



Smart Renewable–Hydrogen Energy Networks and Fusion-Assisted Technologies for Sustainable, Carbon-Free Electricity Generation

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Abstract: Two complementary technological routes, smart renewable–hydrogen energy networks and fusion-assisted electricity generation, are of great interest in the global push towards decarbonised power systems. Renewable-Hydrogen networks combine variable renewables (such as solar, wind, and hydro) and electrolysis with delivery, storage, and digital management to provide dispatchable, carbon-free electricity. Meanwhile, after recent strides in ignition and with rising private-sector funding, fusion energy is becoming a long-term, high-density, low-carbon alternative to renewable-hydrogen generation. This review compiles recent literature (2020-2025) on the various production methods for green hydrogen, hydrogen storage technologies, smart grid management with the aid of artificial intelligence, and the status of magnetic and inertial confinement fusion, before exploring the possibility of using fusion-assisted heat and electricity generation in conjunction with renewable hydrogen infrastructure for augmenting the reliability of the grid and minimising emissions throughout the hydrogen value chain. Three comparative tables summarise hydrogen production routes, hydrogen storage options, and fusion confinement approaches, and four proposed schematic figures visualise network architecture, production growth trends, fusion reactor concepts, and an integrated fusion–hydrogen–renewable smart grid. The paper discusses key barriers (capital cost, materials durability, electrolyser degradation, fusion engineering readiness, etc.) and the policy and research priorities needed to support a resilient, low-carbon electricity future.

Keywords: Green Hydrogen; Smart Grid; Renewable Energy; Nuclear Fusion; Carbon-Free Electricity; Energy Storage; Artificial Intelligence.

Nomenclature:

AI: Artificial Intelligence
NIF: National Ignition Facility
DOI: Digital Object Identifier
PEM: Proton-Exchange Membrane
MOFs: Metal–Organic Frameworks
EMS: Energy Management Systems
HES: Hydrogen Energy Storage Systems
BESS: Battery Energy Storage Systems
ICF: Inertial Confinement Fusion
HTS: High-Temperature Superconducting
MCF: Magnetic Confinement Fusion

I. INTRODUCTION

Limiting global electricity emissions to zero is one of this decade's biggest engineering and policy challenges. While renewables such as wind, solar, and hydro offer an opportunity for a low-carbon energy mix in many places, technical, economic, and regulatory challenges delay deployment of these renewables and grid-scale energy storage [1]. Renewables like solar PV and wind are now price-competitive in most markets. Still, their variability and geographic vulnerability require reliable energy carriers and energy storage systems to maintain grid reliability [2]. With renewable electricity-powered electrolysis, H₂ has become a versatile energy vector that can be stored for long periods, coupled with different sectors, and dispatched as a dispatchable energy source; it has also been identified as a central pillar of the “hydrogen economy” in national decarbonisation strategies worldwide [2,3].

Meanwhile, digitalisation and artificial intelligence (AI) are reshaping how renewable and hydrogen assets are forecast, coordinated, and dispatched, creating “smart” energy networks that optimise generation, storage, and demand in near real time [4, 5]. Meanwhile, nuclear fusion, long considered a long-term option, has made significant strides since the 2022 ignition breakthrough at the National Ignition Facility (NIF). Progress in public and private fusion projects has renewed interest in fusion as a potential long-term goal for firm, low-carbon electricity generation beyond intermittent renewables and hydrogen networks.

This review aims to consider the three strands, renewable–hydrogen production and storage, smart digital network management and fusion-assisted generation, in the context of their potential contribution to a resilient, carbon-free

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electricity system. Section 2 discusses hydrogen production technologies and storage methods. Section 3 discusses digitalised, AI-based smart hydrogen–renewable networks. Section 4 reviews the state of fusion energy technologies. Section 5 provides insights into integration opportunities, and Section 6 highlights challenges and future research directions.

II. METHODOLOGY

This article adopts a narrative/scoping review methodology suitable for synthesising an ever-expanding and methodologically diverse literature spanning computational chemistry, data science, and electrochemical engineering. No experimentation or computation is presented; all results, data, and graphs are taken from and credited to published sources.

