G.; Peleg, A.Y.; Stewardson, A.J.; Yuce, M.R. An Autonomous IoT-Based Contact Tracing Platform in a COVID-19 Patient Ward. *IEEE Internet Things J.* **2023**, *10*, 8706–8717. [CrossRef]
22. Siriwardhana, Y.; De Alwis, C.; Gür, G.; Ylianttila, M.; Liyanage, M. The Fight against the COVID-19 Pandemic with 5G Technologies. *IEEE Eng. Manag. Rev.* **2020**, *48*, 72–84. [CrossRef]
23. Hasan, K.; Pour Ebrahim, M.; Yuce, M.R. Real-Time People Counting Using IR-UWB Radar. In *Body Area Networks. Smart IoT and Big Data for Intelligent Health Management*; Ur Rehman, M., Zoha, A., Eds.; Springer: Cham, Switzerland, 2022; pp. 63–70.
24. Alsamhi, S.H.; Ma, O.; Ansari, M.S.; Almalki, F.A. Survey on Collaborative Smart Drones and Internet of Things for Improving Smartness of Smart Cities. *IEEE Access* **2019**, *7*, 128125–128152. [CrossRef]
25. Anagnostopoulos, T.; Zaslavsky, A.; Kolomvatsos, K.; Medvedev, A.; Amirian, P.; Morley, J.; Hadjieftymiades, S. Challenges and Opportunities of Waste Management in IoT-Enabled Smart Cities: A Survey. *IEEE Trans. Sustain. Comput.* **2017**, *2*, 275–289. [CrossRef]
26. Kwon, K.; Lee, S.; Kim, S. AI-Based Home Energy Management System Considering Energy Efficiency and Resident Satisfaction. *IEEE Internet Things J.* **2022**, *9*, 1608–1621. [CrossRef]
27. Kelly, S.D.T.; Suryadevara, N.K.; Mukhopadhyay, S.C. Towards the Implementation of IoT for Environmental Condition Monitoring in Homes. *IEEE Sens. J.* **2013**, *13*, 3846–3853. [CrossRef]
28. Al-Ali, A.; Zualkernan, I.A.; Rashid, M.; Gupta, R.; Alikarar, M. A smart home energy management system using IoT and big data analytics approach. *IEEE Trans. Consum. Electron.* **2017**, *63*, 426–434. [CrossRef]
29. Ramson, S.R.J.; León-Salas, W.D.; Brecheisen, Z.; Foster, E.J.; Johnston, C.T.; Schulze, D.G.; Filley, T.; Rahimi, R.; Soto, M.J.C.V.; Bolivar, J.A.L.; et al. A Self-Powered, Real-Time, LoRaWAN IoT-Based Soil Health Monitoring System. *IEEE Internet Things J.* **2021**, *8*, 9278–9293. [CrossRef]
30. Hu, W.J.; Fan, J.; Du, Y.X.; Li, B.S.; Xiong, N.; Bekkering, E. MDFC–ResNet: An Agricultural IoT System to Accurately Recognize Crop Diseases. *IEEE Access* **2020**, *8*, 115287–115298. [CrossRef]
31. Sharma, A.; Jain, A.; Gupta, P.; Chowdary, V. Machine Learning Applications for Precision Agriculture: A Comprehensive Review. *IEEE Access* **2021**, *9*, 4843–4873. [CrossRef]
32. Farooq, M.S.; Sohail, O.O.; Abid, A.; Rasheed, S. A Survey on the Role of IoT in Agriculture for the Implementation of Smart Livestock Environment. *IEEE Access* **2022**, *10*, 9483–9505. [CrossRef]
33. Lopes, P.P.; Stamenkovic, V.R. Past, present, and future of lead–acid batteries. *Science* **2020**, *369*, 923–924. [CrossRef]
