

Analysis of Application Potential of Calcium-Carbon Mineral Battery in Renewable Energy Storage

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ABSTRACT

As a new energy storage technology, calcium-carbon mineral battery has become a research hotspot because of its advantages of low cost, high safety, potential long cycle life and abundant resources. In this paper, the technical principle, performance characteristics and application potential of calcium-carbon mineral battery in renewable energy storage are systematically analyzed. Calcium-carbon mineral batteries are made of calcium-based materials and carbon-based conductive agents. The working voltage is 2.0-3.5V, the theoretical energy density is 200-400 Wh/kg, which can actually reach 100-250 Wh/kg, and the cycle life can reach 500-1000 times under laboratory conditions. It has high safety, low cost and excellent performance in the range of -20°C to 60°C. In terms of application scenarios, calcium-carbon batteries are suitable for a variety of settings, including grid-scale, distributed, and mobile energy storage. They can effectively smooth the fluctuations in renewable energy generation, provide stable power to remote areas, and enhance the driving range of electric vehicles. Economic evaluations show that the levelized cost of storage (LCOS) for calcium-carbon batteries is \$68/kWh, significantly lower than the \$92/kWh for lithium-ion batteries. However, calcium-carbon batteries still face challenges in commercialization, such as technical bottlenecks, an imperfect market and policy environment, and an immature industrial chain. In the future, further optimization of materials and processes, improvements in battery performance, and the establishment of stronger policy support systems will be necessary to promote the widespread adoption of calcium-carbon batteries.

KEYWORDS

Renewable Energy Storage; Application Potential; Calcium-Carbon Mineral Battery.

1. INTRODUCTION

The intermittent and fluctuating characteristics of renewable energy lead to the mismatch between power generation output and power demand, which seriously restricts the large-scale consumption of renewable energy and the stability of power grid. As a key means to balance power supply and demand and improve the flexibility of power grid, energy storage technology has become the core link to realize efficient utilization of renewable energy. At present, lithium-ion batteries occupy a dominant position in the energy storage market with their high energy density and mature industrial chain, but their high cost, scarce resources and potential safety hazards limit their application in long-term energy storage scenarios. In this context, calcium-carbon mineral batteries have become the research focus of new energy storage technology with the advantages of low cost, high safety and potential long cycle life. Calcium-carbon mineral battery is rich in core materials and simple in preparation process, which is expected to provide an economical and reliable solution for renewable energy storage.

Perovskite battery is a new type of solar cell using perovskite-type organic-inorganic hybrid metal halide semiconductor as light absorbing material [1]. Its general chemical structure is ABX_3 , where A and B are cations with different sizes, and X is halogen anion [2]. The basic structure of perovskite battery includes metal counter electrode, hole transport layer, perovskite layer, electron transport layer and transparent conductive glass. The research of perovskite battery began in 2009, and since then, its photoelectric conversion efficiency has increased rapidly, and now it has exceeded 25%, which is close to or even exceeds the traditional silicon-based solar cell [3-4]. China has made remarkable progress in the field of perovskite batteries, and many enterprises and research institutions have set new world records in the efficiency and stability of perovskite batteries [5]. Perovskite battery has high photoelectric conversion efficiency, which means that under the same lighting conditions, perovskite battery can generate more electricity, thus improving the overall efficiency of energy storage system [6]. The preparation cost of perovskite battery is low, which helps to reduce the cost of the whole renewable energy storage system and make it more competitive [7]. Perovskite batteries can be made into flexible components, which are suitable for surfaces of various shapes and sizes, providing more application scenarios for renewable energy storage [8].

As a new technology of renewable energy storage, perovskite battery shows great application potential, but its development still faces some challenges. The main problems include insufficient long-term stability of perovskite materials, which affects the reliability and durability of batteries; Large-scale production technology is not yet mature, and further technical research and development and optimization are needed; And the environmental problems caused by heavy metal elements in perovskite, such as lead, promote the demand for lead-free or low-toxic alternative materials. Faced with these challenges, researchers need to devote themselves to material improvement and technological innovation to promote the wide application and development of perovskite batteries. This paper systematically analyzes the technical principle, performance characteristics and application potential of calcium-carbon mineral battery in renewable energy storage. This paper reveals the electrochemical mechanism and material advantages of calcium-carbon mineral batteries, evaluates their technical adaptability in grid-level, distributed and mobile energy storage scenarios, discusses the challenges faced by commercialization, and provides theoretical reference for the industrial application of calcium-carbon mineral batteries.