A. Literature Search Strategy

A comprehensive search was carried out in a variety of bibliographic and publisher databases, namely PubMed/MEDLINE, Google Scholar, Web of Science-indexed publisher platforms (American Chemical Society Publications, Wiley Online Library, the Royal Society of Chemistry, Elsevier ScienceDirect, and Springer Nature/Nature Portfolio journals) and the arXiv preprint repository (only to track the citation's provenance and not as a primary source of evidence). The following words were used to search: “machine learning electrocatalyst,” “density functional theory machine learning catalysis,” “high-throughput screening electrocatalyst,” “graph neural network interatomic potential catalysis,” “single-atom catalyst machine learning,” “perovskite oxygen evolution machine learning,” “high-entropy alloy Bayesian optimisation electrocatalysis,” “CO₂ reduction reaction machine learning,” “active learning catalyst discovery,” “self-driving laboratory catalyst,” and “interpretable/explainable machine learning catalysis.”

B. Inclusion Criteria

Sources were selected if they explicitly related to one of the following: (i) machine learning, DFT, or high throughput/autonomous screening for the discovery of electrocatalysts for H₂ production, oxygen production/reduction, or CO₂ reduction; (ii) were written explicitly in the context of electrocatalyst discovery for hydrogen production, oxygen production/reduction, or CO₂ reduction; and (iii) were referenced to a verifiable digital object identifier (DOI) independently from the publisher record or PubMed or an institutional repository (e.g., OSTI, NSF PAR) at the time of writing.

C. Exclusion Criteria

Studies were excluded if they: (i) could not be checked against an authoritative bibliographic source (publisher web page, PubMed, or equivalent), unless the history or citation-provenance of the paper contributed to the scientific

content; (ii) were preprints without a corresponding verifiable DOI, unless they were cited solely for history/citation-provenance reasons (i.e. the history or citation-provenance of the paper contributed to the scientific content); (iii) occurred outside the 2020-2025/26 period unless they had a foundational role in the scientific content; or (iv) added nothing to the scientific content of an already-included, more comprehensive source.

D. Screening and Data Extraction

We screened sources identified by the search strategy by title and abstract for topical relevance, then by full text or full abstract for methodological detail (reaction type studied, ML algorithm, dataset scale, and reported outcome). We verified the bibliographic information for all included sources (author(s), title, publication year, journal, page range, and DOI) against at least one other source before adding it to the reference list. No numerical results were estimated, extrapolated or invented beyond those that were reported in the abstract and results of the included sources, or explicitly stated in the datasets; information synthesised into the tables of this review (Tables I–III) was extracted directly from the abstract and results of the included sources.

III. RENEWABLE–HYDROGEN ENERGY NETWORKS

A. Hydrogen Production Pathways

Hydrogen comes from various feedstocks and processes and is generally categorised into a series of colours, each representing a different source or process based on the carbon emissions associated with each process. Most policy and investment interest lies in green hydrogen, produced by water electrolysis using renewable electricity, which fully eliminates fossil-fuel carbon [2,3]. Electrolyser technologies (alkaline, proton-exchange membrane (PEM), and solid oxide) vary in efficiency, capital cost, response time, and durability, and the choice of production route depends on feedstock availability, renewable-resource quality, and end-use requirements [6]. In addition, biohydrogen can be generated through dark fermentation, photo fermentation, or biomass gasification, providing an alternative pathway to valorise agro- and organic waste streams. However, yields and scalability remain below those of electrolytic hydrogen production [7,8]. Comparative techno-economic assessments consistently show that producing hydrogen from renewable electricity is more expensive than from fossil fuels, but still more competitive because of expected decreases in solar and wind costs and economies of scale in electrolyser manufacturing [4,5]. Table I shows the Comparative overview of hydrogen production pathways.





Table I: Comparative Overview of Hydrogen Production Pathways

Production Route	Feedstock/Energy Input	Typical Efficiency	Relative Cost	Carbon Intensity	Key Ref(s)
Alkaline/PEM electrolysis (Green H ₂)	Renewable electricity + water	60–80%	High (declining)	Near-zero	[2,3,6]
Solid oxide electrolysis	Renewable/waste-heat electricity	80–90% (high temp.)	High (early stage)	Near-zero	[6]
Biohydrogen (dark/photo-fermentation, gasification)	Biomass, organic/agricultural waste	30–60%	Moderate	Low	[7,8]
Steam methane reforming (Grey/Blue H ₂ , reference)	Natural gas ± carbon capture	70–85%	Low–Moderate	High (Grey)/Moderate (Blue)	[4,5]

