

Fast-Charging Magnesium Batteries for Commercial Electric Trucks

Nidhi

Department of Physics, Govt. P.G. College, Guna, M.P. 473001, India

Abstract— The rapid electrification of commercial transportation has intensified the demand for high-capacity, safe, low-cost, and fast-charging battery technologies. While lithium-ion batteries currently dominate the electric vehicle market, their limitations in terms of resource scarcity, thermal instability, and charging degradation have encouraged exploration of alternative chemistries. Magnesium batteries have emerged as a promising next-generation energy storage technology due to magnesium's high volumetric capacity, natural abundance, low dendrite formation tendency, and improved safety profile. This research paper examines the feasibility of fast-charging magnesium batteries for commercial electric trucks. It analyzes the electrochemical properties of magnesium, recent advancements in electrolytes and cathode materials, charging mechanisms, thermal management, and infrastructure requirements. Furthermore, the paper discusses technical challenges including sluggish ion diffusion, electrolyte incompatibility, and cycle stability. Comparative analysis with lithium-ion systems demonstrates the potential advantages of magnesium batteries for heavy-duty transportation applications. The study concludes that despite existing technological barriers, ongoing research in materials science and electrochemistry may enable magnesium batteries to become a viable solution for future fast-charging electric truck fleets.

Keywords—Magnesium Batteries, Charging and discharging, Volume charge density, Dendrite growth and Electric vehicles.

I. INTRODUCTION

The transportation industry contributes significantly to global greenhouse gas emissions, leading governments and industries worldwide to accelerate the transition toward electric mobility. Commercial electric trucks are expected to play a central role in sustainable logistics and freight transportation. However, current lithium-ion battery systems face several challenges for heavy-duty vehicles, including long charging times, thermal runaway risks, high material costs, and limited resource availability.

Fast charging is particularly important for commercial trucks because fleet operations require minimal downtime and maximum operational efficiency.

Traditional lithium-ion systems experience severe degradation under ultra-fast charging conditions due to lithium plating, overheating, and structural damage to electrodes.

Magnesium batteries have recently gained attention as an alternative energy storage technology because magnesium metal offers:

- High volumetric energy density
- Greater elemental abundance than lithium
- Improved safety characteristics
- Reduced dendrite growth
- Lower raw material cost

These advantages make magnesium batteries attractive for heavy electric vehicles such as long-haul commercial trucks, buses, and industrial transport systems.

This paper investigates the potential of fast-charging magnesium batteries for commercial electric trucks and evaluates their opportunities and technological limitations.

II. FUNDAMENTALS OF MAGNESIUM BATTERY TECHNOLOGY

2.1 Magnesium as an Anode Material

Magnesium is the eighth most abundant element in Earth's crust and possesses several favorable electrochemical properties.

Key characteristics include:

Property	Magnesium	Lithium
Valence	+2	+1
Volumetric Capacity	3833 mAh/cm ³	2062 mAh/cm ³
Abundance	High	Moderate
Dendrite Formation	Low	High
Melting Point	650°C	180°C

The divalent nature of magnesium allows the transfer of two electrons per ion, theoretically enabling higher energy storage capacity.

2.2 Working Principle of Magnesium Batteries

A magnesium battery consists of:

1. Magnesium metal anode
2. Electrolyte containing Mg^{2+} ions
3. Cathode material capable of reversible magnesium insertion

During discharge:

- Magnesium oxidizes at the anode
- Mg^{2+} ions migrate through the electrolyte
- Electrons travel through the external circuit
- Cathode undergoes reduction reactions

During charging, the reverse process occurs.

III. IMPORTANCE OF FAST CHARGING FOR COMMERCIAL ELECTRIC TRUCKS

Commercial trucking operations require:

- Minimal charging downtime
- Long driving range
- High energy density
- Stable thermal performance
- Long cycle life

Fast charging infrastructure significantly influences fleet economics and operational efficiency.

3.1 Challenges with Current Lithium-Ion Systems

Current lithium-ion batteries face several issues during fast charging:

- Lithium plating
- Excessive heat generation
- Capacity degradation
- Fire hazards
- Cooling system complexity

Heavy trucks demand megawatt-scale charging systems, increasing these challenges further.

IV. ADVANTAGES OF MAGNESIUM BATTERIES IN FAST CHARGING APPLICATIONS

4.1 Reduced Dendrite Formation

Unlike lithium metal, magnesium deposits more uniformly during charging, reducing the risk of dendritic growth that can cause short circuits.

4.2 Higher Safety

Magnesium is less reactive with air and moisture than lithium, significantly lowering thermal runaway risks.

4.3 High Volumetric Energy Density

The high volumetric capacity of magnesium is advantageous for commercial trucks where space optimization is critical.

4.4 Material Abundance and Cost Efficiency

Magnesium resources are more abundant globally, potentially lowering production costs and supply chain dependency.

V. ELECTROLYTE DEVELOPMENT FOR FAST-CHARGING MAGNESIUM BATTERIES

Electrolytes are among the most critical components in magnesium battery performance.

5.1 Challenges in Magnesium Electrolytes

Magnesium forms passivating layers on many electrolyte systems, preventing efficient ion transport.

Major issues include:

- Low ionic conductivity
- Narrow electrochemical stability window
- Poor compatibility with cathodes

5.2 Advanced Electrolyte Technologies

Recent developments include:

a) Organohaloaluminate Electrolytes

These provide reversible magnesium deposition but suffer from corrosiveness.

b) Borate-Based Electrolytes

Offer improved electrochemical stability and reduced corrosion.

c) Solid-State Electrolytes

Potentially enable safer ultra-fast charging with improved thermal stability.

