RICERCA, INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH AND INNOVATION
ISSN: 2583-083X
Peer Reviewed Journal, www.rijmri.com

RECENT PROGRESS IN ELECTROCHEMICAL ENERGY STORAGE SYSTEMS FOR MODERN POWER SYSTEMS: FABRICATION STRATEGIES, PERFORMANCE AND ECONOMIC ASPECTS

Sumit Kumar Bhati
Research Scholar, Department of Physics, Jayoti Vidyapeeth Women's University, Jaipur

Abstract

Electrochemical energy storage systems play an increasingly important role in modern power systems by improving energy reliability, supporting renewable energy integration, and balancing electricity supply and demand. This review examines recent advances in electrochemical energy storage technologies, focusing on fabrication strategies, electrochemical performance, practical applications and economic considerations. The discussion covers rechargeable batteries, including lead-acid, nickel–metal hydride, zinc-based, sodium-ion, sodium–sulfur, and lithium-polymer batteries, as well as redox and hybrid flow batteries, electrochemical capacitors, and fuel cells. Recent developments in electrode modification, electrolyte engineering, nanostructured materials, biomass-derived carbon, membrane electrode assembly fabrication and cell architecture are evaluated. The reviewed studies show that optimized electrode composition, controlled pore structures, stable electrode-electrolyte interfaces, and improved reactant management can enhance device performance and durability. Simplified cell designs, low-cost precursors, reduced dependence on expensive catalysts, and longer service life also offer opportunities to lower energy storage costs.

Keywords: Electrochemical energy storage; rechargeable batteries; redox flow batteries; electrochemical capacitors; fuel cells.

1. Introduction: -

Energy is an essential part of our daily lives and is used directly or indirectly in residential, commercial and industrial activities. It is one of the basic requirements for human life and development, as it supports everyday activities and makes many tasks easier. The need for a reliable and affordable energy supply has remained important over time. Meeting the world's energy demand requires long-term planning, continuous monitoring, considerable investment and the development of reliable and efficient energy-generation infrastructure [1]. Energy also plays a major role in modern development and economic progress. It is closely connected with economic growth, as almost every sector depends on a steady energy supply for its activities. As economies expand, their energy requirements also tend to increase. However, conventional energy sources such as coal, petroleum and natural gas are finite and cannot meet growing energy needs indefinitely. This has increased the importance of exploring alternative energy sources that are renewable, widely available and capable of providing energy over the long term. Many countries are focusing on these alternatives to maintain economic growth and achieve greater energy self-sufficiency while reducing costs and environmental impacts [2,3]. Energy is necessary for human survival, development and overall well-being. Energy resources also influence the political, economic, cultural and social conditions of countries around the world. For instance, changes in international oil prices can directly affect production costs, trade and the growth of several economic sectors. Unexpected events, including the COVID-19 pandemic and geopolitical conflicts such as the Russia–Ukraine war, have also caused considerable fluctuations in oil prices. As energy systems develop and energy production changes or expands, the availability of new energy sources, particularly those derived from natural resources, becomes increasingly important [4,5].

Energy storage systems designed for microgrids have gained considerable attention as a practical solution to several challenges in the energy sector. They play an important role in maintaining the stable and sustainable operation of microgrids by helping to balance energy supply and demand [6]. More broadly, energy storage systems are essential components of modern power networks because they help maintain a continuous electricity supply and improve overall system reliability. These systems are available in different forms and sizes, and their cost, capacity and potential for expansion depend largely on the method used to store energy. Depending on the technology, energy can be stored in the form of potential, kinetic, chemical, electromagnetic, or thermal energy. Each storage method has its own characteristics, making some technologies more suitable for small-scale applications, while others are better suited to large-scale energy storage [7,8]. Energy storage technologies have become increasingly important in modern society, particularly as countries move towards cleaner and more sustainable energy systems. Among the available options, electrochemical energy storage (EES) technologies, including batteries and supercapacitors, have attracted considerable interest because of their high energy and power densities, good

efficiency and potential for use at different scales. These devices support a wide range of applications, including portable electronic equipment, electric vehicles and large-scale electricity storage for power grids [9].

The basic principles of electrochemical energy conversion were established through the work of Alessandro Volta in the late eighteenth century. Since then, electrochemical energy storage devices have become important in the development of reliable and sustainable energy technologies. Batteries are among the most widely used electrochemical storage devices. They can be classified into primary batteries, which are non-rechargeable and secondary batteries, which can be recharged and used repeatedly. Primary batteries, often called dry cells, are generally discarded after their stored energy has been used because the electrochemical reactions involved are not readily reversible under normal operating conditions. As a result, electrical energy cannot be restored to these batteries through ordinary recharging [10]. Different energy storage technologies are suitable for different applications, depending on their operating characteristics and performance requirements. For example, flywheel energy storage systems, supercapacitors and superconducting magnetic energy storage (SMES) systems can deliver high power over short periods and are therefore suitable for applications that require rapid responses and improved power quality [11]. In view of these developments, the present paper aims to examine recent advances in electrochemical energy storage systems, with particular attention to their fabrication strategies, performance characteristics, applications and economic aspects in modern power systems.