B. Water Electrolysis

Hydrogen demand does not always align with renewable electricity generation, making effective storage key to a successful hydrogen economy. Physical storage approaches are mature (compressed gaseous hydrogen, cryogenic liquid hydrogen, and cryo-compressed hydrogen) and offer advantages in energy density, compression/liquefaction penalties, and boil-off losses [9,10]. Material-based storage systems such as metal hydrides and chemical hydrogen carriers, porous adsorbents like metal–organic frameworks

(MOFs), and other materials show high volumetric storage densities and safety profiles. However, they still suffer from slower dynamics, high material costs, and limited cycling stability [11]. These considerations include how long the storage needs to last.

(diurnal or seasonal storage), how far the hydrogen is to be transported, and whether it will be used as a fuel for combustion, reconverted to electricity via fuel cells, or fed into industries. [9,12]. Table II gives a comparative overview of hydrogen storage technologies.

Table II: Comparative Overview of Hydrogen Storage Technologies

Storage Method	Typical Storage Density	Operating Conditions	Advantages	Limitations	Key Ref(s)
Compressed gaseous H ₂	Low–moderate volumetric density	350–700 bar	Mature, fast refuelling	Heavy tanks, compression energy	[9,10]
Liquid/cryo-compressed H ₂	High volumetric density	~ -253 °C	High density, established for transport	Boil-off losses, liquefaction energy	[9,10]
Metal hydrides	High volumetric density	Near-ambient	Safe, compact	Slow kinetics, weight	[9,11]
Metal–organic frameworks (MOF)/adsorbents	Moderate–high (material-dependent)	Low temperature/moderate pressure	Tunable porosity, reversible	Cost, cryogenic requirement	[11]

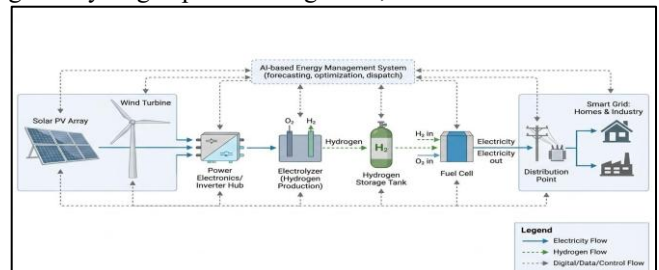
The combined hydrogen energy storage systems (HES), such as hydrogen electrolyzers, compressed or metal-hydride storage, and fuel cells, combined with battery energy storage systems (BESS) have been adopted to create a hybrid storage architecture that can achieve near-zero-emission, “carbon-free” operation even in rural or islanded locations [13,14].

C. Smart, AI-Enabled Renewable–Hydrogen Networks

The “smart” renewable-hydrogen network fuses digital sensing, communication, and optimisation layers with physical generation, storage, and distribution infrastructure. Artificial intelligence and machine-learning methods such as deep neural networks, reinforcement learning, and hybrid metaheuristic algorithms are increasingly used to predict renewable energy generation, forecast electrolyser degradation, and optimise real-time dispatch for electrolysis, storage, and grid injection [15]. These AI-based energy management systems (EMS) can reduce renewable curtailment, prolong the lifetime of electrolyzers and fuel cells by mitigating load transients, and optimise the economic dispatch of hybrid hydrogen–battery microgrids under uncertain renewable supply and demand [13,14]. For stand-alone carbon-free hydrogen-based microgrids, model predictive control and convex optimisation-based planning frameworks have been shown to achieve reliability objectives at lower cost than battery-only systems [13].

