

A Comprehensive Study of the Importance of Materials for Renewable Energy Generation

Jubaer Akon Pranto¹, Md Moin Kadir², Md. Yakub Ali Khan³

¹ Department of Electrical and Electronic Engineering, Prime University, Dhaka Bangladesh

^{2,3} Department of Electrical and Electronic Engineering, World University of Bangladesh, Uttara, Dhaka Bangladesh

Email: ¹ jubaerakonpranto@gmail.com, ² moinkadir443@gmail.com, ³ yakub.bimt@gmail.com

*Corresponding Author

Abstract—The main objective of this review is to show the importance of materials in renewable energy generation. Making the switch to renewable energy sources is essential for promoting sustainable growth and halting global warming. This extensive study looks at the critical role that materials play in the production of renewable energy, emphasizing how important they are for improving efficiency, cutting costs, and guaranteeing the longevity of energy systems. Key components of solar, wind, hydro, and biomass energy technologies are the subject of this study. Examples of these components are silicon for solar cells, rare earth metals for wind turbines, and organic matter for biomass conversion. It also examines the effects of cutting-edge energy storage technologies, such as supercapacitors and lithium-ion batteries, on the stability and dependability of renewable energy systems. Materials play a key role in increasing the performance and lowering the cost of renewable energy generation technologies, including fuel cells, wind turbines, solar panels, and batteries. Due to its high energy conversion efficiency and widespread availability, silicon continues to be the most widely used material in photovoltaic (PV) solar panels. However, novel materials such as perovskites offer promise for obtaining higher efficiencies at reduced manufacturing costs. The difficulties in extracting, processing, and recycling materials are discussed, highlighting the necessity of sustainable methods and creative approaches in the field of material science. Many high-performance materials are costly or challenging to manufacture on a large scale, such as advanced composites and some rare earth elements. A big problem is cutting prices and locating more plentiful alternatives. The study highlights the vital need for ongoing research and development in materials to optimize renewable energy technologies and support the worldwide move towards a low-carbon future by examining existing advancements and future potential.

Keywords—Materials, Importance, Solar, Wind, Hydro Energy, Challenges

I. INTRODUCTION

In addition to being a vital answer to the pressing need for sustainable development, the global move towards renewable energy is also a key tactic to lessen the negative effects of climate change. It is impossible to overestimate the significance of the materials that support renewable energy technologies in light of the global commitment made by governments to cut carbon emissions and switch to cleaner energy sources. This study explores the critical role these materials play in renewable energy systems' durability, cost-effectiveness, and efficiency. In addition to being a vital answer to the pressing need for sustainable development, the global move towards renewable energy is also a key tactic to

lessen the negative effects of climate change. It is impossible to overestimate the significance of the materials that support renewable energy technologies considering the global commitment made by governments to cut carbon emissions and switch to cleaner energy sources [1]. The foundation of renewable energy technologies are materials, which are essential for improving performance, economy, and efficiency in a range of applications. Material science advancements speed up the shift to sustainable energy sources by putting renewable energy sources on par with more conventional energy sources. Due to its high energy conversion efficiency and stability, silicon has long been the standard material for photovoltaic (PV) cells in the solar energy industry. However, other materials like perovskites are being investigated for their potential to provide higher efficiencies at lower costs. Cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), two more thin-film technologies that offer lightweight, flexible substitutes with lower material usage. Advanced composites, such as carbon fiber and fiberglass, enable the manufacture of longer-lasting turbines in the wind energy industry. Strong magnetic fields are produced in wind turbine generators by rare earth magnets, such as those manufactured of neodymium, which raises the efficiency of energy generation. Innovations in electrode materials, such silicon anodes and solid electrolytes, help lithium-ion batteries store more energy for longer periods of time at lower costs. Other battery chemistries, such as lithium-sulfur or sodium-ion, are also being investigated in order to solve the problems of material scarcity and expense. The development of non-precious metal catalysts and improved proton exchange membranes (PEMs) in fuel cells lowers costs while improving the longevity and efficiency of the cell.

This study explores the critical role these materials play in renewable energy systems' durability, cost-effectiveness, and efficiency. The performance and viability of renewable energy solutions are directly impacted by the choice and quality of materials, which range from the silicon used in solar cells to the rare earth metals essential for wind turbine magnets. The performance and viability of renewable energy solutions are directly impacted by the choice and quality of materials, which range from the silicon used in solar cells to the rare earth metals essential for wind turbine magnets [2]. In addition, the research delves into cutting-edge materials for energy storage, including supercapacitors and lithium-ion batteries, which are essential for mitigating the intermittent nature of renewable energy sources [3]. It also discusses the

difficulties in extracting, processing, and recycling these materials, emphasizing the necessity of sustainable methods and continuous innovation. This study intends to highlight the importance of these materials in achieving global energy goals and building a sustainable future by offering a thorough examination of the components essential to the generation of renewable energy [4].

