International Journal of Integrated Research and Practice (IJIRP)

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

Metal-Organic Frameworks (MOFs) for Clean Energy Applications

Pankaj Madhukar Mansute
Extended Essay Coordinator cum Chemistry Facilitator
Department of Chemistry
Bliss International School (IB Continuum School)

Abstract
With the increasing need for clean, sustainable and efficient energy technologies, the study of advanced materials that can help facilitate the global shift towards low-carbon energy systems has become even more urgent. Metal-Organic Frameworks (MOFs) are a novel type of porous crystalline material comprised of metal ions or clusters linked together by organic molecules. They have been found to be potentially useful for many clean energy applications. Their highly tunable pore structures, high specific surface areas, adjustable chemical compositions and functional properties provide significant opportunities for their use in energy storage, energy conversion and gas separation processes. In this paper, the potential applications of MOFs in clean energy technologies are explored with a focus on hydrogen storage, carbon dioxide capture, methane storage, electrochemical energy storage, photocatalytic applications and development of fuel cells. It examines the effects of structural change, choice of metal-nodes, linker functionalization and composite engineering on their adsorption capacity, catalytic activity, charge transfer interaction and overall operational efficiency. Additionally, the study underscores the role of MOF-based materials in advancing renewable energy integration and environmental sustainability by optimizing the use of resources and minimizing carbon emissions. Though these properties are promising the problems of moisture stability, thermal resistance, electrical conductivity, synthesis costs, and large-scale production still need to be overcome to make it widespread in industry. The paper highlights the need to build robust cost-effective and scalable MOF based system to address these limitations. It concludes that the ongoing development of materials, modelling and hybrid nanocomposites can enhance the application of MOFs in the future generation of clean energy technologies and play a significant role in global sustainable energy goals.

Keywords: Metal-Organic Frameworks (MOFs), Clean Energy, Hydrogen Storage, Carbon Capture, Renewable Energy, Energy Conversion, Photocatalysis, Sustainable Materials.

Publication History
Received: 11 September 2026**, Accepted:** 28 September 2026**, Published:** 20 October 2026

Introduction

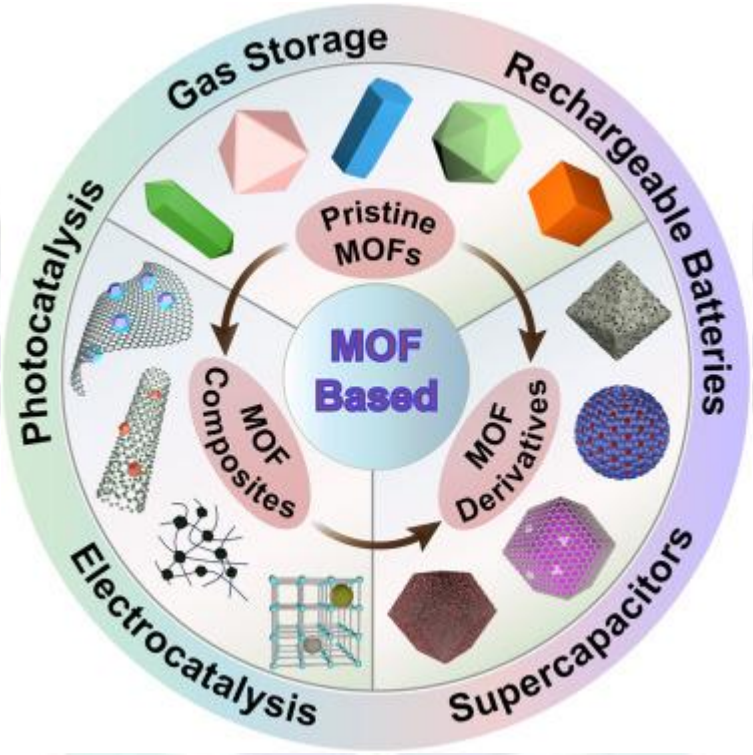
With the escalating demand for energy, rising environmental pollution and the pressing requirement of energy efficient and clean energy technologies, the global efforts have been redoubled to develop energy technologies that have low carbon emission and are sustainable. The increasing environmental pollution and urgent need to reduce the greenhouse gas emissions have given a much-boosted push to the development of sustainable and clean energy technologies all over the world. The use of conventional energy systems that heavily rely on fossil fuels, drives a great deal of climate change, air pollution, and natural resource depletion. Consequently, researchers are increasingly interested in developing novel materials that are capable of supporting renewable energy generation, efficient energy storage, hydrogen production, carbon capture and environmentally friendly fuel technologies. The uniqueness of the structure, tunable chemical properties and wide potential applications in several clean energy systems make Metal-Organic Frameworks (MOFs) one of the emerging materials that are gaining scientific interest.