In addition to individual microgrids, smart hydrogen networks are being envisioned at a broader system level, where several renewable-hydrogen nodes are linked to each

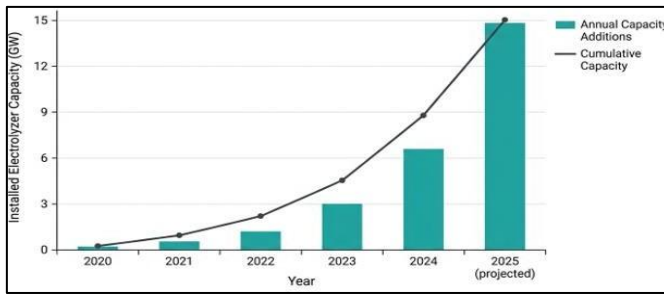
other via gas pipelines or dedicated hydrogen corridors, and digitally coordinated to match the supply-side and demand-side for hydrogen use within a given geographic area, similar to a smart electricity grid. Techno-economic evaluations of hybrid energy storage technologies (batteries, compressed-air storage, and hydrogen) show that hydrogen offers greater potential benefits as storage times increase and serves as a “backbone” for smart, multi-vector energy networks [16]. However, practical challenges such as data availability, cybersecurity, and interoperability across different hardware and software platforms still limit the integration and deployment of fully autonomous smart hydrogen–renewable networks [15]. Figure 1 shows the Schematic architecture of a smart renewable-hydrogen energy network, while Figure 2 below presents the Global green hydrogen production growth, 2020–2025.



[Fig.1: Smart Renewable-Hydrogen Energy Network Architecture]

Sources: Adapted from References [2,13,14,15].





[Fig.2: Global Green Hydrogen Production Growth, 2020–2025]

Sources: Adapted from References [2,3,4].

IV. FUSION-ASSISTED TECHNOLOGIES FOR CARBON-FREE ELECTRICITY

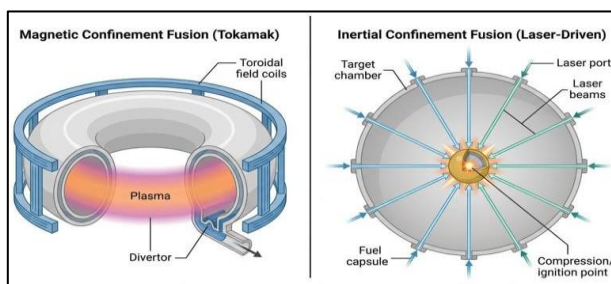
A fundamentally different approach to generating carbon-free electricity is through nuclear fusion, the production of energy from the fusion of light nuclei (usually in the form of deuterium and tritium), which yields energy many millions of times more per unit mass than chemical combustion, without the production of long-lived high-level radioactive waste or greenhouse-gas emissions [17]. Two main confinement methods are being studied. Magnetic Confinement Fusion (MCF): Hot plasma is contained in strong magnetic fields, which are increasingly produced by High-Temperature Superconducting (HTS) magnets, long enough for the fusion reaction to take place, such as in Tokamaks (e.g., ITER) and Stellarators (e.g., Wendelstein 7-X) [17]. By contrast, inertial confinement fusion (ICF) relies on powerful lasers to compress and heat a tiny capsule of fuel in a fraction of a second: In 2022, the National Ignition Facility, which has recently set a record for

achieving 100% efficiency, achieved its first laboratory demonstration of nuclear fusion that met the Lawson criterion for ignition, and in 2024 it reported a first-ever energy gain of more than 1. In 2022, the National Ignition Facility, which recently set a new record for efficiency of 100%, achieved, for the first time in a laboratory setting, a nuclear fusion reaction that met the Lawson criterion for ignition; in 2024, the facility reported a new energy gain of over 1.

These milestones have fueled a flurry of private-sector fusion ventures developing compact tokamak, stellarator, and alternative fusion concepts; so far, investments have reached billions of dollars, and several organisations are planning grid-connected demonstration facilities in the coming decade or two [18,19,20]. The IAEA has similarly strengthened its coordination work, producing outlook statements on the safety, security, and deployment pathway of fusion as an emerging element of the international low-carbon energy portfolio [19]. Comparative economic modelling indicates that, when commercial, fusion electricity could be cost-competitive with, and ultimately replace, part of conventional generation, but most analyses place commercial maturity in the 2030s–2050s, with significant uncertainty around engineering, materials, and tritium-breeding readiness [17]. Country-level assessments in the UK, USA, China, Japan, and Russia also point to two key current challenges to grid deployment: device efficiency and sustainable funding, alongside facility safety [21]. Table III provides a comparative overview of fusion confinement technologies, while Figure 3 shows a schematic comparison of magnetic and inertial confinement fusion (ICF) concepts.

