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Hydrogen applications in buildings: A systematic review of decarbonization pathways☆

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ABSTRACT

The building sector is a major contributor to global energy use and carbon emissions, positioning it as a key target for decarbonization. Hydrogen, as a clean and flexible energy carrier, offers significant potential in supporting this transition. This review synthesizes recent advances in hydrogen applications for buildings, highlighting experimental findings, technological feasibility, socio-technical considerations, and policy developments. Key deployment models include hydrogen fuel cell integration, hydrogen-based microgrids, and combined heat and power systems. Emerging innovations such as renewable-powered hydrogen production, decentralized storage, and cross-sector integration with transport systems are also examined. In particular, the role of hydrogen-powered vehicles as energy buffers is emphasized for enhancing building energy autonomy. Despite its promise, hydrogen deployment faces technical, economic, and institutional challenges. The study calls for coordinated strategies that integrate hydrogen with other renewables, improve policy frameworks, and foster public acceptance. Future research should prioritize system integration pathways, techno-economic optimization, real-world demonstrations, and interdisciplinary collaboration. This review offers a strategic reference for scaling up hydrogen use in the built environment and underscores its critical role in achieving net-zero emissions and sustainable urban energy systems.

Nomenclature

AHP	Analytic hierarchy process
LPSP	Loss of power supply probability
ACS	Annualized cost of systems
MCDA	Multi-criteria decision analysis
ACER	Annual carbon emission reduction
MHHS	Metal hydride hydrogen storage
AROI	Annual return on investment
MILP	Mixed-integer linear programming
ASHPs	Air source heat pumps
mCHP	Micro-combined heat and power
BEV	Battery electric vehicle
NOx	Nitrogen oxides
BESS	Battery energy storage system
NCA	Necessary condition analysis
BIPV/T	Building-integrated photovoltaic-thermal
NPC	Net present cost
CCC	Committee on Climate Change
NSGA-II	Non-dominated Sorting Genetic Algorithm II
CCS	Carbon capture and storage
NZEB	Net-zero energy building
CRR	Carbon reduction rate
nZEB	Near-zero energy building
CHP	Combined heat and power
Ofgem	Office of Gas and Electricity Markets
CCHP	Combined cooling, heating, and power
PV	Photovoltaics
DER	Distributed energy resource
PEBs	Positive energy buildings
DHW	Domestic hot water
PCA	Principal component analysis

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DOE	Department of Energy (U.S.)
PEC	Photoelectrochemical
DRP	Demand response programs
PEM	Proton exchange membrane
EHT-HS	Electricity–hydrogen–thermal hybrid storage system
PSA	Pressure swing adsorption
FC	Fuel cell
P2H	Power-to-hydrogen
FES	Future Energy Scenarios
PEWP	Potential energy waste probability
FCES	Fuel cell electric scooters
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
FCEVs	Hydrogen fuel cell electric vehicles
PLS-SEM	Partial least squares structural equation modelling
FCEV2G	Fuel cell electric vehicle-to-Grid
PEMFC	Proton exchange membrane fuel cells
GWP	Global warming potential
P2H2P	Power-to-hydrogen-to-power
GSHPs	Ground source heat pumps
RER	Resource efficiency ratio
HT	Hydrogen tank
ROI	Return on investment
HS	Hydrogen storage
RHS	Renewable hydrogen-based systems
HVs	Hydrogen vehicles
REVB	Retired electric vehicle batteries
H_2B	Hydrogen boilers
SMR	Steam methane reforming
HHS	Hybrid heating systems
SOFC	Solid oxide fuel cells
HHPs	Hybrid heat pumps
TEA	Techno-Economic Analysis
HRE	Heat recovery efficiency
TREES	Total residential end-use energy simulation
HFCVs	Hydrogen fuel cell vehicles
V2B	Vehicle-to-building
HESS	Hydrogen Energy Storage Systems
V2G	Vehicle-to-grid
HVAC	Heating Ventilation Air Conditioning
V2L	Vehicle-to-Load
HRES	Hybrid renewable energy system
WHR	Waste heat recovery
ICEVs	Internal combustion engine vehicles
WoS	Web of Science
LCCA	Life Cycle Cost Analysis
LCA	Life cycle assessment
LTCs	Load Tap Changers
LFP	Lithium iron phosphate
LRA	Linear regression analysis
LOHCs	Liquid organic hydrogen carriers
LCOE	Levelized cost of energy
LPSR	Loss probability of supply reliability

1. Introduction

With the increasingly severe climate change caused by greenhouse gas emissions and the global focus on sustainable development, the average global temperature has risen by 1.2 °C above pre-industrial levels [1]. This has driven nations worldwide to adopt agreements such as the Paris Agreement and the Glasgow Climate Pact to address climate challenges [2,3]. The significance of energy transition has grown steadily, attributed to its role in meeting rising energy demands, reducing reliance on fossil fuels, and increasing the share of renewable energy in the energy mix [4]. The building sector has a persistent and significant impact on energy demand and the environment. According to European Parliament [5], buildings in Europe account for 40 % of total energy consumption. About 75 % of these buildings are more than 25 years old and operate with low energy efficiency [6]. This is particularly true when considering the European Union's goal to increase renewable energy's share in building to 70 % by 2050 [7]. Additionally, in Spain, apartments and single-family homes allocate the significant energy consumption to space heating and domestic hot water, with 47 % of this energy still derived from fossil fuels which reliance on non-renewable energy sources highlights the current gap in meeting Europe's goal of achieving net-zero greenhouse gas emissions by 2050 [8].

Hydrogen is regarded as a key enabler of sustainable energy solutions due to its carbon-free combustion process, which does not directly contribute to greenhouse gas emissions [9]. Additionally, hydrogen's potential as a clean energy carrier and fossil fuel substitute has been widely acknowledged by researchers. By offering energy storage and aiding decarbonization, hydrogen reduces dependence on fossil fuels across various sectors, thereby effectively lowering greenhouse gas emissions [4,10–12] and supporting a smooth transition in energy systems. Hydrogen is categorized using a color-coding system to represent its varying levels of cleanliness, with the primary types being green, blue, and grey. Blue hydrogen and grey hydrogen are produced from similar fossil fuel resources; however, the former incorporates carbon capture and storage (CCS) during the production process to reduce emissions compared to the latter. Brown hydrogen is produced through coal-based fuel gasification, while turquoise hydrogen is obtained by pyrolyzing or cracking natural gas (methane), yielding hydrogen and carbon as by-products [13]. To date, green hydrogen has emerged as a new alternative to traditional hydrogen produced from natural gas and coal. Derived mainly through electrolysis powered by renewable energy sources such as solar and wind, green hydrogen is a clean and sustainable resource with zero carbon emissions. Consequently, hydrogen, along with its derivatives and fuels, is gaining increasing popularity across diverse applications [12], including the transportation sector, metal and chemical production, and building energy systems [14,15].

In the current context, various renewable energy and hydrogen based technological systems in the building sector have emerged as a viable alternative to conventional energy solutions. The study by Badrivarayanan et al. [16] demonstrated that hydrogen based micro combined heat and power (mCHP) units can reduce residential energy consumption by 22 % and carbon emissions by 18 %. By integrating hydrogen with other renewable sources such as photovoltaics and wind power, these systems can effectively meet household demands for electricity and heating. The study further noted that in countries such as Japan and Finland, the large-scale deployment of hydrogen fuel cell micro combined heat and power systems, supported by government subsidies, has led to significant progress in the transition of the residential energy structure [16]. To date, the synergistic application of renewable energy and energy storage systems has been extensively explored [17,18]. Hydrogen, as a representative renewable energy carrier, has garnered significant attention for its versatile applications across various sectors. Examples include using hydrogen fuel cells to power shoreside electricity systems for docked ships at ports, constructing hydrogen refueling stations at ports for large vehicles [19], and integrating hydrogen fuel cells with battery-electric vehicles to enhance sustainability in transportation, space, and aviation sectors [20]. Wu and Skye [21] reviewed a case study on the integration of hydrogen fuel cell vehicles and net-zero buildings in Helsinki, Finland. Their analysis indicated that surplus renewable energy, such as solar photovoltaic (PV) or wind power, can be utilized to produce hydrogen via electrolysis for both electricity and heat supply [22]. The study found that a single 14 kW wind turbine or a 178 m^2 PV array could nearly achieve net-zero emissions for the building. Additionally, the research highlighted that, compared to battery electric vehicle (BEV) integration systems, hydrogen fuel cell vehicle (HFCV) systems exhibit lower efficiency [22]. Consequently, achieving net-zero emissions with HFCV integration requires a larger 4 kW wind turbine or an additional 35.6 m^2 of PV capacity [22]. Furthermore, recent studies have highlighted novel devices for the building sector, such as micro-trigeneration systems based on solid oxide fuel cell technology fueled by green hydrogen. These systems can simultaneously meet cooling and heating demands while providing electricity to buildings via fuel cells [23]. Pugsley et al. [24] compared the performance of combined heat and power (CHP), combined cooling, heating, and power (CCHP), and building-integrated photovoltaic-thermal (BIPV/T) systems across different scenarios. Their study identified that CHP, CCHP, and BIPV/T systems exhibit optimal adaptability in cold, temperate, and tropical climates, respectively. The authors highlighted the advantages of polygeneration systems in high-density urban areas, particularly in energy-intensive buildings such as hospitals, data centers, and commercial complexes. Polygeneration systems effectively reduce peak power demand and enhance energy utilization efficiency through waste heat recovery [24].

With the accelerating pace of urbanization and the increasing urgency of low-carbon transitions, the building sector faces significant challenges in integrating clean energy to mitigate environmental impacts. Among various alternatives, hydrogen has emerged as a promising pathway for deep decarbonization in buildings due to its high energy density and zero-carbon emission characteristics. A range of studies on hydrogen applications in the building sector worldwide have highlighted efforts in developed European economies to harness hydrogen's potential in this domain. Meanwhile, many researchers have explored the applications and benefits of hydrogen in buildings within emerging economies such as China, India, and Iran (see Table 1) [25–28]. However, the widespread adoption of hydrogen in buildings remains constrained by significant technical, economic, and policy barriers. Many researchers have identified challenges related to the economic viability of hydrogen storage systems, the overall efficiency of hydrogen-based heating solutions, the broader environmental impacts of these systems, and regional policy perspectives [29–32]. Current academic reviews on hydrogen applications in the building sector remain insufficient and fragmented. Existing studies are limited in number and depth, often treating the topic as a peripheral or supplementary subject rather than a focused research area. Ghisellini et al. [33] reviewed power systems driven by renewable energy and green hydrogen; however, their discussion is confined to scattered examples and a few case illustrations, lacking dedicated sections on building-related applications and offering minimal technical detail. Wang et al. [34] explored the potential of combined heat and power (CHP) systems in buildings, covering scenarios such as residential and public facilities. Nevertheless, the study falls short in providing a sufficiently detailed classification of building types and a robust set of case analyses, making it inadequate for establishing a comprehensive knowledge framework to track current research trends in hydrogen applications within the building sector. Kaabinejadian et al. [35] reviewed the thermal uses of hydrogen in buildings, drawing on cross-regional case comparisons and addressing technical configurations, system architectures, economic assessments, and control integration. It is important to note, however, that their work focuses exclusively on residential heating applications, omitting other building types as well as cross-sector integrations such as building-to-transport energy systems, thereby lacking a horizontal perspective.

A comprehensive understanding of hydrogen technology deployment models, infrastructure development requirements, and policy support frameworks in the building sector is critical for architects, engineers, policymakers, and all stakeholders involved in urban sustainability. While the low-carbon transition of the building industry has gained considerable attention, systematic reviews of how hydrogen applications in buildings can be reshaped remain limited. Further research is needed to identify the persistent uncertainties in technological, policy, and implementation pathways across different countries as they advance hydrogen adoption in buildings, as well as to explore strategies for accelerating the sector's transition toward a hydrogen-driven, low-carbon future. This study focuses on technological solutions for hydrogen applications in buildings, systematically reviewing existing implementation pathways, potential impacts and feasibility, and applicability across different regional and policy contexts. Through a comprehensive assessment of relevant literature, this study not only reshapes the knowledge framework but also proposes directions for future research and technological innovation, aiming to accelerate the evolution of the building sector toward a sustainable hydrogen energy system.

To strengthen the study's internal logic, we structure the review around an evidence-to-inference chain that links: (i) technology configurations and operational roles of hydrogen in buildings (storage, CHP/CCHP, microgrids, hybrid heating); (ii) performance metrics reported in original studies (efficiency, capacity, consumption, lifespan); (iii) system-level integration pathways with renewables, thermal networks and mobility (e.g., V2B/V2G); (iv) techno-economic feasibility under explicit boundary conditions (climate, building typology, demand profiles, hydrogen price, grid carbon intensity); (v) environmental outcomes and policy–societal enablers. This chain underpins how we assemble and interrogate the PRISMA-derived evidence base, and it explains why later sections move from descriptive mapping to integrative assessment of implementability.

This review makes three contributions aligned to the above framework. First, it constructs an evidence map of hydrogen deployment archetypes in buildings (Table 1), locating each study in terms of methods, typologies and geographies to expose concentration and gaps. Second, it integrates technical, economic and environmental dimensions into a coherent assessment lens, connecting reported metrics to system-level implications for buildings and urban energy systems. Third, it synthesizes implementability conditions—when hydrogen is a primary option versus a complementary buffer to electrification—and translates these into policy priorities and research agenda for technology development (Sections 4 to 6). This paper is structured into six main sections. Section 1 introduces the research topic and outlines the contextual background. Section 2 details the methodology employed for the literature review, including the selection and screening procedures. Section 3 critically examines the current state of research, approaches, reported benefits, and results. Section 4 identifies key barriers and challenges associated with the topic. Section 5 discusses the feasibility of implementation based on the reviewed evidence. Finally, Section 6 synthesizes the findings and provides recommendations for future research directions. Fig. 1 shows the framework of the review.

2. Material and methods

To ensure that the research objectives addressed in the systematic review are comprehensively examined, this study applies the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to structure the research process, specifically for the collection of evidence and information on research trends. PRISMA is a standardized framework for reporting systematic analyses, first introduced in 2009 and later updated in 2020 (PRISMA 2020) to enhance the transparency, reproducibility, and clarity of systematic review procedures [36]. Initially, PRISMA was widely applied in the medical and health sciences but has since been increasingly adopted across multiple disciplines to enhance the transparency and rigor of systematic reviews. These disciplines include the built environment [37], the energy sector [38], linguistics [39], and agronomy [40], among others. The adaptability of this systematic review protocol reflects the broader disciplinary demand for optimizing research paradigms and standards. Moreover, it underscores PRISMA's inclusiveness as a reliable method for

Table 1
The summary of the research approaches applied in reviewed studies.

Reference	Location	Study Type	Research Method	Building Type	Main Findings
[28]	Iran	Simulation study	Dynamic modelling (TRNSYS) Steady-State Modelling (EES: Engineering Equations Solver)	Educational buildings	Blending green hydrogen with syngas improves SOFC efficiency and lowers CO_2 emissions, providing a sustainable energy solution for medium-sized buildings.
[25]	China	Simulation study	System Dynamics-Building Life Cycle Carbon Emission , SD-BLCA	Existing buildings; Reconstructed buildings; Green buildings; Zero energy buildings, ZEBs	Beijing's construction sector aims for carbon neutrality by 2050. This relies on renewable energy use and green building retrofits during operation.
[61]	Hong Kong	Simulation–optimization study	System Modelling and Simulation (TRNSYS 18) Multi-objective optimization (Non-dominated Sorting Genetic Algorithm II (NSGA-II))	High-rise residential building	Hydrogen storage offers wider applicability, while batteries suit large-scale renewables. Hydrogen systems recover waste heat with over 95 % efficiency, improving energy use.
[62]	Netherlands	Experimental–simulation study	Field Test Simulation Study (MATLAB)	Residential building	Hydrogen FCEVs can support all-electric homes via V2G, reducing grid reliance, especially at night and in winter. As hydrogen prices fall, FCEV2G becomes viable.
[26]	China	Simulation–optimization study	System modelling (GUROBI optimization solver; MATLAB)	Residential building	An optimized rooftop PV system with electricity-hydrogen-thermal storage ensures stable supply and cuts grid reliance. Hydrogen handles seasonal gaps.
[67]	Italy	Simulation study	0-D dynamic simulation modelling (MATLAB/Simulink)	Educational buildings	Batteries and hydrogen storage manage seasonal PV fluctuations, prioritizing electricity use and storing excess as hydrogen. Larger batteries or PV ensure energy balance.
[27]	India	Simulation–optimization study	Hybrid Optimization Model (HOMER)	Residential building	Off-grid PV with hydrogen offers high reliability, zero emissions, and better urban sustainability.
[6]	Spain, France, Portugal	Simulation–optimization study	Simulation modelling and optimization (HOMER Pro)	Residential building	In solar-rich areas like Portugal, renewable hydrogen systems (S3) become technically viable.
[59]	Australia	Simulation–optimization study	Mixed Integer Linear Programming (MILP) Optimization Models	Residential building	For buildings lacking local renewables and with high heating needs, hydrogen is preferable, viable below AUD 4/kg.
[65]	United Kingdom	Decision-analytic study	PESTLE Analysis Multi-Criteria Decision Analysis (MCDA)	Residential building	Fuel cells are efficient and green but costly with slow startup. It holds the most promise for homes, pending cost and startup improvements.
[44]	Nigeria	Simulation–optimization study	Multi-objective Optimization (Non-dominated Sorting Genetic Algorithm (NSGA-II)) Innovative battery degradation modelling	Residential building	When LPSP >1 %, battery ESS is ideal; for LPSP ≤1 %, battery-hydrogen hybrids reduce outages.
[68]	Italy	Experimental study	Experimental studies of the system (field deployment, monitoring, data sampling)	Residential building	SOFC delivers 45 % electrical and up to 93 % total efficiency at rated power, with stable high-load performance.
[66]	Canada	Optimization study	Mixed Integer Linear Programming (MILP) Optimization Algorithm (Python/Pulp)	Residential, educational buildings and medical facilities	MILP optimizes systems with renewable and hydrogen fuel cells, cutting costs and emissions by managing energy flow and feeding surplus to the grid.
[32]	United Kingdom	Empirical study	Online questionnaire survey Partial Least Squares Structural Equation Modelling (PLS-SEM)	Residential building	In the UK, public acceptance of hydrogen homes depends mainly on safety, performance, and production methods.
[63]	Iran	Simulation–optimization study	Dynamic Simulation (TRNSYS) Multi-objective Optimization (TOPSIS)	Residential building	The system cuts CO_2 emissions and offers a 5–6.5-year payback, proving its economic and environmental value.
[60]	Japan	Simulation study	Bottom-Up Simulation Modelling (TREES: Total Residential End-use Energy Simulation)	Residential building	Seasonal PV gaps need hydro or hydrogen storage. Insulation and heat pumps are vital. Detached homes boost PV but hinder urban density.