Metal-Organic Framework is a crystalline porous material in which the metal ions or metal-containing clusters are coordinated with the organic ligands. They possess highly ordered structures which produce interconnected

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

pores and large surface areas within the structure, which is ideal for adsorption, separation and storage of various molecules. MOFs are flexible in structure design, as the metal centres, organic ligands, pore sizes and functional groups can be tailored to the needs of the specific application under consideration. This structural flexibility enables the creation of materials with enhanced selectivity, adsorption, catalytic and chemical efficiency.



Source: *https://www.sciencedirect.com/science/article/pii/S2451929423004643*

MOFs can be applied in various important clean energy applications. Their porous structures can be used to catalyse hydrogen adsorption and offer potential for hydrogen storage systems which are low in weight and efficient. Selected MOF structures can selectively capture the carbon dioxide from the industrial emissions and other gas mixtures, helping in carbon management and reduction. Their use in photocatalysis and electrocatalysis also has great importance, especially for hydrogen production, oxygen evolution, oxygen reduction, and carbon dioxide conversion. Additionally, the structural characteristics of these materials have been explored for their potential applications in electrochemical energy storage devices, such as batteries and supercapacitors, where they can contribute to the improvement of ion transport and electrochemical reactions (Abdelkareem et al., 2024; Zhu et al., 2024).

Thermal treatment, chemical modification, and controlled structural transformation are other key steps that have led to the transformation of MOFs into functional materials. MOFs can retain some of their original framework structures and gain enhanced electrical conductivity and catalytic activity in the porous carbon, metal oxides, metal sulfides and metal–carbon composites. These materials have been the subject of interest for electrodes in energy storage, fuel cells, and renewable energy conversion systems. The flexibility of modifying the original system and its products opens the door to designing multifunctional materials for various energy needs (Zhang et al., 2024).

While MOFs have exciting properties, there are scientific and engineering challenges to harness them for clean

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

energy technologies. Some MOFs have poor electrical conductivity, moisture absorption, or poor chemical stability under extreme working conditions. Moreover, the selected organic linkers used are expensive, and the synthesis is tedious and complex, with MOF powders not always scalable to commercial devices. To overcome these limitations, additional studies on economical synthesis, structural optimization, conductive improvement, long-term stability and environmental-friendly materials' production are needed. New reviews also highlight the need to link laboratory-level material properties with real device needs or real industrial applications.

The current research paper aims to explore the capabilities of Metal-Organic Frameworks as promising materials for clean energy applications. It highlights the basic structural features, synthesis strategies, functional properties and applications of these materials in the fields of hydrogen storage, carbon capture, renewable energy conversion, photocatalysis, electrocatalysis, and electrochemical energy storage. The study also examines the significant technological challenges they face and investigates potential solutions to enhance their stability, efficiency, economic viability and scalability.

The progress of MOF-based materials is a promising avenue for materials science and sustainable energy studies. Their flexible architecture and versatility could be used to solve multiple problems related to the generation, storage and use of clean energy. Further research, development and implementation of their design may help shape the creation of more efficient energy technologies and as part of the overall shift in energy transition towards a low-carbon and environmentally sustainable future.

Background of the Study

With the rising demand for energy from all parts of the world and the exhaustion of conventional fossil fuel resources, and environmental concerns, sustainable and environmentally friendly energy technologies have become more important. As long as coal, petroleum and natural gas rely on, these are responsible for a major share of greenhouse gas emissions, climate change and atmospheric pollution. Researchers and policymakers are therefore looking for new materials and novel technologies to help the advancement of clean energy sources, energy conversion and energy storage. In the context, the research and development of high-performance functional material has become an important research area.

Metal-Organic Frameworks (MOFs) are a promising class of advanced porous materials that show great potential for applications in clean energy. These materials are crystals that are structurally organized and interconnected through the coordination of metal ions or metal clusters by organic linkers, forming highly porous structures. They have unique structure features such as high specific surface area, tunable pore size, tunable chemical composition and various structural configurations. The properties of MOFs are especially promising in applications involving gas adsorption, molecular separation, catalysis and electrochemical energy systems.

MOFs can capture, store and selectively separate gases like hydrogen, carbon dioxide, and methane, one of the significant advantages. Hydrogen is considered a promising clean energy carrier because it can be used in fuel cells to create electricity and water is the major direct product of the reaction. Efficient storage and transport of hydrogen are still significant technological challenges, however. MOFs can overcome these limitations by utilizing their porous structure that could allow hydrogen adsorption and storage under certain operating conditions. Likewise, their ability to selectively adsorb, they can be useful in capturing, separating and future technologies for carbon management, which is significant in reducing the amount of carbon dioxide from industrial emissions.

