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Review

Magnesium–Air Batteries: Manufacturing, Processing, Performance, and Applications

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Abstract: Magnesium–air (Mg–Air) batteries are emerging as a sustainable and high-energy-density solution to address the increasing global energy demands, utilizing abundant and environmentally friendly materials. This review paper examines their fundamental electrochemical mechanisms, focusing on magnesium anodes, cathode design, and electrolyte formulations. While discussing key advancements in manufacturing techniques that enhance scalability and performance, this article underscores the wide range of potential applications of Mg–Air batteries, including portable electronics, electric transportation, and off-grid energy systems. Despite persistent challenges such as anode passivation and limited rechargeability, significant progress in material engineering and process optimization is accelerating their pathway to commercialization. These developments highlight the synergy between material science and sustainable manufacturing, positioning Mg–air batteries as a promising solution for next-generation energy storage technologies.

Keywords: Mg–air batteries; magnesium anode; sustainable energy; electrolyte; electric vehicles

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1. Introduction

Energy storage plays a critical role in modern technology, enabling energy to be captured and used when needed rather than only at the time of generation. Renewable energy sources like solar and wind produce electricity intermittently, making it essential to store excess energy for periods of high demand. Similarly, portable electronic devices rely on stored energy in batteries to function at the user's convenience. There are several methods for storing energy, including mechanical, thermal, and electrochemical. Batteries utilize electrochemical storage, converting chemical energy into electrical energy during discharge and back into chemical energy during charging [1].

Batteries have widespread applications, from consumer electronics and electric vehicles to large-scale energy storage systems for power grids. Lithium-ion batteries are commonly used in portable devices such as smartphones and laptops and are favored for their high energy density and long cycle life [2,3]. Lead–acid batteries, while less energy-dense, offer a high power-to-weight ratio and remain prevalent in automotive and industrial uses. Nickel–metal hydride batteries, once used in consumer electronics and hybrid vehicles, have been largely replaced by lithium-ion technology due to their superior energy density and higher voltage output [4].

As global development accelerates, the need for sustainable energy solutions becomes increasingly urgent. Magnesium–air (Mg–Air) batteries, a promising type of metal–air battery, offer several advantages over conventional battery technologies, including high energy density, low cost, and reduced environmental impact. These features position Mg–Air batteries as a

strong candidate for a wide range of applications [5]. Mg–Air batteries represent a promising and sustainable alternative to current energy storage technologies due to their high theoretical energy density, low environmental impact, and use of abundant, non-toxic materials. Mg has been gaining a lot of attention lately for its exciting potential in a variety of applications, especially in energy and environmental sustainability. One of the most promising areas is its use in CO_2 conversion. Researchers are exploring ways to use magnesium-based materials to capture and convert carbon dioxide (CO_2) into useful chemicals or fuels, offering a potential solution to help reduce atmospheric CO_2 levels and combat climate change [6].

Unlike widely used lithium-ion and lead–acid batteries, Mg–Air batteries offer potential advantages in terms of energy density, cost, and eco-friendliness, making them a promising candidate for diverse applications ranging from portable electronics and medical devices to electric vehicles and large-scale energy storage systems.

Mg–Air batteries offer a high theoretical energy density of around 4000 Wh/kg, surpassing zinc–air (Zn–Air) batteries (1100 Wh/kg) but falling short of the theoretical potential of lithium–air (Li–Air) batteries, which can reach up to 11,140 Wh/kg. While Mg–Air batteries benefit from the lightweight and high electrochemical potential of magnesium, they face challenges with passivation and corrosion at the magnesium anode, requiring protective coatings or surface modifications. In contrast, Zn–Air batteries, commonly used in small applications, have a more stable anode but suffer from issues like dendrite formation and limited rechargeability. Li–Air batteries, though theoretically superior in energy density, face significant practical challenges with efficiency losses and instability due to side reactions at the lithium anode. One of the key benefits of Mg–Air batteries is their exceptional energy density [7]. As shown in Table 1, the Mg oxide couple has a specific energy density of 4032 Wh/kg and a volumetric energy density of 14,400 Wh/L, trailing only lithium oxide and aluminum oxide. Notably, Mg oxide also offers a higher theoretical voltage than lithium and aluminum oxide, making it an even more attractive option for high-performance energy storage systems [8]. Mg–Air batteries, although more energy-dense, face significant challenges, including the passivation of the magnesium anode and corrosion issues, which can impact their cycle life and efficiency. Li–Air batteries, on the other hand, have a theoretical energy density that far exceeds both Mg–Air and Zn–Air batteries, but they are hindered by major challenges, including high over-potentials, poor stability, and inefficiencies from side reactions at the lithium anode. While Mg–Air batteries show great potential, their commercial application is still hindered by material and electrochemical challenges, unlike Zn–Air batteries, which are more stable but less energy-dense, and Li–Air batteries, which face stability issues despite their high theoretical performance. With these characteristics, Mg–Air batteries hold great potential for applications ranging from portable electronics to large-scale energy storage, offering a sustainable alternative to traditional battery technologies.

Table 1. Theoretical metal oxide energy density.

Metal Oxide	Bandgap (eV)	Potential (V)	Energy Density, Weight Basis (W h/kg)	Energy Density Volume Basis (W h/L)	Reference
CaO	6.25	3.11	2972	9960	[8,9]
MgO	7.8	3.03	4032	14,400	[8,10]
Li_2O_2	4.60	2.96	3456	7983	[11]
Li_2O	8.0	2.91	5216	10,501	[11]
Al_2O_3	7.6	2.75	4332	17,300	[8,12]
NaO_2	1.09–1.11	2.27	1105	2431	[11]
Na_2O	2.94	1.95	1687	3828	[11]
Na_2O_2	4.4–5.8	2.33	1602	4493	[11]
ZnO	650	1.68	1109	6220	[8]

While experimentally tested Mg–Air batteries have yet to achieve their theoretical performance values and may not even match the performance of current lithium-ion batteries, advancements in manufacturing processes are essential to bridge this gap [13]. Key issues affecting the performance of Mg–Air batteries include metal corrosion, dendrites formation, the sluggish kinetics of oxygen reaction at the cathode, and passivation caused by aqueous electrolytes [5,14]. Additionally, many performance challenges are application-dependent, whether the battery is intended as a primary (single-use) or rechargeable system. These challenges are the focus of ongoing research to improve battery performance across various applications.

A significant advantage of Mg–Air batteries is their low cost compared to competing technologies. According to the U.S. Geological Survey, Mg is the eighth most abundant element on Earth [15]. This abundance leads to lower production costs. Moreover, Mg's lightweight nature reduces transportation expenses, creating a price advantage over battery technologies that rely on less abundant or heavier metals.

The environmental friendliness of Mg–Air batteries is perhaps their most substantial benefit over other battery technologies. During operation, Mg–Air batteries produce Mg hydroxide precipitates, which are non-toxic to the environment and humans and can be recycled into Mg ingots [16]. Additionally, these batteries exhibit a degree of biodegradability, which is advantageous at the end-of-life stage, especially for primary battery applications [17]. Although Mg–Air batteries are not yet mass-produced, their lightweight nature would reduce the energy required for transportation if scaled up, further enhancing their environmental benefits.

The potential applications of Mg–Air batteries are crucial to their development. For instance, electric vehicles represent a promising area due to the high theoretical energy density of Mg–Air batteries compared to lithium-ion batteries. Their lightweight and high energy density also makes them suitable for portable power supplies, particularly as primary batteries in field operations, emergency supplies during disaster relief, and other scenarios requiring reliable, lightweight energy sources. Furthermore, the non-toxicity of Mg–Air batteries suggests potential use in biomedical applications. These diverse applications highlight the broad benefits of Mg–Air batteries. High energy density, portability, and non-toxicity make them a desirable choice across various fields. While the current state of Mg–Air batteries may not yet fulfill all these applications, addressing existing challenges is crucial to advancing the technology toward viability.