(continued on next page)

Table 1 (*continued*)

Reference	Location	Study Type	Research Method	Building Type	Main Findings
[31]	United Kingdom	Sustainability Modelling Study	Life Cycle Assessment (ISO 14040/14044; ReCiPe 2016 v1.1)	Residential buildings; services buildings	Hydrogen boilers cut carbon, with SMR + CCS become more sustainable. Adoption needs CCS and infrastructure upgrades.
[73]	United Kingdom	Mixed-methods assessment study	Spatial resolution analysis Scenario Analysis Expert Consultation	Residential buildings	This study compares hydrogen, electrification, and hybrid heating paths for urban decarbonization, highlighting the need for local adaptation.
[64]	N/A	Techno-economic modelling study	Techno-Economic Analysis (TEA) Life Cycle Cost Analysis (LCCA) Scenario Analysis	NA	Hydrogen is most effective for retrofitting existing homes when its price drops below 5.40 USD/kg; repurpose gas networks offering a promising delivery route.
[74]	Europe	Optimization study	Open Energy Systems Modelling (PyPSA-Eur-Sec) Myopic Optimization	N/A	High carbon pricing is key to cutting fossil fuel use.
[72]	Switzerland	Optimization study	Energy System Optimization Model (Swiss-Calliope)	N/A	Switzerland's winter shortages stem from solar and hydro limits. Gas, Alpine PV, wind, and renewable methane improve stability.
[45]	Italy	Optimization study	Mixed Integer Linear Programming (MILP) Optimization Models	Residential buildings	Off-grid case studies show a hydrogen-battery-PEMFC setup is more cost-effective than standalone systems.
[46]	Canada	Simulation study	Simulation Design	Residential buildings	Using surplus power to make and store hydrogen, then generating electricity with fuel cells when needed. With 43 % efficiency, shows hydrogen's value.
[76]	Iran	Simulation–optimization study	Simulation modelling and optimization (HOMER) Techno-economic analysis	Rural residential building	A hybrid system with hydrogen storage cuts energy loss to less than one-sixth.
[70]	Netherlands (laboratory location)	Experimental study	Experimental Setup	N/A (Simulation tests in a laboratory environment)	Hydrogen scooters serve as transport and mobile power sources via V2G and V2L.
[47]	N/A (Simulation studies)	Simulation study	Integrated Systems Modelling	Residential buildings	Integrating PV/T, PEC, and PEMFC meets residential power, hot water, hydrogen, and wastewater needs.
[71]	Saudi Arabia	Simulation–optimization study	System Modelling Analysis of Energy Management Strategy Techno-Economic-Environmental Optimization	Residential buildings	Developed an off-grid hybrid system meets annual home power needs, using surplus to produce hydrogen for vehicles.
[48]	N/A	Simulation–optimization study	Mixed Integer Linear Programming (MILP) System modelling Monte Carlo Simulation	N/A (Residential area)	Demand response shifts loads and manages vehicle energy use, meeting demand and generating revenue.
[49]	United States	Simulation study	Simulation modelling (TRNSYS 18)	Residential buildings	Surplus PV makes hydrogen; vehicles supply power via V2G. Hydrogen use drops to 1.2 kg/vehicle, annual integrated energy costs cut 38.9 %.
[50]	Turkey	Experimental–computational study	Load-driven System Design Energy Flow & Balance Modelling System Integration & Control Programming Real-world Implementation & Evaluation	Mobile House (off-grid)	PV and wind power a self-sustaining system, with surplus (2510 kWh vs. 1550 kWh) used for hydrogen backup.
[51]	Brazil	Simulation study	Simulation study (HOMER)	Community buildings (Residentials, school, clinic)	In the Brazilian Amazon, PV-electrolysis-FC systems enable off-grid power but are costly. PV + battery remains the most practical, cost-effective option.
[69]	United Kingdom	Analytical study	Theoretical integration analysis based on measured data	Residential buildings	In small-scale use, SOFC+liquid desiccant AC systems reach 68–71 % efficiency, 9–15 % higher than SOFCs, and cut carbon emissions by ~50 %.
[52]	Japan	Experimental-optimization study	Experimental set up (Hydro Q-BiC™)	Small low-rise building (Zero Emission Building Validation Platform)	Optimizing hydrogen systems with MHHS boosts efficiency and heat recovery. Fuel cell heat replacing external heating.
[53]	Japan	Experimental-optimization study	Experimental set up	Small low-rise building (Zero Emission Building Validation Platform)	A compact PEM-TiFe hydrogen system enables zero-carbon small buildings. Fuel cell heat powers TiFe desorption without external input.
[54]	United Kingdom	Experimental study	System Modelling and Simulation Experimental set up	Residential buildings	The system showed 52 % round-trip efficiency, with PEM electrolyzer at 66 % and fuel cell at 79 % in CHP use.

(*continued on next page*)

Table 1 (*continued*)

Reference	Location	Study Type	Research Method	Building Type	Main Findings
[55]	United States	Experimental study	Experimental set up	Residential buildings	Electrolyzers and fuel cells perform well under solar and demand shifts; fuel cells with better performance at higher temperatures.
[56]	Italy	Simulation study	System Modelling and Simulation	Public buildings	With PV at 120 % of annual demand and hydrogen generator's rated power is 60 % of the PV systems., buildings reach 77 % self-sufficiency.
[57]	Mexico	Simulation study	System Modelling and Simulation	Residential buildings (mobile sustainable house)	A PV–hydrogen system powers a 24 m^2 mobile home year-round, meeting 1825 kWh off-grid with ~65 % mixed efficiency.
[58]	Spain/United Kingdom	Simulation study	System Modelling and Simulation (ODYSSEY)	Off-grid homes; isolated telecom facility	Under low-light conditions, the hydrogen-PV- battery solution is preferable to the battery-only solution.

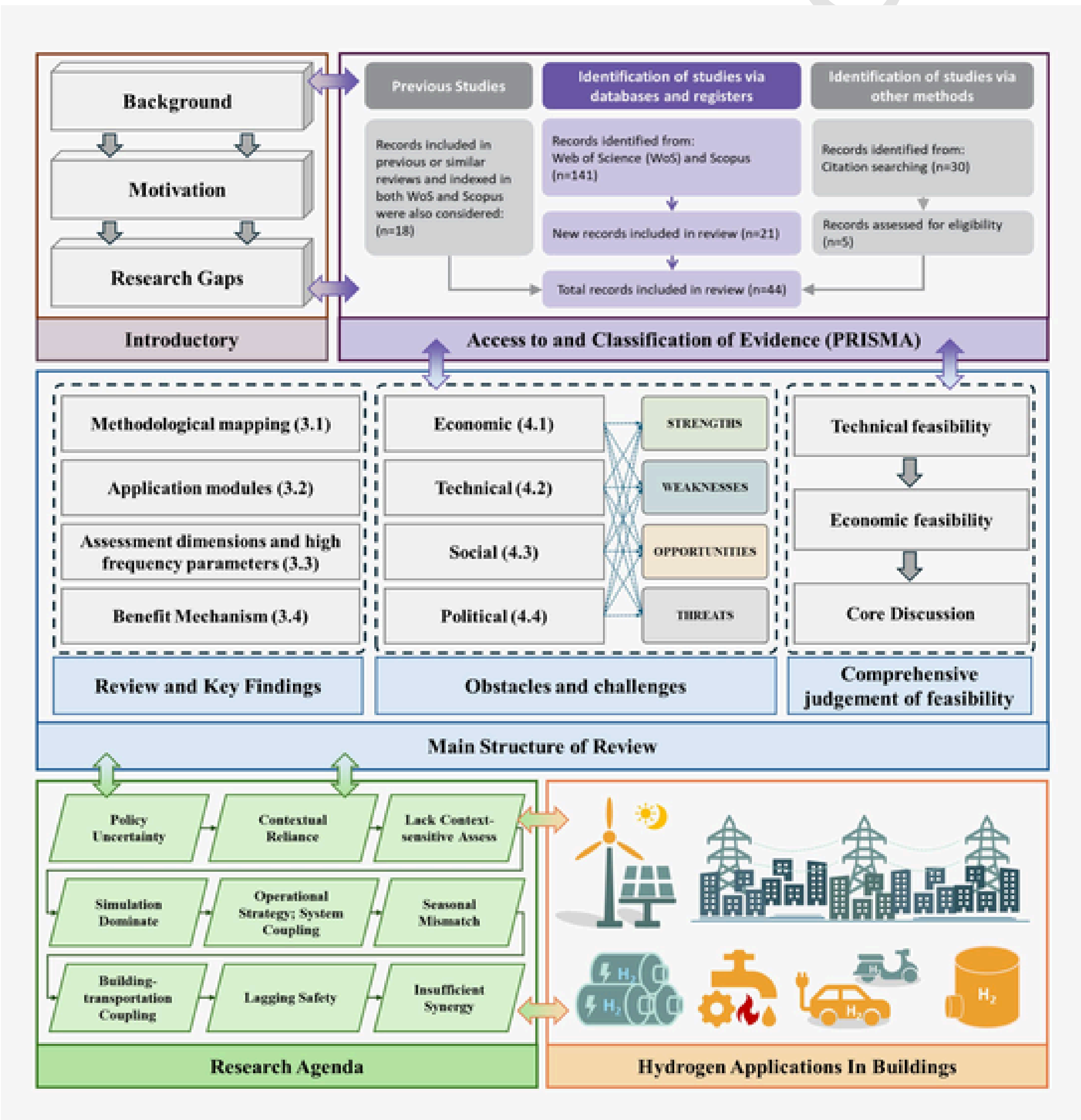

Fig. 1. Systematic framework of the review.

cross-disciplinary knowledge integration, demonstrating its capacity to be embedded within various empirical analysis frameworks.

2.1. Selection of sources and search criteria

Given the nature of this study as a systematic review, its primary objective is to identify critical issues within the selected field and provide a comprehensive overview. Launched in March 2025, the first stage of this review involved data collection through a strategically designed search protocol, with a primary focus on comprehensive data retrieval from two authoritative databases: Web of Science (WoS) and Scopus. WoS and Scopus were selected as the core search engines due to their extensive coverage of peer-reviewed academic journals across multiple disciplines and their advanced search functionalities. These platforms support customizable queries based on parameters such as publication date, research topic, and document type. In addition, they offer advanced search tools, including Boolean operators (e.g., AND, OR), enabling more precise keyword identification. The search protocol was designed to balance semantic breadth and precision. Core thematic pillars—such as "hydrogen technologies in the building sector" and "hydrogen for net-zero buildings"—were used to guide the search. Boolean logic was applied to link multiple key concepts using conjunctions like AND. For example, search strings such as *hydrogen AND technologies AND in AND building* and *hydrogen AND for AND net AND zero AND buildings* were utilized to ensure the retrieved literature simultaneously addressed several critical dimensions of the topic. Both databases also provide detailed metadata for each publication, including document type, citation count, title, abstract, and author information, a total of 141 preliminary documents were found. This facilitates a rapid understanding of the literature landscape and the intellectual structure of the field. Compared to other information sources, WoS and Scopus are widely recognized for their credibility and commitment to high-quality academic content, which is essential for reassessing and updating knowledge related to the current status of the specified industry.

2.1.1. Methodological rationality: Why PRISMA for this review

First, in domains that combine experiments, numerical simulations, field trials and techno-economic assessments, PRISMA's structured items enhance transparency, reproducibility and interpretability by requiring explicit eligibility criteria, comprehensive search reporting, study-level descriptors, risk-of-bias assessments and transparent synthesis methods, features that mitigate reporting ambiguity in heterogeneous evidence bases [41]. Second, PRISMA embeds reliability indicators that are critical for interdisciplinary reviews: prespecification of questions and inclusion and exclusion rules, use of duplicate screening with documented reconciliation, auditability through a flow diagram and a standardized checklist that facilitates external appraisal of reporting completeness [42]. Automation can assist parts of the workflow but does not replace reporting obligations; recent methodological overviews in *Journal of Clinical Epidemiology* document where semi-automation is mature (e.g., abstract screening) and where it remains developing [43]. Third, PRISMA is a reporting guideline that prioritises transparency, completeness and reproducibility rather than prescribing discipline-specific methods; its checklist items are applicable beyond health to many review objectives and designs, making it suitable for synthesizing heterogeneous, cross-field evidence (e.g., at the interface of buildings, energy systems and policy) [41,42].

2.2. Eligibility and ineligibility system

This review aims to conduct a systematic analysis of hydrogen technologies in the built environment, focusing on research methodologies, key performance indicators, specific applications, associated benefits, and prevailing challenges. To ensure academic rigor and relevance, strict inclusion criteria were established to identify original research articles from academic databases. The goal is to systematically examine and reconstruct technical insights in the field while comprehensively assessing the feasibility of hydrogen technologies, along with their economic, environmental, and policy-related implications and impacts.

In addition, this study further investigates the challenges associated with hydrogen applications in building heating, power generation, and energy storage systems. By identifying the key drivers behind the development of hydrogen-enabled buildings, this review seeks to offer an integrated overview and forward-looking guidance for future research, large-scale deployment, and practical adoption of hydrogen technologies in the architecture and construction sectors.

Eligibility criteria

Research Relevance: All selected studies must focus specifically on hydrogen technologies and their applications within the built environment. Studies centered on hydrogen use in other sectors, such as transportation or industry, are excluded from consideration. Type of Studies with Review Value: Only original research providing primary data on hydrogen technologies in the context of buildings is eligible for systematic review. This includes experimental studies, field investigations, and simulation-based research. Consequently, secondary literature such as review articles within the same domain is not included in the analysis. Availability of Sources: All included publications must be accessible in full-text format through the Web of Science and Scopus databases. Moreover, only studies published in English are considered.

Ineligibility criteria

Potentially Redundant Literature Types: Review articles focused on hydrogen technologies in the building sector are excluded from the dataset. Including such literature may overlook the identification and synthesis of recent original findings, potentially resulting in redundancy and limited contribution to current academic discourse.

Studies Lacking Substantive Analytical Value: Publications failing to offer substantive examinations regarding hydrogen utilization within constructed environments are omitted from consideration. This exclusion specifically applies to research absence of empirical results, applicable implementations, or well-defined obstacles, as such studies demonstrate limited contribution to knowledge advancement.

Potentially Outdated Studies: Research published more than 15 years prior to the review (i.e., before 2010) is not considered, to ensure that the analysis reflects the most recent developments, trends, and technological progress in the application of hydrogen within the building sector.

2.3. Screening procedure and final selection

During the actual retrieval process, a total of 141 preliminary records were obtained, with each title or abstract containing one or more occurrences of the predefined search keywords (Fig. 2). These initial studies underwent rapid screening at the title and abstract level to assess relevance, based on keyword presence. To refine the dataset with a focus on recency and thematic alignment, two preliminary exclusion criteria were applied: (1) studies published before 2010, and (2) papers whose titles and abstracts were clearly misaligned with the core topics of hydrogen technologies in the building sector or hydrogen applications in net-zero buildings. Following this filtering stage, 51 publications were identified as potentially valuable and included in the final analysis. In the subsequent screening phase, a secondary review of titles and abstracts was conducted, with a narrowed focus on the core theme of "hydrogen applications in the building sector." This process led to the exclusion of 17 studies that were clearly misaligned with the research topic (Reason 1). Next, non-original research such as review articles was removed from the dataset to concentrate solely on peer-reviewed journal publications presenting primary data. This step resulted in the exclusion of an additional 13 records (Reason 2). As a result, the remaining 21 studies collectively address both the intersection of current technological developments and the practical application of

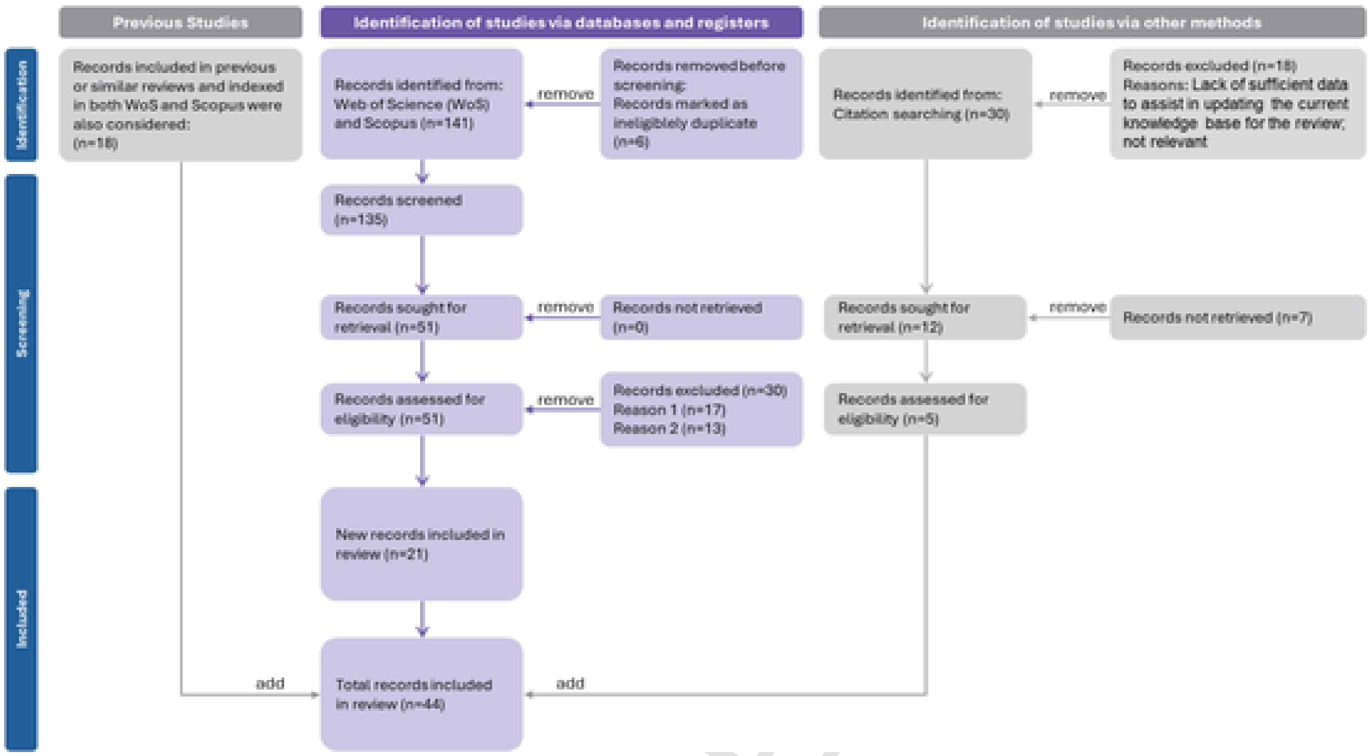

Fig. 2. PRISMA flowchart of systematic review.

hydrogen in buildings. These studies offer empirical evidence and conceptual insights into the multifaceted challenges surrounding hydrogen integration in the built environment. To further reinforce the rigor and comprehensiveness of this review, 18 additional original studies from prior review in the same field and 5 grey literature that met the inclusion criteria of this paper were incorporated.