2. Electrochemical Batteries and Their Types: -

Battery energy storage systems (BESS) offer several advantages over conventional energy sources, including rapid and stable responses, operational flexibility, effective control, reduced environmental impact and independence from geographical conditions. These features make BESS a promising technology for supporting sustainable energy systems and helping to address the challenges associated with global warming [12]. Figure 1 shows the classification of electrochemical energy storage and conversion technologies into three major categories: electrochemical batteries, electrochemical capacitors and fuel cells. It further illustrates their major subtypes, including rechargeable and flow batteries, electric double-layer capacitors, pseudo-capacitors, hybrid capacitors and different fuel cell technologies, along with representative battery chemistries and electrode materials.

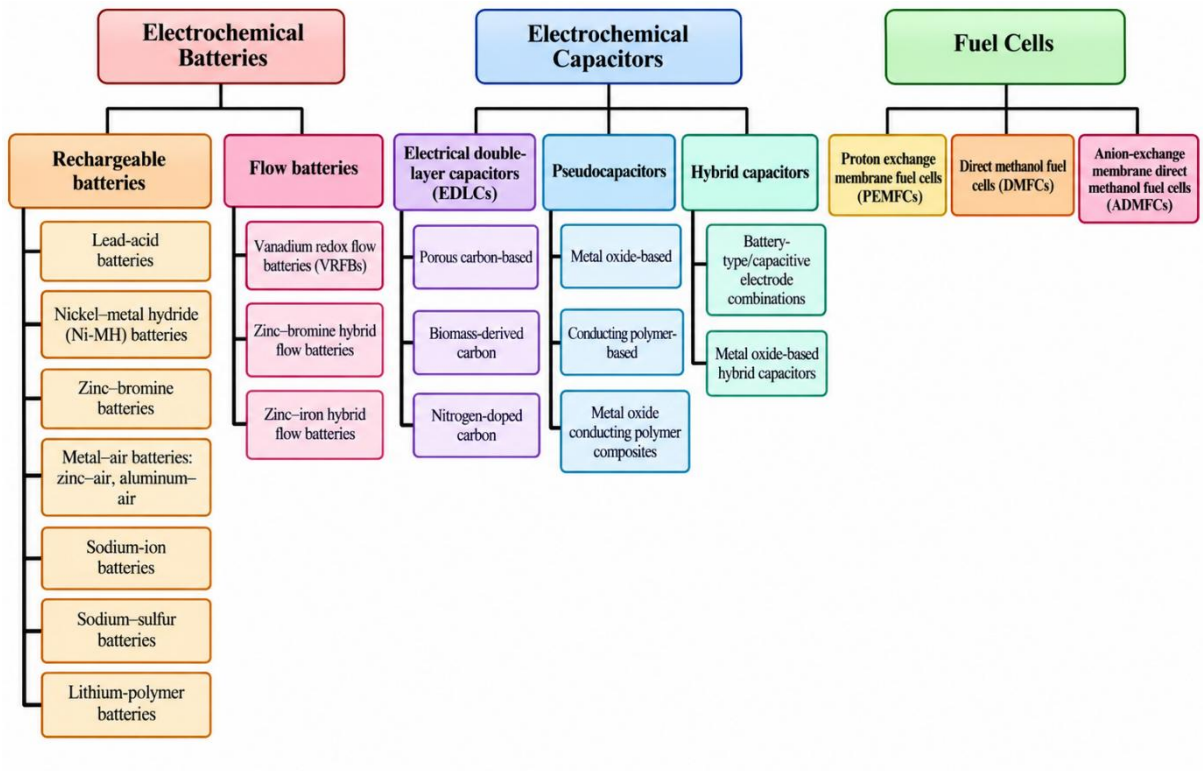


Fig.1. Classification of Electrochemical Energy Technologies

2.1. Rechargeable Batteries:

Lead-acid batteries remain relevant for energy storage because of their established technology and potential for high-power applications. However, their cycle life and electrode stability can limit long-term performance. A

fabrication strategy involving the addition of a small amount of two-dimensional MXene ($Ti_3C_2T_x$) to the positive electrode improved conductivity, modified pore structure and enhanced electrolyte accessibility. At the optimized loading of 0.1%, the battery achieved 7,231 cycles compared with 3,101 cycles for the unmodified cell. The improvement was associated with lower charge-transfer resistance and a higher oxygen-evolution overpotential, which helped reduce water loss. However, performance declined at a higher MXene loading of 0.2%, highlighting the importance of optimizing additive concentration rather than simply increasing it. These results indicate that electrode modification can improve durability, although material costs and large-scale manufacturing feasibility require further evaluation [13].

