Recent Advancement of Metal oxide Semiconductors for Energy Storage Applications: A Review

Nima P. Golhar

Associate Professor,
Department of Physics, Nanasaheb Y. N. Chavan Arts, Science and Commerce College, Chalisgaon, Dist-Jalgaon, Maharashtra, India (424101)

Abstract

Metal oxide semiconductors have emerged as promising materials for energy storage applications due to their unique structural, electrical, and electrochemical properties. This review presents a comprehensive overview of recent advancements in metal oxide-based semiconductors, focusing on their roles in supercapacitors, lithium-ion batteries, sodium-ion batteries, and other emerging energy storage technologies. The paper highlights various synthesis techniques, such as sol-gel, hydrothermal, co-precipitation, and electrospinning, which significantly influence the morphology, surface area, and electrochemical performance of the materials.Present review also discusses the charge storage mechanisms, challenges in large-scale applications, and the future perspectives for optimizing performance and scalability. By consolidating the recent progress in material design and application strategies, this review aims to guide future research directions in the development of efficient, sustainable, and high-performance metal oxide semiconductor-based energy storage systems.

Keywords: Energy Storage, Supercapacitors, Surface Area, Sustainable, Scalability

1. Introduction:

The need for efficient and reliable energy storage devices has become increasingly critical in the current century due to the growing global demand for sustainable energy solutions and the rapid transition towards renewable energy sources. As solar, wind, and other intermittent energy systems gain prominence, there arises an urgent requirement for advanced storage technologies that can buffer fluctuations and ensure a stable and continuous power supply [1, 2]. Energy storage devices are essential for balancing supply and demand, enhancing grid stability, and enabling energy access in remote and off-grid areas. The surge in portable electronic devices, electric vehicles (EVs), and smart technologies has intensified the demand for compact, lightweight, and high-performance energy storage systems [3, 4]. These devices also play a pivotal role in reducing greenhouse gas emissions by facilitating the shift away from fossil fuels and promoting the use of clean energy [4]. Furthermore, in the face of climate change and energy insecurity, energy storage solutions offer resilience by supporting backup power during outages and emergencies. Innovations in battery technologies, supercapacitors, and hybrid storage systems are vital for enabling a sustainable energy future [5, 6]. As such, developing advanced, scalable, and environmentally friendly energy storage devices is not just a technological goal but a societal imperative for economic growth, environmental protection, and improved quality of life in the 21st century [7-9].

The use of metal oxide semiconductors (MOS) for energy storage devices has a rich and evolving history, rooted in the broader exploration of semiconductor materials for electrochemical applications [10]. Initially, metal oxides like TiO_2 and ZnO were primarily investigated for their roles in photocatalysis and sensing applications during the mid-20th century. However, as interest in energy storage technologies grew in the 1970s and 1980s driven by the oil crisis and the search for alternative energy solutions researchers began to explore the potential of these materials in batteries and capacitors. Transition metal oxides such as MnO_2 and RuO_2 were among the first to be applied in supercapacitors due to their excellent redox properties and high capacitance values. The 1990s and early 2000s witnessed a significant shift as nanotechnology enabled the fabrication of nanostructured metal oxides, which offered enhanced surface area, improved ion diffusion, and better electrochemical performance [10-12]. This period also marked the rise of lithium-ion batteries, where metal oxides like Co_3O_4, NiO, and Fe_2O_3 became crucial components in anode and cathode materials. As the need for more sustainable and efficient storage solutions intensified in the 21st century, the development of binary and ternary metal oxides, along with hybrid composites incorporating carbon-based materials, gained momentum [13, 14]. These advancements allowed researchers to address limitations such as poor conductivity and volume changes during cycling. Today, MOS are at the forefront of energy storage research, forming the backbone of innovative systems like lithium-sulfur batteries, sodium-ion batteries, and hybrid supercapacitors. Their historical progression reflects a continual adaptation to meet the energy challenges of each era, driven by both technological advances and global energy needs [14, 15].