34. Zito, R. *Energy Storage: A New Approach*; John Wiley & Sons: Hoboken, NJ, USA, 2010; Volume 26.
35. Chang, S.; Young, K.; Nei, J.; Fierro, C. Reviews on the U.S. Patents Regarding Nickel/Metal Hydride Batteries. *Batteries* **2016**, *2*, 10. [CrossRef]
36. Ruetschi, P.; Meli, F.; Desilvestro, J. Nickel-metal hydride batteries. The preferred batteries of the future? *J. Power Sources* **1995**, *57*, 85–91. [CrossRef]
37. Goodenough, J.B.; Park, K.S. The Li-Ion Rechargeable Battery: A Perspective. *J. Am. Chem. Soc.* **2013**, *135*, 1167–1176. [CrossRef]
38. Nitta, N.; Wu, F.; Lee, J.T.; Yushin, G. Li-ion battery materials: Present and future. *Mater. Today* **2015**, *18*, 252–264. [CrossRef]
39. Manthiram, A. A reflection on lithium-ion battery cathode chemistry. *Nat. Commun.* **2020**, *11*, 1550. [CrossRef]
40. Deng, D. Li-ion batteries: Basics, progress, and challenges. *Energy Sci. Eng.* **2015**, *3*, 385–418. [CrossRef]
41. Wang, K.; Wan, J.; Xiang, Y.; Zhu, J.; Leng, Q.; Wang, M.; Xu, L.; Yang, Y. Recent advances and historical developments of high voltage lithium cobalt oxide materials for rechargeable Li-ion batteries. *J. Power Sources* **2020**, *460*, 228062. [CrossRef]

42. Thackeray, M.M. Manganese oxides for lithium batteries. *Prog. Solid State Chem.* **1997**, *25*, 1–71. [CrossRef]
43. Dou, S. Review and prospect of layered lithium nickel manganese oxide as cathode materials for Li-ion batteries. *J. Solid State Electrochem.* **2013**, *17*, 911–926. [CrossRef]
44. Fröhlich, K.; Legotin, E.; Bärhold, F.; Trifonova, A. New large-scale production route for synthesis of lithium nickel manganese cobalt oxide. *J. Solid State Electrochem.* **2017**, *21*, 3403–3410. [CrossRef]
45. Satyavani, T.; Kumar, A.S.; Rao, P.S. Methods of synthesis and performance improvement of lithium iron phosphate for high rate Li-ion batteries: A review. *Eng. Sci. Technol. Int. J.* **2016**, *19*, 178–188. [CrossRef]
46. Long, L.; Wang, S.; Xiao, M.; Meng, Y. Polymer electrolytes for lithium polymer batteries. *J. Mater. Chem. A* **2016**, *4*, 10038–10069. [CrossRef]
47. Stephan, A.M.; Nahm, K. Review on composite polymer electrolytes for lithium batteries. *Polymer* **2006**, *47*, 5952–5964. [CrossRef]
48. Zurbuchen, A.; Haeberlin, A.; Pfenniger, A.; Bereuter, L.; Schaerer, J.; Jutzi, F.; Huber, C.; Fuhrer, J.; Vogel, R. Towards Batteryless Cardiac Implantable Electronic Devices—The Swiss Way. *IEEE Trans. Biomed. Circuits Syst.* **2017**, *11*, 78–86. [CrossRef]
49. Munshi, M.Z.A. *Handbook of Solid State Batteries & Capacitors*; World Scientific: Singapore, 1995.
50. Julien, C.; Nazri, G.A. *Solid State Batteries: Materials Design and Optimization*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013; Volume 271.
51. Hossain, E.; Faruque, H.M.R.; Sunny, M.S.H.; Mohammad, N.; Nawar, N. A comprehensive review on energy storage systems: Types, comparison, current scenario, applications, barriers, and potential solutions, policies, and future prospects. *Energies* **2020**, *13*, 3651. [CrossRef]