Nickel-based batteries, particularly nickel–metal hydride (Ni-MH) systems, offer a combination of rechargeable operation, useful capacity and established applications in hybrid electric vehicles and consumer electronics. Their performance depends on both electrode composition and battery maintenance. Experimental evaluation of different storage and maintenance procedures showed that carefully selected protocols can improve capacity recovery and reduce maintenance time. However, stored modules experienced substantial reductions in charge and discharge power, indicating that retaining capacity alone is insufficient for assessing battery condition. In parallel, improvements in rare-earth–magnesium-nickel superlattice alloys for negative electrodes enhanced oxidation resistance, electrochemical capacity and cycle durability. Commercial Ni-MH cells using these materials achieved higher capacity than earlier models based on conventional alloys. Together, these findings suggest that optimized alloy composition and maintenance procedures can improve service life and usability, but maintenance requirements and power degradation remain important considerations for operational cost [14,15].

Zinc-based batteries, including zinc–bromine and zinc–air systems, are promising alternatives because their performance can be improved through electrolyte engineering and relatively simple cell designs. In zinc–bromine batteries, a water-free deep eutectic solvent (DES) electrolyte prepared using zinc bromide, zinc chloride and a bromine-capturing agent enabled closed-cell operation by limiting bromine evaporation and unwanted gas generation. Adjusting the zinc chloride content improved ion mobility, electrode reaction kinetics and cycle life, while a flexible pouch cell maintained stable operation during folding tests. A separate membrane-free zinc-bromine design simplified the cell architecture by eliminating costly components. It achieved coulombic efficiency above 90%, energy efficiency above 60% and stable operation for more than 1,000 cycles, with an estimated system cost below US$100 per kWh at scale. These approaches demonstrate the potential of electrolyte optimization and simplified fabrication to improve durability and reduce costs, although practical assessments must also consider electrolyte management, safety and performance under commercial operating conditions [16,17].

In zinc–air batteries, electrode arrangement, air access and the distance between electrodes strongly influence power output. Experiments comparing four cell configurations showed that increasing the zinc-to-air electrode area ratio and reducing the distance between the electrodes improved performance. Carbon paste on the air electrode also increased power density under forced-air conditions. The configuration with closely positioned electrodes performed best in terms of volumetric power density, making it potentially suitable for portable devices. Aluminium-air batteries, another metal–air technology, are similarly affected by operating conditions. Ambient temperature, alkaline electrolyte concentration and anode composition influenced open-circuit voltage and heat generation. Aluminium alloys produced voltages of approximately 1.5-1.95 V across the tested conditions, while electrolyte temperature rose by no more than 7°C; pure aluminium, however, caused much greater heating, reaching 100°C in the reported experiments. These findings emphasize that cell geometry, airflow and anode selection are important fabrication and operating variables. Despite their potential for high energy output, thermal management and practical operating stability need careful consideration [18,19].

Sodium-ion batteries are receiving attention as potential alternatives to lithium-based systems, particularly where cost and the availability of electrode materials are important. Hard carbon is a promising anode material and its performance depends strongly on pore structure, particle morphology, interlayer spacing and surface chemistry. Hard carbon produced from filter paper through high-temperature pyrolysis and KOH activation achieved an initial coulombic efficiency of 81% and a reversible capacity of 286 mAh g^{-1} after 100 cycles. Its interconnected micro-nano structure supported electron and sodium-ion transport while limiting irreversible capacity loss during the first cycle. More recent work has linked sodium-ion diffusion and storage capacity to interlayer spacing, defects and structural curvature. Biomass-derived hard carbon with controlled microstructure was also tested in industrially manufactured cylindrical cells, demonstrating operation over a broad temperature range from -40 to 100°C. Collectively, these results show that low-cost carbon precursors and controlled fabrication can improve electrochemical performance and support scale-up. Nevertheless, production consistency, processing costs and long-term full-cell performance remain important factors in determining commercial viability [20,21].

Room-temperature sodium–sulphur batteries offer another promising approach to high-capacity energy storage, but their performance is often limited by the dissolution of polysulfides, loss of active material and degradation of the sodium anode. Electrolyte engineering provides one route to addressing these problems. A combination of propylene carbonate, fluoroethylene carbonate, concentrated sodium salt and indium triiodide reduced polysulfide dissolution, supported the formation of a stable protective layer on the sodium anode and improved reaction kinetics at the cathode. This strategy enabled high reversible capacity and improved cycling stability at room temperature. However, electrolyte composition and additive requirements must be considered when assessing cost, scalability and practical cell design [22].