One of the most promising renewable energy sources is solar energy, which depends mostly on semiconductor elements like silicon for photovoltaic cells, which turn light from the sun into electrical current [5]. Thin-film technologies and perovskite materials, among other developments in material science, have resulted in more economical and efficient solar panels [6]. Another essential renewable energy source is wind energy, which requires resources like rare earth metals to make strong, long-lasting magnets for wind turbines. By maximizing wind energy systems' longevity and efficiency, these materials help them to become more competitive with other energy sources. Hydropower and biomass energy systems operate more efficiently and sustainably thanks to specialized materials [7]. For hydropower turbines and other mechanical components to last a long time, materials must be strong and resistant to corrosion. Modern materials are necessary for efficient conversion processes and emissions control in the production of biomass energy, ensuring the ecological benignity of this renewable energy source.

Photovoltaic (PV) cells are especially well suited for silicon because of its distinct electrical characteristics, stability, and abundance. Because of its crystalline form, silicon functions as a semiconductor and can effectively use the photovoltaic effect to turn sunlight into electricity. An electric current is produced when sunlight strikes a silicon solar cell, excitation electrons and forming electron-hole pairs. Because silicon has an ideal bandgap of 1.1 eV, it can absorb a large portion of the solar spectrum and is hence very effective at turning sunlight into useful energy. Additionally, silicon's ability to produce a persistent oxide layer minimizes surface recombination losses, further enhancing energy conversion efficiency. In addition to its efficiency, silicon is non-toxic and widely available, making it a more cost-effective and environmentally friendly choice for large-scale manufacturing. Energy storage is a crucial field in which materials science is vital [8]. The development of high-performance batteries like lithium-ion, solid-state batteries, and supercapacitors is essential to overcoming the intermittent nature of renewable energy sources. These storage choices enable the dependable integration of renewable energy sources into the grid, ensuring a consistent and stable energy supply. The goal of this extensive study is to offer a thorough examination of the materials essential to the production of renewable energy. Through an analysis of present developments, obstacles, and opportunities, it emphasizes how crucial materials are to achieving global energy targets and building a sustainable future. We can support the worldwide shift to a low-carbon economy by improving the performance, lowering prices, and increasing the sustainability of renewable energy systems through ongoing material science research and innovation [9]. Improvements in manufacturing techniques, like the creation of anti-reflective coatings and high-purity silicon wafers,

have consistently raised its performance and lowered its costs. Because of these variables together, silicon dominates the photovoltaic (PV) sector and is used in over 90% of solar panels made worldwide. Silicon is the preferred material for photovoltaic cells due to its efficiency, availability, and long-term stability, which has fueled the extensive use of solar energy.

II. RENEWABLE ENERGY

The performance, cost, and environmental impact of renewable energy sources are largely determined by their materials, which form their foundation. The creation and application of innovative materials will be crucial to overcoming obstacles and building a reliable and effective renewable energy infrastructure as the world continues its shift to sustainable energy sources [10]. These materials will guarantee that the world transitions to a cleaner, more sustainable energy future through sustained innovation and dedication to sustainable practices. Renewable energy comes from natural processes and refills at a rate that is at least as fast as it is consumed. Unlike fossil fuels, which are scarce and significantly contribute to pollution and climate change, renewable energy sources are sustainable and have less of an adverse effect on the environment. There are many renewable energy sources which are shown in Fig. 1.

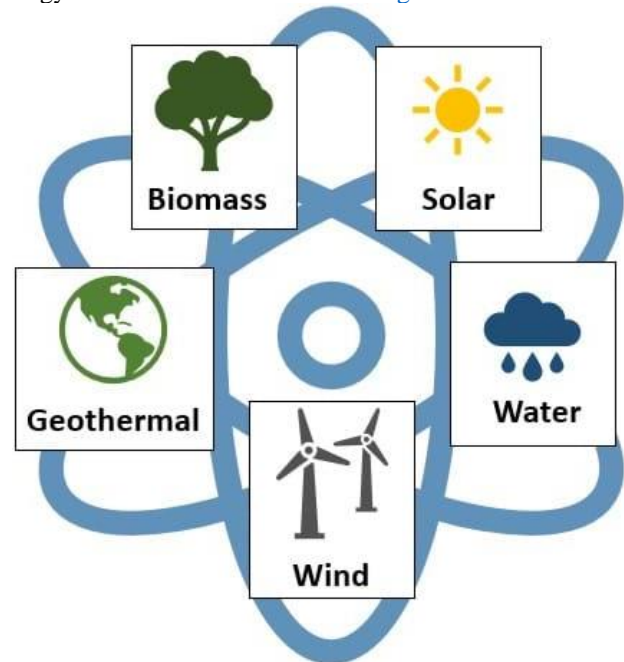


Fig. 1. Renewable energy sources

These are some of the main sources of renewable energy:

- Solar Energy
 - Photovoltaic (PV) Systems: Directly convert sunlight into electricity using solar cells made of semiconductor materials, often silicon [11].
 - Solar thermal systems: They harness solar radiation to produce heat that can be immediately consumed or utilized to drive steam turbines, which in turn generates electricity.
- Wind Power
 - Onshore Wind Farms: Produce power by using wind turbines erected on land.

Wind turbines situated in bodies of water to take advantage of stronger and more reliable wind patterns are known as offshore wind farms [12].

- **Hydropower**
 - **Run-of-the-River Systems:** Generate electricity by diverting a portion of river flow through turbines without the need for large dams [13].
 - **Reservoir Systems:** Use dams to store water in reservoirs, releasing it through turbines to generate electricity as needed.
 - **Pumped Storage:** A type of hydroelectric power used for energy storage, where water is pumped to a higher elevation during low demand and released to generate electricity during high demand.

- **Energy from Biomass**

Direct combustion is the process of burning organic resources to create heat and energy, such as garbage, wood, and agricultural wastes.

Transforming organic materials into liquid fuels for use in transportation, such as ethanol and biodiesel, is known as biofuels [14].

- **Biogas:** Methane produced by anaerobic digestion of organic waste that can be utilized as fuel for cars, as well as for heating and power generation.
- **Geothermal Power**
 - **Direct Use Applications:** Direct application of geothermal heat for industrial processes, buildings, and greenhouses.
 - **Geothermal Power Plants:** These facilities use steam turbines to generate power from geothermal heat, either by introducing water into heated rocks or using naturally occurring steam [15].
 - **Stainless Steel and High-Temperature Alloys in Biomass Energy:**

Utilized in gasifiers and biomass boilers to endure harsh conditions and elevated temperatures while converting organic molecules into energy.

- **Activators**

To improve the effectiveness of chemical reactions during the conversion of biomass into biofuels like ethanol and biodiesel, certain catalysts are employed in the biofuel manufacturing process.

- **High-Temperature Geothermal Energy Alloys**

To withstand the high temperatures and corrosive conditions of geothermal fluids, materials like Inconel and Hastelloy are employed in geothermal power facilities [16].

- **Materials for Insulation**

For geothermal energy systems to remain safe and efficient, high-performance insulation is necessary, especially when building pipelines and other plant equipment [17].

- **Lithium Energy Storage**

An essential component of lithium-ion batteries, which are highly efficient and have a high energy density when employed as energy storage in renewable energy systems.

- **Nickel and Cobalt**

used to improve longevity and performance in lithium-ion battery cathodes.

- **Graphite:**

Its exceptional electrical conductivity and durability make it a preferred material for lithium-ion battery anodes.

III. MATERIALS FOR RENEWABLE ENERGY GENERATION

The main objective of this paper is to explore the critical role of materials in advancing renewable energy technologies by examining how innovations in material science enhance the performance, efficiency, and cost-effectiveness of energy generation systems. In order to illustrate the revolutionary effect of material improvements on the development and scalability of sustainable energy solutions, this article focuses on important materials used in solar photovoltaics, wind turbines, energy storage systems, and other renewable energy technologies. In order to address the technological and financial obstacles preventing the widespread adoption of renewable energy, it is crucial to comprehend the unique contributions made by materials like silicon in solar cells, rare earth metals in wind turbines, and sophisticated composites in energy storage. Materials are essential to the effectiveness, affordability, and sustainability in the production of renewable energy. MOF-based materials with different functionalities by tuning the constituent components of renewable energy generation shown in Fig. 2. The following is a summary of essential ingredients found in different renewable energy technologies:

- **Sunlight Silicon**

Photovoltaic (PV) cells are mostly made of crystalline silicon. Silicon, both monocrystalline and polycrystalline, is well-liked for its great durability and efficiency.

Amorphous silicon, copper indium gallium selenide (CIGS), and cadmium telluride (CdTe) are examples of thin-film materials. Thin-film solar cells, which are flexible and less expensive to make, use these materials [18].

- **Materials for Perovskites**

A group of substances that are being studied for their potential to produce inexpensive, highly efficient solar cells. Perovskites are simpler to make than conventional silicon cells and have demonstrated quick increases in efficiency.

- **Wind Power Seldom Found Metals**

Used to create strong permanent magnets for wind turbine generators are neodymium and dysprosium. The production of wind turbines with great efficiency requires these materials.