Besides gas storage and separation, MOFs have been the subject of considerable interest in electrochemical energy storage technology such as lithium-ion batteries, sodium-ion batteries, supercapacitors and hybrid energy storage devices. The porous structure offers exposed reaction sites for electrochemical reactions and can

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

enable the transport of ions in electroactive materials. Moreover, MOFs can be chemically functionalized, composited and converted to form conductive carbon materials, metal oxides and other functional composites. These changes can be exploited to enhance the electrical conductivity, structural stability, charge transfer characteristics and electrochemical performance. Their potential in the field of developing new generation energy storage systems with high efficiency and durability has been highlighted by recent research (Sandhu et al., 2024).

The other application area is renewable energy conversion including photocatalysis and electrocatalysis. MOFs can also contain different metal centres and organic functional groups that can be designed with a specific catalytic or electronic property. The selected MOF structures and derivatives are studied with regard to photocatalytic hydrogen production and carbon dioxide reduction in solar energy conversion. These processes can convert solar energy to chemical energy, and help produce cleaner fuels and utilise carbon. Similarly, MOF-based catalysts are being investigated for various electrochemical reactions that are critical to the operation of fuel cells, such as hydrogen evolution, oxygen evolution, oxygen reduction, and water electrolysis, which are important in the areas of clean energy (Abdelkareem et al., 2024).

MOFs also have relevance to carbon capture/ utilization technologies because of their versatility. They have a variable pore structure and surface chemistry that allows materials to be created that will selectively attract carbon dioxide from industrial gas streams. The captured CO2 can then be used as a feedstock for catalytic conversion to useful chemicals and fuels. The use of MOFs in CCS systems is therefore an interesting research direction to consider in order to achieve lower environmental impacts for energy intensive industrial processes. But their effectiveness in practice will rely on their moisture resistance, adsorption selectivity, regeneration requirements, and long-term structural stability.

However, due to several scientific and technological challenges, the commercialization of MOFs in clean energy systems is hindered. Some MOF structures are not very conductive, poorly resistant to harsh operating conditions, and also have lower mechanical strength. Furthermore, high-quality MOFs can be synthesized using the expensive precursors, sophisticated processing methods, and high amount of energy. There are also challenges to the large-scale manufacturing, material recovery, recyclability and long life cycles of performance. Thus, the recent research is concentrated on the development of stable, conductive, economic and environmentally sustainable materials based on MOF.

The recent advances in the study of MOF highlight the value of experimental study and modeling as well as advanced materials characterization. The computational methods can help in predicting the structures of pores, gas adsorption behaviour and eventual material performance prior to experimental synthesis. Likewise, the design of MOF composites and their derivatives offers a chance to address some of the drawbacks of the traditional MOF structures. In the field of carbon capture, gas separation and energy applications, computational discovery has emerged as a key method in the identification of MOF adsorbents, as highlighted by the recent research published in Nature Energy (Moghadam et al., 2024).

In this context, the present study, "Metal-Organic Frameworks (MOFs) for Clean Energy Applications", is aimed at understanding the structure, functionality and technological applications of MOFs in emerging clean energy systems. It outlines their potential applications for hydrogen storage, carbon dioxide capture, electrochemical energy storage, photocatalytic hydrogen production and catalytic energy conversion. The study also takes into account the restrictions of material synthesis, stability, conductivity, scalability and economic feasibility. The study seeks to gain a deeper understanding of how MOF materials can be utilized in sustainable energy technologies and contribute to the shift towards a more sustainable and efficient energy future by exploring these aspects.

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

Justification

With the world's ever increasing energy demands, escalating environmental issues, and a pressing need to decrease carbon emissions, the need for developing advanced materials for clean and sustainable energy technologies is becoming very strong. Even with conventional energy systems, the issues of resource scarcity, environmental pollution, energy inefficiency and dependence on fossil fuels remain. Metal-Organic Frameworks (MOFs) are an emerging class of advanced materials with unique structural features such as high surface area, tunable pore size, adjustable chemical composition and various functional properties that make them attractive materials for these applications. The motivation to conduct this study is given by the fact that MOFs have great promise to overcome several drawbacks from current clean energy technologies. The porous structures and the tunable chemical properties allow them to be utilized in various applications such as hydrogen storage, carbon dioxide capture, methane storage, gas separation, photocatalytic hydrogen production, and electrochemical energy storage. Moreover, the possibility of tuning the metal centres and the organic linkers enables the development of even more selective materials, with higher adsorption capacities, catalytic activity and energy efficiency. Although MOF studies have advanced significantly, there are still many challenges to be addressed, such as the durability of the structure over time, its resistance to water, temperature, electrical conductivity, manufacturing cost and scaling. All these constraints result in a difference between the laboratory development of materials and their real industrial use. A systematic study of the properties of MOFs, synthesis method, functional modification and energy-related applications is therefore necessary. The study is also timely with the growing significance of the application of new nanomaterials for renewable energy systems and low carbon technologies. The connection of MOF structure design with energy performance may be helpful to design efficient, economically feasible and environmentally friendly energy solutions. Therefore, this research seeks to investigate the possibility of MOFs for clean energy applications, discuss about the technological advancements and challenges of MOFs and potential future research avenues. The results will help advance scientific knowledge and be the backbone for future material innovation, sustainable energy development, and advancement of environmentally responsible energy materials.