This paper seeks to provide readers with a comprehensive understanding of Mg–Air batteries, bridging the gap between their underlying electrochemical processes and their practical applications across various industries. This paper aims to highlight the versatility and value of Mg–Air batteries, raising awareness among researchers, policymakers, and industry stakeholders about the significant role these batteries can play in the transition to sustainable energy solutions. By presenting the latest advancements in their development and addressing the ongoing efforts to overcome technical challenges, it emphasizes the relevance of Mg–Air batteries in achieving a sustainable energy future [18]. Lastly, this study seeks to inspire future research in the field of energy storage. By outlining the potential and current challenges of Mg–Air batteries, this paper encourages scientists and engineers to explore innovative solutions that enhance performance, scalability, and integration across various applications. In doing so, it contributes to shaping a greener, more energy-efficient future, with Mg–Air batteries positioned as a transformative technology [19].

2. Working Principles of Mg–Air Batteries

Mg–Air batteries work through the chemical reaction of metal Mg as an anode and O_2 from ambient air as the cathode. During operation with an aqueous electrolyte, Mg at the anode

oxidizes, generating electrons and forming magnesium ions (Mg^{2+}). Concurrently, O_2 from the atmosphere moves through the porous Air cathode, reacts with water, and gets reduced to hydroxide ions (OH^-). The reaction combines Mg^{2+} and OH^- in the electrolyte into magnesium hydroxide ($Mg(OH)_2$) as a byproduct. Electrons released at the anode flow through an external circuit to deliver electrical power, whereas Mg ions and hydroxide ions migrate within the electrolyte to complete the ionic circuit [20]. The fundamental and theoretical chemical reactions governing these processes are represented by Equations (1)–(3) [20].

In contrast, with the aprotic (nonaqueous) electrolyte, the discharge products are MgO and/or MgO_2, as given by Equations (4) and (5). A basic Mg–Air battery schematic configuration with both aqueous and aprotic electrolytes is shown in Figure 1, along with the reactions at the anode and cathode sides.

$$\textbf{Anode: } Mg \rightarrow\ Mg^{2+} + 2e^- \quad (1)$$

$$\textbf{Cathode: } O_2 + 2H_2O + 4e^- \rightarrow\ 4OH^- \quad (2)$$

$$\textbf{Overall reaction: } 2Mg + O_2 + 2H_2O\ \rightarrow\ 2Mg(OH)_2 \quad (3)$$

$$Mg^{2+} + O_2 + 2e^- \rightarrow\ MgO_2 \quad (4)$$

$$2Mg^{2+} + O_2 + 4e^- \rightarrow\ 2MgO \quad (5)$$

$$2H_2O + 2e^- \rightarrow\ 2OH^- + H_2 \quad (6)$$

$$Mg^{2+} + 2OH^- \rightarrow\ Mg(OH)_2 \quad (7)$$

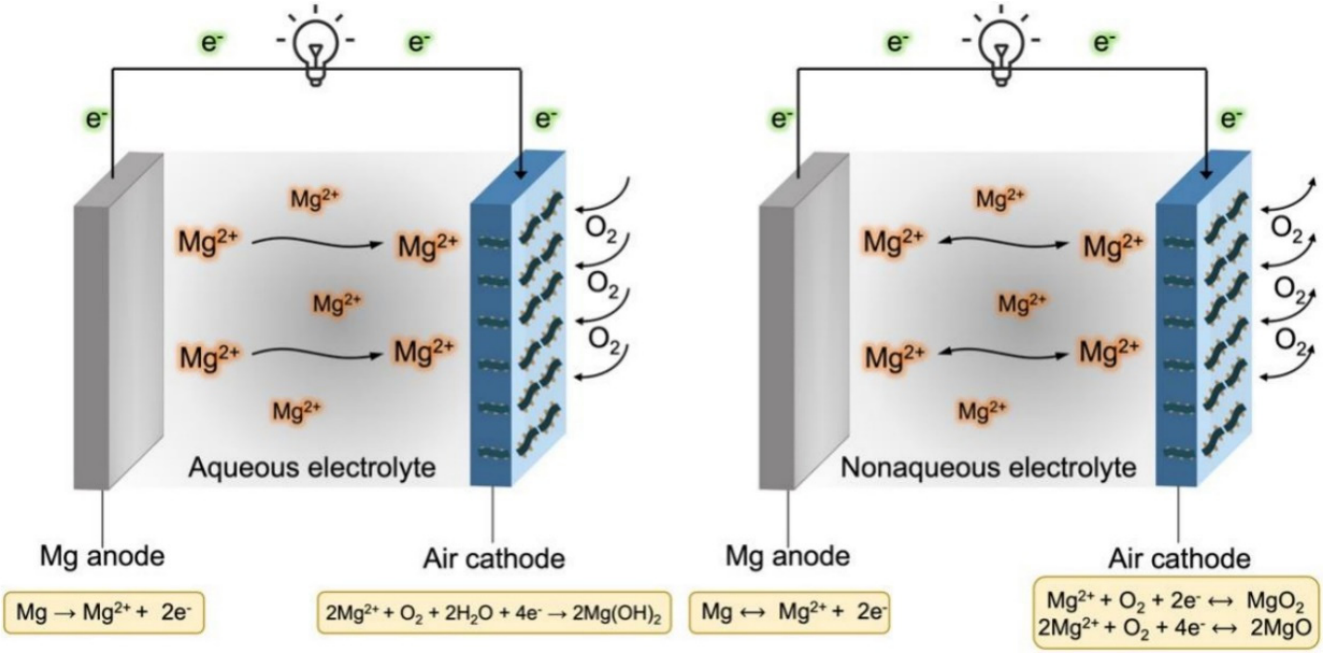


Figure 1. Schematic diagram of Mg–Air battery configuration. Reproduced by copyrights from [5], open access, Energy Materials, 2022.

One of the key side reactions involves the Mg anode, as shown in Equation (6). This Hydrogen Evolution Reaction (HER), caused by the negative standard potential of Mg, diverts some of the free electrons from Equation (1) into the aqueous electrolyte rather than the external circuit. These electrons reduce hydrogen ions, producing hydrogen gas, significantly affecting subsequent reactions. Mg is prone to corrosion under typical Mg–Air battery operating voltages. In neutral and acidic environments, Mg oxidizes to form Mg^{2+} ions, contributing electrons to the HER process. In acidic conditions, this corrosion is

exacerbated, leading to the preference for neutral electrolytes in Mg–Air batteries [20]. The formation of MgO and MgO_2 products in organic electrolytes possess stable thermodynamics and are often difficult to decompose. This results in large polarization and inferior cycling performance [5].

The hydroxide ions (OH^-) from Equation (6) in a neutral solution trigger the reaction in Equation (7), which results in the deposition of ($Mg(OH)_2$) on the surface of the anode. While this film can act as a protective layer against further corrosion, it can also grow thick enough to impede the electrochemical reactions due to the high interfacial impedance, ultimately hindering battery performance [20].

Current research on Mg–Air battery technology focuses on improving cathode catalysts to enhance cycle life and battery longevity. One major challenge is the formation of magnesium oxide (MgO) and magnesium peroxide (MgO_2) films during discharge, which are "electrochemically inert" and difficult to reverse back into metallic Mg within the battery components [21]. These are the most common discharge products in Mg–Air cells. Further studies have revealed that defects and impurities in these films can improve their conductivity, leading to two potential strategies for enhancing rechargeability.