- **Composite Substances**

High strength-to-weight ratios and fatigue resistance are provided by fiberglass and carbon fibre, which are used to make turbine blades. These properties are critical to the longevity and effectiveness of wind turbines [19].

- **Stainless Steel Hydropower**

Because of its resistance to corrosion and wear, it is used to create turbine blades and other components, guaranteeing long-term durability in aquatic settings.

- **Concrete**

vital for providing the required strength and stability while building dams and other hydropower plant structural elements.

IV. IMPORTANCE OF MATERIALS FOR RENEWABLE ENERGY GENERATION

Materials are fundamental to the development and optimization of renewable energy technologies. Their importance lies in several critical aspects, which influence the efficiency, cost-effectiveness, sustainability, and overall feasibility of renewable energy systems. The fundamental components of renewable energy technologies are materials, which have an impact on all aspects including cost, sustainability, and scalability as well as efficiency. To overcome present obstacles and realize the full potential of renewable energy, material science must continue to improve. A cleaner, more sustainable energy future is within reach if we prioritize inventive research, sustainable sourcing, and effective material utilization. Here are key reasons why materials are vital for renewable energy generation:

- **Efficiency of Photovoltaics**

The efficiency of converting sunlight into electricity is directly impacted by materials found in solar panels, such as high-purity silicon. Technological developments in materials, such as perovskites, have the potential to greatly increase solar cell efficiency over present thresholds [21].

- **Turbine Sturdiness**

High-strength materials, such as carbon fiber composites, maximize wind energy extraction by ensuring performance and longevity in challenging climatic circumstances. These materials are employed in wind turbine blades [22].

- **Heat Conductivity**

High thermal conductivity materials, such as certain alloys and ceramics, are necessary for efficient heat transmission in geothermal and solar thermal systems, enhancing the efficiency of these energy sources.

- **Effectiveness of Cost-Effective Materials**

The total cost of renewable energy systems is heavily influenced by the cost of materials. Advances in the field of materials science have the potential to lower the cost of renewable energy by producing less expensive substitutes or reducing the quantity of costly materials required [23].

- **Longevity and Durability**

Materials that lengthen the life of renewable energy equipment save money on repairs and replacements. For example, energy storage systems with long-lasting batteries and hydropower plants with corrosion-resistant materials both have reduced long-term operating costs.

- **Sustainable Sourcing**

The environmental footprint of extracting and processing materials, such as rare earth metals for wind turbines or lithium for batteries, is a major concern. Sustainable sourcing practices and recycling can mitigate these impacts, making renewable energy technologies more environmentally friendly.

- **Waste Reduction**

Materials that are easier to recycle or that degrade safely at the end of their lifecycle help reduce waste. This is crucial for managing the environmental impact of large-scale deployment of renewable energy technologies. To fully comprehend the environmental impact of renewable energy materials, from extraction to disposal, a thorough life cycle analysis (LCA) is essential. While renewable energy technologies have a much lower carbon footprint than

conventional fossil fuels, certain of the materials required in their development, such as high-purity silicon, rare earth metals, and sophisticated composites, can have major environmental effects. For example, energy-intensive mining techniques that generate significant volumes of hazardous waste and have the potential to contaminate land and water are frequently used in the extraction of rare earth metals, which are necessary for electric car motors and wind turbine generators. In a similar vein, producing high-purity silicon for photovoltaic (PV) cells involves a large energy input that is typically obtained from non-renewable sources and results in the development of hazardous byproducts.

- **Advanced Substances**

Advanced materials like graphene for next-generation batteries are developed through ongoing materials science research; these batteries offer better energy densities and faster charging periods, hence redefining energy storage systems.

- **Systems Hybrid**

New materials make it possible to build hybrid renewable energy systems that can use several energy sources at once, increasing the overall dependability and efficiency of the system.

- **Energy Security**

Reducing reliance on politically sensitive resources through the development of renewable energy technologies that use widely available materials can improve both national and international energy security [24].

- **Regional Production**

Employing locally obtained and processed commodities boosts regional economies and lowers the danger of global supply chain disruptions.

Potential Futures for Emerging Technologies:

Emerging renewable energy technologies, like better biofuels, solid-state batteries, and flexible solar panels, are evolving due to novel materials. These technologies have the potential to break through existing constraints and find new uses.

- **Scalability**

Meeting the increasing demand for clean energy worldwide requires materials that allow for the scalable development of renewable energy systems. In order to address climate change and energy needs, renewable energy must be scalable in order to be implemented quickly and effectively [25].

