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THE GLOBAL ARTIFICIAL INTELLIGENCE INDUSTRY: ENERGY CHALLENGES (The Global Artificial Intelligence Industry: Emerging Challenges, Threats to Energy Infrastructure, and Potential Solutions)

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Abstract

This publication examines an emerging challenge facing the global artificial intelligence industry, where the primary constraint is no longer software development or the availability of advanced semiconductor chips, but the growing limitations of energy infrastructure. As artificial intelligence technologies continue to expand, the increasing demand for computational capacity has resulted in the rapid construction of large-scale data centers, placing unprecedented pressure on existing electrical power systems.

The study analyzes the relationship between the accelerated growth of artificial intelligence applications and the continuously increasing electricity consumption of modern data centers. It demonstrates that, in many regions, electrical grid capacity is approaching its operational limits, creating significant challenges for the further expansion of AI infrastructure and the deployment of next-generation computing facilities.

Particular attention is devoted to the conventional backup power solutions currently employed by data centers. For many years, industrial diesel generators have represented the standard technology for ensuring uninterrupted power supply during grid outages. However, these systems are becoming the subject of increasing environmental, regulatory, and public criticism. The publication highlights the example of the U.S. state of Virginia, widely recognized as the world's largest concentration of data centers, where more than 10,500 diesel generators are currently connected to data storage and processing facilities. Their extensive deployment has generated growing public concern and intensified regulatory pressure regarding environmental emissions and infrastructure sustainability.

Keywords: *Artificial intelligence industry; Energy infrastructure; Software; Emerging challenge; Technology companies and data centers; Backup power solutions; Industrial diesel generators; Integration with data storage and processing facilities; Alternative backup power supply system based on Aluminum-Air technology; Electrochemical reaction between aluminum plates and oxygen from ambient air; Such participation has highlighted*

the growing interest of technology giants in next-generation energy solutions; Global backup power market for data centers; Metal-air battery technology; The oxygen cathode consists of a hollow air-filled structure that allows oxygen to circulate freely within the battery

Against this background, considerable attention has been drawn to Phinergy, a company developing alternative energy technologies. At the Datacloud Global Congress held in Cannes, the company presented an alternative backup power supply system based on Aluminum-Air technology.

The company's Chief Executive Officer shared the stage with executives from Google and Microsoft, highlighting the growing interest of leading technology companies in next-generation energy solutions for critical infrastructure.

The Phinergy system generates electricity through an electrochemical reaction between aluminum plates and oxygen extracted from the ambient air. According to the company's Chief Executive Officer, the market requires a backup power solution capable of providing the same level of reliability and rapid start-up as conventional diesel generator systems, while eliminating their environmental impact.

Figure 1.

A key feature of the proposed technology is the absence of self-discharge. During standby operation, the liquid electrolyte is stored separately, while the aluminum elements remain dry. In the event of an emergency power outage, the electrolyte is automatically supplied to the system, initiating the electrochemical reaction and enabling immediate power generation.

A single power module is capable of providing uninterrupted electrical power for up to 48 hours. If the emergency extends beyond this period, the aluminum plates can be replaced without interrupting the operation of the equipment, thereby ensuring continuous power supply.

Introduction

Last year, Phinergy's solution was selected as one of the winners of the Net Zero Innovation Hub program. The consortium is led by Google and Microsoft in cooperation with Danfoss, Data4, Vertiv, and Schneider Electric. The proposal was selected from more than 70 competing projects submitted by participants from around the world.

The company is currently implementing a funded pilot project with a rated capacity of 500 kW and an energy storage capacity of 10 MWh at a demonstration site selected by the program participants.

According to industry experts, the global market for backup power systems for data centers is expected to reach USD150–200 billion within the next five years. Against this backdrop, Phinergy has already signed a preliminary agreement with one of the world's largest cloud service providers regarding the potential deployment of backup power systems with an aggregate capacity on the gigawatt scale by 2030.

The technology has already entered practical application. In Switzerland, the company cooperates with Swisscom Broadcast. In Israel, the deployment of backup power systems at 300 major road intersections began in April in cooperation with Netivei Israel. The solution enables critical infrastructure to remain operational for three to four days in the event of a power outage.

According to published reports, during the attack of October 7, backup power systems developed by Phinergy were automatically activated at mobile communication facilities located near the border with the Gaza Strip, helping to maintain the operation of the cellular communication network during the initial hours of the emergency.