The first strategy involves the rapid discharge of large packs of lower-capacity cells, which could increase the number of defects in the MgO/MgO_2 films, thereby enhancing rechargeability. The second, more promising approach suggests introducing impurities such as lithium into the electrolyte solution. These impurities could integrate into the developing discharge films, making the films more conductive and easier to reverse [22].

Additional research has focused on modifying the electrolyte and cathode to improve electron transfer efficiency. A 2021 study on organic and double electrolytes showed improved discharge performance using a combination of 0.5 M $Mg(ClO_4)_2$-Dimethylformide (DMF) and 0.6 M NaCl-H_2O. It also found that organic electrolytes shielded the Mg anode from the corrosive NaCl aqueous electrolyte, significantly enhancing anodic utilization rates in rechargeable cells [23]. In 2022, a fully rechargeable Mg–Air battery was developed that demonstrated stable electrochemical performance over multiple cycles. This was achieved using a Pt/C on carbon fiber paper (Pt/C@CFP) oxygen cathode and $Mg((CF_3SO_2)_2N)_2$-$MgCl_2$ in diglyme (G2) electrolyte, effectively resolving electrode passivation issues that had plagued earlier designs [24].

Recent advances in gel-based electrolytes have also shown promise in reducing the corrosive properties typical of traditional electrolytes. Figure 2 illustrates a dual-layer gel electrolyte, similar to the previously discussed double aqueous system. This gel electrolyte successfully prevented the corrosion and buildup on the Mg anode, preserving the metallic Mg and improving the cell's energy density and capacity during discharge [25]. In summary, ongoing advancements in Mg–Air battery components, particularly in cathodes, electrolytes, and anode protection, are steadily overcoming the electrochemical limitations of theoretical Mg–Air batteries, bringing the technology closer to practical, scalable applications.

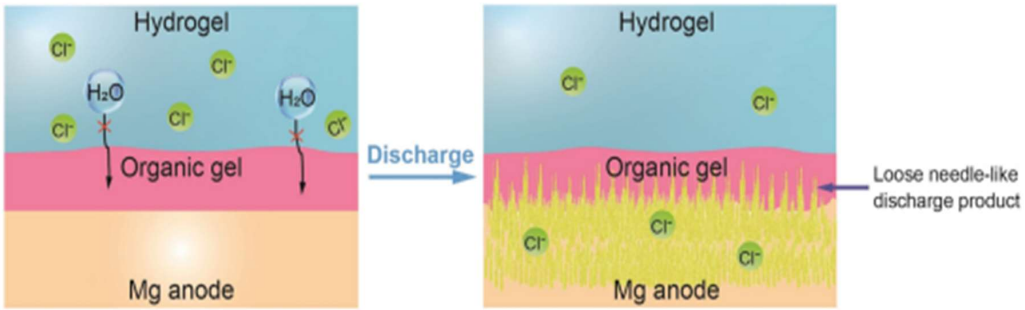


Figure 2. Dual-layer gel electrolyte. Reproduced with permission from [25].

Battery Components

Mg–Air batteries function similarly to other batteries, using a cathode and an anode to transfer electrons between the two terminals, either powering an electronic device or recharging the battery's potential. In Mg–Air batteries, Mg serves as the anode, and the cathode is an air matrix. Mg–Air batteries have the potential to perform comparably to lithium-based MABs while offering greater environmental benefits. They are particularly safe to use, as the Mg reacts with neutral saltwater, producing non-toxic Mg hydroxide precipitates [16]. A significant advantage of Mg–Air batteries is their lack of dendrite formation, a metallic structure that can cause battery failure by short-circuiting [26].

In Mg–Air batteries, O_2 from the air reacts with the Mg anode, causing oxidation. The air cathode, however, is not an empty space but is often designed as a porous foam, which supports the battery structure while allowing a large volume of air to interact with the active material. The design of this foam structure is critical for ensuring optimal battery performance. The air cathode plays a key role in MABs, and its properties are essential for efficient operation. A high-performing air electrode should enable the rapid diffusion of oxygen and facilitate fast migration of hydroxide ions (OH^-), while preventing water permeation. It must exhibit high activity for oxygen reduction reactions (ORRs) in primary MABs and for both ORRs and oxygen evolution reactions (OERs) in rechargeable (secondary) MABs. Additionally, it should maintain physical and electrochemical stability in alkaline environments and at high potentials [27]. A typical air cathode consists of three parts: an electrocatalyst, a gas diffusion layer, and a current collector that transfers electrons to or from the catalyst layer [27].

The electrolyte is another crucial component in MABs. In most cases, MABs use an aqueous electrolyte, and Mg–Air batteries follow this convention. A common and effective electrolyte for Mg–Air batteries is neutral saltwater, which offers the added benefit of being environmentally friendly. However, using aqueous electrolytes introduces challenges, such as self-corrosion, surface blockage, and the "chunk effect"—a phenomenon where Mg detaches in chunks, reducing battery efficiency. To address these issues, researchers are exploring thermo-mechanical treatments to refine the microstructure of Mg-based anodes, mitigating self-corrosion and the chunk effect [28].

More recent innovations have focused on gel-based electrolytes, which eliminate the aqueous phase and allow for broader applications. Dual-layer gel electrolytes have been shown to prevent corrosion of the Mg anode and the formation of dense passive layers, thus reducing Mg consumption due to side reactions and increasing anode utilization during discharge [25]. These gel electrolytes, combined with Mg's non-toxic properties, enhance the reliability of Mg–Air batteries without compromising their high energy density.

Another vital component in metal–air batteries is the separator, which prevents physical contact between the anode and cathode, which is one of the leading causes of battery failure. The separator can either be a standalone part or integrated into the electrolyte. A significant challenge that remains is the need for cost-effective separators, as the currently used bipolar polymer films and ceramic solid-state membranes are expensive, offer limited ionic conductivity, and struggle with unwanted ion crossing between hydrogen (H^+) and hydroxide (OH^-) [29].

3. Manufacturing of Mg–Air Batteries

With a clear understanding of the key components and electrochemical processes involved in Mg–Air batteries, the next step is manufacturing these components to produce functional batteries. While lab-made metal–air batteries help researchers identify ways to improve the technology, they are often produced differently from those intended for

large-scale manufacturing. This section covers the basic production processes for the anode, cathode, and electrolyte of Mg–Air battery.

Battery manufacturing, in general, is relatively straightforward, since batteries have few components and no moving parts. Each part of the metal–air battery—anode, cathode, and electrolyte—has its own specific requirements based on the chosen metal alloy and electrolyte composition. Experimental improvements in efficiency and performance must be rigorously tested for their viability in mass production. Additionally, depending on the type of Mg–Air battery, novel production methods may need to be developed to accommodate the improved designs and materials.

3.1. Creating Mg Anodes

In typical metal–air batteries, the anode is constructed from the metal, which reacts with the air cathode and electrolyte to generate the ion transfer needed to power an external circuit. During discharge, the Mg anode reacts with oxygen from the air at the cathode, forming MgO or $Mg(OH)_2$, as described in the above sections, and releases electrons to power an external circuit. Mg–Air batteries, despite their significant theoretical potential, face challenges related to the corrosion of the Mg anode when operating at normal voltages. The magnesium anode, unlike in rechargeable systems, is consumed during the discharge process, meaning the anode material gradually depletes as the battery operates. While these batteries can be manufactured from readily available natural resources, much recent research focuses on overcoming corrosion-related issues [30].

