DOI: 10.54254/2755-2721/70/20241008

Research on integrating hydrogen energy storage with solar and wind power for Net-Zero energy buildings

Taojun Sun

Nanjing University of Information Science & Technology, Nanjing, Jiangsu, China, 210044

staojun@163.com

Abstract. Net Zero Energy Buildings (NZEBs) are evolving as a pillar concept as it fits in with the global Net Zero Energy Target strategy and the decarbonisation strategy of the building sector, which has been developed in response to climate change. The shift from existing building types to Net Zero Energy Buildings is a predominant trend. Net Zero Energy Buildings. This review paper explores the use of solar and wind energy as new sources of energy to generate electricity and hydrogen to store electricity as revolutionary solutions to achieve Net Zero Energy Buildings. It provides insights into the technological advances and challenges associated with hydrogen energy systems, including electrolyser efficiency, storage solution resolution, and fuel cell innovation. In addition, the paper highlights the key role of hydrogen in addressing the intermittency of renewable energy generation and enhancing the resilience and sustainability of Net Zero Energy Buildings systems. The potential for scaling up and commercialising hydrogen storage in the building sector is assessed through a detailed examination of current technologies, performance evaluations, and case studies. Despite facing a number of barriers from technical, economic, and policy perspectives, this paper argues that hydrogen storage can make a significant contribution to the decarbonisation of the built environment through continued technological innovation and framework improvement.

Keywords: Hydrogen Energy Storage, Net-Zero Energy Buildings, Renewable Energy Integration, Electrolyzer Technology, Energy Resilience

1. Introduction

In the global building sector, Net Zero Energy Buildings (NZEBs) have evolved as a pillar concept as it is in line with sustainability and decarbonisation strategies. The transition from existing building types to NZEBs is a major trend. This is critical to the global strategy to combat climate change and decarbonise the building sector, which is a significant contributor to global greenhouse gas emissions. The International Energy Agency (IEA) has emphasised the role of NZEBs in addressing global energy and climate issues. It highlights that by 2050, NZEBs have the potential to reduce emissions from the building sector by up to 50% compared to 2010 levels [1]. NZEBs are designed to rely heavily on renewable energy sources - generating as much or more energy than is consumed in a year. Of these, solar and wind stand out for their ubiquity, high energy yield and ability to significantly reduce carbon emissions. By 2020, solar and wind combined will account for about 10% of global electricity generation, a figure that is expected to rise significantly as these technologies become more efficient and cheaper [2]. Studies have estimated that solar alone has the potential to provide more than 1,000 times the total global energy demand, and wind could theoretically provide 40 times the current global electricity use, suggesting that they have a crucial role to play in achieving net-zero energy goals [3,4].

Despite their enormous potential, the intermittent nature of solar and wind energy poses considerable challenges. Solar photovoltaic (PV) systems have average efficiencies of 15-20%, while wind turbine efficiencies vary depending on location and design, but are typically only 20-50% of the theoretical maximum output [5]. In addition, on cloudy or windless days, the generation of electricity from these sources can drop dramatically compared to weekdays, thus failing to meet the energy needs of the NZEBs. This intermittency can lead to unmet energy supply needs, thus undermining the reliability and stability required by NZEBs.

Hydrogen storage is a viable solution to the problem of intermittency. It stores excess power generation and releases it when needed. Modern electrolysers, especially those utilising polymer electrolyte membrane (PEM) technology, have demonstrated efficiencies of up to 70-80%, allowing for a relatively efficient storage process [6,7]. Additionally, overall round-trip efficiencies of 30% to 50% can be achieved when converting stored hydrogen to electricity via fuel cells, making them a competitive option for energy storage and supply at times of peak demand or low supply [8].