In the further stage of the study, a multidimensional analytical framework was developed to systematically categorize and interpret the 44 selected publications. Moving beyond a basic categorical framework, this classification system seeks to elucidate the fundamental research value of individual studies. Its focus lies in assessing their relevance to decarbonizing buildings via hydrogen and achieving net-zero carbon objectives, with specific emphasis on the practical deployment and enhancement routes for the involved technologies. This approach not only clarifies the technological priorities across different application types but also enables the identification of associated research methodologies, reported benefits, implementation barriers and challenges, as well as the frequency and trajectory of key parameter dimensions observed across the literature.

3. Review and findings

3.1. Summary of research approaches in building hydrogen application

This section primarily aims to present and review the research pathways adopted in relevant original studies, summarizes research methods and key findings from studies on hydrogen technology applications in the building sector worldwide. To maintain coherence with the research framework, we read Table 1 not merely as a catalogue of methods, but as a structured map from configurations and metrics to system-level roles and feasibility claims later synthesized in Sections 4 to 5. The columns of Table 1 include research sources, study locations, research methods, building types involved, and major findings. The research methods column outlines the specific methodological approaches adopted in various studies, including multiple simulation and modelling techniques such as dynamic modelling, multi-objective optimization, system modelling, mixed-integer linear programming (MILP), partial least squares structural equation modelling (PLS-SEM), analytic methods and open energy system modelling. This information facilitates a comparative analysis of hydrogen-related technologies and research methodologies across different building types and locations globally. Additionally, it enables further assessment based on the key findings of each study. The content in the research methodology column of the table is explicitly stated, with parentheses used to provide additional details on specific methodological pathways and platforms. The precision of the table's content largely depends on the completeness of the original sources, which may result in variations in data accuracy across different entries. The methods employed in studies on hydrogen applications in the building sector are crucial for understanding the extent of hydrogen integration and its feasibility in this domain. The diversity of research methods reflects the various approaches to hydrogen adoption in buildings and the level of attention the topic has received.

Table 1 provides a detailed overview of the research methods, objectives, and findings associated with different locations, revealing key insights as well as similarities and differences among these original studies. Specifically, many of the sources compiled in the table focus on simulation modelling and further strategic optimization of hydrogen technology applications in the building sector. Many of these studies explore cross-sectoral integration, such as the role of hydrogen-powered vehicles as core components of hydrogen-based building energy systems, which play a significant role in achieving emissions reduction and sustainability in the built environment. This suggests that research dedicated to assessing the practical implementation of hydrogen technologies in existing buildings remains limited. The application of hydrogen in the building sector is still not widely adopted, with much of the discussion centered on its potential benefits rather than its real-world deployment. Although the studies included in the table cover a global range of regions, the research remains predominantly concentrated in Europe. As a result, the findings may not be broadly generalized for understanding the actual state of hydrogen applications and contributions in the building sector across different geographical and economic contexts.

It is important to note that **N/A** in the table typically indicates that certain information or data could not be retrieved directly or indirectly from the respective sources. Additionally, it may signify that the study's data and findings are applicable to a broader set of scenarios or systemic contexts, demonstrating a generalized paradigm. Therefore, despite the presence of missing data, the table provides a snapshot of the current global research landscape on hydrogen applications in buildings. From another perspective, the absence of certain data may highlight its potential representativeness in real-world studies, indicating areas where further research and validation are needed.

3.2. Analysis of hydrogen applications in the building sector

3.2.1. Hydrogen as an energy storage pathway for buildings

Hydrogen fuel cell systems highlight the energy storage role of hydrogen in buildings. Maestre et al. [6] evaluated the feasibility of renewable hydrogen-based systems (RHS) for decarbonizing social housing in the SUDOE region (south-western of Europe), encompassing Spain, France, and Portugal. The research identified Vila Nova de Gaia in Portugal as the most suitable location for RHS deployment due to its high solar radiation and elevated electricity prices, making renewable hydrogen more competitive. The study also highlighted that hydrogen-based systems offer complete energy independence, providing a sustainable, zero-carbon energy solution for buildings. However, a trade-off exists in energy storage selection: regions with higher battery storage capacities require less hydrogen storage, whereas areas with smaller battery capacity must rely on larger hydrogen fuel cells to meet energy demands [6]. Adeyemo and Amusan [44] conducted a multi-objective optimization study on an off-grid photovoltaic–battery–hydrogen hybrid renewable energy system (HRES) for a net-zero detached residential building in Lagos, Nigeria. The study evaluated the performance of battery-fuel cell hybrid storage configurations based on three key optimization objectives: annualized system cost (ACS), loss of power supply probability (LPSP), and potential energy waste probability (PEWP) [44]. These configurations were compared against single-battery storage setups to determine the economic feasibility of hybrid storage under different operating conditions. Fig. 3 shows the hydrogen application in buildings.

Baldi et al. [45] proposed a hybrid system integrating solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC). In this configuration, hydrogen-rich exhaust gas produced by the SOFC is purified and stored, subsequently being converted back into electricity via PEMFC during peak demand periods. A combined cooling, heating and power (CCHP) system for buildings based on the SOFC-PEMFC hybrid can simultaneously deliver electricity and thermal energy to satisfy heating and hot water requirements. Similarly, Sorgulu and Dincer [46] observed that when the electricity generated by wind turbines and solar steam turbines exceeds the real time energy demand of building communities, for example during sunny conditions or periods of high wind speed, the surplus power can be converted into hydrogen through electrolysis, which provides a means of medium energy storage. Karaca and Dincer [47] highlighted the dual role of hydrogen in the building sector as both an energy storage medium and a tool for environmental remediation. Hydrogen is utilized as an energy carrier to store solar energy generated during the day, enabling electricity supply during nighttime hours. Specifically, the system employs a photoelectrochemical (PEC) reactor that harnesses solar energy to drive water-splitting reactions for hydrogen production during the day. The hydrogen is stored in tanks and later supplied to a proton exchange membrane fuel cell (PEMFC) at night, where it undergoes electrochemical conversion to generate elec-

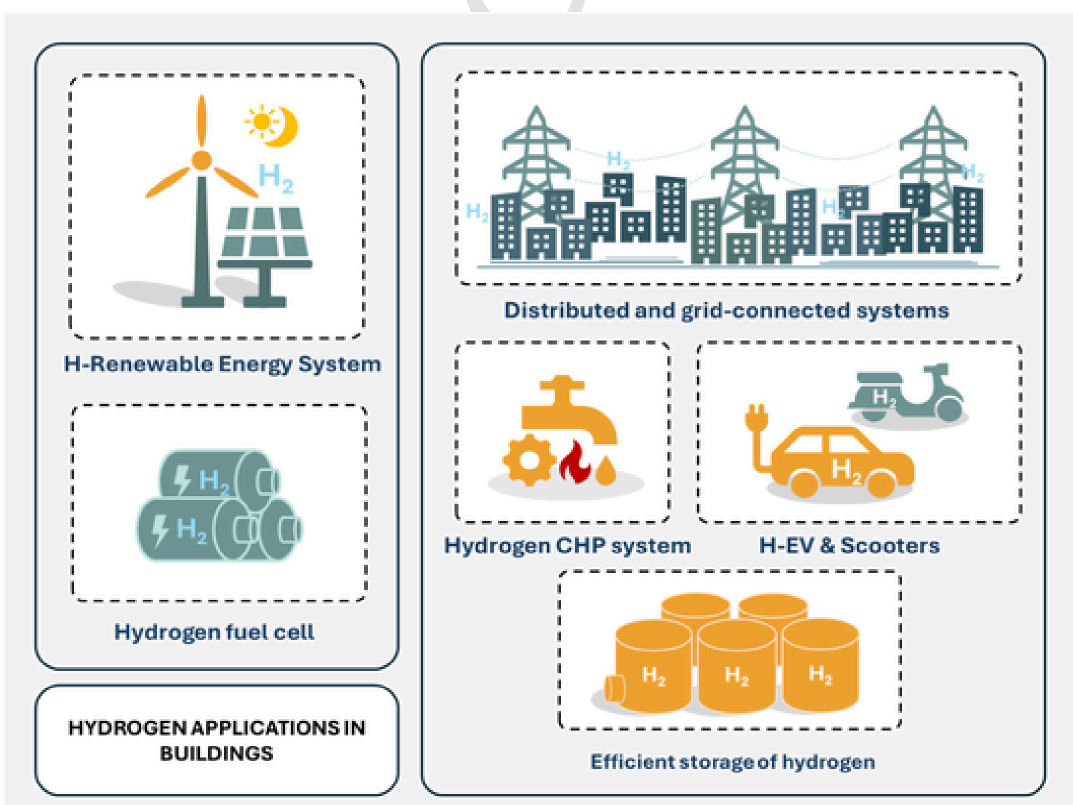

Fig. 3. Summary of the hydrogen applications in buildings.

tricity for residential nighttime demand. In addition, the PEC reactor incorporates a proton exchange membrane structure that integrates the hydrogen energy system with water recycling processes, allowing for the simultaneous treatment of domestic wastewater in residential applications [47].

Xu et al. [48] identified hydrogen as a key energy storage medium within the system. They proposed an innovative integrated framework in which, when photovoltaic (PV) power generation exceeds the instantaneous electricity demand of residential areas, the surplus electricity is converted into hydrogen via a proton exchange membrane (PEM) electrolyzer and stored in a hydrogen tank (HT). This process enables both intraday and seasonal energy shifting, providing a stable and long-term storage solution for buildings while effectively addressing the intermittency of renewable energy supply. Furthermore, Xu et al. [48] noted that the system is capable of refueling hydrogen vehicles (HVs), thereby not only meeting the energy demands of the building itself but also promoting deep integration between the building energy system and the transportation energy infrastructure. He et al. [49] also emphasized the critical role of hydrogen as a supplementary energy carrier in building energy supply. During periods of insufficient photovoltaic (PV) generation, hydrogen vehicles (HVs) can convert stored hydrogen into electricity and feed it back into the building's power system to compensate for energy shortfalls. In their study, He et al. [49] designed a dual-stage heat recovery system to improve the energy efficiency of hydrogen-related equipment. Waste heat generated during the operation of the electrolyzer and PEM fuel cells (PEMFCs) is efficiently recovered and utilized via a cooling system to supply domestic hot water (e.g., for bathing).

Moreover, numerous studies have identified hydrogen as an effective medium for energy storage and utilization in energy systems [50–58]. Collectively, these studies demonstrate that hydrogen can not only store surplus electricity effectively during periods of power overproduction but also release energy flexibly through fuel cells or thermochemical conversion during times of peak demand, thereby enhancing the stability and dispatchability of the entire energy system. Hydrogen is widely regarded as a bridging vector across electricity, gas, and thermal systems, with its ability to mitigate grid fluctuations and demand-side uncertainties becoming particularly critical in renewable-integrated scenarios. In addition, hydrogen's potential as a cross-sectoral energy carrier has been broadly recognized. Compared with conventional storage technologies, hydrogen offers greater system scalability, making it suitable for a wide range of spatial scales, from microgrids to distributed energy systems.

Vecchi et al. [59] applied the systematic analysis of cost-effective decarbonization pathways for residential energy supply under temperate and subtropical climate conditions. The analysis encompassed both detached houses and apartment buildings in Australia, incorporating various energy supply technologies, including electrification, natural gas, and hydrogen. The research further assessed the economic feasibility of grid transmission, natural gas, hydrogen, and distributed renewable energy (e.g., PV + storage) in achieving net-zero emissions. Shimoda et al. [60] utilized the Total Residential End-use Energy Simulation (TREES) model to project Japan's residential energy demand and decarbonization potential by 2050. Their findings indicated that 26 % of residential energy demand must rely on non-battery storage solutions, with 22 % requiring long-term storage solutions, such as hydrogen energy, to achieve seasonal energy supply-demand matching. Specifically, during periods of excess photovoltaic (PV) generation, electrolysis technology can convert surplus electricity into stored hydrogen, which can later be utilized in fuel cells during winter, when PV generation is insufficient, to supply electricity for buildings. Similar applications have also been highlighted in many studies [26,61–64]. Furthermore, Shimoda et al. [60] emphasized the critical role of hydrogen in Japan's energy structure. If PV becomes the dominant renewable energy source, similar electricity supply-demand imbalances will arise in other sectors, including commercial, industrial, and transportation industries, and grid-based regulation alone may be insufficient to effectively address these challenges. Therefore, in the absence of other stable renewable energy sources such as wind, solar, or biomass, hydrogen is regarded as a key technology for achieving energy balance in the residential sector.

3.2.2. *Hydrogen as a sustainable energy solution for buildings*

Hydrogen has also been explored as a sustainable energy source for micro-combined heat and power (micro-CHP) systems and hybrid renewable energy systems (HRES). Khan and Gohari Darabkhani [65] assessed the feasibility and challenges of various micro-CHP technologies in residential applications, while multi-criteria decision analysis (MCDA) was employed to identify the most suitable technological pathway for residential buildings. A key focus of the study was evaluating the applicability of hydrogen in micro-CHP systems and quantifying the impact of different fuel sources on system efficiency and carbon emissions. Hemied and Gabbar [66] modelled and optimized deployment strategies for hybrid renewable energy systems (HRES) comprising wind power, photovoltaics (PV), hydrogen fuel cells, and hydrogen storage. Their study aimed to identify pathways for minimizing electricity costs and reducing greenhouse gas emissions through intelligent optimization algorithms that manage and regulate renewable energy flows. Using hourly building energy consumption data from the Durham region of Ontario, Canada, the study compared system performance under both grid-connected and off-grid scenarios. Xin et al. [25] employed a system dynamics-based building life cycle carbon assessment model to dynamically forecast carbon emission trends in Beijing's building sector. Green hydrogen can be utilized for heating, power generation, and other energy demands, reducing reliance on fossil fuels, particularly in high-density urban environments. In construction and demolition, hydrogen serves as an alternative energy source for construction machinery and equipment, such as excavators and cranes, as well as for demolition operations, replacing traditional diesel or other fossil fuels to cut carbon emissions [25]. Furthermore, the integration of hydrogen in construction processes has the potential to reduce carbon emissions by approximately 0.7 Mt. (million tons) [25], providing a practical and viable pathway for the decarbonization of the building sector.

3.2.3. *Hydrogen integration in microgrid systems and off-grid applications*

In regions with limited grid access or high renewable energy potential, hydrogen-based microgrid solutions are gaining traction. In India, Mohammad and Iqbal [27] simulated and optimized various microgrid systems. A key focus was on photovoltaic (PV) systems integrated with hydrogen, where the researchers innovatively proposed a microgrid framework combining proton exchange membrane fuel cells (PEMFC) with lithium-ion batteries. Brancaleoni et al. [67] employed zero-dimensional (0-D) simulation modelling to analyze an off-grid sustainable energy system powered by solar and hydrogen energy. The research focused on a university building complex in Bologna, Italy, exploring how solar and hydrogen energy can enable complete grid independence. Additionally, different proton exchange membrane (PEM) electrolyzer capacities were evaluated to accommodate seasonal energy surpluses and shortages. A fuel cell (FC) model was also developed to facilitate hydrogen-to-electricity conversion. Based on the findings, two optimization strategies were proposed: increasing battery storage capacity or expanding PV system capacity [67].

De Masi et al. [68] conducted a systematic experimental characterization of the operational performance of a 1 kW-class solid oxide fuel cell (SOFC) in a real residential environment. The research team installed the SOFC in a near-zero energy building (nZEB) in southern Italy and primarily focused on evaluating the feasibility and performance of SOFCs in residential applications. Additionally, the study evaluated the synergistic operation of the SOFC with a photovoltaic (PV) system, battery energy storage, and thermal water storage, assessing its off-grid operation potential under different solar irradiation conditions [68]. Sami et al. [63] highlighted the critical role of hydrogen energy in building power supply. Their study demonstrated that during periods of insufficient solar supply, such as cloudy days or nighttime, proton exchange membrane fuel cells (PEMFCs) can function as a backup power source by converting stored hydrogen into electricity to maintain the power supply of buildings. Under grid-connected operation, surplus electricity can be sold back to the grid during periods of excess generation, while electricity can be purchased from the grid during peak demand periods [63].

3.2.4. Hydrogen in distributed building energy systems

Beyond microgrids, hydrogen is also being integrated into distributed building energy systems, including transportation-energy interactions. Mehr et al. [28] explored a distributed building energy system based on solid oxide fuel cells (SOFCs), utilizing green hydrogen (produced via PV-powered electrolysis) and syngas (obtained through gasification) as fuel sources to supply both electricity and thermal energy for buildings. By increasing the proportion of hydrogen in the fuel mix, the study demonstrated that the system could achieve up to a 58 % reduction in CO_2 emissions [28]. Additionally, the results of on-site hydrogen production from a rooftop photovoltaic system (PV-PEM electrolysis) indicated that even without grid reliance, the system could produce 10,588 kg of hydrogen annually, sufficient to meet the building's energy demands. System efficiency evaluations showed that hydrogen blending improved SOFC power generation efficiency to 29.32 %, while the overall combined heat and power (CHP) system efficiency increased to 63.56 %, highlighting the high application potential of PV-electrolysis integration in building energy systems [28]. Elmer et al. [69] also emphasized that hydrogen, as the primary reactant in the power generation process of solid oxide fuel cells (SOFCs), can significantly enhance the efficiency of SOFCs compared with internal combustion engines, while simultaneously reducing pollutant emissions.