Creating an anode for a Mg–Air battery involves selecting and preparing Mg metal or Mg alloys that can effectively participate in the electrochemical reactions during battery operation. Because Mg–Air batteries are still in the prototype phase, high-purity Mg is essential to eliminate variables arising from impurities and defects. The high-purity Mg is shaped into the desired form, often thin sheets or plates, through methods like casting or extrusion. Figure 3 highlights the importance of ultra-pure Mg for these applications. In response to the demand from high-tech and medical industries, Mg producers have refined methods to meet these new industrial requirements. One such method is vacuum distillation, the only commercially viable approach for producing ultra-high-purity (XHP) Mg, achieving purities as high as 5N8 (99.9998%) with an impurity content of just 2.08 ppm [31]. Unlike electro-refining, which has higher energy costs, vacuum distillation offers an environmentally friendly, low-cost solution. Zinc is the most prominent remaining impurity at 1.7 ppm, even after a second distillation cycle.

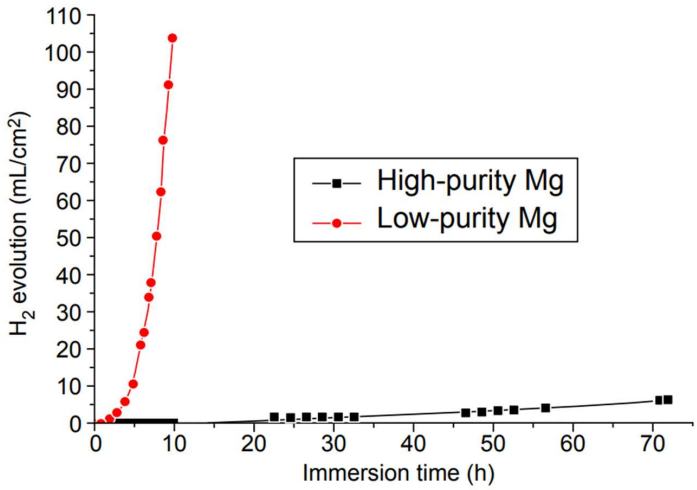


Figure 3. Comparison of H_2 evolution with magnesium purity. Reproduced with permission from [32].

Using ultra-high-purity Mg for the anode in a typical Mg–Air battery has helped researchers understand the discharge issues linked to anode corrosion. In experiments using 99.999% pure crystalline Mg ingots and a 3.5% NaCl electrolyte solution, both simulation and real-world testing revealed that efficiency still declined over time due to discharge products and subsequent voltage drops [33]. To address this, various surface treatments are applied to the anode, such as protective coatings (e.g., polymer films, metallic layers, or ceramic coatings) that help prevent direct contact between the Mg and the electrolyte, reducing the formation of unwanted byproducts like magnesium hydroxide. Additionally, alloying Mg with other metals, such as aluminum or zinc, is another strategy used to enhance its corrosion resistance and improve its electrochemical performance.

Researchers have explored new anode designs, including adding corrosion inhibitors and Mg alloys. These approaches move experimental voltage and capacity values closer to their theoretically transformative potential. For instance, a 2017 study investigated Mg alloy foils for anode development, manufacturing alloys such as Mg–1.63 wt.% Zn, Mg–1.55 wt.% Gd, and Mg–1.02 wt.% Zn–1.01 wt.% Gd. By using Rietveld refinement of XRD data, the researchers concluded that zinc and gadolinium (Gd) formed solid solutions with Mg, improving the workability of the material to create 100 μm thin foils suitable for rechargeable Mg–Air batteries, with minimal impact on corrosion potential [34].

Another promising avenue involves pretreating Mg anodes with titanium to prevent surface oxidation before insertion into the battery. This pretreatment helps combat the formation of MgO, which impairs reaction kinetics. When the anode was dipped in $Ti(TFSI)_2Cl_2$ and combined with glyme-based electrolytes, the treated anode showed improved performance. This two-step approach has potential applications beyond Mg, extending to metals like aluminum, zinc, and titanium, which also suffer from poor kinetic behavior due to native oxide layers [35].

Further, research on solid–electrolyte interphase (SEI) layers has proven effective in preventing parasitic reactions while maintaining efficient ion transfer. A stable SEI layer formed from lithium-based electrolyte decomposition enabled smooth cycling on the Mg anode surface. This study demonstrated high performance, with the SEI layer enduring over 6000 cycles at a current density of 10C and achieving greater than 99% Coulombic efficiency [36].

Although ultra-high-purity Mg alone may not solve the challenges of Mg–Air anodes, surface treatments and alloy developments have shown promising results. These methods offer cost-effective solutions and bring Mg–Air batteries closer to meeting commercial demands, paving the way for future advancements.

3.2. Designing Cathodes

In metal–air batteries, the air cathode primarily utilizes O_2 from the atmosphere. Since ambient air contains sufficient oxygen for the electrochemical reaction to generate electricity, the cathode only requires a structure capable of trapping air. Metal foams, particularly nickel foam (NF), have emerged as an ideal material for these cathode structures due to their unique properties. The interlinked three-dimensional (3D) structure of metal foams not only provides an efficient shape for the electrode but also creates an effective connection between the active material and the external circuit [37]. In the case of Mg–Air batteries, the metal foam promotes the reaction between Mg in the anode and oxygen in the foam cathode. Nickel is the preferred metal for these foams due to its exceptional mechanical strength, electrical conductivity, and stability. Nickel foam, in particular, has gained widespread use in various electrochemical applications because of its high porosity, lightweight nature, and uniform structure [38]. Nickel alloys have proven to be highly effective as cathodes in metal–air batteries, offering enhanced performance due to their superior properties.

Several methods exist for creating metal foams, but they vary in terms of foam quality, structure, and production speed. One such method is the foaming by gas injection (shown in Figure 4), which rapidly produces metal foams by injecting gas into molten metal. As the metal cools, air bubbles become trapped, creating the foam structure. This process uses a nozzle tip to produce fine, homogeneous gas bubbles in the molten metal, with reinforcing particles ranging from 10 to 20% volume and a mean particle size of 5 to 20 μm [39]. However, while this process is efficient, the quality of the metal foam produced is suboptimal for high-energy-density Mg–Air batteries, where more precise structural characteristics are required.

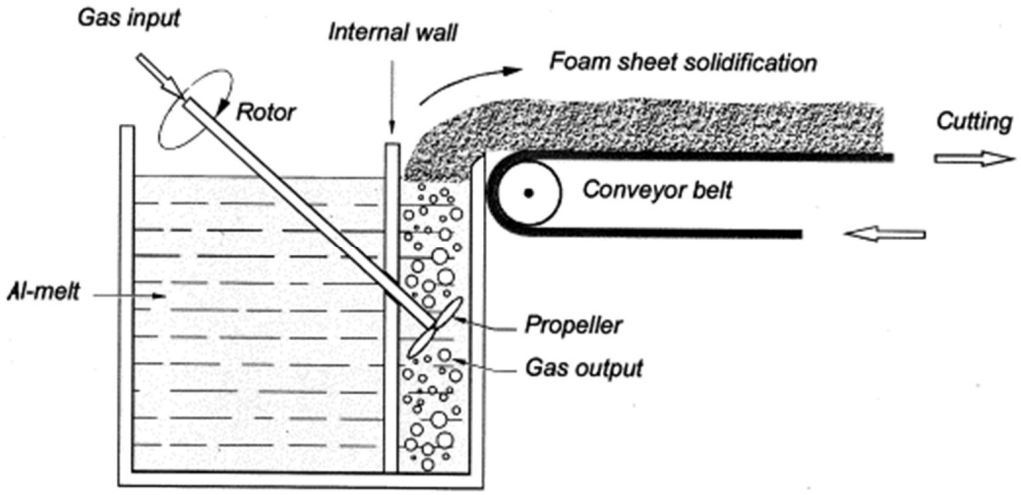


Figure 4. Gas injection for direct foaming of melts. Reproduced with permission from [40].