2. TECHNICAL PRINCIPLE AND PERFORMANCE CHARACTERISTICS OF CALCIUM-CARBON MINERAL BATTERY

2.1. Technical Principle

Calcium-carbon mineral batteries are constructed by using calcium-based materials such as calcium carbonate or perovskite oxides as active substances, combined with solid or liquid electrolytes and carbon-based conductive agents such as graphene or carbon nanotubes. During the charging process, calcium ions are deintercalated from the perovskite structure of the positive electrode, migrate through the electrolyte to the negative electrode, and are embedded in the layered structure of carbon-based materials; The discharge process is the opposite, and calcium ions migrate from the negative electrode to the positive electrode, realizing the storage and release of charges (Figure 1). The reaction mechanism of this battery involves the process that the perovskite structure on the anode is dissociated into calcium ions and titanate, and the calcium ions on the cathode combine with carbon-based materials to form calcium carbide [9-10].

The working voltage of calcium-carbon mineral battery is about 2.0-3.5V, depending on the combination of anode and cathode materials used. The charge-discharge rate is limited by the migration rate of calcium ions, and the typical rate performance is 0.5C-2C, which is lower than that of 5C-10C of lithium-ion batteries. This battery has excellent temperature adaptability, can work

stably in the range of -20°C to 60°C , and its performance is better than that of lithium-ion battery at low temperature.

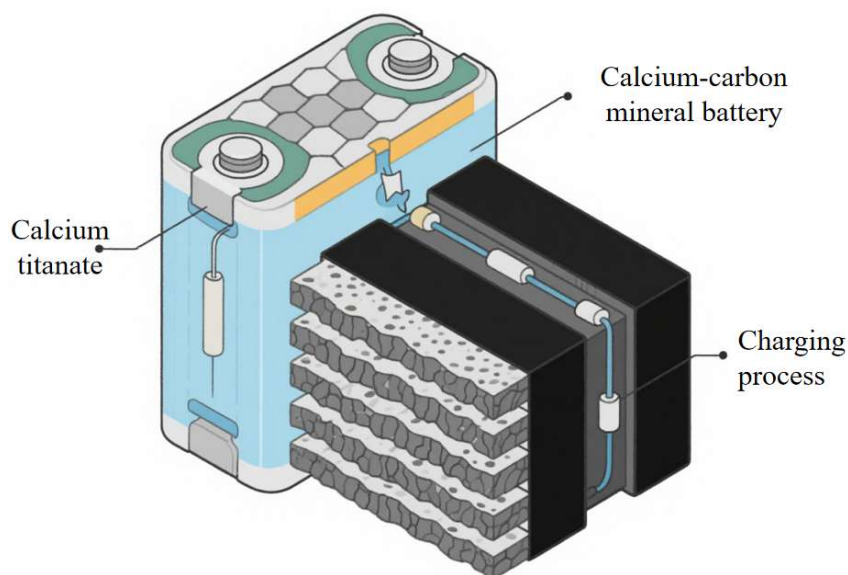


Figure 1. Structure and principle of calcium-carbon mineral battery

2.2. Performance Characteristics

The theoretical energy density of perovskite battery is 200-400 Wh/kg, but the current actual energy density is between 100-250 Wh/kg, which is limited by material stability and ion migration rate and needs to be improved by material modification. Its cycle life can reach 500-1000 charge-discharge cycles under laboratory conditions, and the capacity retention rate exceeds 80%, but the problem of material structure degradation in long-term cycle still needs to be solved in industrial application. In terms of safety, due to the low working voltage, about 2.0-3.5 V, the common risk of thermal runaway of lithium-ion batteries is avoided, and the use of solid electrolyte can inhibit dendrite growth and reduce the risk of short circuit. In terms of cost, thanks to the abundant reserves of raw materials such as calcium carbonate and perovskite and simple preparation processes, such as low-temperature sintering and hydrothermal synthesis, its cost is only 1/10 to 1/5 of that of lithium resources, showing a significant cost advantage.

2.3. Technical Superiority

Perovskite battery has many technical advantages, including low cost, high safety and environmental friendliness. Calcium resources are abundant in the earth's crust, and the preparation process is simple, which makes its material cost much lower than that of lithium-ion batteries, and avoids the need for expensive lithium resources. The chemical properties of calcium ions are stable, and the working voltage of the battery is lower than 3.5V, which reduces the risk of thermal runaway and has higher safety. Cathode materials can be prepared from industrial wastes or natural minerals, and cathode materials are widely available, which meets the requirements of sustainable development. In addition, the high diffusion coefficient of calcium ions in solid electrolyte is helpful to reduce the structural degradation of electrode materials, showing the potential advantage of long cycle life.