In order to integrate hydrogen storage and renewable energy generation systems into NZEB, the balance between energy production, storage capacity and energy demand needs to be carefully considered. Studies have shown that by using an integrated renewable energy generation and hydrogen storage system, NZEB can achieve energy savings of up to 30%-40% per year compared to conventional energy systems [9,10]. and reduce dependence on the grid by 70% [11]. In addition, the use of advanced hydrogen storage technologies enhances the resilience and self-cycling capabilities of the NZEB, making a significant contribution to achieving and surpassing net-zero energy targets [12]. And its scalability allows it to be applied in both individual buildings and the wider energy community, making it a key technology in the transition to a more sustainable and energy independent future [8].

The aim of this review is to explore approaches to integrating hydrogen storage with solar and wind power generation systems as a means of advancing the development of NZEBs. The study complements the analysis with data on the current status, technological advances, performance assessments, and the potential for overcoming the challenges of renewable energy integration in the quest for sustainable and decarbonised NZEBs scenarios. In addition, the paper will also provide a comprehensive understanding of the role and impacts of such integration in achieving the global net-zero energy goal.

2. Integration of hydrogen storage with solar and wind energy

The integration of hydrogen storage with solar and wind energy systems in NZEBs depends on strategic coupling to maximise efficiency and energy self-sufficiency. Intelligent energy management systems play a key role in this integration, dynamically balancing energy production, storage and consumption. These systems can predict fluctuations in energy demand and supply, optimise the operation of electrolysers and fuel cells, and ensure that energy is stored when there is a surplus and converted to electricity when needed [1]. Mehrjerdi et al demonstrated that NZEBs with integrated solar, wind and hydrogen storage systems can achieve up to 95% energy self-sufficiency, significantly reducing dependence on the grid [2].

The efficiency of NZEBs incorporating hydrogen storage is assessed through energy conversion ratio, storage capacity and overall system sustainability. The round-trip efficiency of hydrogen storage (from electricity to hydrogen to electricity), although it does not appear to be high compared to other storage technologies, the advantages of hydrogen, such as long-term storage capacity and versatile applications beyond power generation, make it a sustainable option for NZEBs.

The Life Cycle Assessment (LCA) study highlights the environmental benefits of combining hydrogen storage with renewable energy sources. Sarker et al. emphasised that the production of green hydrogen from solar and wind energy can significantly reduce carbon emissions compared to conventional energy storage systems [11]. In addition, the scalability of hydrogen systems allows them to be applied to residential and commercial NZEBs, further contributing to the decarbonisation of the building sector [13].

A high-rise residential building in Europe rooftop solar panels, a wind turbines and an electrolyser-based hydrogen storage system to achieve annual net-zero energy status. This project reduced grid electricity consumption by 80% and a significant reduce carbon emissions by enabling the integration of hydrogen storage with solar and wind energy [8].

Additionally, the integration of a hydrogen storage system in a net-zero energy community in North America utilises solar arrays and wind turbines to power hydrogen production in electrolysers, which are then used to fulfil different energy needs. This hydrogen storage system provides the community with a stable energy supply throughout the year, and also facilitates peer-to-peer energy trading among residents, increasing energy resilience and community sustainability [14].

These case studies highlight the technical feasibility and environmental benefits of combining hydrogen storage with solar and wind energy in NZEB. They highlight the potential of such systems to significantly reduce energy costs, reduce carbon emissions and increase energy independence, thus aligning with global sustainable development goals.

3. Hydrogen energy technology innovation and progress

3.1. Recent Developments in Electrolyser Technology

Developments in electrolyser technology are critical to enhance the integration of hydrogen storage with solar and wind energy systems. Advanced electrolysers such as PEM and Solid Oxide Electrolysers (SOE) offer significant improvements in efficiency, durability, and scalability.PEM electrolysers are known for their fast response times and high purity hydrogen production, with efficiencies up to 70-80% under optimal operating conditions [6]. SOE technology operates at even higher temperatures with even higher efficiencies, potentially in excess of 80%, thereby facilitating more efficient water separation and synergistic effects with high temperature industrial processes [7].