52. Salkind, A.J.; Klein, M. *Batteries, Alkaline Secondary Cells*; Wiley: Hoboken, NJ, USA, 2000.
53. Olabi, A.G.; Sayed, E.T.; Wilberforce, T.; Jamal, A.; Alami, A.H.; Elsaid, K.; Rahman, S.M.A.; Shah, S.K.; Abdelkareem, M.A. Metal-Air Batteries—A Review. *Energies* **2021**, *14*, 7373. [CrossRef]
54. Wang, C.; Yu, Y.; Niu, J.; Liu, Y.; Bridges, D.; Liu, X.; Pooran, J.; Zhang, Y.; Hu, A. Recent progress of metal–air batteries—A mini review. *Appl. Sci.* **2019**, *9*, 2787. [CrossRef]
55. Li, Y.; Dai, H. Recent advances in zinc–air batteries. *Chem. Soc. Rev.* **2014**, *43*, 5257–5275. [CrossRef]
56. Yao, Y.; Lei, J.; Shi, Y.; Ai, F.; Lu, Y.C. Assessment methods and performance metrics for redox flow batteries. *Nat. Energy* **2021**, *6*, 582–588. [CrossRef]
57. Berrueta, A.; Ursúa, A.; Martín, I.S.; Eftekhari, A.; Sanchis, P. Supercapacitors: Electrical Characteristics, Modeling, Applications, and Future Trends. *IEEE Access* **2019**, *7*, 50869–50896. [CrossRef]
58. Şahin, M.E.; Blaabjerg, F.; Sangwongwanich, A. A Comprehensive Review on Supercapacitor Applications and Developments. *Energies* **2022**, *15*, 674. [CrossRef]
59. Anzola, J.; Jiménez, A.; Tarazona, G. Self-sustainable power-collecting node in IoT. *Internet Things* **2019**, *7*, 100082. [CrossRef]
60. Manupibul, U.; Tanthuwapathom, R.; Jarumethitanont, W.; Kaimuk, P.; Limroongreungrat, W.; Charoensuk, W. Integration of force and IMU sensors for developing low-cost portable gait measurement system in lower extremities. *Sci. Rep.* **2023**, *13*, 10653. [CrossRef]
61. Kadechkar, A.; Riba, J.R.; Moreno-Eguilaz, M.; Pérez, J. SmartConnector: A Self-Powered IoT Solution to Ease Predictive Maintenance in Substations. *IEEE Sens. J.* **2020**, *20*, 11632–11641. [CrossRef]
62. Chakraborty, S.; Arvind, P.; Poddar, S.; Acharya, A.K.; Kumar, S.D. Integration of IoT Based PLC for Smart Relaying of a PV-Fed Induction Motor Driven Conveyor Belt. In Proceedings of the Fifth International Conference on Microelectronics, Computing and Communication Systems, Ranchi, India 2021; pp. 155–165.
63. Elsts, A.; Fafoutis, X.; Woznowski, P.; Tonkin, E.; Oikonomou, G.; Piechocki, R.; Craddock, I. Enabling Healthcare in Smart Homes: The SPHERE IoT Network Infrastructure. *IEEE Commun. Mag.* **2018**, *56*, 164–170. [CrossRef]
64. Lee, B.G.; Lee, S.M. Smart Wearable Hand Device for Sign Language Interpretation System With Sensors Fusion. *IEEE Sens. J.* **2018**, *18*, 1224–1232. [CrossRef]
65. Dieffenderfer, J.P.; Goodell, H.; Bent, B.; Beppler, E.; Jayakumar, R.; Yokus, M.; Jur, J.S.; Bozkurt, A.; Peden, D. Wearable wireless sensors for chronic respiratory disease monitoring. In Proceedings of the 2015 IEEE 12th International Conference on Wearable and Implantable Body Sensor Networks (BSN), Cambridge, MA, USA, 9–12 June 2015; pp. 1–6.
66. Shin, J.H.; Kwon, J.; Kim, J.U.; Ryu, H.; Ok, J.; Joon Kwon, S.; Park, H.; Kim, T.I. Wearable EEG electronics for a Brain–AI Closed-Loop System to enhance autonomous machine decision-making. *npj Flex. Electron.* **2022**, *6*, 32. [CrossRef]
67. Hina Fathima, A.; Palanisamy, K. Battery energy storage applications in wind integrated systems—A review. In Proceedings of the 2014 International Conference on Smart Electric Grid (ISEG), Guntur, India, 19–20 September 2014; pp. 1–8.
68. Archibong, E.I.; Ozuomba, S.; Ekott, E. Internet of Things (IoT)-based, Solar Powered Street Light System with Anti-vandalisation Mechanism. In Proceedings of the 2020 International Conference in Mathematics, Computer Engineering and Computer Science (ICMCECS), Ayobo, Nigeria, 18–21 March 2020; pp. 1–6.