Objectives of the Study

1. To examine the structural properties, chemical composition, porosity and functional properties of Metal-Organic Frameworks (MOFs) for clean energy applications.
2. To investigate the application of MOFs for hydrogen storage, carbon dioxide capture and other new clean energy technologies.
3. To study the scope of MOF based materials in the field of energy storage systems such as batteries, supercapacitors and fuel-cells.
4. To evaluate the effectiveness of MOFs as catalysts and photocatalysts in renewable energy conversion processes such as carbon dioxide reduction and hydrogen production.
5. To determine how pore size, surface area, metal centres and organic linkers affect the energy-related performance of MOF materials.

Literature Review

With the increased need for sustainable energy sources and the pressing need to decrease carbon emissions, researchers have turned their attention to new materials that can aid in clean energy production, storage, and conversion. The unique characteristics of Metal-Organic Frameworks (MOFs), including their porous structure, high surface area, tunable pore size, and chemical versatility have garnered significant scientific interest. Metal-

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

organic frameworks with extended porous structures have been demonstrated by Yaghi et al. (1995), laying an important groundwork for the following studies to develop functional applications of MOFs. Porous coordination solids (PCS) and their structure and applications were discussed by Férey (2008) and their relevance to gas adsorption/separation and catalysis was outlined. Kitagawa et al. (2004) talked about the porous coordination polymers and their potential use in molecular recognition, gas storage and gas separation technologies. Murray et al. (2009) gave a comprehensive knowledge about the structural variety and functional properties of MOFs and discussed their applications in various technological areas. Li et al. (2020) reviewed the use of MOFs in clean energy technologies such as hydrogen and methane storage, solar energy conversion, and electrochemical energy storage, and showed that MOFs can play a role in sustainable energy systems. Furukawa et al. focused on the development of porous coordination networks and emphasized that it is important to control framework structures to achieve better gas adsorption and separation performance (2013). Sumida et al. (2012) studied the use of MOFs in CO2 capture and the possibility of using them for selective gas adsorption for greenhouse gas (GHG) emission reduction. To discuss the effect of framework structure and functional groups on the adsorption of carbon dioxide, Caskey et al. (2008) studied this. In the context of hydrogen energy, Rowsell and Yaghi (2005) noted the potential of nanoporous materials for hydrogen storage and highlighted the role of surface area, pore structure and adsorption properties. Murray et al. (2009) also pointed to the potential of the design of MOFs for gas storage in energy applications. Choi et al. (2009) reviewed the potential of metal-organic frameworks as electrode materials and its suitability for energy storage system in electrochemical energy technologies. Xia et al. (2015) reviewed MOF derived nanostructures for electrochemical energy storage and conversion with special focus on the benefits of MOF-derived high performance electrodes and catalysts. Wang et al. (2017) studied the preparation of MOF materials for energy storage and conversion with special emphasis on batteries, supercapacitors and electrocatalytic systems. Sun, et al. (2016) studied the possibility of applications of MOF-based materials in photocatalytic field, and the capability of supporting chemical reactions under the influence of the light. Gascon et al. (2014) have studied the catalytic behaviour of the metal-organic frameworks and introduced the role of active sites, pore accessibility and structural stability in improving catalytic behaviour. Kreno and coworkers (2012) summarized the functional applications of MOFs, and showcased their versatility in chemical sensing, molecular recognition and other advanced technologies. Furukawa et al. (2013) also highlighted the importance of rational framework design for the development of materials that are better at adsorption and separation. Recently, Abdelkareem et al. (2024) summarized the developments of MOFs and derivatives as energy conversion devices, such as electrochemical technologies, production of hydrogen by photocatalysis, and reduction of CO2. Sher et al. (2024) discussed advanced MOFs for carbon capture, energy storage and environmental photocatalysis, demonstrating their multifunctional capabilities and the significance of optimizing materials. In recent years, efforts have been made to enhance the stability, conductivity, catalytic activity and scalability of MOF materials, which are the critical limitations in the practical application of MOFs. Overall it can be concluded that the existing literature is evidence that MOFs are an interesting material for application in clean energy, especially hydrogen storage, carbon capture, production of renewable fuels, electrochemical energy storage, and photocatalysis. But there are still issues such as production costs, structural durability, water sensitivity, electrical conductivity and scale-up. More studies are needed to make MOF-based materials more economically viable, environmentally friendly, and high performance to effective contribute to the global transition towards clean and renewable energy systems.