Table III: Comparative Overview of Fusion Confinement Technologies

Confinement Approach	Representative Facility/Concept	Confinement Principle	Current Status (2020–2025)	Key Ref(s)
Magnetic confinement – Tokamak	ITER (under construction); private compact tokamaks	Magnetic field confines toroidal plasma	Engineering construction/design phase; private Demonstrators targeted for the 2030s	[17,18,20,21]
Magnetic confinement – Stellarator	Wendelstein 7-X; private stellarator ventures	Twisted magnetic coils confine plasma without net current	Operating experimental device; private designs in early demonstration	[17,18]
Inertial confinement fusion (ICF)	National Ignition Facility (NIF)	High-power lasers compress/heat fuel capsule	Ignition achieved (2022); target gain > 1 achieved (2024)	[23,24]
International coordination/outlook	IAEA fusion programs	Cross-cutting safety, security, and deployment oversight	Active global coordination and outlook reporting	[19]



[Fig.3: Schematic Comparison of Magnetic and Inertial Confinement Fusion Concepts]

Sources: References Informing Design: [17,23,24]

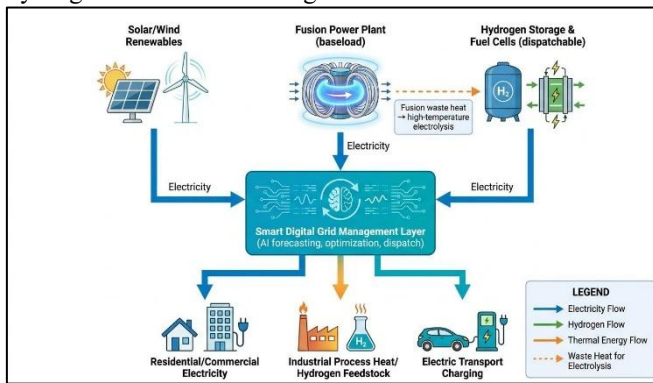
A. Integrating Fusion with Smart Renewable–Hydrogen Networks

Fusion power plants are not commercial, but when they do come online, they will be technically interesting to integrate with renewable-hydrogen networks for several reasons. First, fusion plants are expected to generate firm, high-capacity-factor baseload electricity, which could be used by large-scale, continuously operating electrolyzers at high utilisation rates, optimising the economics of both fusion and electrolysis compared with stand-alone operation



[17,19]. Secondly, fusion reactors may, in principle, produce significant amounts of high-temperature waste heat that can be used in conjunction with electrolysis, for example, for high-temperature electrolysis or thermochemical hydrogen production, increasing the overall efficiency of the system over electrolysis alone [21]. Thirdly, a digitally coordinated “smart” layer, as developed for renewable-hydrogen microgrids, may help coordinate complementary output profiles for variable renewables, dispatchable hydrogen storage, and ultimately fusion baseload to maintain grid stability, minimise curtailment, and maximise use of low-carbon assets [13,15]. Early conceptual and socio-economic studies by fusion

research consortia have begun modelling such integrated future energy scenarios, making fusion an increasingly carbon-free complement to renewables in a wider, multi-vector energy system managed by digital tools [21,22]. Figure 4 illustrates the Conceptual integrated fusion–hydrogen–renewable smart grid architecture.



[Fig.4: Conceptual Integrated Fusion–Hydrogen–Renewable Smart Grid Architecture]

Sources: Author's Conceptual Diagram Adapted from References [13,17,19,21,22].

V. CHALLENGES AND FUTURE PERSPECTIVES

However, several obstacles must be overcome to achieve this vision. Capital costs of electrolyzers, catalyst scarcity (such as iridium for PEM), and degradation under variable renewable input remain the main factors driving the LHC in renewable-hydrogen networks [3,6]. Storage technologies involve trade-offs among energy density, safety, and cost, and none is optimal for all applications [9,11]. In the digital arena, the cybersecurity, transparency, and reliability of AI-driven energy management systems are still to be proven before regulators and grid operators can remain confident in the autonomous dispatch decisions made by AI systems [15]. To achieve fusion, the next step from record-breaking laboratory experiments to continuous, tritium self-sustaining, and economically viable power plants requires advances in materials science, breeding-blanket engineering, and demonstration of safety in plant operation, as well as continued public and private funding [18,20,21]. Deploying smart renewable hydrogen networks and fusion-assisted technologies to provide reliable, carbon-free electricity at scale will depend on coordinated research investments, harmonised international standards for hydrogen safety and fusion licensing, and

lower renewable generation costs.