Aluminum-Air backup power systems represent an environmentally sustainable electricity generation technology that produces electrical energy through the electrochemical reaction of aluminum, atmospheric oxygen, and water or an alkaline electrolyte. These systems operate as high-energy electrochemical power sources, providing high energy density together with extended autonomous operating time.

Operating Principle

Energy carrier. Replaceable metallic aluminum anodes serve as the primary energy source.

Oxidation process. Aluminum reacts electrochemically with atmospheric oxygen and an aqueous solution or alkaline electrolyte.

Electricity generation. The electrochemical reaction releases electrons, producing electrical current together with heat and hydrogen.

Environmentally safe by-product. The reaction produces aluminum hydroxide as its final product. This environmentally safe material can be collected and recycled into pure aluminum, thereby supporting a circular materials cycle.

Principal Advantages

- Zero self-discharge. During standby operation, the electrolyte and aluminum plates are stored separately, allowing the system to remain fully operational for many years without energy loss;
- High specific energy density. The technology provides substantially higher energy density than conventional lithium-ion and lead-acid batteries of comparable weight and volume;
- Zero local emissions. The system produces no harmful exhaust emissions at the point of use, unlike conventional diesel generators;
- Extended autonomous operation. The technology is particularly suitable for multi-day backup power applications.

Technological Limitations

- Fuel replacement requirement. As the aluminum plates are gradually consumed during operation, they must be physically replaced;
- Management of reaction by-products. Conventional systems required complex electrolyte purification; however, modern technological developments, including those introduced by Phinergy, address this challenge through closed-loop processing;
- Infrastructure requirements. While certain compact aluminum-air generators may be activated using either fresh water or seawater, stationary megawatt-scale installations require dedicated servicing and operational infrastructure.

Application Areas in 2026

The principal application areas for aluminum-air backup power systems include:

- Industrial facilities and data centers. Major technology companies, including Microsoft and Google, in cooperation with Phinergy, are evaluating aluminum-air technology as an environmentally sustainable alternative to conventional diesel backup generators;
- Autonomous residential buildings and microgrids. The technology provides reliable backup power for several days without noise, vibration, or harmful emissions;
- Portable emergency generators. Compact generators with output capacities ranging from 500 to 1,000 W can be activated using only water, making

them suitable for emergency and field applications.

The Future of Energy Storage: Metal-Air Batteries

Rechargeable batteries are currently used across a broad spectrum of technologies, including mobile devices, electric vehicles, renewable energy systems, and numerous industrial applications. However, existing battery technologies remain constrained by limitations in energy density and overall efficiency.

In recent years, metal-air batteries have attracted considerable research interest as one of the most promising approaches for substantially increasing energy density while improving the overall efficiency of electrochemical energy storage systems.

This article examines the design, operating principles, principal types, advantages, and limitations of metal-air batteries, together with their prospective applications in future energy systems.

Design and Operating Principle of Metal-Air Batteries

Metal-air batteries (Metal-Air Batteries) are a class of electrochemical energy storage devices in which electrical energy is generated through the oxidation of a metallic electrode using oxygen from the ambient air.

These batteries are characterized by exceptionally high energy density, enabling them to provide significantly greater energy storage capacity than many conventional battery technologies.

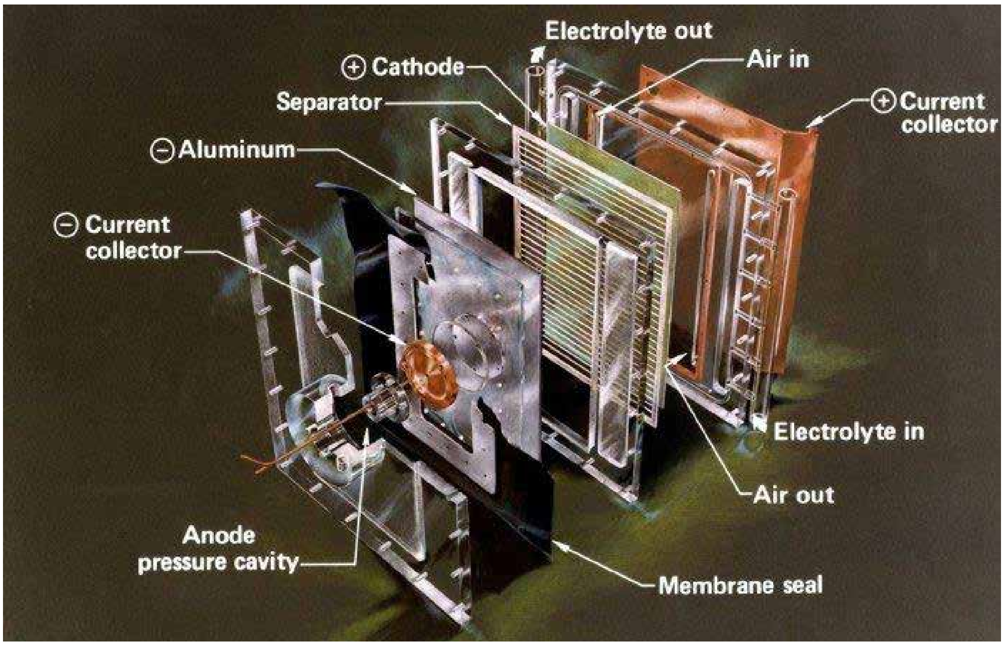
A metal-air battery consists of several principal components. The primary elements include a metallic anode (typically zinc or aluminum), an oxygen cathode, and an electrolyte.