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

Results and Discussion

In the present study, the advanced functional materials, Metal-Organic Frameworks (MOFs), have been reviewed with a special focus on their application in clean energy storage systems, such as hydrogen storage, CO2 capture, methane storage, photocatalytic hydrogen production and electrochemical energy storage. This analysis is conducted by surveying the present scientific publications and published data related to the structural features, adsorption features, catalytic properties and energy-related performance of MOF-based materials. The results show that the MOFs have significant merits due to the ability to incorporate various metal centres, adjust pore size and have crystalline structures and high surface area. This renders them potential options for tackling significant issues related to the implementation of renewable energy and environmental sustainability.

1. Structural Characteristics and Energy Storage Potential of MOFs

The results show that the flexibility of the structure is an important factor in the ability of MOFs to be useful for clean energy applications. They have a porous structure that has a large number of accessible adsorption sites and the varying metal nodes and organic linkers can be used to modify the physical and chemical properties. MOF families exhibit different performances based on their pore volume, surface area, thermal stability, and chemical composition. MOF-5, HKUST-1, UiO-66 and ZIF-8 are some of the materials that have gained significant research interest due to their unique structural properties and gas storage and separation applications.

Table 1: Structural characteristics and potential energy applications of selected MOFs

MOF material	Important structural characteristics	Potential clean energy application
MOF-5	High porosity and large internal surface area	Hydrogen and methane storage
HKUST-1	Copper-based framework with accessible metal sites	Gas adsorption and carbon capture
UiO-66	High chemical and thermal stability	CO_2 capture and gas separation
ZIF-8	Adjustable microporous structure and chemical flexibility	Gas separation and hydrogen-related applications
MIL-101	Large pore volume and accessible internal surface	Hydrogen storage and CO_2 adsorption
MOF-74	Open metal sites and strong gas interaction	CO_2 capture and gas adsorption

Source: Compiled from published literature on MOF structures and their energy-related applications.

The comparative analysis in Table 1 showed that the individual MOF materials have different functional advantages. The porous structures of MOF-5 and MIL-101 make them interesting in gas-storage studies, while the accessible metal centres of HKUST-1 and MOF-74 can enhance interactions with specific molecules in the gaseous state. UiO-66 is of special interest for applications where a higher structural stability is desired in harsh operating environments. The microporous framework of ZIF-8 provides opportunities for selective gas separation. The performance of these materials, however, is dependent on the operating temperature, pressure, activation procedures, moisture exposure and the presence of competing gas molecules. So it is not only important to use surface area to pick an appropriate MOF but also to consider practical operating conditions in

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

addition to its adsorption capacity.

2. MOFs for Hydrogen Storage and Carbon Dioxide Capture

Two key research areas of sustainable energy technologies are hydrogen storage and carbon dioxide capture. The use of hydrogen as an energy carrier is an emerging subject of interest with respect to clean energy and CO_2 capture is regarded as a key method to reduce CO_2 emissions from energy and industrial production. According to the literature reviewed, both applications could benefit from MOFs and their tunable pore structures and chemical functionality. Hydrogen adsorption is typically by physical interaction between the molecules of hydrogen and the inside surface of porous materials. This means that surface area, pore size, temperature and operating pressure all affect the adsorption capacity. Conversely, the incorporation of appropriate functional groups, open metal sites and components containing nitrogen can facilitate the adsorption of CO_2.

Table 2: Major clean energy applications of MOFs and their functional advantages

Application	Relevant MOF characteristics	xpected functional benef	Major research challenge
Hydrogen storage	High surface area and microporosity	Increased hydrogen adsorption	Low adsorption at ambient temperature
CO_2 capture	Open metal sites and functionalized pores	Improved CO_2 selectivity and adsorption	Moisture sensitivity and regeneration cost
Methane storage	Suitable pore volume and adsorption sites	Enhanced methane storage potential	Volumetric storage limitations
Photocatalytic hydrogen production	Light-responsive metal centres and linkers	Solar-driven hydrogen generation	Charge recombination and stability
Electrochemical energy storage	Conductive networks and redox-active centres	Improved charge-storage characteristics	Low intrinsic electrical conductivity

Source: Author's synthesis based on published MOF research.

Table 2 illustrates the various clean energy technologies where MOFs can be used in a multifunctional manner. The study of hydrogen storage shows that it is vital to optimize the size or shape of the pores and favourability of the adsorption environment for enhancing the performance of hydrogen storage under practical conditions. However, many conventional MOFs have better adsorption properties for hydrogen at cryogenic temperatures which poses some problems for practical application. Likewise, the chemical modification of MOF structures to optimize the adsorption selectivity and minimize the effect of moisture is also advantageous for CO_2 capture applications. The interactions between CO2 molecules and functionalized MOFs can be improved, but with the consideration of regeneration needs and long-term stability. The comparison also shows that the structural and chemical properties are different for methane storage, photocatalytic hydrogen generation and electrochemical energy storage. Therefore, for different energy applications, the composition of the MOF could be different from one application to another to achieve optimal performance.