An alternative approach for producing higher-quality nickel foams is outlined in a patent by Babjak et al. [41]. This method involves using nickel carbonyl gas, which decomposes on a foam structure to form a nickel-plated foam. The nickel-plated structure is then sintered, resulting in an open-cell nickel network that forms the nickel foam. Babjak's process utilizes a thermally decomposable material to create the premade foam structure, which is subsequently plated with nickel. The resulting nickel foam is ideal for Mg–Air cathodes due to its improved conductivity, porosity, foam cell size, capacity to hold active mass, and mechanical strength. This method also supports large-scale production, making it a viable option for industrial applications.

Once the nickel foam is created, it can be further modified by adding alloying elements to enhance the cathode's performance. These alloys offer the flexibility needed to optimize cathode performance in Mg–Air batteries, making them suitable for future advancements in battery technology.

3.3. Mixing the Electrolyte

The electrolyte in a battery is the medium that facilitates the flow of ions between the anode and cathode, enabling the generation of electrical power. For metal–air batteries, aqueous solutions are commonly used as electrolytes, much like those found in lead–acid batteries. In Mg–Air batteries, a neutral saltwater solution is often chosen as the electrolyte, due to the challenges associated with Mg corrosion in acidic or alkaline environments. Acidic electrolytes cause severe corrosion, while alkaline ones promote passivation reactions, hindering battery efficiency. Thus, neutral salt solutions are favored for the Mg anode [42].

One advantage of using saltwater as the electrolyte in Mg–Air batteries is that it is non-toxic. However, the saltwater also corrodes the Mg, reducing the battery efficiency

and preventing multiple recharging cycles. To mitigate these corrosive effects, additives are mixed into the electrolyte. Research has shown that sodium nitrate (NO_3), salicylate (SAL), or a combination of both can significantly suppress the self-corrosion of Mg and improve its dissolution during discharge [43]. Table 2 demonstrates that these additives maintain equivalent voltage levels while reducing H_2 gas evolution at the Mg anode. The combination of SAL and NO_3 was particularly effective, reducing H_2 evolution and suppressing nitrite formation (NO_2^-). The inhibition efficiency for the Mg anode was calculated to be 77% for the SAL + NO_3 mixture.

Table 2. Discharge potential and mixture improvements for NaCl electrolyte mixes compared to baseline NaCl electrolyte. Reproduced with permission from [44].

Electrolyte	Average Discharge Potential (V vs. Ag/AgCl)	H_2 Evolution During Discharge (μmol cm^{-2} min^{-1})	Inhibition Efficiency of HER (%) *	NO_2^- Evolution During Discharge (μmol cm^{-2} min^{-1})
3.5% NaCl	−1.52 ± 0.05	1.89 ± 0.62		
3.5% NaCl + NO_3^-	−1.42 ± 0.01	1.00 ± 0.21	47	0.08 ± 0.002
3.5% NaCl + SAL	−1.16 ± 0.05	1.64 ± 0.29	13	
3.5% NaCl + MIX	−1.50 ± 0.02	0.43 ± 0.19	77	0.02 ± 0.005

* Calculations are based on hydrogen evolution rate during discharge.

Although aqueous electrolytes have been widely used, recent advancements suggest that gel-based "quasi-solid-state" electrolytes offer significant benefits in terms of energy efficiency and safety. One major safety concern in traditional liquid electrolytes is the potential for leakage, which can be mitigated by replacing the liquid with a gel polymer electrolyte (GPE). This approach not only prevents oxygen diffusion but also maintains relatively high ionic conductivity [43]. A dual-gel Mg–Air battery design has shown promising results by reducing the formation of hydroxide ions (OH^-) at the Mg anode while increasing the availability of protons (H^+) for the air cathode (Figure 5).

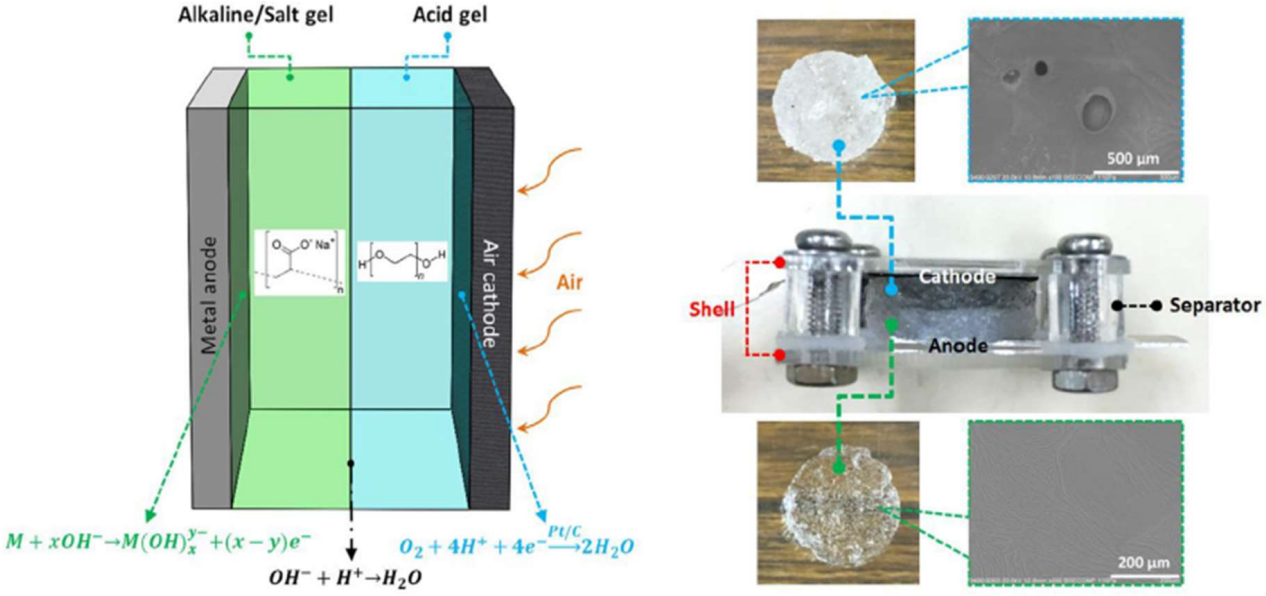


Figure 5. Dual-gel set-up for the researcher's experiments for dual-gel metal–air batteries. Reproduced with permission from [45].

The gel preparation process is straightforward: Polyethylene oxide (PEO), with a molecular weight of 2,000,000 is used for the acid gel, and sodium polyacrylate with a molecular weight of 6,000,000 for the alkaline gel. The process involves dissolving 120 mg

of polymer powder in a cylindrical container, followed by the gradual addition of 300 mL of either 3 M H_2SO_4 or 6 M KOH solution. The container is then sealed, allowing the gel to form over a 12 h period. The resulting product is a semi-transparent, viscous gel with good elasticity, which can be stacked to create a dual-gel electrolyte. For Mg–Air batteries, the gel is modified to a salt-based formulation using PEO and a saturated K_2SO_4 solution, prepared in a similar manner [45].

Initial experiments with the dual-gel electrolyte have demonstrated improvements over previous gel-based designs for Mg–Air batteries. Further research is needed to assess the feasibility of mass-producing the salt and acid gels, but early results suggest that dual-gel Mg–Air batteries hold promise for enhancing both the performance and safety of these systems.

4. Properties and Performance of Mg–Air Batteries

4.1. Energy Storage

Mg and other metal–air batteries offer significantly higher energy density compared to conventional alkaline or lithium-ion batteries. Although metal–air battery technology is not yet widely commercialized, their exceptional energy storage potential makes them ideal for applications that require lightweight batteries with extended energy capacity [14].

Battery capacity, or the amount of energy a battery can store, is typically measured in watt-hours (Wh) or kilowatt-hours (kWh). However, it is crucial to understand that battery capacity depends heavily on size and design. Consequently, design plays a key role in determining a battery's energy storage and performance. To enable comparisons across different battery types and sizes, energy density—the energy storage capacity per unit mass—serves as a useful metric. Energy density is measured in watt-hours per kilogram (Wh/kg) [46].

