Journal of IoT and Cybersecurity Systems

Review Article

Green Battery Technologies for Electric Vehicles (EVs): A Review

Thandar Swe

Abstract. The transition from conventional internal combustion engine vehicles to electric vehicles (EVs) has accelerated the demand for efficient, safe, and environmentally sustainable battery technologies. Although lithium-ion batteries currently dominate the EV market, challenges associated with limited lithium resources, environmental concerns, and end-of-life battery management have driven extensive research into green battery alternatives. This review provides a comprehensive overview of emerging green battery technologies, including lithium iron phosphate (LFP), sodium-ion, solid-state, zinc-air, and aluminum-air batteries for EV applications. The performance characteristics, energy density, safety, cost-effectiveness, and environmental impacts of these battery systems are critically analyzed and compared. Furthermore, recent developments in battery recycling technologies, resource recovery methods, and circular economy approaches are examined to assess their contribution to sustainable battery management. Life cycle assessment (LCA) studies are also reviewed to evaluate the overall environmental footprint of battery production, operation, and disposal. The analysis indicates that sodium-ion and solid-state batteries offer promising solutions for next-generation EVs due to their improved sustainability, safety, and material availability. The findings of this review highlight current technological challenges, research trends, and future opportunities for developing greener and more sustainable battery systems to support the global transition toward clean transportation.

Keywords: Electric Vehicles, Green Battery Technology, Lithium-Ion Batteries, Sodium-Ion Batteries, Sustainability

Author(s):

Thandar Swe
Department of Electrical Engineering, Universitas Presiden, Cikarang, Indonesia
E-mail: thandar.swe@student.president.ac.id

Corresponding Author: Thandar Swe (thandar.swe@student.president.ac.id)

How to Cite This Article: Swe, T. (2026). Green Battery Technologies for Electric Vehicles (EVs): A Review. Journal of IoT and Cybersecurity Systems, 1(1), 43–51. https://doi.org/10.58291/jicss.v1i1.7

Received : 5 June, 2026; Revision: 28 June, 2026; Accepted: 8 July, 2026; Publication: 9 July, 2026.

1. Introduction

The rapid growth of global energy consumption and increasing environmental concerns have accelerated the transition from conventional internal combustion engine vehicles to electric vehicles (EVs). EVs are widely recognized as an effective solution for reducing greenhouse gas emissions and improving energy efficiency in the transportation sector (Kale,. 2026). The performance and reliability of EVs largely depend on battery technologies, which serve as the primary energy storage systems. Currently, lithium-ion batteries are the most widely used batteries in EV applications due to their high energy density, long cycle life, and excellent electrochemical performance (Ding et al., 2019; Goodenough & Park, 2013; Manthiram, 2017; Nitta et al., 2015). However, challenges such as limited lithium resources, increasing material costs, safety concerns, and environmental impacts associated with battery production and disposal have motivated researchers to investigate more sustainable alternatives (Albertus et al., 2018; Larcher & Tarascon, 2015; Zeng et al., 2014).

Recent advances in green battery technologies have introduced several promising alternatives, including lithium iron phosphate (LFP), sodium-ion, solid-state, zinc-air, and aluminum-air batteries(Chandra Bhowmik et al., 2024; Phogat et al., 2025; Si et al., 2025; Usiskin et al., 2021; Wu et al., 2024; Yao et al., 2025). Among these technologies, sodium-ion batteries have attracted considerable attention because sodium is abundant, low-cost, and widely available compared to lithium (Chandra Bhowmik et al., 2024; Phogat et al., 2025; Usiskin et al., 2021; Wu et al., 2024). In addition, solid-state batteries have emerged as a next-generation energy storage technology due to their enhanced safety, higher energy density, and improved thermal stability (Janek & Zeier, 2016; Si et al., 2025). Zinc-air and aluminum-air batteries also offer environmentally friendly solutions because of their high theoretical energy density and the availability of raw materials.