Lithium-polymer batteries also benefit from combining experimental characterization with electrochemical modelling. A model developed using parameters measured through laboratory experiments was used to examine the distribution of concentration, current and electrical potential within the cell under different charge-discharge conditions. This approach helps identify the processes that restrict performance and provides a basis for optimizing electrode and cell design. Compared with relying solely on experimental testing, modelling can reduce the need for repeated trials and support more efficient development. Nevertheless, the reliability of its predictions depends on the accuracy of the measured parameters and the ability of the model to represent actual operating conditions [23].

Further progress in room-temperature sodium-sulphur batteries has been achieved through the development of sulfurized polyisoprene as a cathode material. The sulphur is chemically bound within the polymer structure, helping suppress the formation of soluble long-chain polysulfides and reducing the shuttle effect. The resulting cathodes delivered a discharge capacity of 325 mAh g^{-1} at a high rate of 3C, retained 99.36% of their capacity after 250 cycles at C/2 and operated for more than 1,000 cycles at 1C with an average capacity decay of only 0.048% per cycle. Structural analysis also indicated that the electrodes maintained good integrity during cycling. These results suggest that polymer-bound sulphur can improve durability while offering a potentially scalable fabrication route. However, further testing under higher sulphur loading and lower electrolyte-to-sulphur ratios is needed to establish its suitability for commercially competitive batteries [24]. Therefore, the studies indicate that electrochemical battery performance depends on the combined optimization of electrode materials, electrolyte composition, cell architecture and operating conditions. Improved conductivity, controlled pore structures, stable electrode–electrolyte interfaces and reduced active-material loss can enhance capacity, power output and cycle life. From an economic perspective, simplified cell designs, low-cost precursors and longer service life may reduce overall storage costs. However, promising laboratory results do not automatically establish commercial viability. Future evaluation should therefore place greater emphasis on full-cell performance, manufacturing reproducibility, material and processing costs, safety, maintenance requirements and long-term operation under realistic conditions.

2.2. Flow Batteries: -

Redox flow batteries offer flexible energy storage because their energy capacity depends largely on the volume and concentration of the electrolyte, while their power output is influenced by cell design and electrode area. In vanadium redox flow batteries (VRFBs), vanadium species dissolved in sulfuric acid serve as the active materials in both half-cells. Laboratory testing has shown that electrolyte concentration, operating temperature, current density and flow rate strongly affect voltage and energy efficiency. Under optimized conditions, a small cell achieved an energy efficiency of approximately 82% at 308 K and a current density of 60 mA cm^{-2}. A separate 64 cm^2 cell achieved coulombic, voltage and energy efficiencies of 97%, 74.5% and 72.3%, respectively. These results highlight the importance of balancing electrolyte transport and electrochemical losses rather than relying on a single operating parameter [25,27].

Flow-field configuration and electrolyte distribution are also important fabrication and design considerations. Serpentine and interdigitated flow fields influence pressure drop, electrolyte distribution and total overpotential differently. Interdigitated designs can reduce pressure drop, whereas serpentine designs may provide more uniform electrolyte distribution at higher electrode porosity. At lower porosity, however, their relative performance can reverse, particularly when current density increases, electrolyte flow decreases, or the electrode becomes thinner. This indicates that no single flow-field design is optimal under all operating conditions. Similarly, adjusting the positive and negative electrolyte flow rates independently can improve performance. Asymmetric flow rates produced approximately 5% greater discharge capacity and a 3% improvement in energy efficiency after 50 cycles compared with symmetric flow rates at 100 mA cm^{-2}. Excessive asymmetry, however, may promote unwanted species crossover. Therefore, optimized flow management and electrode-flow-field matching can improve efficiency and capacity retention while potentially reducing pumping requirements [26,28].

Hybrid flow batteries combine a circulating electrolyte with a metal-deposition reaction at one electrode, offering a different balance between energy capacity, efficiency and system complexity. In zinc–bromine systems, carbon-

plastic composite or non-porous graphite electrodes support zinc deposition and dissolution, making zinc utilization and deposit structure important determinants of performance. Experimental results showed that increasing zinc utilization and using higher-purity zinc bromide electrolyte improved Faradaic efficiency. X-ray diffraction analysis also revealed preferential zinc crystal growth, demonstrating that electrodeposition characteristics influence the effective use of the active material. However, incomplete zinc utilization can limit capacity, while uneven deposition may create stability concerns and increase maintenance requirements [29].