Integration of renewable energy sources with these advanced electrolysers allows hydrogen production to be dynamically adjusted according to the availability of solar and wind energy, thus improving the overall efficiency of the NZEBs energy system. Xia et al highlights the development of an adaptive control system that optimises the operation of the electrolysers based on real-time energy prices and renewable energy outputs, thereby significantly reducing operating costs and improving the economic viability of hydrogen storage.

3.2. Advances in hydrogen storage solutions

Hydrogen storage technologies are critical for the efficient use of hydrogen as an energy carrier in NZEBs. Recent advances have focused on improving the density, safety and cost-effectiveness of hydrogen storage methods. Physical hydrogen storage methods, including compressed hydrogen and liquid hydrogen, have benefited from material science innovations that have improved the efficiency and safety of hydrogen storage. Meanwhile, chemical hydrogen storage methods such as metal hydrides and liquid organic hydrogen carriers offer solutions with higher energy density and potential for thermal management [8].

Emerging research has also explored novel materials and technologies for hydrogen storage, such as advanced porous materials such as metal-organic frameworks (MOFs) for hydride storage and novel alloys aimed at surpassing current limitations in storage capacity and release kinetics [13]. These innovations are not only expected to increase the viability of hydrogen storage for NZEBs energy applications, but also contribute to the broader goal of a hydrogen economy by facilitating the transport and delivery of hydrogen across industries.

3.3. Innovative Fuel Cell Design Improves Energy Conversion Efficiency

Fuel cell technology, which is the key to converting stored hydrogen into electricity, has also come a long way. Recent developments in fuel cell design have increased efficiency, lowered costs, and enhanced durability, making them more suitable for integration into off-road electrical equipment. Proton exchange membrane fuel cells (PEMFCs) and solid oxide fuel cells (SOFCs) are at the forefront of these advances. PEMFCs offer the advantages of low operating temperatures and short start-up times, making them ideally suited to dynamic energy demands, while SOFCs are characterised by their high efficiency and fuel flexibility, enabling the use of a wide range of fuels including hydrogen, natural gas and biogas [15].

Innovative approaches to fuel cell manufacturing, such as the use of novel catalyst materials and three-dimensional printing techniques, have further reduced the cost and improved the performance of fuel cells [11]. These advances not only improve the energy conversion efficiency of hydrogen storage systems, but also support the integration of renewable energy sources in NZEBs, contributing to the reduction of carbon emissions and the advancement of sustainable energy solutions.

3.4. Comparative analysis with other energy storage technologies

Hydrogen storage has unique advantages over other energy storage technologies, such as batteries and pumped storage, particularly in terms of scalability and versatility. While batteries have higher round-trip efficiencies (up to 90% for some lithium-ion batteries), they face challenges in terms of scalability and resource availability for large-scale applications. Pumped storage, while having high storage capacity and long life, requires specific geographic conditions that limit its applicability. Hydrogen storage, although currently less efficient, stands out for its potential for large-scale energy storage and its versatility of application in various fields, including transport and industry, and is not limited to power generation [1,13].

4. Benchmarking against performance benchmarks and best practices

Measuring the performance of hydrogen-based storage systems against established performance benchmarks and best practices is critical for continuous improvement and integration into NZEBs. The International Renewable Energy Agency (IRENA) and the Hydrogen Energy Council (HEC) provide guidelines and benchmarks for hydrogen energy technologies, emphasising the need for increased efficiency, reduced costs and environmental sustainability. Based on these benchmarks, researchers and practitioners aim to develop and implement hydrogen storage solutions that meet or exceed these criteria [16,17].

European project in the commercial building sector have combined a hybrid renewable energy system with hydrogen storage achieved significant improvements in energy self-sufficiency and carbon footprint reduction, in line with best practices for renewable energy integration in NZEBs [18]. Similarly, advances in electrolyser technology and fuel cell design have been benchmarked against industry standards, demonstrating progress in improving efficiency and reducing costs, contributing to wider adoption of hydrogen storage in renewable energy systems [11,12].