VI. CATHODE MATERIALS FOR HIGH-PERFORMANCE MAGNESIUM BATTERIES

The cathode largely determines battery capacity and charging rate.

6.1 Transition Metal Sulfides

Materials such as MoS_2 and TiS_2 exhibit layered structures favorable for magnesium intercalation.

6.2 Vanadium-Based Cathodes

Vanadium oxides demonstrate relatively high capacity but face structural degradation over repeated cycles.

6.3 Organic Cathodes

Organic compounds offer flexible molecular design and potentially faster ion transport.

VII. FAST-CHARGING MECHANISMS AND LIMITATIONS

Fast charging requires rapid ion movement and efficient electron transfer.

7.1 Ion Diffusion Constraints

Mg²⁺ ions possess:

- Higher charge density
- Stronger electrostatic interactions
- Slower diffusion kinetics

These factors limit ultra-fast charging performance.

7.2 Thermal Management

Fast charging generates substantial heat due to internal resistance.

Advanced cooling systems include:

- Liquid cooling
- Phase-change materials
- AI-driven thermal control

Effective thermal management is essential for commercial truck battery packs.

VIII. INFRASTRUCTURE REQUIREMENTS FOR COMMERCIAL TRUCK CHARGING

Future magnesium battery deployment requires:

- Megawatt charging stations
- High-voltage DC systems
- Smart grid integration
- Renewable energy support

Fleet depots may integrate solar energy and stationary storage systems for optimized charging schedules.

IX. COMPARATIVE ANALYSIS WITH LITHIUM-ION BATTERIES

Parameter	Magnesium Batteries	Lithium-Ion Batteries
Safety	High	Moderate
Dendrite Risk	Low	High
Material Cost	Lower	Higher
Fast Charging Potential	Promising	Mature
Energy Density	Moderate-High	High
Technology Readiness	Emerging	Commercialized
Thermal Stability	Better	Limited

Although lithium-ion technology remains more mature, magnesium batteries present strong long-term advantages for heavy transportation.

X. RECENT RESEARCH AND INDUSTRIAL DEVELOPMENTS

Several research institutions and companies are actively exploring magnesium battery technologies.

Notable advancements include:

- Nanostructured cathode engineering
- Hybrid solid-liquid electrolytes
- Artificial intelligence for battery management systems
- Magnesium-sulfur battery architectures

Research collaborations between automotive manufacturers and universities are accelerating development toward commercial feasibility.

XI. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

Despite promising characteristics, magnesium batteries face major challenges:

11.1 Slow Mg²⁺ Diffusion

Developing materials with rapid ion transport remains a top priority.

11.2 Electrolyte Compatibility

Stable, non-corrosive electrolytes with wide voltage windows are needed.

11.3 Cycle Life Improvement

Repeated magnesium insertion can degrade cathode structures.

11.4 Manufacturing Scalability

Industrial-scale magnesium battery manufacturing infrastructure is still underdeveloped.

Future research should focus on:

- Nanomaterial engineering
- Solid-state magnesium systems
- Machine-learning-based electrolyte discovery
- Hybrid magnesium-lithium architectures

XII. CONCLUSION

A. Fast-charging magnesium batteries represent a highly promising alternative to conventional lithium-ion systems for commercial electric trucks.

Their superior safety, reduced dendrite formation, abundant raw materials, and high volumetric capacity make them particularly suitable for heavy-duty transportation applications.

B. However, significant scientific and engineering challenges remain before commercialization becomes viable. Slow magnesium ion diffusion, electrolyte instability, and limited cathode compatibility currently hinder large-scale implementation.

C. Continued advances in electrochemistry, nanotechnology, and materials engineering are expected to accelerate the development of high-performance magnesium batteries. With sustained research investment and industrial collaboration, magnesium battery technology may play a transformative role in the future electrification of commercial trucking.

REFERENCES

- [1] Yoo, H. D., et al. "Mg Rechargeable Batteries: An On-going Challenge." *Energy & Environmental Science*, vol. 6, no. 8, 2013, pp. 2265–2279.
- [2] Muldoon, J., et al. "Electrolyte Roadblocks to a Magnesium Rechargeable Battery." *Energy & Environmental Science*, vol. 5, 2012, pp. 5941–5950.
- [3] Canepa, P., et al. "Odyssey of Multivalent Cathode Materials." *Chemical Reviews*, vol. 117, no. 5, 2017, pp. 4287–4341.
- [4] Davidson, R., et al. "Formation of Magnesium Dendrites During Electrodeposition." *ACS Energy Letters*, vol. 4, no. 2, 2019, pp. 375–376.
- [5] Mohtadi, R., and Mizuno, F. "Magnesium Batteries: Current State of the Art." *Beilstein Journal of Nanotechnology*, vol. 5, 2014, pp. 1291–1311.
- [6] Liang, Y., et al. "Rechargeable Mg Batteries with Graphene-like MoS₂ Cathode and Ultrasmall Mg Nanoparticle Anode." *Advanced Materials*, vol. 23, 2011, pp. 640–643.
- [7] Aurbach, D., et al. "Prototype Systems for Rechargeable Magnesium Batteries." *Nature*, vol. 407, 2000, pp. 724–727.
- [8] Tepavcevic, S., et al. "Nanostructured Layered Cathodes for Rechargeable Mg-Ion Batteries." *ACS Nano*, vol. 9, no. 8, 2015, pp. 8194–8205.
- [9] Gregory, T. D., et al. "Nonaqueous Electrochemistry of Magnesium." *Journal of the Electrochemical Society*, vol. 137, no. 3, 1990, pp. 775–780.
- [10] Ling, C., et al. "First-Principles Investigation of Mg Diffusion in Cathode Materials." *Chemistry of Materials*, vol. 27, no. 16, 2015, pp. 5799–5807.