3. Photocatalytic and Electrochemical Applications of MOFs

The results also suggest that MOFs can be used for solar energy conversion and electrochemical energy storage. They can be used to absorb light and catalyze reactions because their clusters are made of metals and their linkers are made of organic compounds. Solar-driven water-splitting processes are one way that MOFs could be involved in hydrogen production in photocatalytic systems. They are effective when light is absorbed,

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

charges separate, electron transfer is efficient and the catalytic sites are accessible. In a number of MOF-based photocatalytic systems, however, the limitation of electrical conductivity and the fast electron-hole recombination are still significant issues.

For electrochemical energy applications, MOFs are studied as electrode materials, precursors for porous carbon and metal-based composites, and catalytic supports. They have ordered structures which allow the incorporation of electrochemically active components in a porous network. The carbonized MOF derivatives can exhibit better electrical conductivity and better accessibility of active sites. These properties can be of interest to batteries, supercapacitors, and fuel-cell technologies. However, it is still a desideratum to maintain the structural integrity, control material degradation and to ensure effective charge transport for practical applications.

Table 3: Performance-related parameters, advantages, and limitations of MOFs in clean energy technologies

Performance parameter	Potential advantage of MOFs	Existing limitation	Suggested improvement
Surface area	Provides numerous adsorption sites	High surface area alone does not ensure high storage capacity	Optimize pore dimensions and accessibility
Gas adsorption	Supports hydrogen, methane, and CO_2 adsorption	Performance may decrease under practical operating conditions	Introduce functional groups and suitable metal centres
Thermal stability	Selected MOFs maintain framework integrity at elevated temperatures	Some frameworks undergo structural degradation	Develop thermally stable metal-linker combination
Photocatalytic activity	Offers tunable light-responsive structures	Charge recombination reduces catalytic efficiency	Integrate semiconductor and co-catalyst components
Electrical conductivity	Supports the development of electrochemical materials	Many pristine MOFs have poor conductivity	Develop conductive MOFs and carbon-based composites
Chemical durability	Enables selective adsorption and catalytic applications	Moisture and chemical exposure may affect stability	Employ water-resistant frameworks and protective modifications
Scalability	Offers opportunities for customized material synthesis	Complex synthesis and production costs	Develop economical and scalable manufacturing method

Source: Author's synthesis based on comparative analysis of published research.

As shown in Table 3, the effectiveness of MOFs in practice relies on multiple material properties that are interdependent. However, the ability of pores to access the surface of the material, the adsorption enthalpy, the selectivity of the material, and the ease of regeneration determine the utility of the material. In a similar manner, the photocatalytic performance can be enhanced with efficient charge separation and proper catalytic sites, and the electrochemical applications can be enhanced by efficient electrical conductivity and structural stability. The results indicate the potential to enhance the functional characteristics of MOFs through composite

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

formation, functionalization control, modification of the metal sites, and post-synthetic modification. However, these changes need to be carefully optimized as excessive modification of structure may decrease porosity and/or impact the original structure architecture.

4. Overall Discussion and Research Implications

Overall, it is established that Metal-Organic Frameworks are a promising class of engineered materials for helping to make the transition towards sustainable energy systems. Their flexibility opens up the potential to tailor them to be used in application-specific materials for gas storage, carbon capture, solar fuel production, and electrochemical energy technologies. The comparative results show that the most important is the tunability of the pore size, the active metal centres, and the surface functionality of MOFs, making it obtainable to modify it based on the desired energy requirements.

A successful commercialization of MOF-based technologies from an industrial point of view will require more than laboratory scale adsorption and/or catalytic performance. Before going to large-scale applications, production costs of the material, the reproducibility of synthesis, mechanical strength, moisture resistance, regeneration energy, and long-term operating stability must be assessed. Moreover, it is required to conduct environmental assessment for metal precursors, organic linkers, solvents, and disposal of materials to assess the overall sustainability of MOF technologies.

Yet another important observation is that the role of hybrid MOF-based materials is increasingly becoming important. The incorporation of graphene, carbon nanotubes, metal oxides, and semiconductor materials with MOFs can enhance their conductivity, catalytic properties, and stability. These combined material systems may enable enhanced hydrogen production, carbon capture and energy storage systems. Thus, future studies should focus on multifunctional MOF composites, low cost synthesis methods, and testing these MOFs at pilot scale in real environmental and industrial conditions.

Overall, the findings suggest that MOFs could play a significant role in the advancement of clean energy development, as they have unique properties and structures that make them highly versatile and effective. While issues of stability, conductivity, production costs and scale are still to be addressed, ongoing developments of new materials and composites could further establish their practical relevance. The final move from laboratory research to industrial use will necessitate a systematic performance evaluation, life cycle assessment and the development of economically viable manufacturing processes.