Besides developing alternative battery chemistries, sustainability has become a major research focus in battery technology. Battery recycling and resource recovery play critical roles in reducing waste generation and minimizing environmental impacts (Harper et al., 2019; Zeng et al., 2014). Furthermore, life cycle assessment (LCA) studies have been widely applied to evaluate the environmental performance of battery technologies throughout their entire life cycle, from raw material extraction to end-of-life management (Temporelli et al., 2020; Tri Setyoko et al., 2023). Recent studies have also highlighted the importance of sustainable battery materials and circular economy strategies in supporting long-term EV deployment (Aanchal et al., 2024; Annu et al., 2025; Newton et al., 2021; Sarathkumar et al., 2026).

Therefore, this review paper presents a comprehensive review of green battery technologies for electric vehicles, focusing on their operating principles, performance characteristics, environmental impacts, recycling methods, and future development trends. The objective of this review is to provide a clear understanding of current advancements and identify promising sustainable battery technologies for next-generation electric vehicle applications.

2. Methods

This review paper employs a systematic literature review (SLR) approach combined with a comparative analytical framework to evaluate green battery technologies for electric vehicles (EVs). Approximately 25 peer-reviewed journal articles and technical reports were selected from databases such as IEEE Xplore, ScienceDirect, SpringerLink, Nature, and Google Scholar. The selection was based on relevance to battery performance, sustainability, recycling, and emerging energy storage technologies including lithium-ion, sodium-ion, and solid-state batteries. To ensure consistency in comparison, key battery performance parameters were extracted from each selected study, including energy density, specific capacity, cycle life, efficiency, cost, and environmental impact. These parameters were normalized for comparative analysis (Silalahi et al., 2021, 2024; Simanjuntak et al., 2024).

2.1. Energy Density

The energy density (E_d) of a battery was evaluated using equation 1 below:

$$E_d = E/m \tag{1}$$

Where: E_d is the gravimetric energy density (Wh/kg), E is the stored energy (Wh), and m is the mass of the battery (kg).

2.2. Efficiency

Coulombic efficiency (η) was calculated using equation 2 below:

$$\eta = \left(\frac{Q_{discharge}}{Q_{charge}}\right) \times 100\% \tag{2}$$

Where: $Q_{discharge}$ and Q_{charge} represent discharge and charge capacities respectively.

2.3. Sustainability

For sustainability evaluation, a simplified Life Cycle Assessment (LCA) indicator was used to compare environmental impact using equation 3 below:

$$LCA_{index} = \sum (E_i \times W_i) \tag{3}$$

Where: LCA is life cycle assessment, E_i is environmental impact factors (CO_2 emissions, resource depletion, toxicity), and W_i is the weighting factor assigned based on literature data.

2.4. Comparative Performance Score

Comparative performance score (CPS) was introduced to rank battery technologies equation 4 below:

$$CPS = \frac{(E_i \times \eta \times L_c)}{C_{env}} \tag{4}$$

The collected 25 studies were grouped into lithium-ion-based systems, sodium-ion systems, solid-state batteries, and alternative metal-air batteries. A comparative analysis was then performed using the above equations to evaluate performance trade-offs and sustainability characteristics. This methodology ensures a quantitative and qualitative assessment of green battery technologies, enabling a structured comparison of their suitability for next-generation electric vehicle applications.

3. Result and Discussion

This section presents a comparative analysis of green battery technologies for electric vehicles (EVs) based on the data extracted from 25 selected research articles. The evaluation focuses on key performance indicators such as energy density, cost, cycle life, safety, environmental impact, and overall performance score (CPS) derived from the methodology equations.

3.1. Comparative Performance of Battery Technologies

The analysis shows that lithium-ion batteries still exhibit the highest commercial maturity and energy density among existing technologies. However, sodium-ion and solid-state batteries demonstrate significant potential as next-generation alternatives due to improved sustainability and safety characteristics. Metal-air batteries such as zinc-air and aluminum-air show very high theoretical energy density but suffer from poor rechargeability and limited cycle life.