MOS have garnered significant attention in recent years for their potential in energy storage applications due to their versatile physicochemical properties, abundant availability, and tunable electronic structures. These materials exhibit high theoretical capacitance, multiple oxidation states, and strong redox activity, making them highly suitable for devices like supercapacitors, lithium-ion batteries (LIBs), sodium-ion batteries (SIBs), and other advanced energy storage systems. In supercapacitors, metal oxides such as MnO_2, NiO, Co_3O_4, and Fe_2O_3 contribute to pseudocapacitive behavior, enabling high energy density and fast charge-discharge capabilities. Similarly, in lithium-ion and sodium-ion batteries, metal oxides like TiO_2, SnO_2, and MoO_3 serve as efficient anode materials owing to their ability to accommodate Li^+/Na^+ ions through intercalation or conversion reactions, offering high storage capacity and good cycling stability [15, 16]. The electrochemical performance of these oxides can be significantly enhanced through nanostructuring, doping, and forming composites with conductive materials such as graphene, carbon nanotubes, and conducting polymers, which help overcome issues like poor conductivity and volume expansion during charge/discharge processes [17, 18]. Moreover, binary and ternary metal oxides provide synergistic effects that improve ion diffusion and electron transport pathways. Advanced synthesis techniques like hydrothermal synthesis, sol-gel, co-precipitation, and electrospinning allow precise control over the morphology, surface area, and crystallinity, directly influencing energy storage characteristics. Despite these advancements, challenges such as structural degradation, low cyclic stability in some oxides, and complex fabrication processes remain. Ongoing research focuses on optimizing material compositions, developing scalable and cost-effective synthesis methods, and enhancing the integration of these materials into commercial energy storage devices. The metal oxide semiconductors hold immense promise in addressing the global demand for efficient, sustainable, and high-performance energy storage solutions [18-20].

The aim of the present research paper is to comprehensively explore and analyze the latest developments in the synthesis, structural engineering, and performance optimization of metal oxide semiconductors for various energy storage systems.

2. Types of energy storage devices

Energy storage devices are crucial technologies that store energy for later use, improving energy efficiency and enabling the integration of renewable energy sources like solar and wind [21, 22]. These devices can be broadly categorized into mechanical, electrochemical, chemical, thermal, and electromagnetic storage systems as shown in Fig. 1 [23, 24].