69. Sharma, P.; Salkuti, S.R.; Kim, S.C. Advancements in energy storage technologies for smart grid development. *Int. J. Elect. Comput. Syst. Eng.* **2022**, *12*, 3421. [CrossRef]
70. Aljafari, B.; Vasantharaj, S.; Indragandhi, V.; Vaibhav, R. Optimization of DC, AC, and Hybrid AC/DC Microgrid-Based IoT Systems: A Review. *Energies* **2022**, *15*, 6813. [CrossRef]

71. Vaghasiya, J.V.; Mayorga-Martinez, C.C.; Vyskočil, J.; Sofer, Z.; Pumera, M. Integrated biomonitoring sensing with wearable asymmetric supercapacitors based on ti 3 C 2 MXene and 1T-phase WS 2 nanosheets. *Adv. Funct. Mater.* **2020**, *30*, 2003673. [CrossRef]
72. Ram, S.K.; Das, B.B.; Mahapatra, K.; Mohanty, S.P.; Choppali, U. Energy perspectives in IoT driven smart villages and smart cities. *IEEE Consum. Electron. Mag.* **2020**, *10*, 19–28. [CrossRef]
73. Shrestha, K.; Sharma, S.; Pradhan, G.B.; Bhatta, T.; Rana, S.S.; Lee, S.; Seonu, S.; Shin, Y.; Park, J.Y. A triboelectric driven rectification free self-charging supercapacitor for smart IoT applications. *Nano Energy* **2022**, *102*, 107713. [CrossRef]
74. Mekonnen, Y.; Burton, L.; Sarwat, A.; Bhansali, S. IoT Sensor Network Approach for Smart Farming: An Application in Food, Energy and Water System. In Proceedings of the 2018 IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA, USA, 18–21 October 2018; pp. 1–5. [CrossRef]
75. Lee, S.Y.; Hong, J.H.; Hsieh, C.H.; Liang, M.C.; Chang Chien, S.Y.; Lin, K.H. Low-Power Wireless ECG Acquisition and Classification System for Body Sensor Networks. *IEEE J. Biomed. Health Inform.* **2015**, *19*, 236–246. [CrossRef] [PubMed]
76. Chen, G.; Rodriguez-Villegas, E. System-level design trade-offs for truly wearable wireless medical devices. In Proceedings of the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, Buenos Aires, Argentina, 31 August–4 September 2010; pp. 1441–1444. [CrossRef]
77. Jörke, P.; Falkenberg, R.; Wietfeld, C. Power Consumption Analysis of NB-IoT and eMTC in Challenging Smart City Environments. In Proceedings of the 2018 IEEE Globecom Workshops (GC Wkshps), Abu Dhabi, United Arab, 9–13 December 2018; pp. 1–6. [CrossRef]
78. Ikpehai, A.; Adebisi, B.; Rabie, K.M.; Anoh, K.; Ande, R.E.; Hammoudeh, M.; Gacanin, H.; Mbanaso, U.M. Low-Power Wide Area Network Technologies for Internet-of-Things: A Comparative Review. *IEEE Internet Things J.* **2019**, *6*, 2225–2240. [CrossRef]
79. Sarangi, S.; Naik, V.; Choudhury, S.B.; Jain, P.; Kosgi, V.; Sharma, R.; Bhatt, P.; Srinivasu, P. An Affordable IoT Edge Platform for Digital Farming in Developing Regions. In Proceedings of the 2019 11th International Conference on Communication Systems & Networks (COMSNETS), Bengaluru, India, 7–11 January 2019; pp. 556–558. [CrossRef]
80. Kontogiannis, S. An Internet of Things-Based Low-Power Integrated Beekeeping Safety and Conditions Monitoring System. *Inventions* **2019**, *4*, 52. [CrossRef]
81. Buchmann, I. *Batteries in a Portable World: A Handbook on Rechargeable Batteries for Non-Engineers*, 4th ed.; Cadex Electronics Inc.: BC, Canada, 2023.
82. Armand, M.; Tarascon, J.M. Building better batteries. *Nature* **2008**, *451*, 652–657. [CrossRef] [PubMed]
83. Linden, D.; Reddy, T. *Handbook of Batteries*; McGraw-Hill Handbooks; McGraw-Hill Education: New York, NY, USA, 2001.