3. APPLICATION POTENTIAL

Calcium-carbon mineral battery is a new energy storage technology based on the reaction between calcium metal and carbon material, which has the advantages of rich resources, low cost and

environmental friendliness. Its working principle is reversible intercalation/deintercalation of calcium ions in carbon-based electrodes, which realizes efficient conversion of electrical energy and chemical energy.

3.1. Application Scenario

Calcium-carbon mineral battery has high energy density, theoretical value > 1000 Wh/kg, long cycle life (> 5000 times), and supports wide temperature range (-20°C~60°C), which is suitable for various energy storage scenarios, as shown in Table 1.

Table 1. Application scenario analysis

Application scenario	Demand characteristics	Adaptability of calcium-carbon mineral battery
Grid level energy storage	Large capacity, long cycle and low operation and maintenance cost	High energy density supports large-scale deployment; Long life reduces total cost.
Distributed energy storage	Quick response, flexible installation and high safety.	Modular design adapts to distributed scenes; Strong compatibility in wide temperature range
Mobile energy storage	High energy density, light weight and fast charging ability	Carbon-based materials have great lightweight potential; Calcium ion migration rate is fast.

Calcium-carbon mineral battery has shown its application potential in many typical scenarios, including peak regulation of power grid, and smoothing the power generation fluctuation of these intermittent energy sources by combining with wind power and photovoltaic; In terms of household energy storage, it provides stable power supply for remote areas and replaces traditional diesel generators; In the field of electric vehicles, it can not only be used as a power battery to improve the cruising range of vehicles, but also serve as a range extender to further increase the driving distance. These application scenarios fully reflect the value of calcium-carbon mineral batteries in improving energy efficiency and promoting sustainable development.

3.2. Technical Adaptability

Compared with the mainstream energy storage technology, calcium-carbon mineral batteries show significant advantages in key performance parameters [11], as shown in Table 2. The technical advantages of calcium-carbon mineral batteries are mainly reflected in resource abundance, safety and wide temperature range performance. Both calcium and carbon are abundant elements in the earth's crust, effectively avoiding the limitation of resources such as lithium and cobalt. Its carbon-based electrode material is nonflammable and has no dendrite problem, which improves the safety of use and is suitable for large-scale application. In addition, the capacity retention rate of calcium-carbon mineral battery is over 80% at low temperature, which is better than that of lithium-ion battery which is usually lower than 60%, showing its ability to work stably under various environmental conditions [12].

Table 2. Comparison of technical adaptability

Technical indicators	Calcium-carbon mineral battery	Lithium-ion batteries	NaS Battery	Flow battery
Energy density (Wh/kg)	800-1200	150-250	300-400	20-40
Power density (W/kg)	500-800	300-500	200-300	10-50
Cycle life (times)	>5000	500-1500	>2500	>10000
Response time (ms)	<100	<100	>500	>1000
Material cost (\$/kWh)	Low (calcium/carbon abundance)	Higher (lithium/cobalt)	Medium (sodium/sulfur)	High (electrolyte)
environmental risk	Low (non-toxic material)	Medium (flammable electrolyte)	High (high temperature corrosion)	Low (aqueous electrolyte)

3.3. Economic Evaluation

Take the grid-level energy storage system as an example [13], and compare the life cycle cost (LCOS, unit: \$/kWh) of calcium-carbon battery and lithium-ion battery, as shown in Table 3.

Table 3. Life cycle cost comparison

Cost item	Calcium-carbon mineral battery	Lithium-ion batteries
Initial outlay	120	180
Operation and maintenance cost (year)	5	8
Cycle life (year)	15	8
LCOS	68	92

In the grid-level energy storage system, the LCOS comparison between calcium-carbon battery and lithium-ion battery shows that calcium-carbon battery has obvious advantages in initial investment, operation and maintenance cost and cycle life. Specifically, the initial investment cost of calcium-carbon mineral battery is \$120 /kWh, which is lower than that of lithium-ion battery, which is \$180/kWh. Its annual operation and maintenance cost is \$5 /kWh, which is also lower than \$8 /kWh for lithium-ion batteries. More importantly, the cycle life of calcium-carbon mineral batteries is as long as 15 years, while that of lithium-ion batteries is only 8 years. Based on these factors, the LCOS of calcium-carbon mineral battery is 68 US dollars /kWh, which is significantly lower than that of lithium-ion battery of 92 US dollars /kWh, showing higher economic benefits and competitiveness.