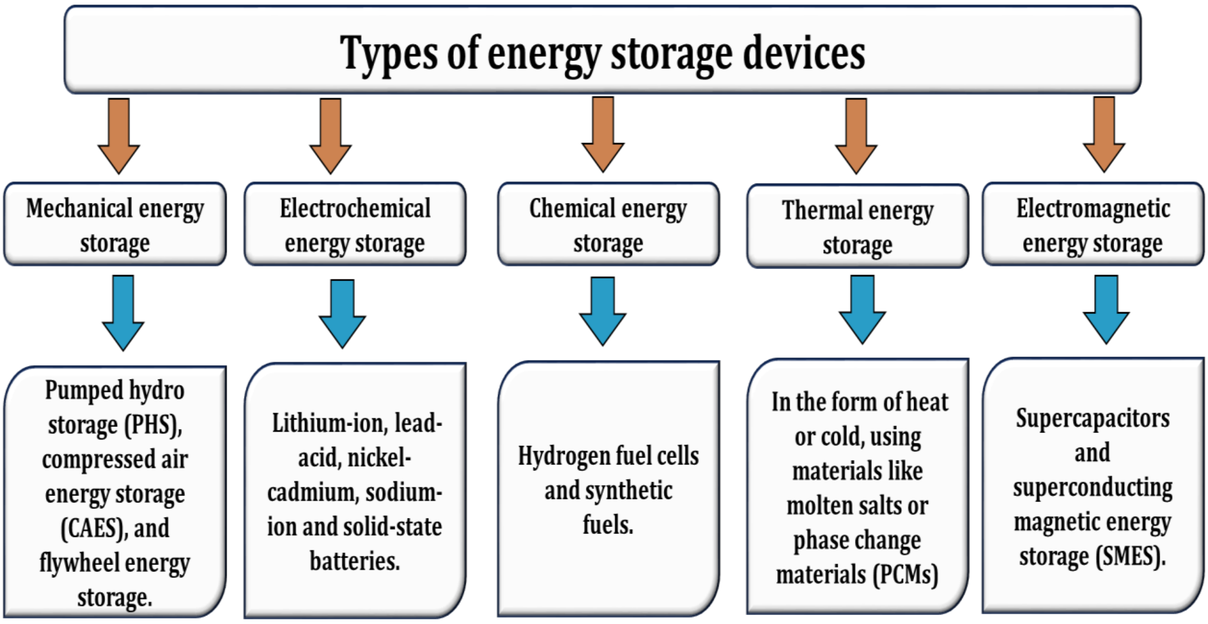

Figure 1. Types of energy storage devices

Mechanical energy storage includes systems like pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheel energy storage. PHS stores energy by pumping water to a higher elevation and releasing it through turbines when needed. CAES compresses air and stores it in underground caverns; when electricity is required, the air is released to drive turbines. Flywheels store kinetic energy in a rotating mass and can quickly deliver bursts of power [25].Electrochemical energy storage mainly involves batteries, such as lithium-ion, lead-acid, nickel-cadmium, and emerging technologies like sodium-ion and solid-state batteries. These store energy through reversible chemical reactions. Lithium-ion batteries dominate portable electronics and electric vehicles due to their high energy density and efficiency [26, 27].Chemical energy storage systems include hydrogen fuel cells and synthetic fuels. Hydrogen can be produced through electrolysis and stored, then later used in fuel cells to generate electricity with water as the only by-product. This method is ideal for long-term and large-scale energy storage [28, 29].Thermal energy storage systems store energy in the form of heat or cold, using materials like molten salts or phase change materials (PCMs). These are commonly used in solar thermal power plants and building temperature regulation, storing solar heat during the day and releasing it at night [30, 31].Electromagnetic energy storage includes supercapacitors and superconducting magnetic energy storage (SMES). Supercapacitors store energy electrostatically and offer rapid charging/discharging, making them suitable for applications needing quick bursts of power. SMES stores energy in a magnetic field created by the flow of direct current in a superconducting coil, providing nearly instant energy release with high efficiency but requiring cryogenic temperatures [32, 33].

3. Working of metal oxide semiconductors for energy storage devices

MOS play a vital role in energy storage devices, particularly in supercapacitors and rechargeable batteries, due to their excellent redox activity, structural stability, and tunable electronic properties. Their working mechanism is primarily based on faradaic (redox) reactions and intercalation/deintercalation processes that enable efficient charge storage and transfer. In supercapacitors, especially pseudocapacitors, metal oxides such as RuO_2, MnO_2, Fe_2O_3, NiO, and Co_3O_4 participate in fast and reversible redox reactions at the electrode–electrolyte interface, contributing to high capacitance and energy density. These redox reactions involve the exchange of electrons and ions (like H^+ or OH^-) with the electrolyte, resulting in faradaic charge storage unlike the purely electrostatic mechanism in electric double-layer capacitors (EDLCs).In batteries, particularly lithium-ion batteries (LIBs), metal oxide semiconductors like $LiCoO_2$, $LiFePO_4$, and TiO_2 act as cathode or anode materials [10, 21]. They work by intercalating lithium ions into their crystal structures during charging and releasing them during discharging [34, 35]. This intercalation process is accompanied by redox changes in the metal cations, allowing efficient and reversible energy storage. The high surface area, porosity, and nanoscale morphology of metal oxide semiconductors enhance ion diffusion and electron transport, further improving storage capacity and rate performance. Recent developments focus on engineering binary and ternary metal oxides, doping, and nanostructuring to improve conductivity, cycle stability, and capacity retention [36]. The unique electronic and structural properties of metal oxide semiconductors make them highly suitable for advanced energy storage technologies.