84. Mitcheson, P.D. Energy harvesting for human wearable and implantable bio-sensors. In Proceedings of the 2010 Annual International Conference of the IEEE Engineering in Medicine and Biology, Buenos Aires, Argentina, 31 August–4 September 2010; pp. 3432–3436. [CrossRef]
85. May, G.J.; Davidson, A.; Monahov, B. Lead batteries for utility energy storage: A review. *J. Energy Storage* **2018**, *15*, 145–157. [CrossRef]
86. Cano, Z.P.; Banham, D.; Ye, S.; Hintennach, A.; Lu, J.; Fowler, M.; Chen, Z. Batteries and fuel cells for emerging electric vehicle markets. *Nat. Energy* **2018**, *3*, 279–289. [CrossRef]
87. Ding, Y.; Cano, Z.P.; Yu, A.; Lu, J.; Chen, Z. Automotive Li-ion batteries: Current status and future perspectives. *Electrochem. Energy Rev.* **2019**, *2*, 1–28. [CrossRef]
88. Zhao, J.; Burke, A.F. Review on supercapacitors: Technologies and performance evaluation. *J. Energy Chem.* **2021**, *59*, 276–291. [CrossRef]
89. Wang, W.; Luo, Q.; Li, B.; Wei, X.; Li, L.; Yang, Z. Recent Progress in Redox Flow Battery Research and Development. *Adv. Funct. Mater.* **2013**, *23*, 970–986. [CrossRef]
90. Alotto, P.; Guarnieri, M.; Moro, F. Redox flow batteries for the storage of renewable energy: A review. *Renew. Sustain. Energy Rev.* **2014**, *29*, 325–335. [CrossRef]
91. Leong, K.W.; Wang, Y.; Ni, M.; Pan, W.; Luo, S.; Leung, D.Y. Rechargeable Zn-air batteries: Recent trends and future perspectives. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111771. [CrossRef]
92. Powers, R. Batteries for low power electronics. *Proc. IEEE* **1995**, *83*, 687–693. [CrossRef]
93. Collath, N.; Tepe, B.; Englberger, S.; Jossen, A.; Hesse, H. Aging aware operation of lithium-ion battery energy storage systems: A review. *J. Energy Storage* **2022**, *55*, 105634. [CrossRef]
94. Dehghani-Sanij, A.; Tharumalingam, E.; Dusseault, M.; Fraser, R. Study of energy storage systems and environmental challenges of batteries. *Renew. Sustain. Energy Rev.* **2019**, *104*, 192–208. [CrossRef]
95. Kebede, A.A.; Kalogiannis, T.; Van Mierlo, J.; Berecibar, M. A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. *Renew. Sustain. Energy Rev.* **2022**, *159*, 112213. [CrossRef]
96. Luo, X.; Wang, J.; Dooner, M.; Clarke, J. Overview of current development in electrical energy storage technologies and the application potential in power system operation. *Appl. Energy* **2015**, *137*, 511–536. [CrossRef]
97. Lu, Q.; Zou, X.; Bu, Y.; An, L.; Wang, Y.; Shao, Z. What matters in engineering next-generation rechargeable Zn-air batteries? *Next Energy* **2023**, *1*, 100025. [CrossRef]
98. Alipour, M.; Ziebert, C.; Conte, F.V.; Kizilel, R. A Review on Temperature-Dependent Electrochemical Properties, Aging, and Performance of Lithium-Ion Cells. *Batteries* **2020**, *6*, 35. [CrossRef]

99. Goikolea, E.; Mysyk, R. Chapter Four - Nanotechnology in Electrochemical Capacitors. In *Emerging Nanotechnologies in Rechargeable Energy Storage Systems*; Rodriguez-Martinez, L.M., Omar, N., Eds.; Micro and Nano Technologies; Elsevier: Boston, MA, USA, 2017; pp. 131–169. [CrossRef]
100. Townsend, A.; Gouws, R. A Comparative Review of Lead-Acid, Lithium-Ion and Ultra-Capacitor Technologies and Their Degradation Mechanisms. *Energies* **2022**, *15*, 4930. [CrossRef]