The economy of calcium-carbon mineral batteries can be further optimized through scale effect and policy subsidies [14]. If the output is increased by 10 times, the material cost is expected to decrease by 30%, and the LCOS will be reduced to \$55 /kWh. In addition, assuming that the energy storage subsidy per kWh is 0.1 yuan, LCOS can be reduced by an additional 12% (Figure 2). When the peak-

valley electricity price difference is 0.5 yuan /kWh, the investment return period of calcium-carbon ore energy storage system is about 4 to 6 years, which is more attractive than 6 to 8 years for lithium-ion batteries (Figure 3).

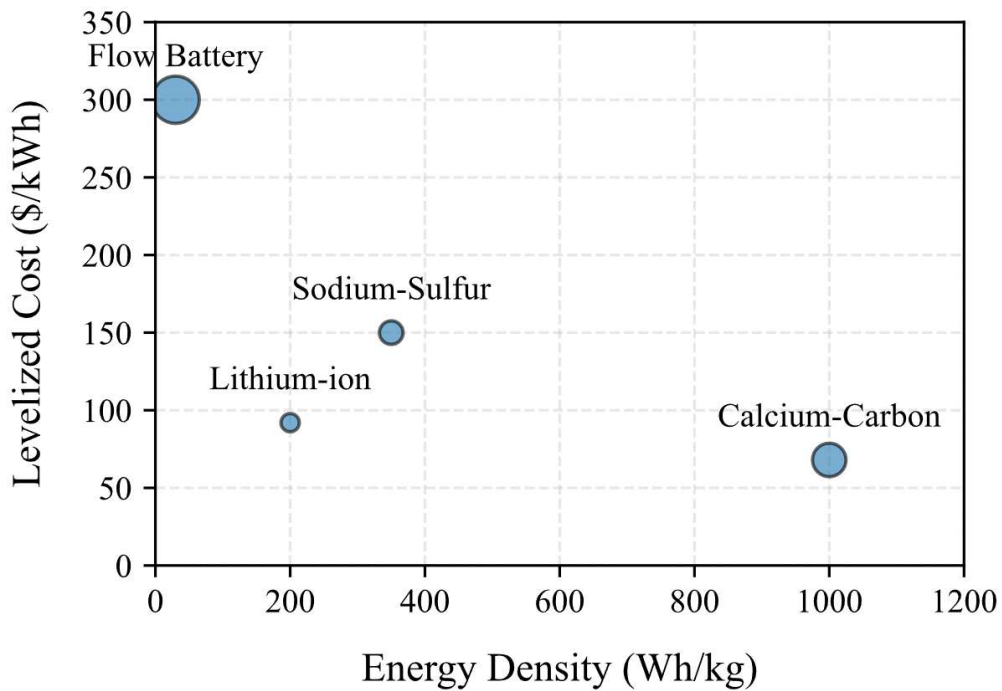


Figure 2. Comparison of energy density and cost of different energy storage technologies

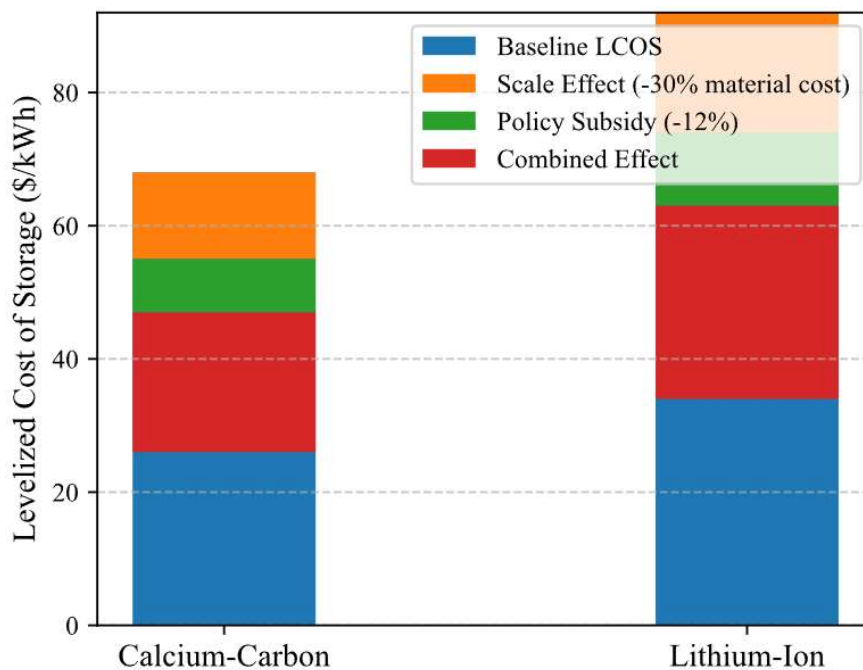


Figure 3. Life-cycle cost sensitivity analysis of calcium-carbon battery and lithium-ion battery