V. CHALLENGES OF RENEWABLE ENERGY GENERATION

While producing renewable energy has a lot to offer in terms of lowering carbon emissions and advancing sustainability, there are a number of obstacles that need to be overcome before its full potential can be reached. A multidimensional strategy including policy support, public participation, and technical innovation is needed to address these difficulties [26]. Renewably supplied energy can reach its full potential and help build a more resilient and sustainable energy future by supporting stakeholder collaboration, investing in research and development, and putting supportive legislation into place. Important difficulties consist of:

Unpredictability and Trustworthiness

- **Variable Output:** Because renewable energy sources like solar and wind are intermittent, the amount of energy they produce varies with the seasons and weather. It may be difficult to provide a steady and dependable energy supply because of this unpredictability [27].

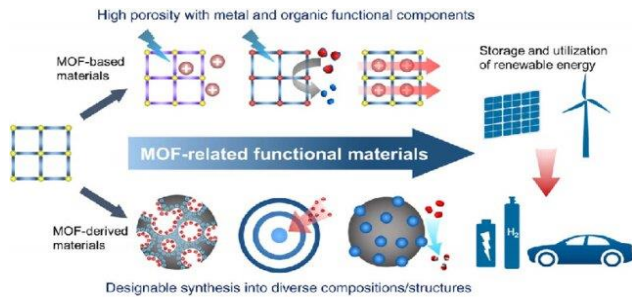


Fig. 2. Schematic of MOF-related materials for renewable energy [20]

- **Cost and Technology of Energy Storage:** Managing the intermittent nature of renewable energy requires efficient energy storage systems. However, the capacity and lifespan of current storage technologies, like lithium-ion batteries, might be limited, and they can be costly [28].
- **Investment and Infrastructure**
- **High Initial Costs:** Installing renewable energy infrastructure, such as solar panels, wind turbines, and grid upgrades, can come with a hefty initial cost. Even while prices are coming down, adoption is still hampered by the initial outlay [29].

Limitations on Materials and Resources

- **Resource Scarcity:** Certain renewable energy technologies depend on rare or scarce elements, such as rare earth metals, which are utilized in some solar panel components and wind turbine components. It is difficult to guarantee a sustained supply of these resources [30].
- **Impact of Land Use on the Environment**
- **Land Requirements:** Substantial land areas are needed for large-scale renewable energy projects like wind and solar farms. Conflicts over land usage may result from this, and local ecosystems may suffer [31].

Regulatory and Policy Difficulties

- **Inconsistent Policies:** The development and implementation of renewable energy projects may be hampered by regional differences in policies and regulations. To encourage investment and innovation, supportive policies and incentives are required [32].

Innovation Gaps in Technology and Research Development: The effectiveness and efficacy of renewable energy systems require ongoing study and development. To overcome current obstacles, breakthroughs in fields like energy storage, grid management, and material science are crucial [33].

VI. DISCUSSION

A The discussion of the comprehensive study on the importance of materials for renewable energy generation highlights several key points. Firstly, the study emphasizes how advanced materials such as high-purity silicon and perovskite compounds significantly enhance the efficiency and performance of renewable energy systems, notably in solar and wind technologies [34]. These improvements not only make renewable energy more competitive with

traditional sources but also drive down costs, facilitating wider adoption. Additionally, the research underscores the crucial role of sustainable sourcing and recycling of materials to minimize the environmental impact of renewable energy technologies. The study does, however, also recognize the difficulties brought on by the lack of some essential elements, such as rare earth metals, and the moral dilemmas raised by their extraction [35]. The necessity of multidisciplinary cooperation is emphasized since, in order to be practically implemented, advances in material science must be in line with engineering, environmental, and policy factors. To support a circular economy, future research initiatives include the creation of more abundant and alternative materials as well as improved recycling technology. All things considered, the study confirms that novel materials are critical to maximizing renewable energy systems, encouraging sustainability, and aiding in the world's shift to low-carbon energy [36].

Several important issues are brought out in the discussion of the extensive study on the significance of materials to produce renewable energy. First, the study highlights how cutting-edge materials, particularly in solar and wind technologies, can greatly improve the efficiency and performance of renewable energy systems [37]. Examples of these materials are high-purity silicon and perovskite compounds. These advancements lower prices for renewable energy and increase its competitiveness against conventional sources, which encourages broader adoption. The study also emphasizes how important it is to recycle and source materials sustainably in order to reduce the environmental impact of renewable energy technology [38]. Sustainable methods of material extraction and processing can lessen the environmental impact of renewable energy systems and encourage more moral and ecologically conscious business practices. The renewable energy sector has considerable hurdles due to the shortage of rare earth metals and the ethical dilemmas surrounding their extraction. However, there are numerous solutions that can be employed to mitigate these issues. Neodymium, dysprosium, and terbium are examples of rare earth metals that are essential to the manufacturing of permanent magnets, which are utilized in electric car motors, wind turbines, and other environmentally friendly technologies. However, because the majority of rare earth production is concentrated in a small number of nations, their extraction is frequently linked to geopolitical tensions, environmental damage, and breaches of human rights.