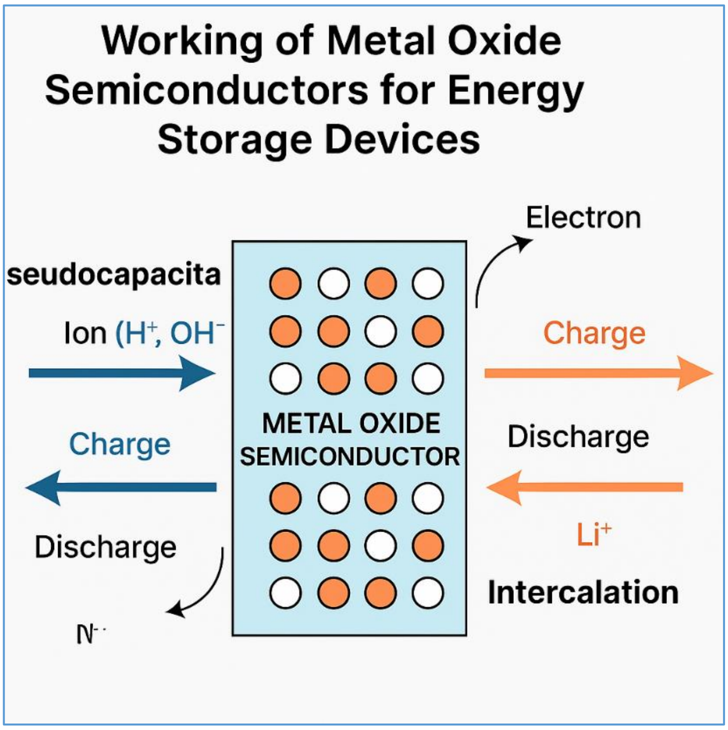

Figure 2. Working of energy storage devices

The working of MOS for energy storage devices is based on two primary mechanisms: pseudocapacitance and intercalation, as illustrated in the Fig. 2. In pseudocapacitive behavior, metal oxide semiconductors such as MnO_2, NiO, and Co_3O_4 store energy through fast and reversible surface or near-surface faradaic redox reactions involving the exchange of protons (H^+) or hydroxide ions (OH^-) from the electrolyte. During the charging process, these ions are adsorbed onto the surface of the metal oxide electrode, accompanied by electron transfer, which is stored as chemical energy. During discharging, the reverse reaction occurs, releasing the stored energy [26, 34]. In the case of intercalation-based storage, common in lithium-ion batteries, lithium ions (Li^+) are inserted into the lattice of metal oxide semiconductors such as TiO_2 or $LiCoO_2$ during charging, while electrons move through an external circuit. During discharging, the ions deintercalate, and electrons flow back, producing electric current. The metal oxide structure facilitates both electron conduction and ion mobility, making it ideal for fast charge/discharge cycles and high energy density [36, 38]. This dual mechanism of redox and intercalation enables metal oxide semiconductors to perform efficiently in modern energy storage technologies.

4. Synthesis method of metal oxide semiconductors for energy storage devices

The synthesis of metal oxide semiconductors for energy storage devices plays a crucial role in determining their structural, morphological, and electrochemical properties, which directly influence device performance. Several synthesis methods have been developed to tailor these materials at the nanoscale, with emphasis on achieving high surface area, controlled porosity, and uniform particle size. Sol-gel synthesis is one of the most widely used methods, involving the transition of a system from a liquid "sol" into a solid "gel" phase, allowing precise control over composition and structure. This technique is ideal for producing homogenous and nanostructured metal oxides with high purity [39, 40]. Hydrothermal and solvothermal methods involve chemical reactions in a sealed autoclave under high temperature and pressure, leading to crystalline nanomaterials with diverse morphologies like rods, spheres, or sheets beneficial for ion diffusion and redox reactions in energy storage devices.Co-precipitation is another cost-effective method that involves the simultaneous precipitation of metal precursors, followed by calcination to obtain the desired oxide phase. It is scalable and suitable for synthesizing binary or ternary metal oxides. Chemical vapor deposition (CVD) and physical vapor deposition (PVD) are used for creating thin films of metal oxides, particularly useful in micro-supercapacitors and flexible energy storage applications [38, 40]. Spray pyrolysis, electrodeposition, and combustion synthesis are also used depending on the application, material type, and desired morphology. Each method influences parameters such as crystallinity, surface area, and conductivity. Hence, optimizing the synthesis route is key to enhancing the electrochemical performance of metal oxide semiconductors for supercapacitors, batteries, and hybrid storage systems [40, 41]. Fig. 3 reveal the different synthesis methods for metal oxide semiconductors for energy storage devices.