Alkaline batteries, commonly used in low-power applications, have an energy density ranging from 100 to 150 Wh/kg. Lithium-ion (Li-ion) batteries, used in consumer electronics and electric vehicles (EVs), generally range from 150 to 250 Wh/kg. While many consumer-grade Li-ion batteries do not exceed 200 Wh/kg, advances in technology have allowed newer EV models to surpass this threshold, reaching over 200 Wh/kg [47].

While Li-ion battery technology has improved in recent years, ongoing research into metal–air batteries has yielded remarkable results. For instance, zinc–air batteries have demonstrated energy densities ranging from 1000 to 2000 Wh/kg and aluminum–air batteries from 1500 to 2500 Wh/kg [48]. Mg–Air batteries, which show the greatest theoretical potential, can theoretically reach energy densities up to 6800 Wh/kg. However, in practical applications, Mg–Air batteries have only achieved around 700 Wh/kg. It is important to note that Mg–Air and other metal–air batteries are still under development, so these figures represent estimates of their potential rather than guarantees of future performance [49].

To put the energy storage capacity of metal–air batteries into perspective, we can examine the energy demands of common applications. A typical smartphone battery stores between 20 and 30 Wh of energy, which translates to 5 to 12 h of use. Assuming a Li-ion battery with a capacity of 200 Wh/kg powers the device, the battery would weigh between 0.1 and 0.15 kg. By comparison, using a conservative estimate for the energy density of a Mg–Air battery (700 Wh/kg), the battery's weight would range from 0.0286 to 0.0429 kg. This suggests that a Mg–Air battery could reduce the smartphone's battery weight by approximately 72% while providing the same amount of energy storage.

In the context of electric vehicles, consider a Tesla Model 3, which has a 75 kWh battery capable of providing a range of 350 miles on a single charge. This battery likely utilizes a high-quality Li-ion battery with an energy density of around 250 Wh/kg. If replaced with a Mg–Air battery, conservatively estimated at 700 Wh/kg, the battery's weight could be reduced by approximately 64%. While the casing and packaging materials contribute to the

overall weight of the battery, which complicates exact calculations, it is clear that Mg–Air batteries could lead to significant weight reductions. This reduction in weight would not only improve vehicle efficiency but could also extend the vehicle's range [50].

Given the extraordinary energy density of Mg and other metal–air batteries, their future use across a wide range of applications seems promising. Mg–Air batteries have the potential to significantly reduce the weight of portable electronics and electric vehicles while offering much greater energy storage [51].

4.2. Energy Discharge

Mg–Air batteries are a promising technology in energy storage, driven by the oxidation of Mg anode and the reduction of O_2 from the air. The discharge process begins when the Mg anode reacts with the electrolyte, producing Mg ions (Mg^{2+}) and electrons (e^-) [52]. Several key factors influence the discharge performance of Mg–Air batteries. The composition of the electrolyte plays a crucial role, as it directly affects the efficiency of both Mg oxidation and oxygen reduction reactions. Enhancing the cathode with catalysts can further improve the oxygen reduction reaction, leading to better overall battery performance. Temperature is another important variable; higher temperatures typically result in faster discharge rates. However, precise temperature control is essential to maintain long-term battery stability and performance. Additionally, the design and materials of the electrodes significantly affect the battery efficiency, making them a critical consideration in optimizing Mg–Air battery performance [53]. With their eco-friendly design and high energy density, Mg–Air batteries hold tremendous potential across a range of applications. From transportation and portable electronics to military uses and emergency backup power, these batteries offer a sustainable, energy-efficient solution for the future.

4.3. Efficiency of Mg–Air Batteries

Mg–Air batteries have the potential to be highly efficient due to their high energy density, abundant Mg supply, and lightweight properties. However, understanding their efficiency requires addressing the key limiting factors inherent in this technology. A significant challenge lies in the passivation and corrosion of Mg, which shortens the battery lifespan and prevents it from reaching its theoretical performance potential, both of which are critical to overall efficiency. Much of the ongoing research focuses on mitigating these issues by optimizing anode materials, improving corrosion resistance, and selecting suitable electrolytes.

Mg-based anodes generally suffer from lower Coulombic efficiency due to self-corrosion, which can negatively impact battery performance. Research in this area often centers on improving anode manufacturing techniques, such as alloy selection and surface treatments. These efforts influence the anode's microstructure, which affects its corrosion resistance, energy output, and long-term stability as the battery generates byproducts that can reduce efficiency. For instance, die-casting techniques have improved anodic efficiency to approximately 53–57%, a notable increase compared to standard Mg anodes, while remaining cost-effective [54].

One of the most studied aspects of Mg–Air battery efficiency is the selection of alloys for the anode. Alloying Mg with metals like zinc (Zn), aluminum (Al), tin (Sn), and calcium (Ca) helps address Mg's primary weaknesses, particularly corrosion. For example, Zn promotes corrosion resistance, while Sn affects voltage and power density. Different alloys have varying effects on efficiency. The alloy TZQ411 achieved an anodic efficiency of around 69.53%, while another study found that the AZ31 M alloy reached up to 73% efficiency [55,56]. These results underscore the importance of selecting the right alloy, as it has a substantial impact on the overall performance of the battery.

The diffusion over-potential caused by the protective product film typically increases resistance, limiting the battery's efficiency and capacity. The study by Yuying He et al. [57] demonstrates that by introducing cation vacancies in the product film on the Mg-Y-Zn anode, ion migration is enhanced, thereby reducing the over-potential and significantly improving both the efficiency and performance of the Mg–Air battery.

Post-processing techniques for Mg anodes, such as extrusion, rolling, and heat treatments, also play a significant role in enhancing battery efficiency. Heat treatments have been shown to increase power and energy density during discharge, while processes like hot extrusion create refined grain structures that improve both discharge performance and corrosion resistance [58]. Some studies have reported anodic efficiencies as high as 86% through these methods [59], highlighting the importance of post-processing in optimizing Mg–Air battery performance.

In addition to the anode, the choice of electrolyte is another critical factor in determining battery efficiency. For example, adding water-soluble graphene to the electrolyte can reduce corrosion while enhancing conductivity and electrochemical activity [60]. Single-salt electrolytes suffer from high charge transfer resistance at the Mg surface due to passivation layers and adsorbed species. For this reason, research is focused on finding additives that can both activate the magnesium surface and form a protective interface. The article by Riedel et al. [61] provides a comprehensive review of the development of electrolytes for Mg batteries, focusing on the chemical and electrochemical aspects.

To maximize the efficiency of Mg–Air batteries, a holistic approach is required, one that combines optimized anode materials, post-processing techniques, and electrolyte selection. This strategy must balance mitigating the limiting factors of corrosion and passivation while leveraging Mg's high energy density and voltage. Furthermore, the manufacturing processes and materials must align with the specific application of the battery, ensuring that improvements in efficiency do not compromise other benefits, such as environmental sustainability or cost-effectiveness.

5. Applications of Mg–Air Batteries

5.1. Portable Devices

Portable devices are an essential part of modern life, driving the demand for efficient, long-lasting power sources. Mg–Air batteries offer a promising solution for portable electronics due to their unique advantages [62]. With a high energy density that surpasses many other battery technologies, Mg–Air batteries can store more energy in a compact form, making them ideal for devices such as smartphones, laptops, and tablets that require substantial power in limited space.

One of the key benefits of Mg–Air batteries is their reliance on Mg, which is a lightweight, abundant, and cost-effective material, unlike lithium-ion batteries, which depend on heavier, sometimes scarce, and expensive materials. This makes Mg–Air batteries an attractive alternative for manufacturers and consumers seeking cost efficiency without compromising performance. In portable electronics, these batteries can significantly extend the runtime of devices, allowing smartphones to last days or even weeks on a single charge and laptops to endure a full workday without needing to be plugged in.