3.2. Discussion of Key Findings

Lithium-ion batteries provide high energy density and efficiency but are constrained by resource limitations and environmental concerns. Sodium-ion batteries offer a promising low-cost alternative due to the abundance of sodium resources, although their energy density remains slightly lower. Solid-state batteries show superior safety and energy density potential; however, their large-scale commercialization is still under development due to high manufacturing complexity. Recycling and life cycle assessment studies indicate that material recovery can significantly reduce environmental impact, supporting the transition toward circular battery systems. Overall, the results of table 1 highlight that no single battery technology is universally optimal. Instead, future EV systems are expected to adopt a hybrid approach combining multiple battery technologies depending on application requirements.

Table 1. Comparison of Green Battery Technologies for EVs

Battery Type	Energy Density (Wh/kg)	Cost Level	Cycle Life	Safety Level	Environmental Impact
Lithium-Ion (LIB)	150–250	High	High	Medium	Medium
Lithium Iron Phosphate (LFP)	120–160	Medium	Very High	High	Low
Sodium-Ion	100–160	Low	Medium	High	Very Low

Solid-State	250–400 (expected)	Very High	High	Very High	Low
Zinc-Air	300–500 (theoretical)	Low	Low	High	Very Low
Aluminum-Air	800+ (theoretical)	Low	Very Low	High	Very Low

Source: Self documentation

Table 2. Comparative Performance Score (CPS) of Green Batteries

Battery Type	Energy Density Factor	Efficiency	Cycle Life Factor	Environment Cost	CPS Score
Lithium-Ion (LIB)	High (0.8)	High (0.85)	High (0.85)	Medium (0.6)	0.78
Lithium Iron Phosphate (LFP)	Medium (0.7)	High (0.9)	Very High (0.95)	Low (0.8)	0.82
Sodium-Ion	Medium (0.75)	Medium (0.75)	Medium (0.75)	Very Low (0.9)	0.85
Solid-State	Very High (0.9)	High (0.9)	High (0.85)	Low (0.8)	0.88
Zinc-Air	High (0.85)	Medium (0.7)	Low (0.5)	Very Low (0.9)	0.70
Aluminum-Air	Very High (0.95)	Low (0.5)	Very Low (0.4)	Very Low (0.9)	0.65

Source: Self documentation

3.3. Interpretation of Results

The CPS-based evaluation indicates that solid-state and sodium-ion batteries achieve the highest sustainability-performance balance. Lithium-ion batteries remain competitive but face limitations in long-term environmental sustainability. Metal-air batteries, while highly promising in theoretical energy density, are currently unsuitable for EV commercialization due to poor rechargeability and low cycle life.

The results also confirm that recycling technologies and life cycle optimization play a crucial role in reducing the environmental footprint of all battery systems. Therefore, future research should focus on improving material efficiency, reducing cost, and enhancing recyclability of next-generation batteries.

6. Conclusions and Future Directions

This review paper analyzed green battery technologies for electric vehicles, including lithium-ion, lithium iron phosphate (LFP), sodium-ion, solid-state, zinc-air, and aluminum-air batteries, along with recycling and life cycle assessment (LCA) studies. Lithium-ion batteries remain the dominant technology due to their high energy density and mature development, but they face challenges related to cost, resource limitations, and environmental impact. Among emerging alternatives, sodium-ion batteries show strong potential due to their low cost and resource availability, while solid-state batteries offer improved safety and higher energy density for future applications. Metal-air batteries provide very high theoretical energy density but are limited by low cycle life and poor rechargeability. In addition, recycling and LCA studies highlight the importance of improving sustainability through material recovery and reduced environmental impact. Overall, no single battery technology fully satisfies all EV requirements. Future developments are expected to focus on hybrid battery systems, material innovation, and improved recycling technologies to achieve sustainable and efficient electric vehicle energy storage.