VI. CONCLUSION

Two complementary paths leading to a sustainable carbon-free electricity supply exist: smart renewable hydrogen energy networks and fusion-assisted technologies. Smart renewable hydrogen energy networks and fusion-assisted technologies are complementary paths toward a sustainable, carbon-free electricity supply. Renewable-hydrogen networks are technically ready for near-term deployment, can help overcome the intermittency challenges of solar and wind energy through AI-driven digital management, and show promise. Fusion energy is pre-commercial but has made significant scientific breakthroughs and is moving toward engineering demonstration; it could provide firm, high-density, low-carbon electricity that can be combined with hydrogen production and smart grid management. These complementary technologies will need continued interdisciplinary research, from materials science to digital control systems and plasma engineering, to make the energy transition to a global, resilient, and fully decarbonised electricity system a reality.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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REFERENCE

1. Papadis E, Tsatsaronis G. Challenges in the decarbonization of the energy sector. *Energy*. 2020; 205:118025.
DOI: [10.1016/j.energy.2020.118025](https://doi.org/10.1016/j.energy.2020.118025)
2. Zhang J, Li J. Revolution in renewables: integration of green hydrogen for a sustainable future. *Energies*. 2024;17(16):4148.
DOI: [10.3390/en17164148](https://doi.org/10.3390/en17164148)
3. Squadrito G, Maggio G, Nicita A. The green hydrogen revolution. *Renew Energy*. 2023; 216:119041.