Electrolyte engineering has also improved the performance of neutral zinc-based hybrid flow batteries. Bromide ions can stabilize zinc ions through complex formation, improving the reversibility of the zinc/zinc-ion reaction. Adding zinc bromide to a neutral zinc–iron electrolyte accelerated this complexation process, enabling stable operation over more than 2,000 cycles. In zinc-bromine flow batteries, a hydrophilic complexing agent, PMDA, helped retain bromine in the positive electrolyte and reduced its permeability by 74%. With an optimized concentration, the system achieved a volumetric operating capacity of 57.2 Ah L^{-1} and a coulombic efficiency of approximately 90%. These findings demonstrate that electrolyte additives can improve active-material utilization, reduce crossover and support longer operating life. Nevertheless, the cost and availability of additives, electrolyte stability and performance at commercial scale must be evaluated before their economic advantages can be confirmed [30,31]. Hence, redox and hybrid flow batteries offer considerable flexibility for stationary energy storage, but their practical performance depends on more than electrochemical efficiency alone. Electrode design, flow-field geometry, electrolyte circulation, species crossover and active-material utilization must be optimized together. Variable flow control and improved electrolyte formulations may enhance efficiency and reduce capacity loss, while simpler cell structures and durable materials can help lower operating costs. Future development should prioritize long-duration testing, pumping-energy requirements, electrolyte management, material costs and system-level techno-economic analysis to determine whether laboratory improvements translate into reliable and commercially viable energy storage systems.

3. Electrochemical Capacitors: Principles and Electrode Materials: -

Electrochemical capacitors are important energy storage devices that provide high power density, rapid charge–discharge capability and excellent cycling stability. They are generally classified into electrical double-layer capacitors (EDLCs), pseudo-capacitors, and hybrid capacitors based on their energy storage mechanisms and electrode materials. Electrical double-layer capacitors (EDLCs) store energy mainly through ion adsorption at the electrode–electrolyte interface. Their performance depends strongly on the surface area, pore-size distribution, electrical conductivity and electrolyte properties of the electrode material. Biomass-derived carbon is a promising option because it can be produced from renewable or waste resources and modified through activation. Potassium hydroxide activation of Miscanthus-derived biocarbon increased its specific surface area from 98 to 3,024 $m^2\ g^{-1}$ by developing a highly porous structure. The resulting EDLC electrodes achieved capacitances of up to 110.8 F g^{-1} at a scan rate of 0.05 V s^{-1} and 65.4 F g^{-1} at 1 A g^{-1}. Similarly, nanoporous carbon derived from waste Swietenia macrophylla leaves was evaluated with polymer-gel, ionic-liquid and water-in-salt electrolytes. The different electrolytes provided distinct operating-voltage windows and energy–power characteristics, demonstrating that electrode performance cannot be assessed independently of electrolyte selection. These findings support biomass-derived carbon as a potentially cost-effective and sustainable electrode material, although activation chemicals, processing requirements and consistency of the resulting pore structure must be considered when evaluating large-scale production [32,35].

Beyond surface area, the arrangement of pores and the chemistry of the electrode surface influence ion transport and device stability. Three-dimensional nitrogen-doped carbon electrodes fabricated using a polydopamine-derived coating, electrochemical oxidation and a sacrificial Cu_2O template achieved an area-capacitance of 2,852 mF cm^{-2} at 1 mA cm^{-2}. A symmetric device delivered an energy density of 16.4 mWh cm^{-3} at a power density of 180 mW cm^{-3} and retained 89% of its performance after 15,000 cycles. Experimental testing and modelling of activated-carbon electrodes with lithium-ion electrolytes further showed that hierarchical pore structures can improve ion transport and influence resistance. However, the benefits depend on the compatibility of pore dimensions with solvated or de-solvated ions, as well as the electrolyte's stability window. Therefore, high surface area alone is not a sufficient design criterion; pore accessibility, surface functionality, electrolyte compatibility and internal resistance must be optimized together. The additional processing steps used to control these properties may also affect manufacturing cost and scalability [33,34].

Pseudo-capacitors store energy through fast surface or near-surface redox reactions, which can provide higher capacitance than conventional EDLCs but may introduce additional challenges related to electrode stability and cycling durability. Manganese dioxide (MnO_2) is an attractive electrode material, while polyaniline (PANI) can improve electrical conductivity and contribute additional electrochemical activity. A core–shell PANI@MnO_2

composite achieved a specific capacitance of 75 F g^{-1} at 0.1 A g^{-1}, compared with 67 F g^{-1} for MnO_2 alone and retained 90% of its initial capacitance after 3,000 cycles. A related fabrication strategy involved depositing MnO_2 nanosheets onto carbon-fibre paper, followed by electrodeposition of a thin PANI coating. This binder-free, three-dimensional architecture provided a capacitance of 437 F g^{-1} at 1 A g^{-1}, retained 62.4% of its capacitance at 15 A g^{-1} and maintained its performance over 3,000 cycles. These results demonstrate the value of combining redox-active materials with conductive polymers and structured current collectors. Nevertheless, the stability of the polymer, fabrication complexity and reproducibility of the electrode coating remain important considerations for practical applications [36,37].