Beyond their practical benefits, Mg–Air batteries are also more environmentally friendly. They utilize oxygen from the air as a cathode reactant rather than relying on rare or toxic materials [63], aligning with the growing demand for sustainable technology solutions. This eco-friendly design contributes to reducing the environmental impact of portable electronics, a critical consideration as the world moves towards greener alternatives. Additionally, Mg–Air batteries offer a higher level of safety, with a reduced risk of

thermal runaway, a condition that can lead to fires or explosions in other battery types, such as lithium-ion batteries [64].

Despite their potential, Mg–Air batteries are still in the research and development phase, with ongoing efforts to address challenges related to electrolyte stability, overall efficiency, and practical integration into portable devices. As scientists and engineers continue to refine this technology, it is likely that Mg–Air batteries will gradually be adopted in a wide range of portable electronics. This will not only enhance user experience with longer-lasting devices but also reduce environmental impact and lessen dependence on lithium-ion batteries.

5.2. Vehicles and Transportation

Mg–Air and other metal–air batteries hold tremendous promise for revolutionizing vehicles and transportation. Their high energy density and lightweight properties make them a viable option across a wide range of applications, including hybrid and electric vehicles (EVs), unmanned aerial vehicles (UAVs), military transport systems, marine vessels, and emergency energy storage for transportation hubs.

One of the primary areas where Mg–Air batteries could have a significant impact is in powering electric vehicles (EVs). Due to their superior energy density, Mg–Air batteries have the potential to provide a much longer driving range compared to conventional lithium-ion batteries. A lighter weight would further enhance performance by reducing the overall mass of the vehicle, allowing for more efficient energy usage [65]. However, since metal–air battery technology is still under development, a more immediate and practical application might be as a range extender. In this scenario, the EV's primary power source would remain a lithium-ion battery, while a smaller Mg–Air battery could act as a supplemental power source, recharging the lithium-ion battery as needed. This hybrid approach could substantially increase the EV's range without requiring large amounts of Mg–Air battery material, offering a cost-effective solution for extending battery life while minimizing the complexity and expense of manufacturing [66].

Another promising application for Mg–Air batteries is in aerospace, particularly for unmanned aerial vehicles (UAVs). These battery-powered aircraft are used in various industries, including infrastructure inspection, agriculture, search and rescue, and military operations. Their lightweight design and high energy density could greatly extend the range and flight time of UAVs, improving their ability to gather critical data from hard-to-reach locations. Currently, flight times for UAVs vary significantly based on the aircraft's quality and weight, with durations ranging from a few minutes in hobbyist models to up to eight hours in high-end military drones. While the exact impact of Mg–Air batteries on UAV flight times remains to be seen, their potential to enhance energy efficiency and reduce weight makes them an exciting prospect for advancing UAV technology [67,68].

In addition to EVs and UAVs, Mg–Air batteries have potential applications in military and marine transport systems, as well as emergency backup power in transportation hubs. In military operations, these batteries offer not only weight savings but also the advantage of providing long-lasting power in remote locations, where recharging infrastructure may be limited [69]. Similarly, in the marine industry, Mg–Air batteries could help reduce emissions and provide a sustainable alternative to fossil fuels, especially in offshore and shipping operations where long-lasting, reliable power is essential [70].

A more speculative but highly valuable use of Mg–Air batteries could be as an emergency power source in transportation hubs such as EV charging stations and airports. In the event of a power outage, Mg–Air batteries could provide a high-energy, long-lasting backup power supply, ensuring uninterrupted operations in these critical infrastructure areas [71].

In summary, Mg–Air batteries offer unique opportunities for improving vehicles and transportation systems. Their lightweight design, high energy density, and ability to deliver long-lasting power make them particularly suitable for a range of applications, including electric vehicles, UAVs, military, marine, and emergency power systems. As this technology continues to evolve, Mg–Air batteries could drive significant advancements in these fields, offering both practical and environmental benefits.

5.3. Remote Power Sources

The demand for advanced battery technology is particularly high in remote applications where access to a stable power grid is limited or nonexistent. This includes everything from remote research equipment and military operations to emergency power supplies for critical infrastructure. Globally, there is a growing effort to reduce dependence on diesel fuels and transition toward renewable, sustainable energy sources. This shift is especially critical in remote locations, where logistical challenges and resource constraints necessitate the use of cutting-edge, cyclical energy systems.

For smaller, portable systems like remote sensors and handheld devices, battery power is essential for meeting operational needs. Larger systems, such as off-grid housing, often rely on solar panels and wind turbines combined with high-capacity batteries to power their daily activities. Hybrid energy systems also play a crucial role in these settings. In these scenarios, the potential advantages of Mg–Air batteries become particularly relevant.

One study explored the concept of a "Micro-Power System" for a neighborhood-sized off-grid community in Africa. This hybrid energy solution was designed to address the region's growing energy demands, considering factors such as economic conditions, environmental impacts, and meteorological data. The system was compared to diesel-only options and incorporated lead–acid batteries, which have an 80% round-trip efficiency, a 10-year lifetime throughput of 800 kWh, and a nominal capacity of 1.0 kWh [72]. Mg–Air batteries could provide a more efficient and cost-effective alternative in such a hybrid system. If Mg can ultimately offer cost advantages over lithium, it could meet the growing demand for renewable energy in remote applications.

Residential solar energy solutions are also gaining popularity, especially for single-family homes seeking off-grid independence. With the right configuration, modern homes can generate excess energy and sustain their electrical needs even when connected to a conventional power grid. These systems typically consist of a photovoltaic (PV) array, a battery, an inverter, and a PV charging controller. The PV array collects solar energy, which is either used directly or stored in the battery to supply power during low production periods [73]. In a 2018 study, researchers analyzed the efficiency of combining roof-mounted PV systems with batteries for emergency blackout scenarios. The study simulated power shortages across different seasons and weather conditions, with batteries such as the Tesla Powerwall 2 (lithium-ion) being the most commonly used [74]. However, a commercially available Mg–Air battery could have further extended the system's lifespan while reducing economic and environmental costs. A remote village experiment in rural Morocco simulated the integration of PV, wind, biomass, and battery systems to provide renewable energy. For an average energy requirement of 91.38 kWh/day and a peak load of 6.44 kW, the cost-effective configuration yielded a unit energy cost of 0.2 USD/kWh, demonstrating the viability of hybrid systems in regional power generation [75]. Mg–Air batteries could further enhance such systems by offering a more sustainable alternative to lithium-ion batteries.

Remote industrial operations also face unique power challenges. For instance, mines in remote locations typically rely on diesel generators for power, which can be costly and environmentally harmful. A study examining clean alternatives for refrigeration

systems in Canadian mines explored integrating renewable energy options like ice storage as an alternative to battery systems, emphasizing the high overhead costs of current battery solutions [76]. Similarly, rural healthcare facilities face power reliability issues, often resorting to diesel generators during periods of low solar production [77]. In both cases, Mg–Air batteries could provide a more affordable and environmentally friendly solution, addressing the growing demand for reliable and efficient power storage in remote applications. Although Mg–Air batteries are not yet widely used in these industries, their theoretical advantages—such as lower costs, higher energy density, and reduced environmental impact—position them as a promising alternative for future energy systems.

6. Challenges and Future Developments

6.1. Large-Scale Production

Scaling up the production of Mg–Air cells could revolutionize energy storage. These batteries are highly attractive due to their eco-friendliness, cost-effectiveness, and high energy density. Expanding Mg–Air battery production presents both opportunities and challenges. Notably, Mg–Air batteries are extremely lightweight and offer some of the highest energy densities among battery types [78], making them ideal for applications where space and weight are critical, such as electric vehicles and renewable energy storage systems.