Conclusion

Metal-Organic Frameworks (MOFs) are highly porous, highly surface area, tunable structural properties, versatile chemical compositions of advanced materials that have made them attractive materials for clean energy applications. They have unique properties that can be used to solve a number of energy challenges including hydrogen storage, CO2 capture, gas separation, electrocatalysis, photocatalysis and energy conversion. Apparatus to tune their metal centres, organic linkers, pore size and functional groups allows for the creation of MOF properties and performance tailored to a specific application. In addition, the use of MOFs in combination with conductive materials, nanoparticles, polymers and other functional nanostructures has opened up new perspectives for the use of MOFs in renewable energy technologies and electrochemical energy storage systems. In spite of these benefits, their usage in the industry is still hindered by some disadvantages, including moisture sensitivity, low electrical conductivity, structural instability under harsh operating conditions, high production cost and large-scale synthesis issues. The next steps are therefore to develop cost-effective synthesis methods, to increase chemical and thermal stability, to increase charge transfer capabilities, and to find environmentally friendly manufacturing processes. There is also a need to pay more attention to the

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

long-term performance evaluation and to the implementation of MOF based materials with the actual infrastructure. In total, as the materials continue to be advanced with material engineering, nanotechnology, and computational design, MOFs may prove to be commercially viable materials in the future. Their future development has great potential to develop renewable energy utilization, lower carbon emissions, increase energy efficiency, and aid in transition towards cleaner and more sustainable and resource efficient global energy system.

References

1. Abdelkareem, M. A., Abbas, Q., Sayed, E. T., Shehata, N., Parambath, J. B. M., Alami, A. H., & Olabi, A. G. (2024). Recent advances on metal-organic frameworks (MOFs) and their applications in energy conversion devices: Comprehensive review. *Energy, 299*, Article 131127. https://doi.org/10.1016/j.energy.2024.131127
2. Bae, Y. S., & Snurr, R. Q. (2011). Development and evaluation of porous materials for carbon dioxide separation and capture. *Angewandte Chemie International Edition, 50*(49), 11586–11596. https://doi.org/10.1002/anie.201101891
3. Caskey, S. R., Wong-Foy, A. G., & Matzger, A. J. (2008). Dramatic tuning of carbon dioxide uptake via metal substitution in a coordination polymer with cylindrical pores. *Journal of the American Chemical Society, 130*(33), 10870–10871. https://doi.org/10.1021/ja8036096
4. Choi, K. M., Jeong, H. M., Park, J. H., Zhang, Y. B., Kang, J. K., & Yaghi, O. M. (2014). Supercapacitors of nanocrystalline metal-organic frameworks. *ACS Nano, 8*(7), 7451–7457. https://doi.org/10.1021/nn5027092
5. D'Alessandro, D. M., Smit, B., & Long, J. R. (2010). Carbon dioxide capture: Prospects for new materials. *Angewandte Chemie International Edition, 49*(35), 6058–6082. https://doi.org/10.1002/anie.201000431
6. Dhakshinamoorthy, A., & García, H. (2012). Catalysis by metal-organic frameworks. *Chemical Society Reviews, 41*, 5262–5284. https://doi.org/10.1039/C2CS35047D
7. Dincă, M., & Long, J. R. (2008). Hydrogen storage in microporous metal-organic frameworks with exposed metal sites. *Angewandte Chemie International Edition, 47*(36), 6766–6779. https://doi.org/10.1002/anie.200801163
8. Férey, G. (2008). Hybrid porous solids: Past, present, future. *Chemical Society Reviews, 37*, 191–214. https://doi.org/10.1039/B618320B
9. Furukawa, H., Cordova, K. E., O'Keeffe, M., & Yaghi, O. M. (2013). The chemistry and applications of metal-organic frameworks. *Science, 341*(6149), Article 1230444. https://doi.org/10.1126/science.1230444
10. Kreno, L. E., Leong, K., Farha, O. K., Allendorf, M., Van Duyne, R. P., & Hupp, J. T. (2012). Metal-organic framework materials as chemical sensors. *Chemical Reviews, 112*(2), 1105–1125. https://doi.org/10.1021/cr200324t
11. Li, J. R., Kuppler, R. J., & Zhou, H. C. (2009). Selective gas adsorption and separation in metal-organic frameworks. *Chemical Society Reviews, 38*, 1477–1504. https://doi.org/10.1039/B802426J
12. Li, S. L., & Xu, Q. (2013). Metal-organic frameworks as platforms for clean energy. *Energy & Environmental Science, 6*, 1656–1683. https://doi.org/10.1039/C3EE40507A
13. Li, X., Yang, X., Xue, H., Pang, H., & Xu, Q. (2020). Metal-organic frameworks as a platform for clean energy applications. *EnergyChem, 2*(2), Article 100027. https://doi.org/10.1016/j.enchem.2020.100027
14. Lin, Y., Kong, C., & Chen, L. (2012). Direct synthesis of amine-functionalized MIL-101(Cr) nanoparticles and their application for CO_2 capture. *RSC Advances, 2*, 6417–6419.