To effectively recover valuable materials from decommissioned renewable energy systems, promote a circular economy, and cut waste, the study emphasizes the need for recycling technology to advance [39]. Future research is deemed essential in the development of high-performance energy storage materials, such as next-generation batteries, in order to mitigate the intermittent nature of renewable energy sources and enhance grid stability. All things considered, the study confirms that novel materials are critical to maximizing renewable energy systems, encouraging sustainability, and aiding in the world's shift to low-carbon energy. Renewable energy may reach its full potential and guarantee a sustainable energy future for all by tackling the identified obstacles and following the recommended avenues for further study.

VII. CONCLUSION

The thorough investigation concludes by highlighting the critical role materials play in the advancement of renewable energy technology. The selection and development of materials has a significant impact on the sustainability, economy, and efficiency of renewable energy systems. Improved functionality and economic viability of these technologies depend on high-performance materials, like improved composites for wind turbine blades and high-purity silicon for solar cells. The study emphasizes that to reduce environmental effects and promote a circular economy, sustainable material behaviors are required. These activities include ethical sourcing and efficient recycling. Even if material scarcity and ethical issues provide difficulties, continuous research and innovation are essential to getting over these obstacles and finding substitute materials that are plentiful and environmentally benign. The optimization of renewable energy systems will be fueled by interdisciplinary cooperation and ongoing investments in material science. This will enable them wider adoption and aid in the world's transition to a cleaner, more sustainable energy future.