The energy density of a battery refers to how much power it holds relative to its size or weight. Mg–Air batteries use Mg anode, a readily available and low-cost material, which contributes to their affordability. Mg is also safer to handle, as it does not overheat like lithium, a key component in lithium-ion batteries [79].

Another advantage of Mg–Air batteries is their quick recharging capability. These batteries can be recharged simply by replacing the Mg anode, a process as fast as refueling a car. In contrast, lithium-ion batteries require significantly more time to recharge, making Mg–Air batteries particularly useful in applications where frequent recharging is necessary, such as in rural areas, electric vehicles, and emergency backup systems [80].

However, several critical issues need to be addressed before Mg–Air batteries can be scaled up for widespread use. Improving battery longevity and performance is essential. Current Mg–Air batteries tend to lose efficiency after several charge and discharge cycles due to the formation of a passivating layer on the Mg anode, which disrupts the electrochemical processes [81]. This degradation issue is the result of surface passivation, which researchers are working to overcome by developing new cathode materials and electrolytes to enhance the stability and reversibility of Mg's electrochemical behavior [82].

In addition to technical improvements, developing a sustainable supply chain for Mg is crucial. The production of Mg–Air batteries hinges on the availability and cost of Mg. Although Mg is abundant in the Earth's crust, environmentally friendly and cost-effective extraction methods are still required [83]. Most Mg is sourced from minerals and brine, but to minimize environmental impact, sustainable extraction and recycling methods need to be developed.

Despite these challenges, Mg–Air batteries hold great promise. With ongoing advancements in material science and technology, their efficiency and longevity will continue to improve. Efforts are also focused on optimizing the design and components of these batteries to make them more competitive with other energy storage solutions [84]. Establishing sustainable Mg production and recycling processes will further enhance the viability of Mg–Air batteries on a larger scale.

Ultimately, Mg–Air batteries could transform energy storage by offering a low-cost, long-lasting solution. Making this technology more widely available will depend on improving efficiency, ensuring a steady Mg supply, and establishing robust recycling

systems [85]. With their potential to power a cleaner and more sustainable future, Mg–Air batteries are poised to play a key role in energy storage, from electric vehicles to renewable energy grids.

6.2. Enhancing Performance

A significant challenge for Mg–Air battery technology is improving its performance. While the technology offers high energy potential, it is hampered by issues such as low efficiency, short life cycles, and slow reaction kinetics, particularly in the anode, cathode, and electrolyte [86]. Addressing these factors is critical to enhancing the overall performance of Mg–Air batteries.

The anode in a Mg–Air battery consists of Mg metal, which faces a major issue: high corrosion rates. As the Mg anode comes into contact with the often-aqueous electrolyte, corrosion occurs, typically as a side reaction of the battery. This leads to the formation of a passivation layer at the anode–electrolyte interface, impeding energy transfer, reducing reaction kinetics, and ultimately shortening the battery's lifespan. Researchers are exploring ways to combat this issue, including alloying Mg with metals such as aluminum, lead, and lithium and using chemical treatments to reduce anode passivation [87]. However, while these methods improve performance in some aspects, they may introduce trade-offs. For instance, alloying Mg with aluminum can enhance voltage discharge and reduce corrosion rates but may lower the battery's energy capacity. Other elements, such as lead and tin, improve capacity and voltage but come with concerns such as toxicity and rarity. Additionally, research on optimizing the current collector contact points, which affect discharge performance, shows that uneven placement can lead to energy losses [88]. Improvements in this area could further enhance battery performance.

The electrolyte in Mg–Air batteries plays a crucial role in their overall performance, as it interacts with both the anode and cathode. The frequent passivation and corrosion at the Mg anode make electrolyte optimization a key area of focus. Research on aqueous electrolytes often explores the use of corrosion inhibitors, such as sodium silicate, which has been shown to reduce corrosion and passivation while improving battery discharge rates [89]. Some researchers are also investigating gel electrolytes as a potential alternative to aqueous solutions. Gel electrolytes prevent passivation and side reactions that lead to anode corrosion, resulting in batteries with higher specific capacities (2190 mAh/g) and energy densities (2282 Wh/kg) [90]. These advancements suggest that optimizing the electrolyte is essential for enhancing the longevity and performance of Mg–Air batteries.

The air cathode in a Mg–Air battery faces challenges related to the sluggish kinetics of the ORR [91]. The cathode's performance relies on several layers, such as hydrophobic surface layers and catalyst layers, which influence ORR kinetics. Research into non-noble metal catalysts has shown promise for improving ORR efficiency while keeping costs low. For example, using $CuMnO_2$ nanoflakes as the cathode catalyst has improved ORR performance [92]. Additionally, using PdSn bimetallic catalysts supported by multi-walled carbon nanotubes has also enhanced ORR kinetics [93]. Future research in this area will likely focus on developing cost-effective, non-toxic catalysts that optimize ORR performance.

Mg–Air batteries have immense potential, but significant performance improvements are necessary for widespread adoption. Enhancements in anode, cathode, and electrolyte design will be key to unlocking the full potential of this technology. As research continues, Mg–Air batteries may become a competitive and sustainable option for energy storage in various applications.

7. Conclusions

Mg–Air batteries are emerging as a promising next-generation energy storage technology, offering a sustainable and high-energy-density alternative to conventional batteries. One of the key advantages of Mg–Air batteries lies in their lightweight, energy-efficient, and cost-effective properties. The natural availability of Mg further enhances the sustainability of this technology. Additionally, rapidly recharging Mg–Air batteries by simply replacing the magnesium anode presents a unique advantage, particularly in applications requiring quick energy replenishment, such as electric vehicles and remote energy storage systems.

Despite their potential, significant challenges must be addressed to enable large-scale commercialization of Mg–Air batteries. A primary obstacle is the degradation of the Mg anode due to oxidation and the formation of passivation layers, which limit battery life and efficiency. Current research efforts focus on developing advanced materials, chemical additives, and optimized electrolyte formulations to mitigate passivation and improve the longevity and reliability of these batteries. Innovations in cathode design, particularly through the use of cost-effective, non-noble metal catalysts, are also addressing the sluggish ORR, further enhancing the overall performance of the technology.

As the production of Mg–Air batteries is still in its nascent stages, scaling up manufacturing processes and optimizing the supply chain remain critical hurdles. Researchers are exploring sustainable magnesium extraction methods and cleaner processing techniques to meet the growing demand and align with global sustainability goals. These efforts aim to minimize the environmental impact of magnesium sourcing and processing, ensuring that Mg–Air batteries contribute to a greener and more circular economy. Laboratory breakthroughs in corrosion reduction, improved energy performance, and enhanced reusability have brought Mg–Air batteries closer to practical application, and ongoing technological advancements are steadily overcoming the barriers to large-scale production.

Looking ahead, Mg–Air batteries have the potential not only to complement but also to eventually surpass traditional battery technologies, such as lithium-ion batteries, in terms of energy density, sustainability, and cost-effectiveness. Their ability to provide high energy density with a more environmentally friendly and safer design makes them ideal candidates for use in automotive applications, consumer electronics, and renewable energy storage systems. The development of more efficient and scalable manufacturing processes, coupled with breakthroughs in material science, will likely accelerate the widespread adoption of Mg–Air batteries in the coming years. With continued research and innovation, Mg–Air batteries could redefine the future of energy storage, offering a cleaner, safer, and more sustainable solution to meet the world's growing energy needs. As these technologies mature, Mg–Air batteries hold the potential to play a pivotal role in the transition to a sustainable energy future, driving advancements in green technology and contributing to a low-carbon global economy.

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