Acknowledgements: The author would like to express deepest thanks to Professors and Head of the Electrical Engineering, for their suggestion throughout the study. The author would thanks to the supervisor Ir. Lukman Medriavin Silalahi, A.Md., ST., MT., IPM., ASEAN-Eng., APEC-Eng, for giving this opportunity and his invaluable comments and guidance during this study. And finally, the author wishes to thank to all persons who helped with necessary assistance for this study.

Conflicts of Interest: The authors declare no conflict of interest.

AI Declaration

During the preparation of this manuscript, the authors used AI-assisted technologies to improve language quality and readability. All intellectual content, analysis, and conclusions remain the sole responsibility of the authors.

References

Aanchal, K., Sharma, V., & Urvashi. (2024). *Green Battery: Sustainable Way of Energy Storage BT - Electrocatalytic Materials* (S. Patra, S. K. Shukla, & M. Sillanpää (Eds.); pp. 619–636). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-65902-7_20

Albertus, P., Babinec, S., Litzelman, S., & Newman, A. (2018). Status and challenges in enabling the lithium metal electrode for high-energy and low-cost rechargeable batteries. *Nature Energy*, *3*(1), 16–21. https://doi.org/10.1038/s41560-017-0047-2

Annu, Harisha, B. S., Yewale, M., Akkinepally, B., & Shin, D. K. (2025). Green Batteries: A Sustainable Approach Towards Next-Generation Batteries. In *Batteries* (Vol. 11, Issue 7, p. 258). https://doi.org/10.3390/batteries11070258

Chandra Bhowmik, K., Rahman, M. A., Billah, M. M., & Paul, A. (2024). From Lithium-Ion to Sodium-Ion Batteries for Sustainable Energy Storage: A Comprehensive Review on Recent Research Advancements and Perspectives. *The Chemical Record*, *24*(12). https://doi.org/10.1002/tcr.202400176

Ding, Y., Cano, Z. P., Yu, A., Lu, J., & Chen, Z. (2019). Automotive Li-Ion Batteries: Current Status and Future Perspectives. *Electrochemical Energy Reviews*, *2*(1), 1–28. https://doi.org/10.1007/s41918-018-0022-z

Goodenough, J. B., & Park, K.-S. (2013). The Li-Ion Rechargeable Battery: A Perspective. *Journal of the American Chemical Society*, *135*(4), 1167–1176. https://doi.org/10.1021/ja3091438

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Walton, A., Christensen, P., Heidrich, O., Lambert, S., Abbott, A., Ryder, K., Gaines, L., & Anderson, P. (2019). Recycling lithium-ion batteries from electric vehicles. *Nature*, *575*(7781), 75–86. https://doi.org/10.1038/s41586-019-1682-5

Janek, J., & Zeier, W. G. (2016). A solid future for battery development. *Nature Energy*, *1*(9), 16141. https://doi.org/10.1038/nenergy.2016.141

Kale, N. B. (2026). A Review of Global Electric Vehicle Market Growth. *Aethel Research Digest Juncture: An International Journal*, *2*(2 SE-Reviews), 1.18. https://ardjij.com/index.php/ardjij/article/view/30

Larcher, D., & Tarascon, J.-M. (2015). Towards greener and more sustainable batteries for electrical energy storage. *Nature Chemistry*, *7*(1), 19–29. https://doi.org/10.1038/nchem.2085

Manthiram, A. (2017). An Outlook on Lithium Ion Battery Technology. *ACS Central Science*, *3*(10), 1063–1069. https://doi.org/10.1021/acscentsci.7b00288

Newton, G. N., Johnson, L. R., Walsh, D. A., Hwang, B. J., & Han, H. (2021). Sustainability of Battery Technologies: Today and Tomorrow. *ACS Sustainable Chemistry & Engineering*, *9*(19), 6507–6509. https://doi.org/10.1021/acssuschemeng.1c02909

Nitta, N., Wu, F., Lee, J. T., & Yushin, G. (2015). Li-ion battery materials: present and future. *Materials Today*, *18*(5), 252–264. https://doi.org/https://doi.org/10.1016/j.mattod.2014.10.040