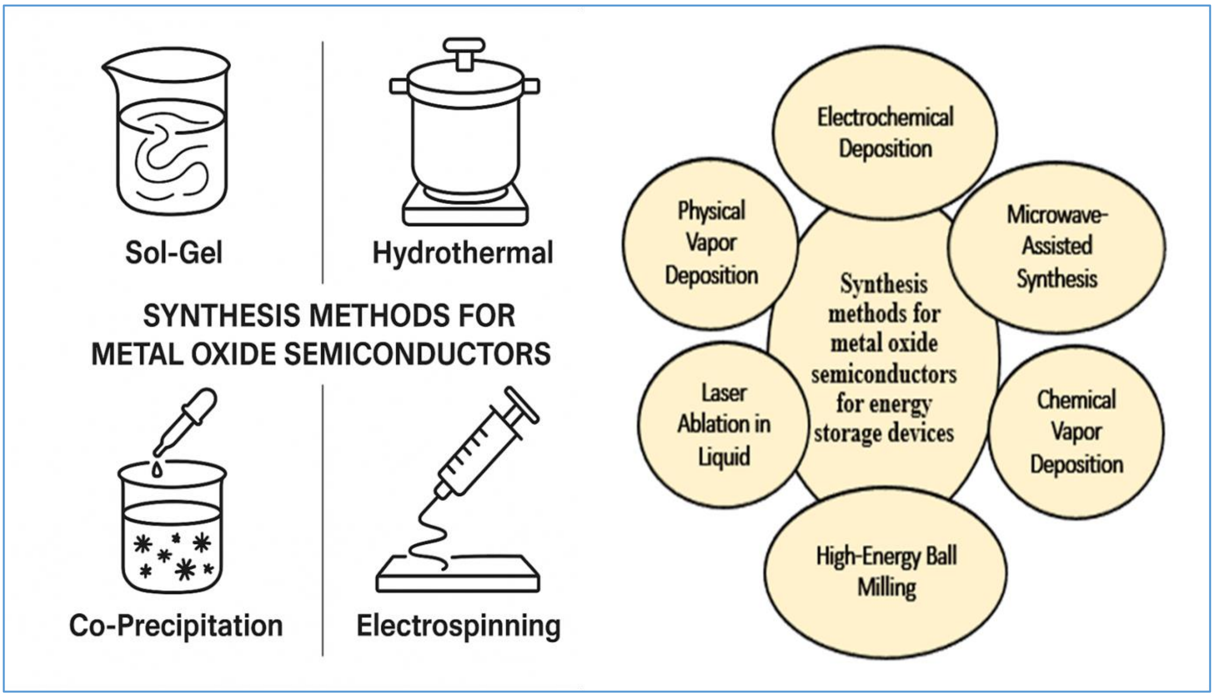

Figure 3. Synthesis methods of MOS for energy storage devices

5. Metal oxide semiconductors based screen printing electrodes for energy storage applications

Screen printing electrodes are a type of printed electrode fabricated using the screen printing technique, which is widely valued for its simplicity, low cost, and scalability. This method involves pushing conductive or functional inks through a patterned mesh screen onto a substrate, allowing for precise control over the shape and thickness of the electrode layers [43]. Screen printing is especially suited for creating flexible, lightweight, and customizable electrodes used in various electrochemical devices, such as sensors, batteries, and supercapacitors. The technique supports a wide range of materials, including carbon-based inks, conductive polymers, and metal oxides, enabling the development of high-performance electrodes with tailored properties. Its compatibility with different substrates, including paper, plastic, and textiles, further enhances its versatility for use in emerging technologies like wearable and printed electronics [43, 44]. Metal oxide semiconductors-based screen printing electrodes are emerging as promising components for energy storage devices due to their unique combination of electrical, chemical, and mechanical properties. MOS exhibit excellent electrochemical activity, high surface area, and good stability, which are essential for efficient charge storage and transfer. Screen printing, a cost-effective and scalable fabrication technique, allows for the deposition of these metal oxides onto various substrates in precise patterns, making it ideal for producing flexible and miniaturized energy storage devices like supercapacitors and batteries. The porosity and thickness of the printed electrodes can be tailored during the printing process to enhance ion diffusion and electron transport, thus improving overall device performance.Screen printing electrodes can be classified into several types based on the materials used and their applications, each offering unique properties suited to specific electrochemical devices [45]. The most common types include carbon-based electrodes, which are widely used due to their good conductivity, chemical stability, and cost-effectiveness. These are often used in biosensors and supercapacitors.Conductive polymer-based electrodes, using materials like PEDOT:PSS or polyaniline, offer flexibility and tunable conductivity, making them suitable for flexible and wearable electronics [44-46].