The oxygen cathode is a hollow air-filled structure that allows atmospheric oxygen to circulate freely within the battery, thereby supplying the oxygen required for the electrochemical reaction.

The electrolyte is typically an alkaline solution, such as potassium hydroxide (KOH), which serves as the ionic conductor between the electrodes while maintaining charge balance throughout the electrochemical process.

The operating principle of a metal-air battery is based on the oxidation of the metallic anode. During discharge, the metal releases electrons into the external electrical circuit while simultaneously forming metal ions within the electrolyte.

Figure 2.



These metal ions migrate through the electrolyte toward the oxygen cathode, where they react with atmospheric oxygen and water to form metal oxides. During this electrochemical reaction, electrons are released and returned to the external electrical circuit, thereby sustaining the flow of electric current.

Accordingly, a metal-air battery generates electrical energy through an electrochemical oxidation-reduction (redox) reaction occurring between the metallic anode and oxygen supplied from the surrounding atmosphere.

Design of an Aluminum-Air Battery

The operating principle of an aluminum-air battery is relatively simple. The system utilizes aluminum alloy plates as the anode, water or an alkaline electrolyte as the electrolyte, and an air electrode as the cathode. Atmospheric air is drawn into the air-cathode assembly, which contains a catalyst.

The oxygen contained in the air is separated and reacts with water to form hydroxide ions (OH^-). These ions subsequently participate in an electrochemical reaction with the aluminum anode, resulting in the formation of aluminum hydroxide ($Al(OH)_3$). This electrochemical process releases energy in the form of electrical power.

Types of Metal-Air Batteries

Metal-air batteries are available in several configurations, each utilizing a different metal as the active anode material. The principal types include:

Zinc-Air Batteries. These batteries employ zinc as the metallic anode and atmospheric oxygen as the oxidizing agent. They offer high energy density and are suitable for applications requiring extended operating time, including electric vehicles and unmanned aerial vehicles (UAVs).

Lithium-Air Batteries. These systems utilize lithium as the metallic anode while oxygen from the atmosphere serves as the oxidant. Their exceptionally high theoretical energy density makes them attractive for electric vehicles and other applications requiring high-capacity energy storage.

Aluminum-Air Batteries. These batteries employ aluminum as the metallic anode and atmospheric oxygen as the oxidizing agent. Owing to their high energy density, they are suitable for a broad range of applications, including unmanned aerial vehicles, electric bicycles, and backup power systems.

Aluminum-Air Battery Technology

Aluminum-air battery technology offers a number of significant advantages. Aluminum is lighter than many conventional battery materials, is abundant in nature, and is widely available through established industrial supply chains.

In addition, the aluminum hydroxide produced during battery operation can be recycled and converted back into metallic aluminum, thereby supporting a circular materials cycle.

Furthermore, aluminum-air batteries are reported to achieve an energy density of approximately 8 kWh/kg, compared with approximately 1–1.5 kWh/kg for conventional lithium-ion and related battery technologies. Consequently, even if only half of the theoretical energy density is achieved under practical operating conditions, an aluminum-air battery could theoretically provide approximately four times the driving range of an equivalent lithium-ion battery system.

Advantages and Limitations of Metal-Air Batteries

Advantages

- High energy density. Metal-air batteries offer significantly higher energy density than most conventional battery technologies, enabling substantially longer operating times;
- Long storage life. These batteries can remain in storage for many years without significant degradation of their performance characteristics;
- Environmental compatibility. Metal-air batteries do not contain heavy metals such as lead or cadmium, thereby reducing potential environmental risks.