5. Challenges, obstacles and future prospects

5.1. Technical and Economic Challenges of Implementing Hydrogen Storage in NZEBs

The integration of hydrogen storage with solar and wind energy in NZEBs faces a number of technical and economic challenges that must be addressed to realise its full potential. Technical challenges include the current limitations of electrolyser and fuel cell efficiencies, which range from 30% to 50% round trip, highlighting the need to further improve the viability of hydrogen as an energy storage medium [6]. In addition, the durability and reliability of hydrogen storage systems need to be improved to match the operational lifetimes of solar and wind systems to ensure long-term sustainability and cost-effectiveness [7].

From an economic point of view, the initial capital costs of electrolysers, hydrogen storage solutions and fuel cells are significant barriers to the widespread adoption of hydrogen storage technologies in NZEBs. Although costs have decreased due to technological advances and scaling up of production, they are still high compared to conventional energy storage solutions [12]. In addition, the economic viability of hydrogen storage is affected by energy price volatility and the availability of financial incentives and subsidies, which vary considerably from region to region [1].

5.2. Policy and regulatory barriers

Policy and regulatory frameworks play a crucial role in the deployment of hydrogen energy storage systems. Currently, the lack of comprehensive policies and standards specifically addressing the integration of hydrogen technologies into the building sector hinders their deployment. This includes issues related to safety regulations, guidelines for hydrogen production and storage, and certification of hydrogen-ready equipment and systems [19]. In addition, the lack of incentives for green hydrogen production and use in NZEBs limits the economic attractiveness of these systems, highlighting the need for supportive policy measures to facilitate their development [15].

5.3. Future research directions and potential for replication and commercialisation

The prospect of storing hydrogen energy in NZEBs is very promising, with many research directions and commercialisation opportunities on the horizon. Current research is focussed on improving the efficiency and reducing the cost of electrolysers and fuel cells through materials innovation and advanced manufacturing techniques [11]. In addition, the development of new hydrogen storage methods with higher density and lower cost will revolutionise the role of hydrogen in energy storage and make it more competitive with other technologies [13].

There is significant potential to scale up and commercialise hydrogen energy storage systems, particularly as part of integrated renewable energy solutions for buildings and communities. Growing interest in the hydrogen economy and increasing investment in renewable energy infrastructure provide opportunities to utilise hydrogen storage as a key component of NZEBs and the wider energy system. Collaboration between government, industry and academia is essential to overcome current challenges and capitalise on these opportunities, to drive the adoption of hydrogen storage and to achieve net-zero energy targets [2,20].

6. Conclusion

This review illustrates the critical role of integrating hydrogen storage with solar and wind energy to advance the development of NZEBs. As the building sector moves towards a decarbonised future, the synergy between renewable energy and hydrogen storage becomes a key solution to overcome the inherent intermittency of solar and wind energy. This integration not only increases the resilience and self-sufficiency of NZEBs, but also contributes significantly to the reduction of greenhouse gas emissions.

Technological innovations in the design of electrolysis tanks, hydrogen storage and fuel cells are driving the efficiency and economic viability of hydrogen energy systems forward. Despite technical, economic and policy challenges, evolving research and development promises to address these barriers. The potential for scaling up and commercialising hydrogen energy storage systems is significant, providing a sustainable pathway to achieving and surpassing net-zero energy goals.

The NZEBs of the future depend on the successful integration of renewable energy with efficient, reliable and economical hydrogen storage solutions. Continuing technological advances, together with supportive policy measures and industry co-operation, will be critical to realising this vision. As this overview highlights, the journey to a sustainable, energy-independent future is complex but achievable, and underscores the need for continued innovation, research and commitment from all stakeholders.

In essence, hydrogen storage is at the intersection of opportunity and challenge, and is key to unlocking the full potential of solar and wind energy to enable NZEBs and a decarbonised built environment.