6. Future perspective ofmetal oxide semiconductors for energy storage devices

The future perspective of metal oxide semiconductors for energy storage devices is highly promising, driven by the urgent global demand for high-performance, cost-effective, and sustainable energy storage systems. As research advances, the focus is shifting toward designing nanostructured and hierarchical architectures of metal oxides to enhance surface area, improve ion/electron transport pathways, and increase active redox sites. The development of binary and ternary metal oxides, doped or composited with conductive materials like graphene or carbon nanotubes, is expected to overcome intrinsic limitations such as low electrical conductivity and volume changes during cycling. The defect engineering, surface modification, and heterojunction formation are emerging as key strategies to tailor the electrochemical behavior and stability of these semiconductors. With the growing interest in alternative energy storage systems like sodium-ion, zinc-ion, and solid-state batteries, metal oxides are being explored for compatibility with diverse electrolytes and operational environments. Furthermore, efforts to employ green synthesis routes and earth-abundant materials will enhance the sustainability and scalability of these technologies. Ultimately, metal oxide semiconductors are poised to play a central role in next-generation energy storage systems, supporting renewable energy integration, electric mobility, and smart grid applications.

Conclusions

Metal oxide semiconductors have demonstrated significant potential as advanced materials for energy storage applications, owing to their distinctive structural, electrical, and electrochemical characteristics. This review has provided a comprehensive analysis of recent developments in the field, encompassing their applications in supercapacitors, lithium-ion batteries, sodium-ion batteries, and other emerging energy storage systems. The discussed synthesis techniques such as sol-gel, hydrothermal, co-precipitation, and electrospinning play a crucial role in tailoring the morphology, surface area, and electrochemical behavior of these materials, thereby enhancing their overall performance. Despite the promising attributes, challenges such as low electrical conductivity, cycling stability, and scalability remain major obstacles to their widespread adoption. This review emphasizes the need for continued interdisciplinary research to develop cost-effective, environmentally friendly, and high-performance metal oxide semiconductor-based energy storage systems that can meet the growing demands of sustainable energy technologies.

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References

1. Dell, R.M. and Rand, D.A.J., 2001. Energy storage—a key technology for global energy sustainability. *Journal of power sources*, *100*(1-2), pp.2-17.
2. Gür, T.M., 2018. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. *Energy & environmental science*, *11*(10), pp.2696-2767.
3. Kalair, A., Abas, N., Saleem, M.S., Kalair, A.R. and Khan, N., 2021. Role of energy storage systems in energy transition from fossil fuels to renewables. *Energy Storage*, *3*(1), p.e135.
4. Sayed, E.T., Olabi, A.G., Alami, A.H., Radwan, A., Mdallal, A., Rezk, A. and Abdelkareem, M.A., 2023. Renewable energy and energy storage systems. *Energies*, *16*(3), p.1415.
5. Chu, S. and Majumdar, A., 2012. Opportunities and challenges for a sustainable energy future. *nature*, *488*(7411), pp.294-303.
6. Mitali, J., Dhinakaran, S. and Mohamad, A.A., 2022. Energy storage systems: A review. *Energy Storage and Saving*, *1*(3), pp.166-216.
7. Larcher, D. and Tarascon, J.M., 2015. Towards greener and more sustainable batteries for electrical energy storage. *Nature chemistry*, *7*(1), pp.19-29.
8. Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., Caldera, U., Sadovskaia, K., Farfan, J., Barbosa, L.D.S.N.S. and Fasihi, M., 2021. Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, *227*, p.120467.
9. Armaroli, N. and Balzani, V., 2007. The future of energy supply: challenges and opportunities. *Angewandte Chemie International Edition*, *46*(1-2), pp.52-66.
10. George, N.S., Jose, L.M. and Aravind, A., 2022. Review on transition metal oxides and their composites for energy storage application. In *Updates on Supercapacitors*. IntechOpen.
11. Huang, A., He, Y., Zhou, Y., Zhou, Y., Yang, Y., Zhang, J., Luo, L., Mao, Q., Hou, D. and Yang, J., 2019. A review of recent applications of porous metals and metal oxide in energy storage, sensing and catalysis. *Journal of Materials Science*, *54*(2), pp.949-973.
12. Yan, S., Abhilash, K.P., Tang, L., Yang, M., Ma, Y., Xia, Q., Guo, Q. and Xia, H., 2019. Research advances of amorphous metal oxides in electrochemical energy storage and conversion. *Small*, *15*(4), p.1804371.
13. Jiang, J., Li, Y., Liu, J., Huang, X., Yuan, C. and Lou, X.W., 2012. Recent advances in metal oxide-based electrode architecture design for electrochemical energy storage. *Advanced materials*, *24*(38), pp.5166-5180.
14. Ellis, B.L., Knauth, P. and Djenizian, T., 2014. Three-dimensional self-supported metal oxides for advanced energy storage. *Advanced Materials*, *26*(21), pp.3368-3397.
15. Zhang, Y., Li, L., Su, H., Huang, W. and Dong, X., 2015. Binary metal oxide: advanced energy storage materials in supercapacitors. *Journal of Materials Chemistry A*, *3*(1), pp.43-59.