Liu et al. [61] proposed a hybrid renewable energy system integrating photovoltaics (PV), wind power, battery storage, and hydrogen storage to supply electricity to high-rise residential buildings. The hydrogen energy system consists of an electrolyzer, compressor, stationary hydrogen storage tanks, proton exchange membrane fuel cells (PEMFC), and mobile hydrogen fuel vehicles. The study further introduced an integrated building-transportation energy management model, where hydrogen fuel vehicles serve as both daily transportation assets and mobile energy storage units for buildings. When parked in residential areas, PEMFCs within the vehicles can supply power to buildings, enabling vehicle-to-building (V2B) bidirectional energy exchange [61]. Additionally, the study proposed utilizing waste heat from PEMFCs and electrolyzers for building heating, air conditioning reheat, and domestic hot water production, thereby improving overall system efficiency and energy utilization [61]. Robledo et al. [62] demonstrated that integrating hydrogen fuel cell electric vehicles (FCEVs) with vehicle-to-grid (V2G) technology can effectively reduce building dependence on the grid and enhance energy self-sufficiency. In a microgrid simulation, the FCEV2G model reduced the annual electricity imports of buildings by approximately 71 %, confirming the role of hydrogen energy as a supplementary power source for building electricity supply. Moreover, buildings incorporating FCEV2G technology can achieve net-zero energy balance and, in some cases, become positive energy buildings (PEBs), producing more energy than they consume. This capability is crucial for the development of future zero-carbon cities, contributing to more sustainable building energy systems. The study also found that the FCEV2G system's power supply pattern aligns well with building load demand, providing stable electricity output during periods of insufficient solar power generation, such as at night and in winter. This improves the overall availability of electrical energy for buildings [62].

Beyond hydrogen-powered vehicles, the potential for deeper energy integration between buildings and transportation has been further explored. Robledo et al. [70] investigated the use of hydrogen fuel cell electric scooters as auxiliary power sources for buildings, enabling energy coupling between building energy systems and mobile transportation units through vehicle-to-grid interaction technologies. Robledo et al. [70] proposed two primary modes of energy exchange: the first is "Vehicle-to-Grid" (V2G), in which parked hydrogen fuel cell scooters supply electricity back to the building's grid via their onboard fuel cell systems, thereby enhancing the reliability of building power supply during peak demand periods or grid instability; the second is "Vehicle-to-Load" (V2L), in which the scooter directly supplies power to household appliances such as mobile phones, computers, and televisions, functioning as a portable generator to provide electricity locally. Supporting this "building–transportation" integrated energy paradigm, Al-Buraiki and Al-Sharafi [71] also demonstrated that the hydrogen produced by the system not only meets the building's internal energy demands but also serves as a fueling source for hydrogen vehicles, forming a vital component of a comprehensive building-integrated energy system.

He et al. [49] also proposed a "vehicle-to-building" hydrogen utilization model, in which hydrogen fuel cell vehicles (HVs) not only serve mobility needs but also provide energy feedback to the grid through their onboard proton exchange membrane fuel cells (PEMFCs) via Vehicle-to-Grid (V2G) interaction. Acknowledging the safety risks associated with high-pressure hydrogen storage in residential settings, He et al. [49] located the electrolyzer and hydrogen storage tanks at a centralized hydrogen station rather than within the building itself. Surplus photovoltaic electricity is transmitted from the building to the hydrogen station via a microgrid for hydrogen production, after which the HVs are refueled and subsequently feed electricity back to the building through V2G operation. This spatial decoupling between buildings and hydrogen infrastructure enables coordinated operation while improving system safety, operational efficiency, and user acceptance [49].

3.2.5. Hydrogen for seasonal energy storage and heating applications

Hydrogen is increasingly being recognized as a viable solution for seasonal energy storage and building heating. Dong et al. [26] argued that hydrogen, as a seasonal energy storage medium, can effectively address the diurnal and seasonal fluctuations inherent in rooftop photovoltaic (PV) generation. This is particularly critical during winter, when insufficient PV output renders short-term battery storage incapable of meeting long-term energy demands. The study employed hydrogen storage (HS) as a long-term solution to balance the mismatch between renewable energy supply and demand. In summer, when PV generation exceeds demand, the electrolyzer converts surplus electricity into hydrogen for storage while recovering waste heat from the electrolysis process to enhance overall system efficiency. Conversely, during winter, when PV output is limited, a PEMFC reconverts the stored hydrogen into electricity and heat, thereby fulfilling the building's power and heating requirements. Moreover, hydrogen can serve as an auxiliary energy source for building heating.

Gordon et al. [32] explored the potential applications of hydrogen in residential heating, hot water supply, and cooking, introducing the concept of "hydrogen homes." The study highlighted that hydrogen heating is considered a possible pathway for decarbonizing the building sector. Additionally, the study examined hydrogen cooking as a potential replacement for traditional gas stoves. The findings revealed that consumer acceptance of hydrogen hobs is lower than that of hydrogen heating, primarily due to significant safety concerns regarding hydrogen-fueled cooking. Fuel-poor households tend to prefer induction cooktops as an alternative, as they perceive them as a safer option that mitigates potential risks associated with hydrogen use [32]. In Switzerland's research, Mellot et al. [72] investigated the role of hydrogen in building heating and found that hydrogen can be utilized for synthesizing renewable methane, which can then be used for heating through gas boilers or combined heat and power (CHP) systems. However, hydrogen can serve as long-term seasonal power storage (P2H2P) to balance across seasons, yet it is not a cost-effective primary pathway and sees only limited application.

3.2.6. Hydrogen boilers and hybrid heating systems

The feasibility research of hydrogen boilers and hybrid heating systems as alternatives to conventional natural gas heating has been receiving increasing attention. Slorach and Stamford [31] conducted an in-depth analysis of hydrogen boilers as an alternative solution for building heating and domestic hot water (DHW) supply. Their findings indicated that hydrogen boilers can replace traditional natural gas boilers through direct hydrogen combustion or be integrated into hybrid heating systems (HHS), where they operate alongside air source heat pumps (ASHPs). Additionally, Slorach and Stamford [31] explored two future hydrogen heating scenarios. The Committee on Climate Change (CCC) scenario (low hydrogen, high heat pump penetration), which primarily relies on ASHPs for heating, with hydrogen boilers serving as supplement for peak demand periods [31]. The study found that CCC scenario could achieve about 95 % reduction in heating-related carbon emissions, making it the most effective option for emission reduction. Besides Future Energy Scenarios (FES) (high hydrogen, low heat pump penetration), this scenario relies on hydrogen boilers for heating, with hydrogen mainly produced via steam methane reforming (SMR) with carbon capture and storage (CCS) and distributed through a nationwide hydrogen pipeline network [31]. However, due to the high energy consumption associated with hydrogen production, the carbon reduction potential (84–87 %) is slightly lower than in the CCC scenario, suggesting certain limitations in emission reduction efficiency [31]. Seward et al. [73] conducted a systematic evaluation of the role of hydrogen boilers in building heating systems. In hybrid heating systems (HHS), hydrogen can be integrated with heat pump technologies to form hybrid heat pumps (HHPs). Under this model, hydrogen boilers primarily operate during cold weather or periods of high heat demand, while air source heat pumps (ASHPs) or ground source heat pumps (GSHPs) are prioritized for regular heating needs. Additionally, based on an assessment of hydrogen heating feasibility in residential units of Cardiff, Swansea, and Newport, Seward et al. [73] noted that these cities already possess well-developed natural gas infrastructure, making them suitable for hydrogen retrofitting as a pathway to decarbonizing building heating. Bristowe and Smallbone [64] identified hydrogen as a viable energy source for building heating, which can be integrated with existing natural gas infrastructure. Hydrogen boilers can be deployed in both residential and commercial buildings, operating similarly to conventional natural gas boilers, but using either pure hydrogen or hydrogen-natural gas blends as fuel. Additionally, the study highlighted that hydrogen could serve as an energy storage medium. Surplus electricity can be converted into hydrogen via electrolysis, which can then be stored and later reconverted into electricity through fuel cells or hydrogen gas turbines during periods of high energy demand [64].

However, hydrogen does not play a dominant role in the building energy sector. A study by Victoria et al. [74] found that district heating systems in urban areas primarily rely on large-scale heat pumps, biomass combined heat and power (CHP) systems, and gas boilers, with hydrogen usage mainly observed in waste heat recovery processes, such as the Fischer-Tropsch synthesis. While a portion of hydrogen can be utilized for synthetic fuel production, its direct use for space heating in buildings remains minimal. In distributed heating systems, heat pumps have emerged as the predominant heating technology [74]. According to Switzerland's case study, Mellot et al. [72] indicated that under a net-zero emissions scenario in 2050, electric heat pump heating solutions are more economically competitive than hydrogen-based alternatives. Moreover, relying solely on imported hydrogen to compensate for winter electricity shortages would significantly increase total energy system costs by 64.3 % [72]. In contrast, alternative solutions, such as gas-fired power plants or Alpine photovoltaic installations, offer more cost-effective options, enhancing the overall economic viability of the energy system.

3.3. Structure of dimensions involved in hydrogen use in building sector

According to the classification framework outlined in the previous section, particularly regarding the methodological focus of each source, Fig. 4 is designed as a heat map to further illustrate the specific aspects of hydrogen applications in the building sector and to identify underdeveloped areas. The figure provides a comprehensive visualization of the frequency with which relevant variables and parameters have been investigated across the reviewed literature. Rows represent three primary analytical dimensions: Technical Dimensions, Economic Dimensions, and Environmental Dimensions [6,25–28,31,32,44–74,76]. Columns list specific variables grouped under three overarching parameter categories: technical, economic, and environmental, for example, efficiency, energy consumption, cost, and sustainability contributions. The color gradient indicates the frequency of investigation for each parameter in the existing literature, with darker shades representing higher frequency. Note that parameters shown are occurrence counts only, not pathway-dependent performance.

In terms of technical parameters, *Efficiency* was the most frequently discussed indicator ($n = 35$), underscoring its central role in evaluating energy systems, mechanical components, and building performance. According to the reviewed literature, this parameter typically refers to the conversion efficiency between input and output in hydrogen-based systems; higher efficiency indicates more effective resource utilization. *Capacity* ($n = 24$) also emerged as a critical factor, particularly in reference to energy storage and system engagement, such as hydrogen production and storage capacity, photovoltaic installed capacity, and the rated capacity of individual components. *Consumption* ($n = 22$) reflects the use of energy or materials during building operation and is closely linked to the technological performance of the system. *Lifespan* ($n = 16$) is used to evaluate the durability of systems or components,

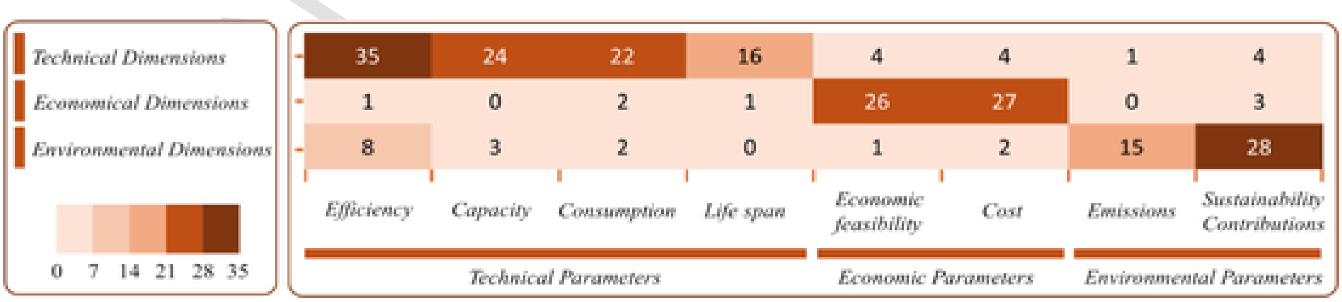

Fig. 4. Summary of the dimensions that involved in the reviewed studies.

encompassing aspects such as operational lifespan, component replacement cycles, and total runtime.

From the economic perspective, *Cost* (n = 27) and *Economic Feasibility* (n = 26) represent the core areas of research interest. Cost encompasses both initial capital investment and operation and maintenance expenditures and is often a decisive factor in technology implementation and procurement decisions. Economic feasibility, on the other hand, reflects a more comprehensive economic evaluation, incorporating indicators such as levelized cost of energy (LCOE), net present cost (NPC), return on investment (ROI), and government subsidies. These metrics offer valuable insights into the practical viability of hydrogen applications in the building sector. Within the environmental dimension, the most emphasized parameter is *Sustainability Contribution* (n = 28), which assesses the extent to which a system supports goals such as carbon neutrality, circular economy, and net-zero buildings. *Emissions* (n = 15) primarily concern the release of greenhouse gases and other pollutants (e.g., NO_x and particulate matter), serving as a key basis for understanding environmental externalities and evaluating regulatory compliance.

As shown in Fig. 4, current research exhibits a marked concentration in the technical dimension, particularly around parameters such as *Efficiency*, *Capacity*, and *Consumption*. This trend reflects the field's strong reliance on technical performance metrics and suggests that research is still in the preliminary stage of validating the technical feasibility of hydrogen technologies in buildings. Notably, the technical parameter *Lifespan*, which is critical in technology assessment, was examined in only 16 studies, indicating that lifecycle considerations have not yet received sufficient attention in technical parameters. Within the economic dimension, the parameters *Economic Feasibility* and *Cost* were examined in 26 and 27 studies, highlighting the growing recognition of economic factors as crucial determinants in the practical deployment of hydrogen technologies in buildings. Environmental dimension is evidently represented, due to *Emissions* and *Sustainability Contributions* appeared in 15 and 28 studies, respectively. It is worth noting that certain parameters exhibit cross-dimensional characteristics. For instance, while *Efficiency* is primarily a technical indicator, it also influences economic returns and environmental impacts. Similarly, *Consumption* pertains not only to operational costs but also to resource utilization and environmental load.

In summary, the overall distribution reveals a clear trend in research focus: technical parameters dominate engineering-oriented studies, economic indicators prevail in feasibility analyses, and although environmental metrics are receiving increasing attention, they remain comparatively underrepresented. Although efficiency, emissions, and cost emerge as the most frequently reported and quantifiable indicators, only few studies provide data in directly comparable form. Because of this limited and heterogeneous sample, a data-based horizontal comparison was not pursued here; instead, the result emphasizes the need for future research to report these indicators in standardized units to enable robust cross-case analysis. Fig. 4 reveals that current research tends to prioritize technical performance and economic feasibility, while systematic assessment of the overall environmental impact remains limited. This distribution suggests that future research should adopt more integrated, multidimensional approaches, particularly by enhancing the coupling between environmental and economic assessments, thereby establishing a more comprehensive evaluation framework for hydrogen-integrated building systems.

3.4. Benefit of applying hydrogen in building sector

With the growing global demand for decarbonizing building energy systems, hydrogen energy has garnered significant attention as a promising clean energy source for applications in the building sector. Numerous studies have demonstrated that hydrogen energy not only substantially reduces carbon emissions in the building sector but also enhances energy efficiency. Fig. 5 illustrates the multidimensional advantages of hydrogen integration within building energy systems, underscoring its pivotal role in achieving low-carbon, resilient, and energy-efficient built environments. Centered around the hydrogen storage system, the diagram links renewable power generation, building-side energy demands, and auxiliary components such as heat pumps and electric vehicles. Unidirectional and bidirectional solid lines represent conversion and collaborative interactions between different system elements or components. Specifically, hydrogen produced from renewable sources enables zero-carbon energy storage, effectively mitigating the intermittency of solar and wind power. The stored hydrogen can subsequently be converted into electricity or thermal energy for heating, cooling, and power supply within buildings, which enhances energy stability and reinforcing system resilience. The integration of hydrogen with heat pump systems further boosts energy efficiency and supports high-performance thermal management. Meanwhile, synergies with electric mobility infrastructure enable vehicle-to-building (V2B) coupling, facilitating cross-sectoral energy integration. Fig. 5 also highlights that the coupling of hydrogen-powered heat pumps with buildings offers potential advantages in terms of social acceptance. Overall, Fig. 5 presents a systemic energy model in which hydrogen serves not only as an energy carrier but also as a strategic enabler for decarbonization and integration within building energy systems, supporting the broader transition toward sustainability and net-zero goals.

3.4.1. Hydrogen as a pathway for efficient and stable energy utilization in buildings

From the perspective of technological optimization in building energy systems, North and Jentsch [30] argued that current decarbonization policies predominantly rely on a linear economic model. While this model reduces energy demand and replaces fossil fuels with low-carbon technologies, it does not fully account for the efficient utilization of energy resources. Their findings indicate that integrating local heat sources with district heating networks can significantly improve energy resource utilization efficiency, offering advantages over conventional heating methods such as gas boilers and resistive heating. While this study provides a theoretical foundation for the application of hydrogen in building heating, Sami et al. [63] further expanded this field by investigating the feasibility of integrating hydrogen storage with multi-source energy systems, including solar and wind energy. Experimental tests conducted in four Iranian cities with distinct climatic conditions demonstrated that this polygeneration system exhibits strong adaptability under dynamic climate conditions. Notably, in extreme climatic

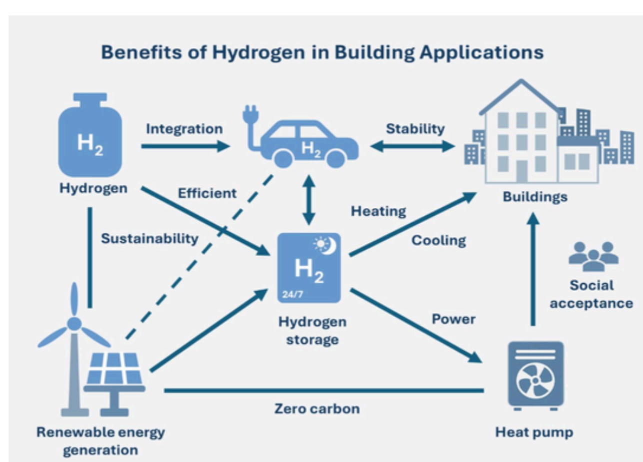

Fig. 5. Summary of benefits of hydrogen in building applications.

regions, such as hot-humid and arid areas, it effectively enhances energy efficiency [63].