However, this paper mainly explores the combination of hydrogen storage with solar and wind energy and the relationship between the development of NZEBs with a review as a research method, and analyses the possibility of its realisation and problems from a qualitative point of view, but it involves fewer empirical contents such as relevant data, experiments, and so on. In the future, the research on relevant cases will be enlarged, and the examination and process of related professional studies will be combined to optimise the problems of the article.

References

[1] Sameti, M. and F. Haghighat, Integration of distributed energy storage into net-zero energy district systems: Optimum design and operation. Energy, 2018. 153: p. 575-591.
[2] Mehrjerdi, H., et al., Daily-seasonal operation in net-zero energy building powered by hybrid renewable energies and hydrogen storage systems. Energy Conversion and Management, 2019. 201: p. 112156.
[3] DeAngelo, J., et al., Energy systems in scenarios at net-zero CO2 emissions. Nature Communications, 2021. 12(1).
[4] Seto, K.C., et al., From Low- to Net-Zero Carbon Cities: The Next Global Agenda. Annual review of environment and resources, 2021. 46(1): p. 377-415.
[5] McKinstray, R., et al., Topographical optimisation of single-storey non-domestic steel framed buildings using photovoltaic panels for net-zero carbon impact. Building and Environment, 2015. 86: p. 120-131.
[6] H., M., et al. Hydrogen Production by Water Electrolysis: Review. in 2023 12th International Conference on Renewable Energy Research and Applications (ICRERA). 2023.
[7] Song, X., et al. Problems and Technology Development Trends of Hydrogen Production from Renewable Energy Power Electrolysis - A Review. 2021: IEEE.
[8] Abdolmaleki, L. and U. Berardi, Dynamic simulation of a hydrogen-fueled system for zero-energy buildings using TRNSYS software. E3S Web of Conferences, 2023. 396: p. 04005.
[9] Liu, J., et al., Energy planning of renewable applications in high-rise residential buildings integrating battery and hydrogen vehicle storage. Applied Energy, 2021. 281: p. 116038.
[10] Liu, J., et al., Hybrid renewable energy applications in zero-energy buildings and communities integrating battery and hydrogen vehicle storage. Applied Energy, 2021. 290: p. 116733.
[11] Sarker, A.K., et al., Prospect of Green Hydrogen Generation from Hybrid Renewable Energy Sources: A Review. Energies, 2023. 16(3): p. 1556.
[12] Xia, Y., et al., Efficiency and consistency enhancement for alkaline electrolyzers driven by renewable energy sources. Communications engineering, 2023. 2(1): p. 22.
[13] Wu, Y. and L. Zhong, Exploring Hydrogen-Based Energy Storage Systems for Canadian Residential Buildings: An Energy Evaluation Methodology. E3S Web of Conferences, 2023. 396: p. 04001.
[14] Liu, J., H. Yang and Y. Zhou, Peer-to-peer trading optimizations on net-zero energy communities with energy storage of hydrogen and battery vehicles. Applied Energy, 2021. 302: p. 117578.
[15] Marouani, I., et al., Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future. Processes, 2023. 11(9): p. 2685.
[16] Council, Hydrogen Insights 2023. The Hydrogen Council, 2023.
[17] IREA, Annual Report of the Director-General on the Implementation of the Work Programme and Budget for 2022-2023. The International Renewable Energy Agency, 2024.
[18] Liu, J., et al., Net-zero energy management and optimization of commercial building sectors with hybrid renewable energy systems integrated with energy storage of pumped hydro and hydrogen taxis. Applied Energy, 2022. 321: p. 119312.
[19] AbuGrain, M. and H. Alibaba, Optimizing Existing Multistory Building Designs towards Net-Zero Energy. Sustainability, 2017. 9(3): p. 399.
[20] Wu, W. and H.M. Skye, Residential net-zero energy buildings: Review and perspective. Renewable and Sustainable Energy Reviews, 2021. 142: p. 110859