REFERENCES

- [1] J. L. Calderon *et al.*, "Reviewing the material and metal security of low-carbon energy transitions," *Renewable and Sustainable Energy Reviews*, vol. 124, p. 109789, 2020, <https://doi.org/10.1016/j.rser.2020.109789>.
- [2] J. Allwood *et al.*, "Absolute zero: delivering the UK's climate change commitment with incremental changes to today's technologies," *University of Bath*, 2019, <https://doi.org/10.17863/CAM.46075>.
- [3] S. Cao, J. Li, "A survey on ambient energy sources and harvesting methods for structural health monitoring applications," *Advances in Mechanical Engineering*, vol. 9, no. 4, 2017, <https://doi.org/10.1177/1687814017696210>.
- [4] G. Kucur, M. R. Tur, R. Bayindir, H. Shahinzadeh and G. B. Gharehpetian, "A Review of Emerging Cutting-Edge Energy Storage Technologies for Smart Grids Purposes," *2022 9th Iranian Conference on Renewable Energy & Distributed Generation (ICREDG)*, pp. 1-11, 2022, <https://doi.org/10.1109/ICREDG54199.2022.9804538>.
- [5] D. E. Ekechukwu, P. Simpa, "A comprehensive review of innovative approaches in renewable energy storage," *International Journal of Applied Research in Social Sciences*, vol. 6, no. 6, pp. 1133-1157, 2024, <https://doi.org/10.51594/ijarss.v6i6.1176>.
- [6] S. Bhattacharya, B. K. Sachdev, "The Role of Hybrid Nanomaterials to Revamp Energy Harvesting and Its Impact on the Environment and Sustainability," *Innovations and Applications of Hybrid Nanomaterials*, pp. 244-275, 2019, <https://doi.org/10.4018/979-8-3693-3268-9.ch011>.
- [7] Y. A. Kumar *et al.*, "Supercharging the future: MOF-2D MXenes supercapacitors for sustainable energy storage," *Journal of Energy Storage*, vol. 80, p. 110303, 2024, <https://doi.org/10.1016/j.est.2023.110303>.
- [8] M. S. Ali, A. Sharma, T. A. Joy, M. A. Halim, "A Comprehensive Review of Integrated Energy Management for Future Smart Energy System," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 43-51, 2024, <https://doi.org/10.59247/csolv2i1.77>.
- [9] H. Ajibade, C. O. Ujah, K. C. Nnakwo, D. V. Kallon, "Improvement in battery technologies as panacea for renewable energy crisis," *Discover Applied Sciences*, vol. 6, no. 7, p. 374, 2024, <https://doi.org/10.1007/s42452-024-06021-x>.
- [10] S. Roga, S. Bardhan, Y. Kumar, S. K. Dubey, "Recent technology and challenges of wind energy generation: A review," *Sustainable Energy Technologies and Assessments*, vol. 52, p. 102239, 2022, <https://doi.org/10.1016/j.seta.2022.102239>.
- [11] V. Verma, S. Thangavel, N. Dutt, A. Kumar, R. Weerasinghe, "Highly Efficient Thermal Renewable Energy Systems: Design, Optimization and Applications," *CRC Press*, 2024, <https://doi.org/10.1201/9781003472629>.
- [12] I. C. Festus-Ikhuoria, N. C. Obiuto, O. K. Olajiga And R. A. Adebayo, "The role of nanomaterials in energy storage: A comparative review of USA and African development," *World Journal of Advanced Research and Reviews*, vol. 21, no. 3, pp. 2073-2083, 2024, <https://doi.org/10.30574/wjarr.2024.21.3.0925>.
- [13] J. Jeong, H. Lee, T. Kyu, "Electrochemical analysis on the role of disulfide bonds in polysulfide-co-polyoxide as cathode active binder for enhanced storage capacity of lithium-metal batteries," *Solid State Ionics*, vol. 399, p. 116292, 2023, <https://doi.org/10.1016/j.ssi.2023.116292>.
- [14] M. N. Hussain, M. A. Halim, M. Y. A. Khan, S. Ibrahim, A. Haque, "A Comprehensive Review on Techniques and Challenges of Energy Harvesting from Distributed Renewable Energy Sources for Wireless Sensor Networks," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 15-22, 2024, <https://doi.org/10.59247/csolv2i1.60>.
- [15] Q. He *et al.*, "Phase engineering and synchrotron-based study on two-dimensional energy nanomaterials," *Chemical Reviews*, vol. 123, no. 17, pp. 10750-10807, 2023, <https://doi.org/10.1021/acs.chemrev.3c00389>.
- [16] W. Wu *et al.*, "Hierarchical Architecture Composite of N-doped Hollow Polyhedrons Anchored on Ti3C2TX Nanosheets for Advanced Lithium-Ion and Sodium-Ion Capacitors," *Journal of Materials Chemistry A*, vol. 12, no. 30, pp. 19470-19484, 2024, <https://doi.org/10.1039/D4TA02646B>.
- [17] L. Tang, Y. Yang, C. K. Soh, "Broadband vibration energy harvesting techniques," *Advances in energy harvesting methods*, pp. 17-61, 2013, https://doi.org/10.1007/978-1-4614-5705-3_2.
- [18] A. Naqvi, A. Ali, W. A. Altabay, S. A. Kouritem, "Energy Harvesting from Fluid Flow Using Piezoelectric Materials: A Review," *Energies*, vol. 15, no. 19, p. 7424, 2022, <https://doi.org/10.3390/en15197424>.
- [19] H. Zhang, J. Wang and L. -B. Qian, "Low Input Power Management Circuit for Ambient Energy Harvesting," *2020 IEEE MTT-S International Wireless Symposium (IWS)*, pp. 1-3, 2020, <https://doi.org/10.1109/TWS49314.2020.9360051>.
- [20] J. L. Holecek, H. M. Geli, M. N. Sawalbah, R. Valdez, "A global assessment: can renewable energy replace fossil fuels by 2050?," *Sustainability*, vol. 14, no. 8, p. 4792, 2022, <https://doi.org/10.3390/su14084792>.
- [21] S. A. R. Khan, D. I. Godil, Z. Yu, F. Abbas, M. A. Shamim, "Adoption of renewable energy sources, low-carbon initiatives, and advanced logistical infrastructure—an step toward integrated global progress," *Sustainable Development*, vol. 30, no. 1, pp. 275-288, 2022, <https://doi.org/10.1002/sd.2243>.
- [22] N. M. Suki, N. M. Suki, A. Sharif, S. Afshan, K. Jermsittiparsert, "The role of technology innovation and renewable energy in reducing environmental degradation in Malaysia: A step towards sustainable environment," *Renewable Energy*, vol. 182, pp. 245-253, 2022, <https://doi.org/10.1016/j.renene.2021.10.007>.
- [23] Y. Chen, J. Xu, J. Wang, P. D. Lund, D. Wang, "Configuration optimization and selection of a photovoltaic-gas integrated energy system considering renewable energy penetration in power grid," *Energy Conversion and Management*, vol. 254, p. 115260, 2022, <https://doi.org/10.1016/j.enconman.2022.115260>.
- [24] X. Qi, J. Wang, G. Królczyk, P. Gardoni, Z. Li, "Sustainability analysis of a hybrid renewable power system with battery storage for islands application," *Journal of Energy Storage*, vol. 50, p. 104682, 2022, <https://doi.org/10.1016/j.est.2022.104682>.
- [25] V. Kumar, A. K. Kaushik, "Solar rooftop adoption among Indian households: a structural equation modeling analysis," *Journal of Social Marketing*, vol. 12, no. 4, pp. 513-533, 2022, <https://doi.org/10.1108/JSOCM-07-2021-0170>.
- [26] S. D. Ahmed, F. S. M. Al-Ismael, M. Shafiqullah, F. A. Al-Sulaiman and I. M. El-Amin, "Grid Integration Challenges of Wind Energy: A Review," *IEEE Access*, vol. 8, pp. 10857-10878, 2020, <https://doi.org/10.1109/ACCESS.2020.2964896>.
- [27] Y. Wu *et al.*, "Recent progress in Biomass-derived nanoelectrocatalysts for the sustainable energy development," *Fuel*, vol. 323, p. 124349, 2022, <https://doi.org/10.1016/j.fuel.2022.124349>.
- [28] M. Milouisi, A. Pappas, A. P. Vouros, G. Mihalakakou, M. Souliotis, S. Papaefthimiou, "Evaluating the Technical and Environmental Capabilities of Geothermal Systems through Life Cycle Assessment,"