Maestre et al. [6] indicated that grid-RHS hybrid system was the most cost-effective solution, achieving a lower levelized cost of energy (LCOE) compared to traditional grid-powered systems while significantly reducing carbon emissions. In contrast, the fully off-grid RHS, despite enabling zero carbon emissions, remained cost-intensive. However, the study suggested that selling surplus energy back to the grid could significantly enhance its economic viability [6]. Vecchi et al. [59] indicated that gradual electrification is the most cost-effective pathway for building decarbonization, while PV + storage systems significantly reduce grid dependence. However, if grid decarbonization progresses slowly, the cost of achieving net-zero emissions will rise considerably, placing a higher carbon abatement cost burden on building users. In this context, hydrogen heating remains viable only under specific conditions, such as when distributed renewable energy resources are limited (e.g., insufficient rooftop space for PV installation), when heating and hot water demand peaks are highly concentrated (e.g., higher winter hot water demand), or when hydrogen retail prices drop below 4 AUD/kg [59].

While building electrification is widely regarded as a cost-effective decarbonization pathway [59], this does not diminish the advantages of hydrogen in building energy systems. He et al. [49] argued that hydrogen technologies demonstrate significant potential in optimizing building operational costs. Through intelligent control and optimized operation of electrolyzers and fuel cells, their study showed that the average annual energy cost per household could be reduced from approximately USD 2000 to USD 1228.5, representing a 38.9 % decrease [49]. Acting as an energy intermediary, hydrogen effectively utilizes surplus electricity generated by on-site photovoltaic systems, thereby enhancing the overall economic performance of the building energy system. Seward et al. [73] highlighted that hydrogen can be transported through retrofitted natural gas pipelines to supply building heating systems, making it a low-cost, low disruption decarbonization solution, particularly for buildings already connected to the gas network. Furthermore, Seward et al. [73] emphasized that full-scale electrification (e.g., widespread heat pump adoption) could significantly increase grid load, especially during peak demand in cold weather, leading to substantial electricity infrastructure upgrade costs. In contrast, hydrogen heating relies solely on existing gas networks, effectively alleviating peak electricity demand pressure. Additionally, the study found that, unlike electrified heating systems (e.g., heat pumps), which may require auxiliary heating devices in low-temperature environments, hydrogen boilers can directly supply high-temperature hot water and indoor heating without additional energy conversion. This ensures greater reliability in severe cold weather conditions [73].

Despite the numerous benefits of hydrogen in the building sector, its role remains largely supplementary. Victoria et al. [74] highlighted that although modelling results indicate that the core strategy for decarbonizing building heating is direct electrification (e.g., heat pumps), hydrogen still offers certain benefits under specific conditions. The study demonstrated that hydrogen could function as a grid-balancing tool within building heating systems, helping to mitigate the intermittency of renewable energy sources. For instance, hydrogen serves as a seasonal energy storage medium, feeding electricity back via fuel cells during periods of low renewable generation output while recovering waste heat for district heating [74]. Additionally, hydrogen boilers can act as auxiliary heating devices, working in conjunction with heat pumps and thermal storage systems to enhance the resilience of energy systems, particularly during extreme cold weather or peak electricity demand periods. Xu et al. [75] further found that through the "electricity–gas–electricity" energy conversion pathway, which include electrolysis, hydrogen storage, and power generation via fuel cells, the system can achieve temporal energy balancing, ensuring reliable supply for residential base loads and electric vehicle charging. This approach enhances the system's load management capability and operational stability.

3.4.2. Hydrogen as a stable long-term energy storage option for buildings

From the perspective of technological feasibility and economic viability, numerous studies have highlighted the critical role of hydrogen systems in building energy management. Brancaleoni et al. [67] conducted a study on a cluster of educational buildings in Italy, demonstrating the application of a solar-hydrogen hybrid system in off-grid power systems. Their findings indicate that the combination of hydrogen storage and battery storage is essential for balancing seasonal energy supply. While battery storage is suitable for short-term fluctuations, hydrogen storage enables long-term seasonal regulation. The self-sufficiency rate of building energy reaches its peak during summer, where surplus solar energy can be converted into hydrogen for energy supply in winter [67]. A study conducted in Japan further support the feasibility of hydrogen energy systems. Shimoda et al. [60] further analyzed the role of hydrogen as a long-term energy storage medium. Their findings revealed a temporal mismatch between electricity supply and demand due to the intermittency of photovoltaic (PV) generation. Specifically, 43 % of electricity demand could be met directly by PV generation without the need for energy storage, while 4 % and 22 % of demand would require non-battery storage solutions such as pumped hydro storage and hydrogen energy, respectively [60]. The study further identified the optimal applications for different storage technologies, indicating that batteries are best suited for daily storage, pumped hydro for short-term (within a week) storage, and hydrogen for seasonal storage [60].

Baldi et al. [45] demonstrated that hydrogen storage systems, when integrated with a SOFC–PEMFC operational mode, can release electricity during peak demand periods, thereby ensuring the stability of building energy supply. They emphasized that the unit cost of hydrogen storage is lower than that of battery storage [45], particularly for long-duration applications, which makes it suitable for large-scale off-grid building scenarios by reducing overall investment in energy storage infrastructure. Additionally, they found that integrating hydrogen storage with PEMFCs enhances the dynamic responsiveness of SOFC-based systems: when building energy demand surges unexpectedly, PEMFCs can rapidly deliver power, ensuring system stability. This configuration improves the adaptability of SOFCs within building energy systems and extends the operational lifespan of the fuel cells [45]. Karaca and Dincer [47] revealed that by functioning as an energy carrier, hydrogen effectively mitigates the intermittency of solar energy supply through a "daytime PV-driven hydrogen production–nighttime fuel cell discharge" pathway, thereby enabling diurnal energy balancing and continuous power delivery in building energy systems. Similarly, in Italy, De Masi et al. [68] confirmed that the SOFC, when combined with a photovoltaic (PV) system, can fully meet the building's energy demand, and even generate surplus electricity under favorable solar conditions. However, on cloudy days or during low-power operation, partial reliance on grid electricity remains necessary, while the SOFC ensures stable nighttime energy supply [68]. These findings align with those of Brancaleoni et al. [67], highlighting the advantages of hydrogen energy systems in managing energy supply fluctuations, offering high reliability and flexibility. Sorgulu and Dincer [46] further substantiated the perspective. They found that hydrogen can store surplus electricity generated from wind or solar power via electrolysis during periods of overproduction and subsequently release it through fuel cells during times of renewable energy shortfall, such as at night, on cloudy days, or during low wind conditions. This not only ensures a stable power supply for buildings but also equips the system with flexibility to accommodate dynamic load variations, thereby enhancing the operational reliability of the energy infrastructure. Similar findings were reported by Razmjoo et al. [76], who simulated a sustainable energy system for remote residential areas such as Rezvan village in Iran. Their system integrated photovoltaic (PV) panels, wind turbines, and hydrogen storage, utilizing a "water electrolysis–hydrogen storage–fuel cell power generation" pathway to enable medium- and long-term energy storage and reuse. The goal was to provide buildings with a stable and reliable electricity supply to meet residents' daily energy demands [76].

3.4.3. Multi-modal hydrogen systems for improving building energy performance

Meanwhile, the study by Mehr et al. [28] further strengthens the theoretical foundation of integrating hydrogen energy with building energy systems from a thermodynamic analysis perspective. They explored the application and performance evaluation of green hydrogen and syngas (synthetic gas) blended fuels in solid oxide fuel cells (SOFCs). Their findings indicate that installing photovoltaic (PV) systems on building rooftops allows hydrogen energy to not only reduce reliance on fossil fuels but also significantly lower CO_2 emissions. Specifically, with a higher hydrogen proportion in the fuel blend, the SOFC system demonstrated an 18 % enhancement in net output power, and a 58 % reduction in CO_2 emissions [28]. This discovery further underscores the irreplaceable role of hydrogen in the decarbonization of building energy systems. Particularly, the integration of hydrogen with solar energy and fuel cell technologies contributes to improved energy efficiency and environmental performance in buildings. Research in Beijing further reinforces the critical role of hydrogen in decarbonizing the building sector. Complementary analysis by Sajjadian [77], examining the UK's net-zero carbon roadmap, further illuminates that hydrogen-based boilers and hybrid configurations, particularly those merging hydrogen with heat pumps show considerable promise in lowering carbon outputs.

However, the application of hydrogen technologies in buildings is not limited to single-mode integration. Dong et al. [26] demonstrated the potential of an electricity–hydrogen–thermal hybrid storage system (EHT-HS) for achieving complete carbon neutrality in residential buildings. The study identified the optimal system configuration, which includes a 204.8 m^2 rooftop photovoltaic (PV) system (32 kW), a 114.8 kWh battery energy storage system (BESS), a 5.0 kW electrolyzer, a 1.1 kW fuel cell, a 113.57 m^3 hydrogen storage tank, and a 65.6 kg thermal storage tank [26]. Under this configuration, the residential building achieved an investment return rate exceeding 36 %, with a levelized cost of energy (LCOE) as low as \$0.1016/kWh, outperforming conventional systems (\$0.1228/kWh) in economic viability. Additionally, the annual carbon emission reduction (ACER) was optimized to 25.5 tCO_2, achieving a 100 % carbon reduction rate (CRR) and demonstrating zero emissions [26]. Khan and Gohari Darabkhani [65] indicated that fuel cells achieved the highest overall score in the micro-CHP technology assessment, primarily due to their low carbon emissions, high efficiency, and low noise levels. Gas engines, on the other hand, emerged as the dominant choice for residential micro-CHP due to their high technological maturity, although issues related to noise and vibration require further optimization. Both micro gas turbines and Stirling engines exhibited distinct advantages. Micro gas turbines, characterized by their lower cost and simple maintenance, were found to be more suitable for cost-sensitive users in regions with high electricity prices. Meanwhile, Stirling engines, known for their low noise levels and strong fuel flexibility, were deemed ideal for small-scale residential applications [65].

While the sustainability advantages of hybrid systems incorporating hydrogen in building energy applications are well recognized, ongoing efforts continue to optimize system performance. Hemied and Gabbar [66] found that hydrogen fuel cells outperform conventional lithium-ion batteries in long-term storage and energy regulation, serving as a reliable backup energy source during nighttime and low-wind conditions. This capability ensures continuous and stable system operation, making hydrogen fuel cells particularly suitable for various building types, including residential, educational, and healthcare facilities. The proposed optimization approach for hybrid renewable energy systems dynamically allocates different energy sources, minimizing grid electricity purchases to enhance building energy self-sufficiency, improve emissions reduction, and maximize energy utilization and overall system efficiency [66]. These findings demonstrate the practical potential of hybrid renewable energy systems in the building sector.

Adeyemo and Amusan [44] research showed that lithium iron phosphate (LFP) and retired electric vehicle batteries (REVB) were the most cost-effective choices, while OPzV lead-acid batteries performed poorly in terms of economic viability due to high maintenance costs and shorter cycle life. For scenarios where loss of power supply probability (LPSP) $>$ 1 %, standalone battery storage using LFP or REVB was found to be the optimal solution. However, when LPSP $\leq$1 %, the battery-hydrogen hybrid storage system proved to be more cost-effective. This is attributed to the fuel cell reducing the frequency of deep battery discharges, thereby extending system lifespan. The economic feasibility of hydrogen fuel cell systems depends on the cost reductions of electrolyzers, fuel cells, and hydrogen storage tanks. At present, hydrogen-based storage only outperforms standalone battery storage under specific power supply constraints [44]. Mohammad and Iqbal [27] found that hydrogen-based microgrids can achieve complete zero greenhouse gas emissions while providing long-term energy autonomy and stability. This makes them particularly suitable for regions with unstable grids and high electricity prices. Liu et al. [61] demonstrated the advantages of hydrogen energy in balancing building energy demand by integrating hydrogen-powered vehicles as mobile storage units with a PV-wind-battery hybrid system. Their study revealed that the hydrogen-prioritized storage strategy (EMS2) not only enhances the energy self-sufficiency of building systems but also reduces reliance on the grid, thereby improving energy independence. While the battery storage system designed for large-scale renewable energy deployment (EMS1) performs well in terms of supply capabilities, including self-consumption ratio, load coverage, and hydrogen system efficiency, as well as grid integration, EMS2 exhibits superior performance and broader adaptability [61]. During operation, hydrogen fuel cells and electrolyzers generate a significant amount of thermal energy. Liu et al. [61] proposed utilizing waste heat recovery (WHR) technology for air conditioning reheat and domestic hot water (DHW) production to reduce the energy consumption of conventional air conditioning systems. Their study found that the heat recovery efficiency (HRE) in buildings could reach 95.17 %–95.46 % [61], significantly improving overall energy utilization efficiency. Robledo et al. [62] explored the multiple advantages of hydrogen energy in the building sector, highlighting that the FCEV2G (Fuel Cell Electric Vehicle-to-Grid) model can significantly enhance building energy self-sufficiency. They found that when hydrogen prices drop below €8.24/kg, the total annual cost of the FCEV2G model becomes comparable to that of traditional internal combustion engine vehicles (ICEVs). If the price of hydrogen further decreases to 3 euros per kilogram, which is the target set by the United States Department of Energy (DOE), users could save 1546 euros in annual energy costs [62]. This indicates that as hydrogen costs decrease, the economic feasibility of the FCEV2G model in buildings will continue to improve. Al-Buraiki and Al-Sharafi [71] also noted that stored hydrogen can be directly used to refuel hydrogen fuel cell vehicles, enabling building districts to function simultaneously as distributed energy hubs and transportation energy refueling stations. Xu et al. [48] similarly highlighted the system's capability to supply hydrogen to hydrogen vehicles (HVs). Moreover, Xu et al. [48] emphasized that by selling hydrogen to external users, such as visiting vehicles and participating in demand response programs (DRP), the system can reduce operational costs and transition from an energy consumer to an energy provider, thereby enhancing the overall economic performance and operational value of the building energy system.

In addition to hydrogen-powered vehicles, Robledo et al. [70] identified hydrogen fuel cell electric scooters (FCES) as distributed, low-carbon mobile energy storage units that can support building power systems through Vehicle-to-Grid (V2G) and Vehicle-to-Load (V2L) modes. When parked, these scooters can supply electricity to buildings, thereby utilizing their stored energy during idle periods while continuing to fulfill their transportation function. Robledo et al. [70] found that under smart grid or microgrid architectures, FCES can operate in coordination with building-integrated photovoltaic systems and battery storage devices, enhancing the overall flexibility and responsiveness of the energy system. This integration significantly improves the energy self-sufficiency of buildings and reduces dependence on external electricity networks. Moreover, during peak grid load periods, FCES can feed electricity back to the building or grid via V2G functionality, contributing to peak shaving and valley filling. This helps optimize building load profiles and supports the stable operation of the broader power system.

4. Barriers and challenges

There are several barriers to the application of hydrogen in buildings including technical, economic, social and political. Fig. 6 shows the summary of the barriers for hydrogen adoption.

4.1. Economic issues

Despite the strong potential of hydrogen energy in building systems, economic feasibility remains a major barrier to its widespread deployment. Anastasovski et al. [29] conducted a systematic evaluation of urban energy storage systems and similarly noted that while hydrogen-based chemical energy storage systems, such as hydrogen fuel cells, exhibit outstanding performance in long-term storage, sustainability, and flexibility, their economic viability is hindered by the high cost of materials, such as platinum. However, in specific applications within the building sector, hydrogen still faces several unique economic barriers. For hydrogen–grid hybrid energy systems, economic performance is sensitive to energy price fluctuations. Vecchi et al. [59] conducted modelling analyses under Australian climatic conditions, revealing that hydrogen boilers (H_2B) are cost-effective only when peak electricity prices are high or distributed energy resource (DER) potential is limited, such as in apartment complexes. Additionally, for retrofitting existing buildings with hydrogen systems, hydrogen prices must fall to below one-fifth of electricity prices to achieve cost competitiveness. Similarly, the deployment of hydrogen boilers in the United Kingdom faces obstacles, primarily due to the higher integrated cost of green hydrogen compared to natural gas and the lack of readiness for large-scale hydrogen boiler deployment [77].