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

Vol 2, Issue 10, October 2026, Page: 39-51 ISSN: 3107-5037

15. Long, J. R., & Yaghi, O. M. (2009). The pervasive chemistry of metal-organic frameworks. *Chemical Society Reviews, 38*, 1213–1214.
16. Lu, W., Wei, Z., Gu, Z. Y., Liu, T. F., Park, J., Park, J., Tian, J., Zhang, M., Zhang, Q., Gentle, T., Bosch, M., & Zhou, H. C. (2014). Tuning the structure and function of metal-organic frameworks via linker design. *Chemical Society Reviews, 43*, 5561–5593.
17. Ma, S., & Zhou, H. C. (2010). Gas storage in porous metal-organic frameworks for clean energy applications. *Chemical Communications, 46*, 44–53.
18. Murray, L. J., Dincă, M., & Long, J. R. (2009). Hydrogen storage in metal-organic frameworks. *Chemical Society Reviews, 38*, 1294–1314. https://doi.org/10.1039/B802256A
19. Rowsell, J. L. C., & Yaghi, O. M. (2005). Strategies for hydrogen storage in metal-organic frameworks. *Angewandte Chemie International Edition, 44*(30), 4670–4679. https://doi.org/10.1002/anie.200462786
20. Sheberla, D., Sun, L., Blood-Forsythe, M. A., Er, S., Wade, C. R., Brozek, C. K., Aspuru-Guzik, A., & Dincă, M. (2014). High electrical conductivity in Ni_3(2,3,6,7,10,11-hexaiminotriphenylene)$_2$, a semiconducting metal-organic graphene analogue. *Journal of the American Chemical Society, 136*(25), 8859–8862. https://doi.org/10.1021/ja502765n
21. Sumida, K., Rogow, D. L., Mason, J. A., McDonald, T. M., Bloch, E. D., Herm, Z. R., Bae, T. H., & Long, J. R. (2012). Carbon dioxide capture in metal-organic frameworks. *Chemical Reviews, 112*(2), 724–781. https://doi.org/10.1021/cr2003272
22. Wang, C., Liu, D., & Lin, W. (2013). Metal-organic frameworks as a tunable platform for designing functional molecular materials. *Journal of the American Chemical Society, 135*(36), 13222–13234.
23. Wang, H., Yuan, X., Wu, Y., Zeng, G., Chen, X., Leng, L., & Li, H. (2015). Synthesis and applications of novel graphitic carbon nitride/metal-organic frameworks mesoporous photocatalyst for environmental remediation: A review. *Applied Catalysis B: Environmental, 174–175*, 445–454.
24. Wang, L., Han, Y., Feng, X., Zhou, J., Qi, P., & Wang, B. (2016). Metal-organic frameworks for energy storage and conversion. *Coordination Chemistry Reviews, 307*, 361–381.
25. Wang, X., Maeda, K., Thomas, A., Takanabe, K., Xin, G., Carlsson, J. M., Domen, K., & Antonietti, M. (2009). A metal-free polymeric photocatalyst for hydrogen production from water under visible light. *Nature Materials, 8*, 76–80. https://doi.org/10.1038/nmat2317
26. Zhang, H., Nai, J., Yu, L., & Lou, X. W. (2017). Metal-organic-framework-based materials as platforms for renewable energy and environmental applications. *Joule, 1*(1), 77–107. https://doi.org/10.1016/j.joule.2017.08.008
27. Zhang, Q., Uchaker, E., Candelaria, S. L., & Cao, G. (2013). Nanomaterials for energy conversion and storage. *Chemical Society Reviews, 42*(7), 3127–3171. https://doi.org/10.1039/C3CS00009E
28. Zhao, S., Wang, Y., Dong, J., He, C. T., Yin, H., An, P., Zhao, K., Zhang, X., Gao, C., Zhang, L., Lv, J., Wang, J., Zhang, J., Khattak, A. M., Khan, N. A., Wei, Z., Zhang, J., Liu, S., Zhao, H., & Tang, Z. (2016). Ultrathin metal-organic framework nanosheets for electrocatalytic oxygen evolution. *Nature Energy, 1*, Article 16184. https://doi.org/10.1038/nenergy.2016.184
29. Zhou, H. C., Long, J. R., & Yaghi, O. M. (2012). Introduction to metal-organic frameworks. *Chemical Reviews, 112*(2), 673–674. https://doi.org/10.1021/cr300014x
30. Zhou, H. C., & Kitagawa, S. (2014). Metal-organic frameworks (MOFs). *Chemical Society Reviews, 43*, 5415–5418.

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.

International Journal of Integrated Research and Practice (IJIRP)

Vol 2, Issue 10, October 2026, Page: 39-51

ISSN: 3107-5037

Open Access (BOAI Compliant) | © 2026 Author(s). Published by IJIRP under Creative Commons CC BY-NC 4.0 License (https://creativecommons.org/licenses/by-nc/4.0/). Official signatory to BOAI.