Hybrid capacitors combine capacitive charge storage with battery-type electrode reactions to improve the balance between energy density and power delivery. One approach uses lanthanum-doped hematite as the negative electrode and hydrous cobalt phosphate as the positive electrode. Hydrothermal synthesis and co-precipitation were used to prepare the respective materials, while lanthanum doping improved the electrochemical activity and reduced electrode resistance. The assembled aqueous hybrid capacitor operated at 1.6 V and achieved an energy density of 83.6 Wh kg^{-1} at a power density of 3.2 kW kg^{-1}, retaining 89% of its specific capacitance after 5,000 cycles. These results indicate that electrode pairing, doping and operating-voltage optimization can substantially influence device performance. However, the performance of individual electrodes should not be directly compared with that of a complete device and practical assessment must also consider electrode mass balancing, electrolyte stability, manufacturing costs and long-term cycling under realistic operating conditions [38]. Thus, EDLCs, pseudo-capacitors and hybrid capacitors offer complementary performance characteristics. EDLCs are attractive for rapid charge–discharge operation and long cycle life, pseudo-capacitors can provide higher capacitance through redox reactions and hybrid capacitors aim to improve energy storage while retaining useful power output. Biomass-derived carbon and simplified electrode fabrication may help reduce material costs, whereas nano-structuring, conductive coatings and doping can improve electrochemical performance. However, comparisons across these technologies require consistent reporting of electrode mass, device configuration, electrolyte, voltage window, energy density, power density and cycle-life testing. These factors are essential for determining whether laboratory-scale advances can translate into economically viable energy storage systems.

4. Fuel Cells: Working Principles: -

Proton exchange membrane fuel cells (PEMFCs) rely on a membrane electrode assembly (MEA), comprising a proton-conducting membrane, catalyst layers and gas diffusion layers, to convert chemical energy into electricity. Their performance depends on the quality of layer fabrication, catalyst loading, uniformity of coating and operating conditions. Experimental evaluation has shown that increasing temperature, maintaining relative humidity between 80% and 100% and supplying oxygen instead of air can improve cell output under the tested conditions. These results highlight the importance of controlling membrane hydration, reactant supply and catalyst distribution during fabrication and operation. However, oxygen supply may increase operating costs compared with using air, so the performance improvement must be balanced against the practical requirements of the system [39].

The manufacturing method used to prepare the MEA also influences fuel-cell efficiency and material utilization. Three approaches, i.e., catalyst-coated substrate (CCS), catalyst-coated membrane (CCM) and low-temperature decal transfer, have been compared under consistent conditions. At a platinum loading of 0.5 mg cm^{-2}, the best configuration achieved a maximum power density of 0.95 W cm^{-2}. When platinum loading was reduced by 75%, performance declined across all methods, but the decrease was particularly severe for CCS, reaching approximately 75%, while the other two methods showed reductions below 30%. Additional Nafion coating improved performance when applied to catalyst layers but had a negative effect when applied to the membrane. These findings indicate that MEA fabrication must be matched to catalyst loading and coating arrangement. Although reducing platinum content can lower material costs, savings may be offset by substantial losses in power output if the manufacturing process is not optimized [40].

Direct methanol fuel cells (DMFCs) use methanol as the fuel and offer a relatively simple fuel-storage and supply arrangement. Their performance depends on cell temperature, methanol concentration, oxygen flow rate and catalyst selection. The stack outperformed a single cell tested under the reported comparison conditions, illustrating the potential benefits of cell integration. However, stack performance also depends on consistent reactant distribution and effective management of operating conditions, which can complicate fabrication and system design [41].

Anion-exchange membrane direct methanol fuel cells (ADMFCs) offer another development pathway by using alkaline membranes and potentially lower-cost, platinum-group-metal-free catalysts. A system based on an Fe-N-C catalyst, a commercial anion-exchange membrane and a compatible ionomer achieved a maximum power density

of 48.2mW cm^{-2} at 60°C with a methanol concentration of 5M. Performance improved as temperature increased from 40°C to 60°C and methanol concentration rose from 1M to 5M, but further increasing the concentration to 10M provided no meaningful improvement and slightly reduced performance. This suggests that higher fuel concentration does not necessarily produce better output and may increase fuel use without corresponding benefits. The use of commercial, platinum-group-metal-free materials is promising for reducing dependence on expensive catalysts, although further improvements in power density, durability and membrane performance are needed for wider commercial adoption [42]. Hence, fuel-cell performance is governed by the combined effects of MEA fabrication, catalyst loading, membrane properties, reactant management and operating conditions. Conventional PEMFCs can achieve high power density but may depend on costly platinum-based catalysts, whereas DMFCs offer convenient liquid-fuel handling and alkaline DMFCs provide opportunities to reduce catalyst costs. From an economic perspective, the most effective design is not necessarily the one with the highest laboratory power output; it must also deliver adequate durability, efficient fuel utilization, manageable manufacturing costs and reliable operation. Future research should therefore prioritize reproducible fabrication, reduced catalyst loading without major performance losses, long-term stability and system-level cost evaluation.