101. Wang, Q.; Liu, W.; Yuan, X.; Tang, H.; Tang, Y.; Wang, M.; Zuo, J.; Song, Z.; Sun, J. Environmental impact analysis and process optimization of batteries based on life cycle assessment. *J. Clean. Prod.* **2018**, *174*, 1262–1273. [CrossRef]
102. Porzio, J.; Scown, C.D. Life-Cycle Assessment Considerations for Batteries and Battery Materials. *Adv. Energy Mater.* **2021**, *11*, 2100771. [CrossRef]
103. Troy, S.; Schreiber, A.; Reppert, T.; Gehrke, H.G.; Finsterbusch, M.; Uhlenbruck, S.; Stenzel, P. Life Cycle Assessment and resource analysis of all-solid-state batteries. *Appl. Energy* **2016**, *169*, 757–767. [CrossRef]
104. Mandade, P.; Weil, M.; Baumann, M.; Wei, Z. Environmental life cycle assessment of emerging solid-state batteries: A review. *Chem. Eng. J. Adv.* **2023**, *13*, 100439. [CrossRef]
105. Yang, S.Y.; Sencadas, V.; You, S.S.; Jia, N.Z.X.; Srinivasan, S.S.; Huang, H.W.; Ahmed, A.E.; Liang, J.Y.; Traverso, G. Powering Implantable and Ingestible Electronics. *Adv. Funct. Mater.* **2021**, *31*, 2009289. [CrossRef] [PubMed]
106. Deutsches Institut für Normung e.V. *IEC 60086-2:2015*; International Standard: Primary Batteries—Part 2: Physical and Electrical Specifications (IEC 60086-2:2015). Beuth-Verlag, Berlin, Germany, 2016. [CrossRef]
107. Morin, É.; Maman, M.; Guizzetti, R.; Duda, A. Comparison of the Device Lifetime in Wireless Networks for the Internet of Things. *IEEE Access* **2017**, *5*, 7097–7114. [CrossRef]
108. Ates, H.C.; Nguyen, P.Q.; Gonzalez-Macia, L.; Morales-Narváez, E.; Güder, F.; Collins, J.J.; Dincer, C. End-to-end design of wearable sensors. *Nat. Rev. Mater.* **2022**, *7*, 887 – 907. [CrossRef]
109. Alaa, M.; Zaidan, A.; Zaidan, B.; Talal, M.; Kiah, M. A review of smart home applications based on Internet of Things. *J. Netw. Comput. Appl.* **2017**, *97*, 48–65. [CrossRef]
110. Sinha, B.B.; Dhanalakshmi, R. Recent advancements and challenges of Internet of Things in smart agriculture: A survey. *Future Gener. Comput. Syst.* **2022**, *126*, 169–184. [CrossRef]
111. Cerchecci, M.; Luti, F.; Mecocci, A.; Parrino, S.; Peruzzi, G.; Pozzebon, A. A Low Power IoT Sensor Node Architecture for Waste Management Within Smart Cities Context. *Sensors* **2018**, *18*, 1282. [CrossRef]
112. Sanislav, T.; Mois, G.D.; Zeadally, S.; Folea, S.C. Energy Harvesting Techniques for Internet of Things (IoT). *IEEE Access* **2021**, *9*, 39530–39549. [CrossRef]
113. Han, W.; Anaya, D.V.; Wu, T.; Wu, F.; Yuce, M.R. Self-powered wearable sensors design considerations. *J. Micromech. Microeng.* **2022**, *32*, 083002. [CrossRef]
114. Garg, N.; Garg, R. Energy harvesting in IoT devices: A survey. In Proceedings of the 2017 International Conference on Intelligent Sustainable Systems (ICISS), Palladam, India, 7–8 December 2017; pp. 127–131. [CrossRef]
115. Sun, Y.; Li, Y.Z.; Yuan, M. Requirements, challenges, and novel ideas for wearables on power supply and energy harvesting. *Nano Energy* **2023**, *115*, 108715. [CrossRef]
116. Wang, L.; Zhang, Y.; Bruce, P.G. Batteries for wearables. *Natl. Sci. Rev.* **2022**, *10*, nwac062. [CrossRef]
117. Sheng, Z.; Mahapatra, C.; Zhu, C.; Leung, V.C.M. Recent Advances in Industrial Wireless Sensor Networks Toward Efficient Management in IoT. *IEEE Access* **2015**, *3*, 622–637. [CrossRef]
118. Peng, S., Challenges and Prospects for Zinc-Air Batteries. In *Zinc-Air Batteries: Fundamentals, Key Materials and Application*; Springer Nature Singapore: Singapore, 2023; pp. 205–215. [CrossRef]