- DOI: [10.1016/j.renene.2023.119041](https://doi.org/10.1016/j.renene.2023.119041)
4. Gómez J, Castro R. Green hydrogen energy systems: a review on their contribution to a renewable energy system. *Energies*. 2024;17(13):3110. DOI: [10.3390/en171331100](https://doi.org/10.3390/en171331100)
 5. Sebbagh T, Şahin ME, Beldjaatit C. Green hydrogen revolution for a sustainable energy future. *Clean Technol Environ Policy*. 2024;26(12):4017–40. DOI: [10.1007/s10098-024-02995-9](https://doi.org/10.1007/s10098-024-02995-9)
 6. Acar C, Dincer I. Selection criteria and ranking for sustainable hydrogen production options. *Int J Hydrogen Energy*. 2022;47(95):40118–37. DOI: [10.1016/j.ijhydene.2022.07.137](https://doi.org/10.1016/j.ijhydene.2022.07.137)
 7. Ferraren-De Cagalitan DDT, Abundo MLS. A review of biohydrogen production technology for application towards hydrogen fuel cells. *Renew Sustain Energy Rev*. 2021; 151:111413. DOI: [10.1016/j.rser.2021.111413](https://doi.org/10.1016/j.rser.2021.111413)
 8. Pal DB, Singh A, Bhatnagar A. A review on biomass-based hydrogen production technologies. *Int J Hydrogen Energy*. 2022;47(3):1461–80. DOI: [10.1016/j.ijhydene.2021.10.124](https://doi.org/10.1016/j.ijhydene.2021.10.124)
 9. Hassan IA, Ramadan HS, Saleh MA, Hissel D. Hydrogen storage technologies for stationary and mobile applications: review, analysis and perspectives. *Renew Sustain Energy Rev*. 2021; 149:111311. DOI: [10.1016/j.rser.2021.111311](https://doi.org/10.1016/j.rser.2021.111311)
 10. Tarhan C, Çil MA. A study on hydrogen, the clean energy of the future: hydrogen storage methods. *J Energy Storage*. 2021; 40:102676. DOI: [10.1016/j.est.2021.102676](https://doi.org/10.1016/j.est.2021.102676)
 11. Shet SP, Shanmuga Priya S, Sudhakar K, Tahir M. A review on current trends in potential use of metal-organic framework for hydrogen storage. *Int J Hydrogen Energy*. 2021;46(21):11782–803. DOI: [10.1016/j.ijhydene.2021.01.020](https://doi.org/10.1016/j.ijhydene.2021.01.020)
 12. Hossain Bhuiyan MM, Siddique Z. Hydrogen as an alternative fuel: a comprehensive review of challenges and opportunities in production, storage, and transportation. *Int J Hydrogen Energy*. 2025; 102:1026–44. DOI: [10.1016/j.ijhydene.2025.01.033](https://doi.org/10.1016/j.ijhydene.2025.01.033)
 13. Wu X, Cao B, Liu B, Wang X. A planning model of standalone hydrogen-based carbon-free microgrid through convex relaxation. *IEEE Trans. Smart Grid*. 2023;14(4):2668–80. DOI: [10.1109/TSG.2022.3224900](https://doi.org/10.1109/TSG.2022.3224900)
 14. Shao Z, Cao X, Zhai Q, Guan X. Risk-constrained planning of rural-area hydrogen-based microgrid considering multiscale and multi-energy storage systems. *Appl Energy*. 2023; 334:120682. DOI: [10.1016/j.apenergy.2023.120682](https://doi.org/10.1016/j.apenergy.2023.120682)
 15. Ukoba K, Olatunji KO, Adeoye E, Jen TC, Madyira DM. Optimising renewable energy systems through artificial intelligence: review and prospects. *Energy Environ*. 2024;35(7):3833–79. DOI: [10.1177/0958305X241256293](https://doi.org/10.1177/0958305X241256293) [Volume, issue and pages added]
 16. Arsad AZ, Hannan MA, Al-Shetwi AQ, Mansur M, Muttaqi KM, Dong ZY, et al. Hydrogen energy storage integrated hybrid renewable energy systems: a review analysis for future research directions. *Int J Hydrogen Energy*. 2022;47(39):17285–312. DOI: [10.1016/j.ijhydene.2022.03.208](https://doi.org/10.1016/j.ijhydene.2022.03.208)
 17. Sadik-Zada ER, Gatto A, Weißnicht Y. Back to the future: revisiting the perspectives on nuclear fusion and juxtaposition to existing energy sources. *Energy*. 2024; 290:129150. DOI: [10.1016/j.energy.2023.129150](https://doi.org/10.1016/j.energy.2023.129150)
 18. Meschini S, Laviano F, Ledda F, Pettinari D, Testoni R, Torsello D, Panella B. Review of commercial nuclear fusion projects. *Front Energy Res*. 2023; 11:1157394. DOI: [10.3389/fenrg.2023.1157394](https://doi.org/10.3389/fenrg.2023.1157394)
 19. International Atomic Energy Agency. IAEA World Fusion Outlook 2023. Vienna: IAEA; 2023. DOI: [10.61092/iaea.chyw-jq1g](https://doi.org/10.61092/iaea.chyw-jq1g)
 20. Fan L, Tu Z, Chan SH. Recent development of hydrogen and fuel cell technologies: a review. *Energy Rep*. 2021; 7:8421–46. DOI: [10.1016/j.egyr.2021.08.003](https://doi.org/10.1016/j.egyr.2021.08.003)
 21. Mohamed M, Zakuan ND, Tengku Hassan TNA, Lock SSM, Mohd Shariff A. Global development and readiness of nuclear fusion technology as an alternative source for clean energy supply. *Sustainability*. 2024;16(10):4089. DOI: [10.3390/su16104089](https://doi.org/10.3390/su16104089)
 22. Karayel GK, Javani N, Dincer I. A comprehensive assessment of energy storage options for green hydrogen. *Energy Convers Manag*. 2023; 291:117311. DOI: [10.1016/j.enconman.2023.117311](https://doi.org/10.1016/j.enconman.2023.117311)
 23. Abu-Shawareb H, Acree R, Adams P, Adams J, Addis B, Aden R, et al.

(Indirect Drive ICF Collaboration). Lawson criterion for ignition exceeded in an inertial fusion experiment. *Phys Rev Lett*. 2022;129(7):075001. DOI: [10.1103/PhysRevLett.129.075001](https://doi.org/10.1103/PhysRevLett.129.075001)

24. Abu-Shawareb H, Acree R, Adams P, Adams J, Addis B, Aden R, et al. (Indirect Drive ICF Collaboration). Achievement of target gain larger than unity in an inertial fusion experiment. *Phys Rev Lett*. 2024;132(6):065102. DOI: [10.1103/PhysRevLett.132.065102](https://doi.org/10.1103/PhysRevLett.132.065102)

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