Calcium-carbon mineral batteries have significant application potential in the field of renewable energy storage. It not only has strong technical adaptability and can meet the needs of grid-level, distributed and mobile energy storage, but also shows advantages in economy. The life cycle cost is

lower than that of lithium-ion batteries and is not affected by resource constraints. At the same time, due to the use of non-toxic materials and high recovery rate, calcium-carbon mineral batteries are environmentally friendly and help to achieve carbon neutrality, which reflects its important position in future energy storage solutions.

4. CHALLENGES FACED BY COMMERCIALIZATION OF CALCIUM-CARBON MINERAL BATTERIES

4.1. Technical Bottleneck

Calcium ion is easy to cause lattice collapse of electrode materials such as perovskite during charging and discharging, resulting in the laboratory cycle life of only 500-1000 cycles, which is far below the theoretical value. Moreover, the capacity of a prototype battery drops to 60% of the initial value after 800 cycles, which is difficult to meet the requirements of grid-level energy storage. The ionic conductivity of solid electrolyte is low, resulting in high internal resistance and differential rate performance, which can not support fast charging scenarios; Although liquid electrolyte has high conductivity, there are leakage risks and long-term stability problems. At present, the energy density of calcium carbonate battery is 60%-80% of that of lithium ion battery. The performance can be improved by material modification, but this may increase the process complexity and cost.

4.2. Market and Policy Environment

Calcium-carbon mineral battery faces cost disadvantage in the early stage of commercialization, and its theoretical low-cost advantage is not fully reflected because of low yield and short cycle life. The actual system cost is 150-200 USD /kWh, which is higher than that of sodium ion battery. In terms of policy, energy storage subsidies in most countries are mainly for lithium-ion batteries, and calcium-carbon mineral batteries lack special support, industry standards and unified performance test specifications and safety certification standards, which limits their large-scale market promotion. In addition, the market recognition of calcium-carbon mineral batteries is insufficient, and end users such as power grid operators and electric vehicle manufacturers are cautious about this emerging technology, preferring mature Ferrous lithium phosphate and ternary lithium battery technologies.

4.3. Industrial Chain Supporting

The calcium-carbon mine battery industry chain is facing the problem of immature supply chain of key materials. High-purity perovskite materials, such as CaTiO_3 , mainly rely on chemical synthesis process, but domestic production capacity is insufficient and they need to be imported, such as purchasing from Japanese and German suppliers, which increases the cost. The large-scale production technology of solid electrolyte is not perfect, especially the materials such as sulfide electrolyte, which are extremely sensitive to humidity, need to be produced in harsh dry environment, which increases the technological difficulty.

In terms of production equipment and technology, calcium-carbon mineral batteries require specific adjustment and investment. For example, because the viscosity of calcium-carbon ore electrode slurry is higher than that of lithium electrolyte slurry, it is necessary to customize the coater and optimize the slit width, resulting in an increase of equipment investment of 20%-30%. In order to adapt to the large radius of calcium ions and increase the thickness of battery pole pieces, the laser cutting equipment needs to upgrade the laser power to more than 50W and improve the cutting accuracy. Although calcium-carbon mineral batteries do not contain toxic elements, the recovery system has not yet been established, especially the immature separation technology of carbon-based anode and perovskite, which may lead to the increase of disposal cost of retired batteries and increase the pressure of environmental protection.

5. CONCLUSION

Calcium-carbon mineral battery has obvious application potential in renewable energy storage, and its low cost, high safety and environmental friendliness make it a research hotspot of new energy storage technology. Despite the challenges of long-term stability and large-scale production of materials, calcium-carbon mineral batteries are expected to overcome these obstacles through material modification and technological innovation. Its excellent performance and economic benefits in grid-level, distributed and mobile energy storage scenarios, as well as its non-toxic materials and high recovery rate are environmentally friendly, indicate its important position in future energy storage solutions. With the improvement of policy support and market recognition, calcium-carbon mineral batteries are expected to realize large-scale commercial application, providing strong support for the efficient utilization of renewable energy and the stability of power grid.

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