5. Conclusion: -

Electrochemical energy storage technologies are essential for improving the reliability, flexibility and sustainability of modern power systems. The review highlights the progress achieved in rechargeable batteries, redox and hybrid flow batteries, electrochemical capacitors and fuel cells through advances in material selection, fabrication methods, electrolyte composition, electrode architecture and operating conditions. The findings indicate that the performance of these technologies depends on the combined optimization of several factors rather than on the properties of individual materials alone. In rechargeable batteries, electrode modification, stable interfaces, optimized electrolytes and alternative materials such as sodium-based compounds and polymer-bound sulphur can improve capacity, cycling stability and material utilization. Flow batteries benefit from appropriate flow-field configurations, controlled electrolyte circulation and reduced active-species crossover, which can improve efficiency and support long-duration energy storage. Electrochemical capacitors demonstrate the importance of porous carbon structures, conductive coatings, redox-active materials and complementary electrode combinations in balancing power delivery, energy density and cycle life. In fuel cells, membrane electrode assembly fabrication, catalyst loading, membrane properties and reactant management strongly influence power output, fuel utilization and manufacturing costs. Hence, these developments demonstrate the potential of materials engineering and optimized fabrication strategies to improve the electrochemical and operational performance of energy technologies.

Economic feasibility remains a major consideration in selecting and deploying these systems. Biomass-derived electrode materials, simplified cell architectures, reduced use of expensive catalysts and extended service life may help lower costs. However, material processing, electrolyte requirements, maintenance, safety, manufacturing consistency and system integration can substantially influence overall economic performance. Furthermore, results obtained under different laboratory conditions cannot always be compared directly, particularly when electrode-level and full-device metrics are reported inconsistently. Future research should therefore prioritize standardized testing protocols, reproducible fabrication, long-term durability, efficient material utilization and validation under realistic operating conditions. Greater emphasis is also needed on lifecycle costs, environmental impacts, recyclability and comprehensive techno-economic assessment. Ultimately, the successful deployment of electrochemical energy storage systems will depend on achieving an appropriate balance among performance, durability, safety, scalability and affordability. Continued progress in these areas can strengthen renewable energy integration, improve grid stability and support the transition towards more sustainable and resilient power systems.

References: -

1. K. Zeb, S. M. Ali, B. Khan, C. A. Mehmood, N. Tareen, W. Din, U. Farid and A. Haider, Renewable and Sustainable Energy Reviews **75**, 1142 (2016).
2. A. J. Al-Yasiri, Akkad Journal of Contemporary Economic Studies **1**, 186 (2022).
3. L. Olatomiwa, H. O. Idakwo, W. S. Olusola and C. Ezeh, DOAJ (DOAJ: Directory of Open Access Journals) (2025).
4. J. K. Emmanuel and F. J. Ngabala, Sustainable Environment **12**, (2026).
5. D. Zhang, C. Rong, T. Ahmad, H. Xie, H. Zhu, X. Li and T. Wu, Engineering Reports **5**, e12584 (2022).
6. A. Aghmadi and O. A. Mohammed, Batteries **10**, 141 (2024).
7. Y. P. Soni and E. Fernandez, in *Elsevier eBooks* (2023), pp. 215–233.
8. B. Kale and S. Chatterjee, Bulletin of Materials Science **43**, (2020).
9. Q. Zhang, W. Pei and X. Liu, Electrochem **3**, 225 (2022).
10. P. P. Abhijith, N. S. Jishnu, N. T. M. Balakrishnan, A. Das, J.-H. Ahn, J. F. M. J and P. Raghavan, in *CRC Press eBooks* (2021), pp. 1–34.