Khan and Gohari Darabkhani [65] assessed the performance and suitability of four major micro-combined heat and power (micro-CHP) prime movers for residential applications. Their study found that although fuel cells offer advantages in terms of low emissions and environmental sustainability, their high cost and prolonged startup time limit their large-scale adoption. These findings highlight the diversity of micro-CHP technology choices depending on specific building types and energy demands. While hydrogen technologies hold immense potential for environmental benefits, current technological advancements have yet to fully overcome challenges related to cost and economic feasibility. Mohammad and Iqbal [27] evaluated the application of hydrogen-supported solar photovoltaic (PV) microgrids in urban apartments and found that despite their zero-carbon emissions and enhanced sys-

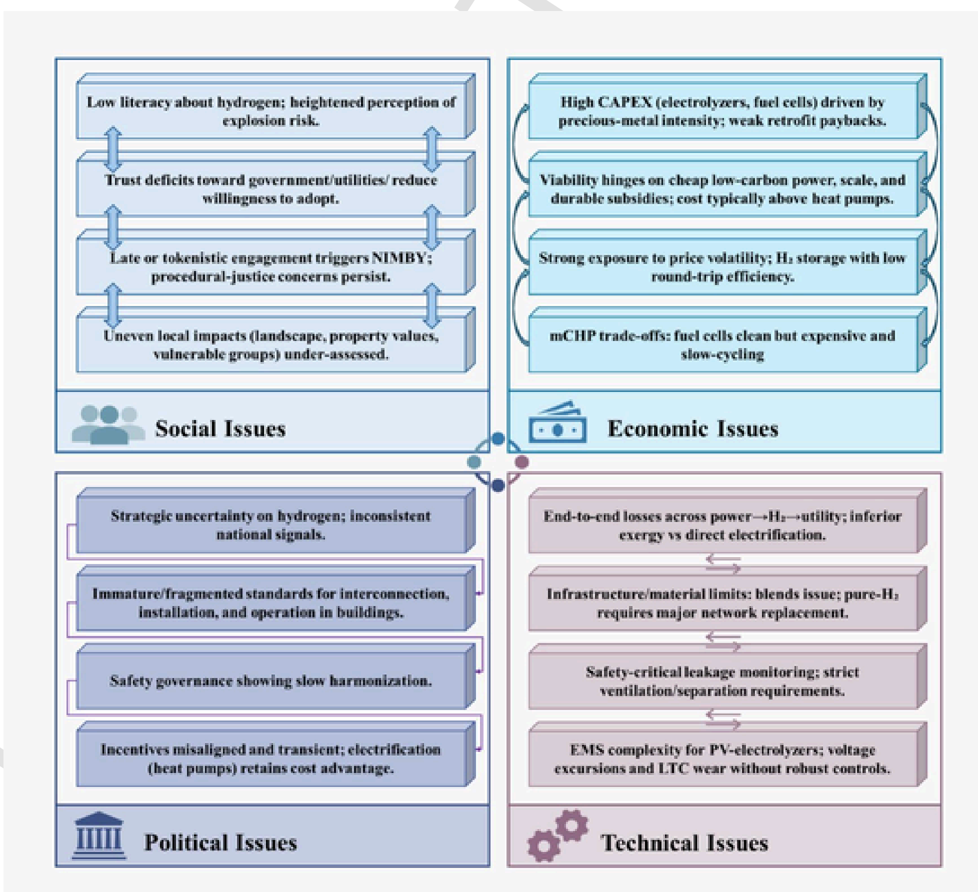

Fig. 6. Summary of challenges and barriers of hydrogen in building applications.

tem reliability, the high initial investment cost remains the primary constraint to widespread adoption. Their study also indicated that with technological advancements and economies of scale, the cost of hydrogen energy systems is expected to decline. This finding aligns with the cost analysis conducted by Bristowe and Smallbone [64], who argued that the reduction in hydrogen energy costs is contingent on the large-scale production of electrolyzer technology. They suggested that mass manufacturing of proton exchange membrane (PEM) electrolyzers could significantly lower hydrogen production costs, making hydrogen a more economically viable option for building heating applications.

In summary, the common economic challenges in the hydrogen industry are largely attributed to the high costs of expensive materials such as stacks and catalyst components, including platinum [29]. In the building sector, however, economic feasibility is influenced by multiple factors. Hydrogen boilers are competitive primarily under conditions of peak electricity pricing, restricted distributed energy resources (DERs), or when the hydrogen price falls below 20 % of the electricity price [59]. In the United Kingdom, retrofit efforts remain constrained by the cost premium of green hydrogen and gaps in deployment readiness [77]. PV-H_2 microgrids can deliver zero-carbon reliability, but high upfront investment remains the principal barrier to adoption [27]. Large-scale manufacturing of proton exchange membrane (PEM) electrolyzers represents a reliable pathway to significantly improving affordability [64].

4.2. Technical issues

Beyond economic feasibility, the common technical challenges in the hydrogen industry are both pervasive and closely interrelated with those specific to its applications in the building sector. The study by Seward et al. [73] provides an alternative perspective on the challenges associated with hydrogen technology deployment. They conducted a spatially explicit modelling analysis of residential heating decarbonization pathways in South Wales, UK, evaluating the feasibility of hydrogen heating, electrified heating, and hybrid heating solutions. Their findings indicate that hydrogen heating systems are most suitable for areas covered by existing natural gas networks; however, challenges related to hydrogen production, transportation, and conversion efficiency may constrain their broader adoption [73]. North and Jentsch [30] conducted an in-depth analysis of the effectiveness and feasibility of hydrogen as a replacement fuel for gas boilers. While hydrogen boilers are promoted as a low-carbon alternative for building heating, and government policies are actively supporting the transition from natural gas to hydrogen, the study highlighted that hydrogen heating exhibits lower overall efficiency and may increase the energy burden. One key issue is the exergy efficiency of hydrogen boilers. Compared to natural gas boilers, which have an exergy efficiency of 3.8 %, hydrogen boilers achieve only 3.2 %, representing a 16 % reduction, which translates into greater resource wastage [30]. Additionally, the resource efficiency ratio (RER) of hydrogen boilers is 0.84, lower than that of natural gas boilers, indicating insufficient energy utilization efficiency in this application [30]. A fundamental challenge of hydrogen heating lies in the energy losses associated with hydrogen production. The study noted that electrolysis operates at approximately 70 % efficiency, meaning that 30 % of the electricity is lost during hydrogen production. Further energy losses occur when hydrogen is combusted in boilers, further reducing the overall system efficiency [30]. Verma et al. [78] pointed out that due to the inherent properties of hydrogen, such as its flammability, the complexity and precautionary measures involved in its handling and storage processes are significantly increased. This imposes higher technical requirements while being closely linked to safety considerations. Badakhsh and Bhagavathy [79] further analyzed barriers within the hydrogen value chain from both technical and environmental perspectives. Their study highlighted that blending 20–23 % hydrogen into existing natural gas pipelines requires only minor infrastructure upgrades while achieving a 7.3 % reduction in CO_2 emissions [79]. However, when the hydrogen blend exceeds 70 %, risks such as hydrogen embrittlement and pipeline degradation emerge. For pure hydrogen heating, a complete overhaul of infrastructure is necessary, leading to a 40–65 % increase in both capital and operational expenditures.

However, hydrogen also faces a series of technology specific challenges within building contexts. The study by Brancaleoni et al. [67] also revealed limitations of hydrogen storage systems, particularly regarding system-scale optimization. Their research shows that the impact of temperature on photovoltaic (PV) power generation cannot be overlooked, necessitating accurate climate forecasting and temperature fluctuation adjustments in system design. Moreover, to accommodate future growth in building energy demand, Brancaleoni et al. [67] recommends either increasing battery storage capacity by 50 % or installing additional PV modules to ensure sufficient energy supply during winter. This perspective aligns with the findings of Maestre et al. [6] and Sami et al. [63]. The former suggests that variations in local energy consumption patterns, such as differences in solar radiation intensity and peak load demands, could explain these discrepancies. The latter emphasizes that in polygeneration systems, hydrogen storage must be closely integrated with other renewable energy sources, particularly solar energy, to enhance overall system efficiency and economic feasibility.

In building distributed energy scenarios, the coordinated control between hydrogen systems and local power grids presents significant challenges. In practical deployment, the high-power, dynamically adjustable load characteristics of hydrogen systems pose significant challenges to power supply reliability. As highlighted by Jain et al. [80], in power-to-hydrogen (P2H) coupled systems, failure of electrolyzers to respond in real time to fluctuations in local renewable generation, such as solar PV, which may result in synchronized power oscillations with distributed energy sources. This synchronicity can amplify voltage deviations within distribution networks, triggering frequent operations of voltage regulation equipment, such as Load Tap Changers (LTCs). Such frequent switching not only increases operational costs and reduces equipment lifespan but also undermines overall system stability. These grid interaction and control issues are less prominent in large centralized hydrogen applications but are particularly significant in building scale or localized energy systems.

Practical building applications impose specific constraints on the operation of hydrogen energy systems. Using the Samcheok campus of Kangwon National University as a pilot site, Kwon et al. [81] integrated BESS and HESS under coordinated control of an Energy Management System (EMS), achieving a stabilization of grid power fluctuations within ± 35 kW, a reduction in electricity costs by approximately 15 %, and an improvement in grid stability by 20 %. While these results demonstrate the operational viability of multi-energy integrated systems within controlled campus microgrids, it is important to note that campus buildings typically exhibit relatively homogeneous load profiles and operate in highly manageable environments. In contrast, high-density urban residential settings are characterized by significant load variability and behavioral uncertainty among end users. In such contexts, real-time EMS-based scheduling of storage assets is often constrained by limited compatibility with existing distribution infrastructure, insufficient physical space for equipment installation, and regulatory restrictions on system control authority.

Achieving building decarbonization and energy self-sufficiency requires addressing the critical challenge of seasonal energy mismatch. This issue is especially acute in mid- to high-latitude regions, where summer photovoltaic surpluses contrast sharply with winter heating peaks. Keiner et al. [82] developed a closed loop residential energy system model across 145 global climate zones, incorporating photovoltaic panels, electrolyzers, hydrogen storage tanks, and fuel cells, to systematically evaluate the role of hydrogen storage in enhancing household energy self-sufficiency and optimizing costs under both grid connected and off grid configurations. The results indicate that hydrogen storage emerges as part of the optimal solution only in specific high-latitude scenarios, such as in Northern Europe, where winter heating demand is substantial and off-grid operation is enforced. However, the study also emphasizes that even under continued cost reduction trajectories, the adoption of hydrogen storage remains constrained by its high capital investment and relatively low round-trip efficiency. Its principal value lies in meeting seasonal balancing requirements over timeframes ranging from several weeks to several months, a demand that conventional battery systems are unable to satisfy. [82]. While the integration of seasonal hydrogen storage can enhance energy self-sufficiency, this mechanism alone is insufficient to resolve distribution-level bottlenecks. The study by Fokkema et al. [83] demonstrates that under conditions of limited grid distribution capacity, hydrogen storage can facilitate temporal load shifting and improve the economic performance of the energy system to a certain extent. However, simulation results reveal that during periods of frequent summer photovoltaic generation peaks, storage systems alone cannot fully substitute the need for grid infrastructure expansion. More critically, as storage capacity increases, the frequency of energy transactions between the system and the grid also rises, potentially exacerbating congestion risks along local transmission pathways [83]. In conclusion, within the context of seasonal energy regulation in buildings, hydrogen systems exhibit certain boundaries of applicability. However, the low storage efficiency represents general technological limitations, which can be regarded as specific manifestations of the common challenges within the hydrogen and building context.

It is worth noting that equipment layout and structural integration issues represent obstacles unique to the application of hydrogen in buildings. In high-density urban environments, one of the foremost challenges in integrating hydrogen energy systems into existing buildings lies in the severe spatial constraints. Most legacy buildings were not originally designed to accommodate modern sustainable energy systems, resulting in structural and spatial layouts that are often incompatible with the installation of new energy-efficient equipment and intelligent control platforms. For instance, efforts to retrofit high-performance HVAC systems, photovoltaic panels, or smart building management systems frequently encounter issues such as insufficient structural load capacity, limited space for equipment placement, and restricted pathways for power and data cabling [84]. Compared with conventional energy saving technologies, hydrogen-based systems such as electrolyzers and hydrogen storage tanks impose more stringent requirements in terms of space, safety, thermal management, and supporting infrastructure. Moreover, most existing buildings lack structural redundancy provisions for accommodating modern energy systems. Rooftop spaces are typically prioritized for the installation of photovoltaic panels, heat pump units, or green roofing elements. Under such limited load-bearing conditions, the concentrated deployment of these systems already imposes substantial structural stress [84]. As a result, the addition of any new system faces even more formidable installation challenges.

Technically, hydrogen in buildings is most plausible where legacy gas networks exist, yet end-to-end efficiency losses, from electrolysis (~70 %) to end-use combustion and exergy, undercut resource efficiency relative to electrification [30,73]. Safety and handling complexities elevate design and O&M requirements [78]. Gas-grid blending can yield near-term decarbonization (≈20–23 % H_2 → ~7.3 % CO_2 cuts) with limited upgrades, but high-blend and pure-H_2 service demands major infrastructure renewal (+40–65 % CAPEX/OPEX) and careful management of leakage [79]. At the system level, PV temperature sensitivity and winter deficits require explicit sizing and forecasting; options include ~50 % battery upsizing or additional PV capacity [67]. Power-to-H_2 coupling introduces grid-interaction challenges: electrolyzer lag can synchronize with DER oscillations, driving voltage excursions and stressing LTCs, necessitating EMS designs with voltage support and coordinated set-point control [80]. Campus-scale demonstrations (coordinated BESS–HESS) show improved stability and cost (±35 kW smoothing; ~15 % cost reduction), but transferability to dense urban housing is limited by load heterogeneity, siting, and regulatory constraints [81]. Finally, seasonal mismatch remains the primary advantage of hydrogen storage, which is highly valuable in high latitude or off grid contexts, although it is capital intensive and has low round trip efficiency [82]; storage alone cannot obviate distribution upgrades and may even increase grid transactions and local congestion under frequent PV peaks [83]; tight urban sites compound retrofit feasibility due to space/structural limits for electrolyzers, tanks, HVAC, and cabling [84].

4.3. Social issues

Although hydrogen has increasingly emerged as a key pathway in the transition to clean energy, the general public still lacks a clear understanding of its production methods, application scenarios, and safety characteristics. In Germany, for instance, a nationally representative survey involving 2054 participants revealed that while 85 % of respondents had heard of "hydrogen," only 26 % demonstrated familiarity with the concept of "green hydrogen" [85]. This knowledge gap is particularly pronounced among older adults and individuals without higher education backgrounds. The public knowledge gap surrounding hydrogen energy is particularly evident in residential applications, where it has contributed to heightened safety concerns and risk amplification. As noted by Gordon et al. [86], hydrogen is often associated with high explosiveness and uncontrollability, leading to its perception as inherently dangerous. This perception has been reinforced and mythologized through historical incidents and prevailing media narratives, resulting in deeply entrenched stereotypes. Such cognitively rooted resistance can evolve into systemic barriers during the implementation of hydrogen pilot projects and demonstration initiatives. In the absence of a clear understanding of both the risks and benefits of green hydrogen systems, public attitudes often become conservative or avoidant in response to uncertainty. Vallejos-Romero et al. [87] highlights that this information asymmetry can undermine trust in emerging energy technologies and, in certain contexts, even trigger collective opposition. Gordon et al. [88] identify public acceptance of hydrogen technologies as a key barrier to deployment, which is largely influenced by stakeholder trust, perceived community benefits, and the general familiarity of the public with hydrogen systems. Trust mechanisms play a pivotal role in shaping residential attitudes toward hydrogen adoption, with social trust emerging as the strongest predictor of public trust, and confidence in the technological quality of hydrogen systems being a necessary condition for wider societal acceptance [88]. In summary, as hydrogen enters residential communities, its proximity to everyday life tends to intensify public knowledge gaps and safety concerns. This reflects an amplified manifestation of the common challenges of the hydrogen industry within the built environment.

Other societal resistance to residential hydrogen applications stems from a lack of public trust in key institutional actors. Unlike technical or informational barriers, which can often be addressed through education or engineering interventions, trust-related issues are deeply embedded in the public's cognitive frameworks regarding fairness, transparency, and prior experiences with governmental or institutional engagement. Häußermann et al. [85] argue that public acceptance of residential hydrogen projects largely depends on perceived trust in and legitimacy of the implementing actors, such as government agencies, private companies, and research institutions, in safeguarding public interests, reflecting local values, and ensuring fair distribution of costs and benefits. Acceptance significantly declines when residents perceive that the driving forces behind such projects are primarily oriented toward corporate profits or political agendas rather than environmental improvement or community well-being. This sense of distrust is particularly pronounced in communities that have previously experienced conflicts over energy infrastructure, perceived inequities in benefit distribution, or exclusion from decision-making processes. In such cases, these perceptions reinforce what Vallejos-Romero et al. [87] describe as a "participatory deficit" and a lasting institutional memory of procedural injustice. Moreover, even when a project is well-intentioned and technically feasible, residents may still express opposition if they feel excluded from early-stage planning and consultation processes. This sense of exclusion can intensify what Gordon et al. [86] describe as a "fracture in social identification," whereby residents ideologically support the green transition but exhibit strong rejection when confronted with energy facilities in close proximity. Consequently, rebuilding and fostering trust should not be treated as a peripheral concern to technological deployment, but rather as a core mechanism for the sustainable implementation of hydrogen in the built environment. In summary, public distrust of institutions and the lack of a sense of participation constitute social challenges widely observed in the implementation of clean energy projects, and can be regarded as part of the common issues within the industry. However, introducing hydrogen into residential communities and buildings involves particular sensitivity, as residents are directly exposed to the impacts of such projects and their daily lives and interests are closely affected. Consequently, the demand for fairness and trust becomes considerably higher, almost turning into a distinctive challenge in this field. This is because individuals experience a much stronger sense of psychological concern when their homes are affected than when distant energy infrastructures are involved.

At a broader institutional level, regulatory frameworks and issues of social equity also influence the acceptance of hydrogen in both the industry and the building sector. Bade et al. [89] emphasize the current lack of a dedicated and comprehensive regulatory framework for green hydrogen, which significantly undermines public confidence in technology. In the United States, this regulatory gap is reflected in the absence of targeted policies, standardized codes, and clear implementation guidelines, making it difficult to integrate hydrogen technologies transparently and coherently into existing energy infrastructure systems [89]. Moreover, there is insufficient attention to the broader societal implications of green hydrogen production and application, particularly regarding localized social and environmental impacts. Vallejos-Romero et al. [87] highlights the need for more robust assessments of potential social risks, including adverse effects on local landscapes, real estate values, economic activities, and community well-being. Equity in the distribution of benefits from hydrogen projects also remains inadequately addressed, especially in relation to Indigenous populations and rural communities [87]. In summary, the social challenges surrounding hydrogen applications in the building sector are not solely rooted in technological or regulatory deficiencies, but rather arise from a complex interplay of factors, including public trust, regulatory governance, and social equity. While existing studies have clearly identified these barriers, most analyses fall short of unpacking the underlying interactions among stakeholders, and deeper structural issues such as unequal benefit distribution and the marginalization of local community voices.

Public acceptance hinges on correcting knowledge gaps (e.g., low familiarity with "green hydrogen"), reframing entrenched safety narratives, and building trust in implementing actors [85–88]. Social trust is the strongest predictor of support [87]; perceived community benefits and confidence in technological quality are necessary conditions, while "participatory deficits" and memories of procedural injustice erode legitimacy [88]. Acceptance is also co-determined by regulatory clarity: absent clear, dedicated codes and governance for green hydrogen, communities perceive higher risk and lower fairness/transparency in local siting and operations [89]. Therefore, a robust engagement strategy, including early consultation, equitable benefit sharing, and reliable safety communication, should be regarded as core infrastructure rather than a peripheral addition.