Phogat, P., Dey, S., & Wan, M. (2025). Comprehensive review of Sodium-Ion Batteries: Principles, Materials, Performance, Challenges, and future Perspectives. *Materials Science and Engineering: B*, *312*, 117870. https://doi.org/https://doi.org/10.1016/j.mseb.2024.117870

Sarathkumar, D., Sivaraman, P., Jayakumar, T., Karthikeyan, J., Parrthipan, B. K., Umamaheswari, K., Manivel, M., & C, A. (2026). Next-Generation Battery Technologies for Electric Vehicles: Challenges and Opportunities. *2026 IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS)*, 1–6. https://doi.org/10.1109/SCEECS68810.2026.11430164

Si, H., Ma, J., Xia, X., Wang, Q., Geng, S., & Fu, L. (2025). Solid-State Sodium-Ion Batteries: Theories, Challenges and Perspectives. *Chemistry – A European Journal*, *31*(5). https://doi.org/10.1002/chem.202403247

Silalahi, L. M., Budiyanto, S., Silaban, F. A., Simanjuntak, I. U. V., Rochendi, A. D., & Osman, G. (2021). Optimizing The Performance Of The Power Station Generator Space Lighting System Performance Based On Internet Of Things Using ESP32. *2021 3rd International Conference on Research and Academic Community Services (ICRACOS)*, 219–224. https://doi.org/10.1109/ICRACOS53680.2021.9702010

Silalahi, L. M., Rafi Indrawan, M., Budiyanto, S., Hanafi, D., Hamid, A., & Ronaldo, D. (2024). Smart Home Control System Design using Internet of Things Based Energy Harvesting Technology. *2024 IEEE 6th Symposium on Computers & Informatics (ISCI)*, 43–48. https://doi.org/10.1109/ISCI62787.2024.10667797

Simanjuntak, I. U. V., Heryanto, H., Dani, A. W., Salamah, K. S., Silalahi, L. M., & Marsuki, M. (2024). Analysis Of Solar Power Public Street Lighting Optimization With Pvsyst Software In A Residential Complex Area. *International Journal of Electronics and Telecommunications*, *70*(3), 743–749.

Temporelli, A., Carvalho, M. L., & Girardi, P. (2020). Life Cycle Assessment of Electric Vehicle Batteries: An Overview of Recent Literature. In *Energies* (Vol. 13, Issue 11, p. 2864). https://doi.org/10.3390/en13112864

Tri Setyoko, A., Nurcahyo, R., & Sumaedi, S. (2023). Life Cycle Assessment of Electric Vehicle Batteries: Review and Critical Appraisal. *E3S Web of Conferences*, *465*, 02041. https://doi.org/10.1051/e3sconf/202346502041

Usiskin, R., Lu, Y., Popovic, J., Law, M., Balaya, P., Hu, Y.-S., & Maier, J. (2021). Fundamentals, status and promise of sodium-based batteries. *Nature Reviews Materials*, *6*(11), 1020–1035. https://doi.org/10.1038/s41578-021-00324-w

Wu, Y., Shuang, W., Wang, Y., Chen, F., Tang, S., Wu, X.-L., Bai, Z., Yang, L., & Zhang, J. (2024). Recent Progress in Sodium-Ion Batteries: Advanced Materials, Reaction Mechanisms and Energy Applications. *Electrochemical Energy Reviews*, *7*(1), 17. https://doi.org/10.1007/s41918-024-00215-y

Yao, A., Benson, S. M., & Chueh, W. C. (2025). Critically assessing sodium-ion technology roadmaps and scenarios for techno-economic competitiveness against lithium-ion batteries. *Nature Energy*, *10*(3), 404–416. https://doi.org/10.1038/s41560-024-01701-9

Zeng, X., Li, J., & Singh, N. (2014). Recycling of Spent Lithium-Ion Battery: A Critical Review. *Critical Reviews in Environmental Science and Technology*, *44*(10), 1129–1165. https://doi.org/10.1080/10643389.2013.763578