- Energies*, vol. 15, no. 15, p. 5673, 2022, <https://doi.org/10.3390/en15155673>.
- [29] Y. Song, P. Liu, R. Zhou, R. Zhu, J. Kong, "SiBNCx ceramics derived from single source polymeric precursor with controllable carbon structures for highly efficient electromagnetic wave absorption at high temperature," *Carbon*, vol. 188, pp. 12-24, 2022, <https://doi.org/10.1016/j.carbon.2021.11.051>.
- [30] Z. A. Dodaev, T. Aziz, M. S. Ali, S. Ibrahim, "Microgrid Technologies for Remote Islands of Bangladesh-A Review," *Control Systems and Optimization Letters*, vol. 2, no. 1, pp. 126-134, 2024, <https://doi.org/10.59247/csol.v2i1.86>.
- [31] A. K. Hamzat, M. I. Omisanya, A. Z. Sahin, O. R. Oyetunji, N. A. Olaitan, "Application of nanofluid in solar energy harvesting devices: A comprehensive review," *Energy Conversion and Management*, vol. 266, p. 115790, 2022, <https://doi.org/10.1016/j.enconman.2022.115790>.
- [32] R. Khan, R. Kumar, Z. Ma, "Experimental investigations on the performance characteristics of plastic surfaces for developing low flow falling film liquid desiccant regenerators," *Solar Energy*, vol. 236, pp. 356-368, 2022, <https://doi.org/10.1016/j.solener.2022.03.012>.
- [33] Y. Cao, M. S. Taslimi, S. M. Dastjerdi, P. Ahmadi, M. Ashjaee, "Design, dynamic simulation, and optimal size selection of a hybrid solar/wind and battery-based system for off-grid energy supply," *Renewable Energy*, vol. 187, pp. 1082-1099, 2022, <https://doi.org/10.1016/j.renene.2022.01.112>.
- [34] M. Mansour, I. Mansour, A. Zekry, "A reconfigurable class-F radio frequency voltage doubler from 650 MHz to 900 MHz for energy harvesting applications," *Alexandria Engineering Journal*, vol. 61, no. 10, pp. 8277-8287, 2022, <https://doi.org/10.1016/j.aej.2022.01.045>.
- [35] S. I. Salah, M. Eltaweel, C. Abeykoon, "Towards a sustainable energy future for Egypt: A systematic review of renewable energy sources, technologies, challenges, and recommendations," *Cleaner Engineering and Technology*, vol. 8, p. 100497, 2022, <https://doi.org/10.1016/j.clet.2022.100497>.
- [36] S. S. Akadiri, T. S. Adebayo, "Asymmetric nexus among financial globalization, non-renewable energy, renewable energy use, economic growth, and carbon emissions: impact on environmental sustainability targets in India," *Environmental Science and Pollution Research*, vol. 29, no. 11, pp. 16311-16323, 2022, <https://doi.org/10.1007/s11356-021-16849-0>.
- [37] L. Zhang, M. Xu, H. Chen, Y. Li, S. Chen, "Globalization, green economy and environmental challenges: state of the art review for practical implications," *Frontiers in Environmental Science*, vol. 10, p. 870271, 2022, <https://doi.org/10.3389/fenvs.2022.870271>.
- [38] A. Q. Al-Shetwi, "Sustainable development of renewable energy integrated power sector: Trends, environmental impacts, and recent challenges," *Science of The Total Environment*, vol. 822, p. 153645, 2022, <https://doi.org/10.1016/j.scitotenv.2022.153645>.
- [39] A. Qazi *et al.*, "Towards Sustainable Energy: A Systematic Review of Renewable Energy Sources, Technologies, and Public Opinions," *IEEE Access*, vol. 7, pp. 63837-63851, 2019, <https://doi.org/10.1109/ACCESS.2019.2906402>.