4.4. Policy issues

Gordon et al. [32] analyzed the challenges associated with hydrogen adoption in the building sector within the UK policy framework. Policy uncertainty remains one of the primary barriers to the deployment of hydrogen heating. While the UK government plans to make a final decision in 2026, the National Infrastructure Commission has already stated that hydrogen heating should not be included in the national policy mix, as electric heat pumps are considered a more economically viable option. Moreover, hydrogen safety remains a topic of debate. Public perceptions of hydrogen safety are divided, some view it as comparable to natural gas, while others express concerns about its potential explosion risks. Additionally, the study highlighted the low economic feasibility of hydrogen heating. The annual cost of hydrogen heating is estimated at £1410–1800 for green hydrogen and £1150 for blue hydrogen, whereas electric heat pumps operate at a significantly lower annual cost of £790–880 [32]. These figures indicate that under the current market conditions, hydrogen heating remains uncompetitive. Fig. 7 presents a SWOT analysis summarizing the current status of hydrogen technologies and applications in the building sector. However, the policy barriers that are commonly observed across the hydrogen industry exhibit a distinctive severity within the building sector.

Even the common challenges of hydrogen development often become more difficult to address in residential building applications due to the particular contextual complexities. Policy uncertainty, such as the pending decision in the United Kingdom scheduled for 2026 and the preference of advisory bodies for heat pumps, has dampened investment signals for hydrogen heating, while current cost comparisons between green or blue hydrogen and heat pumps make hydrogen heating less competitive for ordinary households [32]. Divergent public safety perceptions further complicate policymaking and market formation. In the near term, a coherent and stable policy framework, together with a credible cost reduction trajectory for electrolyzers and clean hydrogen supply, is a prerequisite; otherwise, the contribution of hydrogen in buildings will remain niche and context specific, as summarized in the SWOT analysis.

4.5. Summary of challenges in the hydrogen industry and its application in buildings

Although the above analysis has examined the barriers to hydrogen adoption in the building sector from economic, technological, social, and policy perspectives, it is important to note that many of these challenges are common across the hydrogen industry. For instance, the high costs of hydrogen production and storage, technological efficiency bottlenecks, and public concerns over hydrogen safety are also prevalent in other application domains such as transportation and industry. At the same time, the application environment of buildings introduces a distinct set of challenges and opportunities. On one hand, the limited physical space of buildings, constraints imposed by existing infrastructure, and the degree of user acceptance regarding the indoor use of hydrogen equipment create additional difficulties for practical implementation. On the other hand, in remote or off-grid building scenarios, hydrogen can serve as a long-term energy storage medium, providing seasonal flexibility that is difficult to achieve with other technologies. The interplay between these common and context-specific factors ultimately determines the development prospects of hydrogen in the building sector. Fig. 8 illustrates the current status and interrelations between the general challenges of the hydrogen industry and the specific issues associated with its application in buildings [27,29,30,32,67,73,77–79,82,84,86–89].

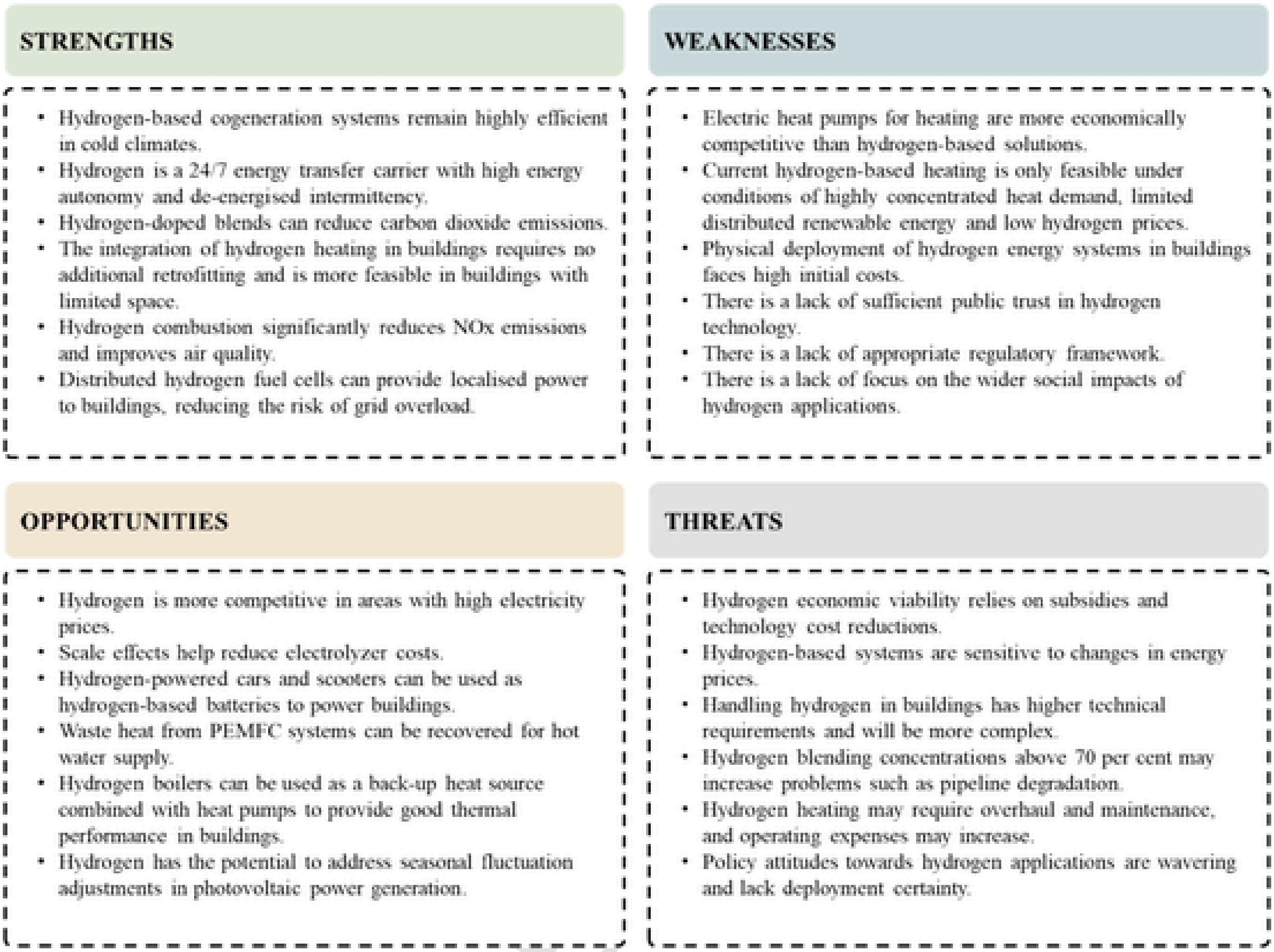

Fig. 7. Summary of SWOT analysis.

5. Discussion

This paper has provided a detailed account of the specific applications, benefits, and associated barriers and challenges of hydrogen technologies in the building sector. Building on this foundation, the present section aims to further examine key issues that may influence the feasibility of hydrogen adoption, with a particular focus on economic and technological dimensions. A comprehensive understanding of these issues is essential for deepening insights into decarbonization pathways in buildings, reframing the knowledge landscape, and advancing the widespread deployment and integration of hydrogen solutions within the building sector. All techno-economic and carbon analyses in this study are conditional on exogenous hydrogen price and carbon intensity parameters, which depend on the assumed production pathway (e.g., green, blue, or grid-mix electrolysis).

5.1. Insights into economic feasibility

The economic dimension of hydrogen applications in the building sector has been widely discussed in the literature. As shown in Fig. 4 of Section 3.3, a preliminary heatmap analysis reveals that the high frequency of references to "economic feasibility" reflects a broad academic consensus on the significant influence of economic factors on the practical adoption of hydrogen technologies in buildings. However, scholarly perspectives on the economic viability of hydrogen in this context remain highly polarized. Many researchers express skepticism regarding hydrogen's cost competitiveness. Mellot et al. [72] argue that electric heat pumps, gas-fired power plants, and photovoltaics offer more economically viable alternatives. Anastasovski et al. [29] attribute hydrogen's weak economic performance to the high cost of materials, while Castle and Hendry [90] highlight the substantial infrastructure investments required for hydrogen deployment, including facility retrofitting. Other scholars, however, maintain a more cautiously optimistic stance, suggesting that economic feasibility can be achieved under specific conditions. For instance, hydrogen systems may become viable when electrolyzers and fuel cells are optimally controlled [49], when system configurations are well-optimized [26], or when excess energy can be sold to offset operational costs [6]. Viability is also enhanced under favorable market conditions, such as lower hydrogen prices [59,62] or within hybrid energy storage solutions involving hydrogen and batteries under specific power supply constraints [44]. Notably, Mohammad and Iqbal [27] as well as Bristowe and Smallbone [64] underscore that technological advancement and large-scale production are critical drivers for reducing hydrogen costs and improving its overall economic feasibility.

This review systematically examines the current research on the economic feasibility of hydrogen applications in the building sector. While there is no unified conclusion in the academic community, studies consistently suggest that the effectiveness of hydrogen deployment is highly contingent upon specific technological conditions, regional

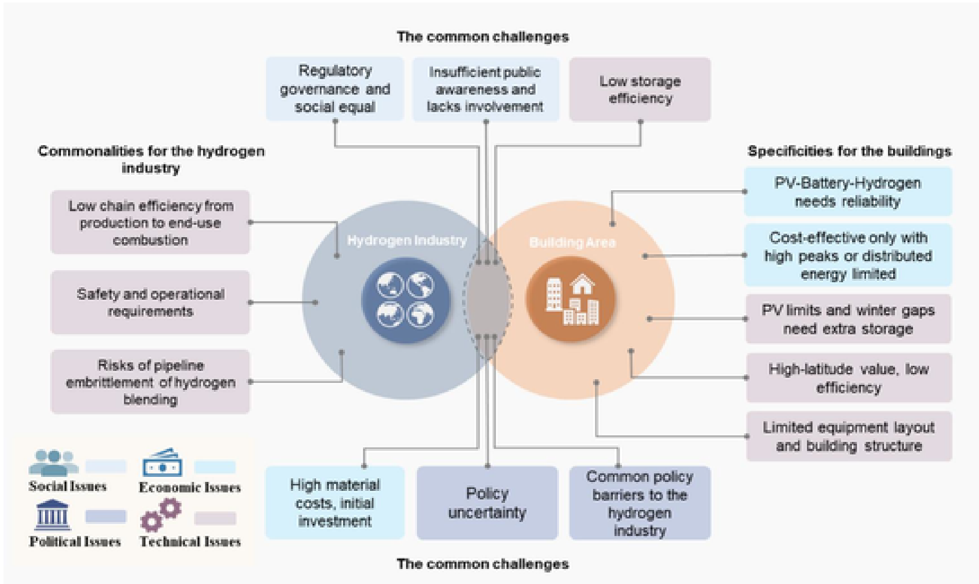

Fig. 8. The current state and relationship between common issues in the hydrogen industry and problems specific to building applications.

characteristics, and policy environments [91]. On the one hand, some studies highlight existing challenges such as high system costs, significant infrastructure requirements, and limited technological maturity. On the other hand, other research indicates that with improvements in electrolysis efficiency, enhanced integration with renewable energy, and continued declines in hydrogen prices, hydrogen-powered building systems show promising economic potential, particularly in contexts with strong system optimization capabilities and supportive policy incentives.

5.2. *Technical feasibility considerations*

In contrast to cost-focused comparisons within the economic dimension, technological feasibility emphasizes the practical operation, and performance of hydrogen systems in buildings. As illustrated in the keyword co-occurrence network generated through bibliometric analysis in Section 3.3, efficiency, capacity, consumption, and lifespan as core technical parameters that are strongly associated with the feasibility of hydrogen-based technologies.

Capacity, as a key indicator of energy reserve levels, is closely linked to the degree of hydrogen integration within building energy systems. Brancaleoni et al. [67] evaluated the hydrogen production, consumption, and storage characteristics of off-grid energy systems powered by solar and hydrogen sources under varying meteorological conditions and energy demand profiles. Their findings suggest that increasing battery storage or photovoltaic capacity can enhance the alignment between energy supply and demand. This implies that, as system energy reserves increase, the capacity and extent to which hydrogen participates in meeting diverse energy scenarios also improves. Consumption, on the other hand, refers to the operational expenditure of energy or materials during system functioning. It also serves as a direct metric of a building's energy autonomy, where net energy consumption below on-site generation indicates the potential for energy self-sufficiency. In microgrid simulations, buildings integrating hydrogen fuel cell electric vehicles (FCEVs) with vehicle-to-grid (V2G) technologies can achieve net-zero energy consumption, and in some cases, generate more energy than they consume [62]. These insights further contribute to understanding the technological feasibility of hydrogen applications in the building.

For hydrogen systems, particularly fuel cell components, lifespan performance is closely tied not only to maintenance frequency and replacement cycles but also to overall life-cycle costs. Extending the operational life of fuel cells is therefore essential for enhancing the technological viability of hydrogen systems. Baldi et al. [45] underscored the importance of optimized integration among internal system components in achieving significant performance improvements. Their study revealed that the coordinated configuration of hydrogen storage systems with PEMFCs can greatly enhance the system's dynamic response capability, especially in hybrid configurations with SOFCs. While SOFCs offer high thermal efficiency and are well-suited for base-load operation, they are limited by slower response times, making it difficult to cope with rapid fluctuations in building energy demand. The incorporation of PEMFCs, which feature shorter response times and flexible start-up capabilities, provides immediate power support during sudden load surges, and effectively mitigates the response lag of SOFCs [45]. This complementary mechanism not only improves the operational conditions of different fuel cell types by reducing performance degradation caused by frequent on-off cycles and abrupt load changes but also contributes to extending SOFC service life. Accordingly, research on service life should move beyond the evaluation of individual components to encompass system-level integration, including the study of synergistic degradation patterns and end-of-life strategies such as component recycling and reuse.

According to Table 1 in Section 3.1, the vast majority of existing studies are based on system simulation experiments, primarily aiming to evaluate the feasibility of hydrogen applications, optimize performance, and explore potential benefits. This indicates that, at least from a technical standpoint, the actual deployment and operation of hydrogen systems in the building sector remain relatively limited. Moreover, current research trends may also suggest that opportunities for hydrogen integration in buildings are not yet widespread. Several scholars have pointed out that hydrogen is more suitable for buildings located in remote, rural, off-grid, or extreme environments [45,47,74,76]. These scenarios often lack mature energy infrastructure, such as grid connections, and are more susceptible to seasonal or renewable energy fluctuations, including limited photovoltaic and wind power generation. Hydrogen, serving as a stable energy carrier, can be produced from surplus renewable energy, and stored long-term, then later converted into electricity via fuel cells to meet building energy demands during high-load periods. This pathway helps to enhance the energy self-sufficiency and operational stability for buildings in such areas, both daily and during critical periods such as winter seasons with low solar irradiance and minimal wind availability.

This review indicates that hydrogen technologies in the building sector remain at a developmental stage primarily characterized by technological validation and demonstration. Large-scale deployment is still constrained by limited maturity system, economic viability, and insufficient infrastructure support. Nevertheless, in building environments where energy access is limited or load fluctuations are significant, hydrogen systems have demonstrated strong adaptability and operational resilience. In particular, when coupled with renewable energy sources such as photovoltaics, their potential as a long-duration energy storage medium and load-balancing mechanism is becoming increasingly evident. In addition, this paper distinguishes three interfaces to summarize the operational evidence reviewed across the grid–building–hydrogen nexus: (i) grid to building (electricity prices, demand response, reliability), (ii) building to hydrogen (electrolyzer throttling, waste-heat utilization, storage sizing), and (iii) hydrogen to grid and building (P2H2P cycling, V2G/V2B buffering, hydrogen blending into pipelines). Within grid-connected settings, bidirectional exchanges (e.g., resale and ancillary-like functions) enable both cost and reliability benefits, whereas off-grid or microgrid configurations rely primarily on hydrogen to provide seasonal shifting and adequacy. Evidence in this paper regards V2G and V2B further indicates that hydrogen coupled with mobility can buffer night-time and winter power shortfalls. Accordingly, in interpreting case studies, this paper treats these dynamics as operational couplings across the three interfaces rather than as isolated configurations, thereby clarifying when hydrogen serves as a complement to electrification and when it functions as a primary resilience asset.

6. Conclusion and future recommendations

This review provides a comprehensive analysis of the role of hydrogen energy in the decarbonization of the building sector, with a systematic exploration of its application progress, benefits, and associated challenges. Drawing from technical and economic perspectives, the review highlights that the practical feasibility of hydrogen in the built environment largely depends on the current status of its techno-economic feasibility and the relationship between them. Although hydrogen energy can enhance the energy autonomy and resilience of buildings in remote locations or under specific environmental conditions, most related technologies are still at the stage of feasibility assessment and pilot demonstration. Economically, the deployment of hydrogen systems continues to be constrained by high costs, infrastructure investment requirements, and uncertainties associated with large-scale implementation. Overcoming these bottlenecks necessitates an integrated pathway that combines technological optimization and innovation, scaling up production, accelerating pilot project deployment, fostering cross-sector collaboration, and securing consistent policy support. It is important to underscore that the long-term sustainability of hydrogen energy in the building sector depends not only on the strategies, but also on a nuanced understanding of its application conditions within the broader context of varying building typologies, regional energy structures, and market mechanisms. As hydrogen increasingly becoming an integral component of low-carbon energy systems in buildings, a thorough understanding of its feasibility characteristics and systemic impacts will serve as a critical foundation for informing future scientific research and policy development.

In conclusion, this review not only provides an assessment of the current state of hydrogen application in the building sector but also calls for a systems-thinking approach to reframe its developmental trajectory. By proposing a comprehensive review framework that integrates multi-dimensional factors, the paper offers a forward-looking perspective on the future of low-carbon transitions in the built environment. The successful integration of hydrogen will ultimately depend on strategically coordinated cross-sectoral efforts that align technological potential with societal goals, a process that must be grounded in rigorous economic evaluation, continuous technological innovation, and adaptive policy refinement.