16. Chavali, M.S. and Nikolova, M.P., 2019. Metal oxide nanoparticles and their applications in nanotechnology. *SN applied sciences*, *1*(6), p.607.
17. Wu, Z.S., Zhou, G., Yin, L.C., Ren, W., Li, F. and Cheng, H.M., 2012. Graphene/metal oxide composite electrode materials for energy storage. *Nano Energy*, *1*(1), pp.107-131.
18. Kochuveedu, S.T., Jang, Y.H. and Kim, D.H., 2013. A study on the mechanism for the interaction of light with noble metal-metal oxide semiconductor nanostructures for various photophysical applications. *Chemical Society Reviews*, *42*(21), pp.8467-8493.
19. Yuan, C., Wu, H.B., Xie, Y. and Lou, X.W., 2014. Mixed transition-metal oxides: design, synthesis, and energy-related applications. *Angewandte Chemie International Edition*, *53*(6), pp.1488-1504.
20. An, C., Zhang, Y., Guo, H. and Wang, Y., 2019. Metal oxide-based supercapacitors: progress and prospectives. *Nanoscale Advances*, *1*(12), pp.4644-4658.
21. Liu, J., Wang, J., Xu, C., Jiang, H., Li, C., Zhang, L., Lin, J. and Shen, Z.X., 2018. Advanced energy storage devices: basic principles, analytical methods, and rational materials design. *Advanced science*, *5*(1), p.1700322.
22. Song, Z. and Zhou, H., 2013. Towards sustainable and versatile energy storage devices: an overview of organic electrode materials. *Energy & Environmental Science*, *6*(8), pp.2280-2301.
23. Sakai, M. and Amano, M., 2013. Energy storage devices and systems. *Hitachi chemical Technical Report*, (55), pp.9-11.
24. Liu, C., Li, F., Ma, L.P. and Cheng, H.M., 2010. Advanced materials for energy storage. *Advanced materials*, *22*(8), pp.E28-E62.
25. Olympios, A.V., McTigue, J.D., Farres-Antunez, P., Tafone, A., Romagnoli, A., Li, Y., Ding, Y., Steinmann, W.D., Wang, L., Chen, H. and Markides, C.N., 2021. Progress and prospects of thermo-mechanical energy storage—a critical review. *Progress in Energy*, *3*(2), p.022001.
26. Goodenough, J.B., 2014. Electrochemical energy storage in a sustainable modern society. *Energy & Environmental Science*, *7*(1), pp.14-18.
27. Mathis, T.S., Kurra, N., Wang, X., Pinto, D., Simon, P. and Gogotsi, Y., 2019. Energy storage data reporting in perspective—guidelines for interpreting the performance of electrochemical energy storage systems. *Advanced Energy Materials*, *9*(39), p.1902007.
28. Revankar, S.T., 2019. Chemical energy storage. In *Storage and Hybridization of Nuclear Energy* (pp. 177-227). Academic Press.
29. Gür, T.M., 2018. Review of electrical energy storage technologies, materials and systems: challenges and prospects for large-scale grid storage. *Energy & environmental science*, *11*(10), pp.2696-2767.
30. Sarbu, I. and Sebarchievici, C., 2018. A comprehensive review of thermal energy storage. *Sustainability*, *10*(1), p.191.
31. Cabeza, L.F., 2021. Advances in thermal energy storage systems: Methods and applications. In *Advances in thermal energy storage systems* (pp. 37-54). Woodhead publishing.
32. Olabi, A.G., Abbas, Q., Al Makky, A. and Abdelkareem, M.A., 2022. Supercapacitors as next generation energy storage devices: Properties and applications. *Energy*, *248*, p.123617.
33. Lai, W., Wang, Y., Wang, X., Nairan, A. and Yang, C., 2018. Fabrication and engineering of nanostructured supercapacitor electrodes using electromagnetic field-based techniques. *Advanced Materials Technologies*, *3*(1), p.1700168.
34. Hu, X., Zhang, W., Liu, X., Mei, Y. and Huang, Y., 2015. Nanostructured Mo-based electrode materials for electrochemical energy storage. *Chemical Society Reviews*, *44*(8), pp.2376-2404.
35. Lamb, J.J. and Burheim, O.S., 2021. Lithium-ion capacitors: A review of design and active materials. *Energies*, *14*(4), p.979.