Limitations

- Limited rechargeability. Metal-air batteries generally provide a limited number of charge-discharge cycles because the oxidation reaction of the metallic anode is not fully reversible;
- Sensitivity to environmental conditions. Certain metal-air battery chemistries are sensitive to moisture and uncontrolled exposure to atmospheric oxygen during storage;
- Application-specific suitability. These batteries are primarily intended for applications where high energy density

is of greater importance than repeated rechargeability.

Zinc-Air Batteries as an Alternative to Lithium-Ion Technology

At present, zinc-air batteries are widely regarded as one of the most promising alternatives to conventional lithium-ion batteries.

Although lithium-ion batteries provide high energy density, they are also associated with several well-recognized limitations. Under unfavorable operating conditions, they may overheat and, in rare cases, experience thermal runaway, resulting in fire or explosion.

In addition, the extraction of raw materials used in lithium-ion batteries – particularly lithium and cobalt – has attracted increasing environmental and ethical concerns. Mining, processing, and disposal of these materials may adversely affect both the environment and human health. For example, cobalt mining in certain developing countries has been associated with child labor and the exploitation of migrant workers.

By comparison, zinc-air batteries are capable of delivering many of the advantages of lithium-ion systems while eliminating the risk of thermal runaway. They also do not require external cooling systems during normal operation.

Furthermore, because zinc-air batteries utilize atmospheric oxygen as the cathode reactant and zinc as the anode material, their manufacture requires fewer rare or environmentally problematic raw materials.

Applications of Metal-Air Batteries

Metal-air batteries have a broad range of military, commercial, and civilian applications.

Military applications benefit from their high energy density and long storage life. These batteries are widely used in communication equipment, optical instruments, portable lighting systems, and unmanned aerial vehicles.

Commercial and civilian applications include electric vehicles, unmanned aerial systems, high-energy portable equipment, and numerous other technologies requiring lightweight, high-capacity energy storage.

Metal-air batteries are also well suited for emergency and backup power systems, including emergency lighting, alarm and notification systems, automatic fire protection systems, telecommunications infrastructure, and other critical facilities requiring reliable standby power.

Despite their numerous advantages, the widespread adoption of metal-air batteries in consumer applications remains limited because of their relatively high manufacturing cost and technological complexity. Nevertheless, continuing advances in materials science and electrochemical engineering are expected to significantly expand their practical applications in the coming years.

Future Development Prospects

Metal-air batteries possess significant potential for future development owing to their high energy density and environmental advantages. The principal directions for the further development of metal-air battery technology include the following:

Technological advancements. Battery manufacturers and research organizations continue to improve metal-air battery technology by increasing energy density, enhancing electrochemical efficiency, extending operational lifetime, and reducing manufacturing costs.

Expansion of applications. Metal-air batteries are expected to find wider application across numerous industries, including the automotive, aerospace, defense, and industrial sectors. Potential applications include electric vehicles, unmanned aerial vehicles (UAVs), portable electronic devices, and stationary backup power systems.

Development of new metal-air battery chemistries. In addition to established technologies such as zinc-air, lithium-air, and aluminum-air batteries, new battery chemistries utilizing more environmentally sustainable and readily available materials are expected to emerge.

Grid-scale energy storage. Metal-air batteries have the potential to become an important component of modern power systems by providing large-scale electrical energy storage capable of supporting grid stability and improving energy security.

Integration with renewable energy sources. Metal-air batteries can be integrated with renewable energy systems, including solar and wind power installations, enabling surplus energy to be stored and subsequently utilized during periods of low renewable energy generation.

Conclusion

Metal-air batteries represent one of the most promising directions in the development of advanced electrochemical energy storage technologies. Their exceptionally high energy density, long storage life, and relatively low material costs make them attractive for applications in defense, aviation, portable electronics, electric transportation, and stationary backup power systems.

Despite these advantages, the technology continues to face several technical challenges, including limited service life, the need for specialized air-management systems, and certain environmental and operational considerations associated with long-term deployment.

Current research and development efforts are focused on improving battery durability, enhancing environmental sustainability, increasing electrochemical efficiency, and expanding the range of practical applications.

One of the most important directions for future development is the introduction of advanced materials capable of improving battery performance, extending operational lifetime, reducing production costs, and minimizing environmental impact.

Accordingly, metal-air batteries constitute a highly promising class of next-generation energy storage technologies with the potential to substantially improve both the energy efficiency and the economic performance of a wide range of electrical and industrial systems.

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