11. V. Arangarajan, A. M. T. Oo, J. Chandran, Gm. Shafiullah and A. Stojcevski, Murdoch University (2015).
12. M. A. Hannan, S. B. Wali, P. J. Ker, A. Rahman, M. Mansor, V. K. Ramachandaramurthy, K. M. Muttaqi, T. M. I. Mahlia and Z. Y. Dong, Journal of Energy Storage **42**, 103023 (2021).
13. C. Huang, S. Li, C. Fu, X. Wan, X. Wang, L. Miao, M. Zhang, Y. Chen, L. Fang, S. Yang, Y. Shao and F. Xie, Journal of Energy Storage **167**, 122575 (2026).
14. S. Qiao, M. Hu, C. Fu, D. Qin, A. Zhou, P. Wang and F. Lin, Applied Sciences **9**, 1742 (2019).
15. S. Yasuoka, Y. Magari, T. Murata, T. Tanaka, J. Ishida, H. Nakamura, T. Nohma, M. Kihara, Y. Baba and H. Teraoka, Journal of Power Sources **156**, 662 (2005).
16. J. Heo, K. Shin and H. Kim, Advanced Science **9**, e2204908 (2022).
17. S. Biswas, A. Senju, R. Mohr, T. Hodson, N. Karthikeyan, K. W. Knehr, A. G. Hsieh, X. Yang, B. E. Koel and D. A. Steingart, Energy & Environmental Science **10**, 114 (2016).
18. C.-T. Lu, Z.-Y. Zhu, S.-W. Chen, Y.-L. Chang and K.-L. Hsueh, Batteries **8**, 92 (2022).
19. T. Hu, K. Li, Y. Fang, L. Su, Z. Song, H. Shen and L. Sheng, International Journal of Energy Research **43**, 1099 (2019).
20. P. Zheng, T. Liu and S. Guo, Scientific Reports **6**, 35620 (2016).
21. C. Wu, Y. Yang, Y. Li, X. He, Y. Zhang, W. Huang, Q. Chen, X. Liu, S. Chen, Q. Gu, L. Li, S. C. Smith, X. Tan, Y. Yu, X. Wu and S. Chou, Energy & Environmental Science **18**, 6019 (2025).
22. X. Xu, D. Zhou, X. Qin, K. Lin, F. Kang, B. Li, D. Shanmukaraj, T. Rojo, M. Armand and G. Wang, Nature Communications **9**, 3870 (2018).
23. D. W. Dees, V. S. Battaglia and A. Bélanger, Journal of Power Sources **110**, 310 (2002).
24. J. M. Blázquez-Moreno, S. Muduli, A. Benítez, Á. Caballero and M. R. Buchmeiser, Journal of Energy Storage **143**, 119583 (2025).
25. Mohamed, P. K. Leung and M. H. Sulaiman, Applied Energy **137**, 402 (2014).
26. A. Karrech, K. Regenauer-Lieb and F. Abbassi, Journal of Energy Storage **45**, 103623 (2021).
27. Z. N. Duan, G. B. Zhang, J. F. Zhang and Z. G. Qu, Frontiers in Thermal Engineering **2**, (2022).
28. A. Fetyan, M. O. Bamgbopa, A. Andisetiawan, A. Alhammadi and R. A. Susantyoko, Batteries & Supercaps **6**, (2023).
29. S. Suresh, T. Kesavan, Y. Munaiah, I. Arulraj, S. Dheenadayalan and P. Ragupathy, RSC Advances **4**, 37947 (2014).
30. M. Yang, Z. Xu, W. Xiang, H. Xu, M. Ding, L. Li, A. Tang, R. Gao, G. Zhou and C. Jia, Energy Storage Materials **44**, 433 (2021).
31. Q. Xiong, M. Huang, T. Ren, S. Wu, W. Wang, Z. Xiang, K. Wan, Z. Fu and Z. Liang, Advanced Energy Materials **15**, (2024).
32. X. You, M. Misra, S. Gregori and A. K. Mohanty, ACS Sustainable Chemistry & Engineering **6**, 318 (2017).
33. J. Joseph, S. K. Kannan, K. K. Surendran, H. Hareendrakrishnakumar and M. G. Joseph, Energy Technology **12**, (2024).
34. X. Lv, S. Ji, V. Linkov, X. Wang, H. Wang and R. Wang, Journal of Materials Chemistry A **9**, 2928 (2020).
35. F. Markoulidis, J. Bates, C. Lekakou, R. Slade and G. M. Laudone, Carbon **164**, 422 (2020).
36. X. Bao, Z. Zhang and D. Zhou, Synthetic Metals **260**, 116271 (2020).
37. M. Yang, S. B. Hong and B. G. Choi, Physical Chemistry Chemical Physics **17**, 29874 (2015).
38. N. S. Shaikh, V. C. Lokhande, T. Ji, S. Ubale, V. J. Mane, C. D. Lokhande, H. M. Shaikh, J. S. Shaikh, S. Praserthdam, S. Sabale and P. Kanjanaboos, Dalton Transactions **51**, 6378 (2022).
39. H. Hesham, M. A. Rahman, G. Bassioni, R. A. Swief, M. Ezzat, S. Helmy and N. M. Elbehairy, Scientific Reports **15**, 42920 (2025).
40. S. Shahgaldi, I. Alaefour and X. Li, Applied Energy **225**, 1022 (2018).
41. A. S. Mathew, B. Naigil, E. George, E. Benny and R. Baby, Materials Today Proceedings **58**, 400 (2022).
42. C. Lo Vecchio, X. Lyu, I. Gatto, B. Zulevi, A. Serov, V. Baglio, C. Lo Vecchio, I. Gatto and V. Baglio, Journal of Power Sources **561**, 232732 (2023).