36. Chen, D., Wang, Q., Wang, R. and Shen, G., 2015. Ternary oxide nanostructured materials for supercapacitors: a review. *Journal of Materials Chemistry A*, *3*(19), pp.10158-10173.
37. Manohar, A., Suvarna, T., Chintagumpala, K., Ubaidullah, M., Mameda, N. and Kim, K.H., 2025. Exploring progress in binary and ternary nanocomposites for photoelectrochemical water splitting: A comprehensive review. *Coordination Chemistry Reviews*, *522*, p.216180.
38. Yuan, C., Wu, H.B., Xie, Y. and Lou, X.W., 2014. Mixed transition-metal oxides: design, synthesis, and energy-related applications. *Angewandte Chemie International Edition*, *53*(6), pp.1488-1504.
39. Kumar, S., Saralch, S., Jabeen, U. and Pathak, D., 2020. Metal oxides for energy applications. In *Colloidal Metal Oxide Nanoparticles* (pp. 471-504). Elsevier.
40. Xia, X., Zhang, Y., Chao, D., Guan, C., Zhang, Y., Li, L., Ge, X., Bacho, I.M., Tu, J. and Fan, H.J., 2014. Solution synthesis of metal oxides for electrochemical energy storage applications. *Nanoscale*, *6*(10), pp.5008-5048.
41. Jin, B., Yan, Q. and Dou, Y., 2012. Materials for energy storage and conversion based on metal oxides. *Recent Patents on Materials Science*, *5*(3), pp.199-212.
42. Yaqoob, A.A., Ahmad, A., Ibrahim, M.N.M., Karri, R.R., Rashid, M. and Ahamd, Z., 2022. Synthesis of metal oxide–based nanocomposites for energy storage application. *Sustainable Nanotechnology for Environmental Remediation*, pp.611-635.
43. Rubio, J.C. and Bolduc, M., 2025. Screen Printing for Energy Storage and Functional Electronics: A Review.
44. Suresh, R.R., Lakshmanakumar, M., ArockiaJayalatha, J.B.B., Rajan, K.S., Sethuraman, S., Krishnan, U.M. and Rayappan, J.B.B., 2021. Fabrication of screen-printed electrodes: opportunities and challenges. *Journal of Materials Science*, *56*, pp.8951-9006..
45. Azadmanjiri, J., Thuniki, N.R., Guzzetta, F. and Sofer, Z., 2021. Liquid Metals-Assisted Synthesis of Scalable 2D Nanomaterials: Prospective Sediment Inks for Screen-Printed Energy Storage Applications. *Advanced Functional Materials*, *31*(17), p.2010320.
46. Johannisson, W., Carlstedt, D., Nasiri, A., Buggisch, C., Linde, P., Zenkert, D., Asp, L.E., Lindbergh, G. and Fiedler, B., 2021. A screen-printing method for manufacturing of current collectors for structural batteries. *Multifunctional materials*, *4*(3), p.035002.