6.1. Recommendations from technical-economic aspect

6.1.1. Economic aspect

Based on current findings, the following practical recommendations can be offered for stakeholders. Pilot projects should be initiated in building types that demonstrate high energy flexibility and access to renewable energy resources, in order to validate the technical adaptability and economic viability of hydrogen system configurations; System design should emphasize integrated optimization with photovoltaic systems, energy storage, and grid connections to enhance overall energy performance and return on investment; Conducting sensitivity analyses covering initial capital investment, operating costs, and hydrogen price volatility is essential to improving risk resilience and attracting project financing. For policymakers, promoting the implementation of hydrogen technologies in the building sector requires coordinated efforts in mechanism design, standard setting, and cross-sector collaboration. It is recommended to enhance financial subsidies and tax incentives for green hydrogen in order to lower the threshold for initial deployment. Developing economic assessment tools tailored to regional building characteristics can improve the precision and scientific rigor of policy formulation. Furthermore, encouraging joint development and shared use of hydrogen infrastructure across buildings, transportation, and industry sectors may yield scale economies that enhance overall system cost-effectiveness. Overall, the economic feasibility of hydrogen in buildings is not inherently constrained but rather is highly dependent on the degree of system-level optimization and the strength of policy support. Future research should focus on the development of context-sensitive economic evaluation methods, the formulation of deployment pathways for representative building types, and the accumulation and open sharing of empirical data. These efforts will help establish a robust quantitative foundation to inform decision-making and accelerate the decarbonization of the built environment.

6.1.2. Technical aspect

For professionals in the building industry, the effective integration of hydrogen technologies requires early-stage incorporation into the overall energy system planning, rather than treating hydrogen as a supplementary or retrofit solution. In scenarios with distinct functional zoning and heterogeneous energy loads, it is advisable to prioritize the deployment of hydrogen-based CHP systems or multi-energy hybrid solutions combining hydrogen with heat pumps and photovoltaics, in order to achieve integrated heating, cooling, and electricity supply and enhance energy self-sufficiency. Moreover, architects and system integration engineers should reserve spatial configurations and technical interfaces for hydrogen equipment during the design phase, ensuring compatibility and operational safety during subsequent construction and commissioning. To enhance the feasibility and precision of hydrogen solutions, design teams are encouraged to utilize digital tools such as Building Performance Simulation and Digital Twin technology to dynamically evaluate hydrogen system performance under varying climatic conditions, load profiles, and operational strategies. These tools enable the optimization of energy configurations and reduction of lifecycle costs. Simultaneously, project developers should accumulate practical experience in the integrated application of hydrogen with photovoltaics, battery storage, and HVAC systems, and promote the development of modular and standardized hydrogen units to support future large-scale replication.

From the perspective of policymakers and regulatory authorities, advancing hydrogen applications in buildings hinges on establishing clear institutional frameworks and pilot incentive mechanisms. Dedicated demonstration projects should be initiated in selected scenarios such as urban regeneration zones, industrial parks, and heating-dominated buildings in cold regions, using real-world operational data to verify technical reliability and economic viability. In parallel, there is an urgent need to develop a hydrogen-specific building code and regulatory framework that addresses key safety aspects such as hydrogen storage, ventilation, leak detection, and emergency response. In terms of policy instruments, it is recommended to incorporate building-scale hydrogen projects into green building incentive schemes or green finance mechanisms, such as green bonds or green credit, and to establish dedicated funding programs for hydrogen buildings to mobilize private capital. More importantly, cross-sectoral policy alignment should be promoted across the building, energy, and transportation sectors. Strategic coupling of building hydrogen systems with hydrogen-powered mobility infrastructure can enable integrated hydrogen utilization within regional energy systems, thereby improving overall system efficiency and investment returns. Moreover, interdisciplinary integration, particularly with architectural design and energy management, will be critical to advancing hydrogen applications in buildings from conceptual exploration to practical deployment.

6.2. Research agenda

To transform the dispersed descriptions of future work into an actionable roadmap, this paper consolidates the gaps identified in Sections 3 to 5 into a structured research agenda. Each item aligns a targeted research question with feasible methods or datasets and specifies the expected contribution, with priority given to issues that (i) recur across different building types and climate conditions, and (ii) exert the greatest constraints on techno-economic viability or policy adoption. Where relevant, we highlight the interactions observed in the review between operational control, the role of long-term storage, and regulatory readiness.

1. Policy and market formation under path-dependency signals.

Review results demonstrate that policy design, price signals, and safety perceptions exert substantial influence on adoption and investment decisions; however, current guidance across jurisdictions remains fragmented. We call for scenario-based studies to map which policy bundles are likely to trigger adoption under varying cost and carbon conditions of green, blue, and grid-mixed hydrogen, and to provide cross-regional comparative inputs that capture heterogeneity. Such analyses would inform the timing of first-mover projects and the design of de-risking instruments.

2. Feasibility frontiers for specific building types and regions.

Economic conclusions remain highly contingent on the specific conditions of climate, load profiles, and price structures. Future work should quantify break-even thresholds by applying parameterized TEA/LCCA to representative building archetypes and regions, incorporating local electricity, hydrogen, and carbon price bands together with measured load curves. This approach would enable the derivation of deployability rankings rather than reliance on generalized averages.

3. Portable and context-sensitive assessment frameworks.

The field still lacks a reusable approach capable of integrating regional parameters and generating deployment pathways and thresholds. We propose an open, modular framework that combines parameter libraries with counterfactual experiments and validate it across multi-city case studies to enhance the portability and comparability of results.

4. From simulation to evidence: real-world performance curves.

Most studies rely on system simulations, while operational datasets remain scarce. We recommend collecting digital twin and EMS data from pilot projects to estimate degradation patterns, cycling behavior, and lifetime cost curves under real operating conditions, and feeding these insights back into simulation assumptions and bankable operation-and-maintenance models for calibration.

5. Joint optimization of hybrid stacks and storage.

The qualitative complementarity between SOFCs (high-efficiency baseload) and PEMFCs (rapid transients) is well recognized, yet the system-level benefits under optimized scheduling remain insufficiently quantified. Leveraging both bench-scale and field data for multi-energy co-optimization (electricity/hydrogen/thermal) can reveal improvements in LCOE and GHG outcomes, as well as control strategies that maintain stability under load variations.

6. Hydrogen as long-duration energy storage.

The seasonal mismatch between renewable supply and heating-dominated demand positions hydrogen as a potential solution of long-duration energy storage. Future work should employ reanalyzed photovoltaic and wind datasets and conduct year-long time-series optimizations to determine hydrogen's marginal winter reliability and peak-shaving value relative to electrochemical storage, expressed both per kilowatt-hour and per ton of CO_2 cost.

7. Building–transport coupling (FCEV/V2G/V2B).

Although V2G and V2B concepts are promising, the economic boundary conditions for net-positive benefits, such as hydrogen prices, dwell times, and tariffs, remain unclear. Agent-based integrated models, combined with parking and charging datasets, should quantify bilateral value streams and inform the design of tariff and market rules at regional and campus scales.

8. Safety codes and standardized designs for deployment.

Within the building context, gaps in regulations, safety protocols, and standards related to storage, ventilation, leak detection, and emergency response constrain large scale adoption. Future research should translate risk analyses (e.g., CFD simulations and leak testing) into equipment- and space-level standards, together with acceptance checklists aligned with building regulations and insurance requirements.

9. Shared infrastructure and open data for economies of scale.

By sharing hydrogen infrastructure and open access datasets of operational experience, cross sector coordination, including buildings, transport, and industry, can achieve economies of scale. Future work is needed on financing, governance, and scheduling mechanisms (e.g., capacity rights and real-options approaches) to align incentives across multiple stakeholders.

Overall, by translating current gaps into testable questions and feasible methods, the agenda seeks to shift research from broad potential to actionable trajectories. If pursued item by item, it would not only strengthen the techno-economic and environmental evidence base but also accelerate the development of policies, standards, and infrastructure, thereby positioning hydrogen as a genuine pillar of building decarbonization.

CRediT authorship contribution statement

Yimeng Li: Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation. **Muhammad Shafique:** Writing – review & editing, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Xiaowei Luo:** Writing – review & editing, Supervision, Resources, Project administration, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] Office Met. HadCRUT5 analysis time series: Ensemble means and uncertainties: Summary, global, annual, Exeter. U.K.: Met Office Hadley Centre; 2023.

[2] UNFCCC. Paris agreement, in Paris climate change conference, Paris, France: United Nations framework convention on climate change (UNFCCC). 2015.

[3] UNFCCC, The Glasgow Climate Pact – Key Outcomes from COP26, United Nations Framework Convention on Climate Change (UNFCCC), 2021. [Online]. Available: https://unfccc.int/process-and-meetings/the-paris-agreement/the-glasgow-climate-pact-key-outcomes-from-cop26 [Accessed: Dec. 11, 2024].

[4] Martins FP, Almaraz SDL, Junior ABB, Azzaro-Pantel C, Parikh P. Hydrogen and the sustainable development goals: synergies and trade-offs. Renew Sust Energ Rev 2024;204:114796. https://doi.org/10.1016/j.rser.2024.114796.

[5] European Parliament. (2010). Directive 2010/31/EU of 19 May 2010 on the energy performance of buildings [Online]. Available: https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:153:0013:0035:en:PDF [Accessed: Dec. 11, 2024].

[6] Maestre VM, Ortiz A, Ortiz I. Implementation and digitalization of a renewable hydrogen-based power system for social housing Decarbonization. Chem Eng Trans 2022;96. https://doi.org/10.3303/CET2296038.

[7] IRENA. (2018). Global Energy Transformation: A Roadmap to 2050 [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Apr/IRENA_Report_GET_2018.pdf [Accessed: Dec. 11, 2024].

[8] Renau J, et al. Novel use of green hydrogen fuel cell-based combined heat and power systems to reduce primary energy intake and greenhouse emissions in the building sector. Sustainability (Switzerland) 2021;13(4). https://doi.org/10.3390/su13041776.

[9] Thomas JM, Edwards PP, Dobson PJ, Owen GP. Decarbonising energy: The developing international activity in hydrogen technologies and fuel cells. 2020. https://doi.org/10.1016/j.jechem.2020.03.087.

[10] Zainal BS, et al. Recent advancement and assessment of green hydrogen production technologies. 2024. https://doi.org/10.1016/j.rser.2023.113941.

[11] Khaligh V, Ghezelbash A, Liu J, Won W, Koo J, Na J. Multi-period hydrogen supply chain planning for advancing hydrogen transition roadmaps. Renew Sust Energ Rev 2024;200:114536. https://doi.org/10.1016/j.rser.2024.114536.

[12] Patel GH, Havukainen J, Horttanainen M, Soukka R, Tuomaala M. Climate change performance of hydrogen production based on life cycle assessment. Green Chem 2024;26(2). https://doi.org/10.1039/d3gc02410e.

[13] Sánchez-Bastardo N, Schlögl R, Ruland H. Methane pyrolysis for zero-emission hydrogen production: a potential bridge technology from fossil fuels to a renewable and sustainable hydrogen economy. Ind Eng Chem Res 2021;60(32):11855–81. https://doi.org/10.1021/acs.iecr.1c01679.

[14] Oliveira AM, Beswick RR, Yan Y. A green hydrogen economy for a renewable energy society. 2021. https://doi.org/10.1016/j.coche.2021.100701.

[15] Ortiz-Imedio R, et al. Power-to-ships: future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050. Energy 2021;228. https://doi.org/10.1016/j.energy.2021.120660.

[16] Badrinarayanan DSR, Bokkassam SD, Krishnan JN. Investigation on implementing hydrogen technology in residential sector. Energy Rep 2024;12(13):920–41. https://doi.org/10.1016/j.egyr.2024.07.005.

[17] Lian J, Zhang Y, Ma C, Yang Y, Chaima E. A review on recent sizing methodologies of hybrid renewable energy systems. 2019. https://doi.org/10.1016/j.enconman.2019.112027.

[18] Khan FA, Pal N, Saeed SH. Review of solar photovoltaic and wind hybrid energy systems for sizing strategies optimization techniques and cost analysis methodologies. 2018. https://doi.org/10.1016/j.rser.2018.04.107.

[19] Pratt JW, Harris AP. Vessel cold-ironing using a barge mounted PEM fuel cell: Project scoping and feasibility. In: Sandia National Laboratories (SNL-CA), Livermore, CA, USA, SAND2013-0501; 2013. https://doi.org/10.2172/1117104.

[20] Gunathilake C, Soliman I, Panthi D, Tandler P, Fatani O, Ghulamullah NA, et al. A comprehensive review on hydrogen production, storage, and applications. Chem Soc Rev 2024;53(22):10900–69. https://doi.org/10.1039/D3CS00731F.

[21] Wu W, Skye HM. Residential net-zero energy buildings: Review and perspective. 2021. https://doi.org/10.1016/j.rser.2021.110859.

[22] Cao S, Alanne K. Technical feasibility of a hybrid on-site H2 and renewable energy system for a zero-energy building with a H2 vehicle. Appl Energy 2015;158:568–83. https://doi.org/10.1016/j.apenergy.2015.08.009.

[23] De Masi RF, Festa V, Penchini D, Ruggiero S, Tariello F, Vanoli GP, et al. State of art of hydrogen utilization for building sector and set-up with preliminary experimental results of 1 kWel solid oxide fuel cell installed in a nearly zero energy house. Energy 2024;302:131810. https://doi.org/10.1016/j.energy.2024.131810.

[24] Pugsley A, Zacharopoulos A, Chemisana D. "Polygeneration systems in buildings," in *Polygeneration Systems: Design,* Processes and Technologies. 2022. https://doi.org/10.1016/B978-0-12-820625-6.00001-3.

[25] Xin L, Li S, Rene ER, Lun X, Zhang P, Ma W. Prediction of carbon emissions peak and carbon neutrality based on life cycle CO2 emissions in megacity building sector: dynamic scenario simulations of Beijing. Environ Res 2023;238. https://doi.org/10.1016/j.envres.2023.117160.

[26] Dong H, Xu C, Chen W. Modelling and configuration optimization of the rooftop photovoltaic with electric-hydrogen-thermal hybrid storage system for zero-energy buildings: consider a cumulative seasonal effect. Build Simul 2023;16(10). https://doi.org/10.1007/s12273-023-1066-5.

[27] Mohammad SS, Iqbal SJ. Hydrogen technology supported solar photovoltaic-based microgrid for urban apartment buildings: techno-economic analysis and optimal design. Energy Convers Manag 2024;302. https://doi.org/10.1016/j.enconman.2024.118146.

[28] Mehr AS, Ilkhani M, Sabernia S, Nooshmand S, Gholamian E, Assareh E. Thermodynamics assessment and dynamic simulation of a low-carbon syngas-fueled SOFC system using a green hydrogen blend. Int J Hydrog Energy 2024;51. https://doi.org/10.1016/j.ijhydene.2023.05.128.

[29] Anastasovski A, Andreucci MB, Kádár J, Delli Paoli M. Energy storage in urban areas: the role of energy storage facilities, a Review. 2024. https://doi.org/10.3390/en17051117.

[30] North P, Jentsch A. A circular economy approach to building heating: the role of exergy in policymaking. Energy Rep 2021;7. https://doi.org/10.1016/j.egyr.2021.08.098.

[31] Slorach PC, Stamford L. Net zero in the heating sector: technological options and environmental sustainability from now to 2050. Energy Convers Manag 2021;230. https://doi.org/10.1016/j.enconman.2021.113838.

[32] Gordon JA, Balta-Ozkan N, Haq AU, Nabavi SA. Heterogeneous preferences for living in a hydrogen home: an advanced multigroup analysis. Sustainable Energy & Fuels 2024;8(12):2601–48. https://doi.org/10.1039/D4SE00392F.

[33] Ghisellini P, Passaro R, Ulgiati S. Is green hydrogen an environmentally and socially sound solution for decarbonizing energy systems within a circular economy transition? Energies 2025;18(11). https://doi.org/10.3390/en18112769.

[34] Wang X, Zhang W, Yang K, Guo J, Li Z, Zou R, et al. The performance enhancement and multi field applications of PVT hydrogen production technology: a review. Sol Energy 2025;297:113626. https://doi.org/10.1016/j.solener.2025.113626.

[35] A. Kaabinejadian, A. Pozarlik, and C. Acar, "A systematic review of predictive, optimization, and smart control strategies for hydrogen-based building heating systems," Appl Energy, vol. 379, 124994, doi: https://doi.org/10.1016/j.apenergy.2024.124994.

[36] Ramasamy A. PRISMA 2020: Key Changes and Implementation Aspects. J Oral Maxillofac Surg 2022;80(5). https://doi.org/10.1016/j.joms.2021.12.018.

[37] Ogunmakinde OE, Egbelakin T, Sher W, Omotayo T, Ogunnusi M. Establishing the limitations of sustainable construction in developing countries: A systematic literature review using PRISMA. 2024. https://doi.org/10.1108/SASBE-10-2022-0223.

[38] Andreo-Martínez P, Ortiz-Martínez VM, Salar-García MJ, Veiga-del-Baño JM, Chica A, Quesada-Medina J. Waste animal fats as feedstock for biodiesel production using non-catalytic supercritical alcohol transesterification: A perspective by the PRISMA methodology. 2022. https://doi.org/10.1016/j.esd.2022.06.004.

[39] Farrús M. Automatic speech recognition in L2 learning: A review based on PRISMA methodology. 2023. https://doi.org/10.3390/languages8040242.

[40] Bastidas-Orrego LM, Jaramillo N, Castillo-Grisales JA, Ceballos YF. A systematic review of the evaluation of agricultural policies: Using prisma. 2023. https://doi.org/10.1016/j.heliyon.2023.e20292.

[41] Page MJ, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372. https://doi.org/10.1136/bmj.n71.

[42] Page MJ, et al. PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews. BMJ 2021;372. https://doi.org/10.1136/bmj.n160.

[43] Khalil H, Murnane T, Kiegaldie D, Leech M, Waller L, McLean A. Tools to support the automation of systematic reviews. J Clin Epidemiol 2022;147:81–9. https://doi.org/10.1016/j.jclinepi.2021.12.005.

[44] Adeyemo AA, Amusan OT. Modelling and multi-objective optimization of hybrid energy storage solution for photovoltaic powered off-grid net zero energy building. J Energy Storage 2022;55. https://doi.org/10.1016/j.est.2022.105273.

[45] Baldi F, Wang L, Pérez-Fortes M, Maréchal F. A cogeneration system based on solid oxide and proton exchange membrane fuel cells with hybrid storage for off-grid applications. Front Energy Res 2019;6. https://doi.org/10.3389/fenrg.2018.00139.

[46] Sorgulu F, Dincer I. A renewable source based hydrogen energy system for residential applications. Int J Hydrog Energy 2018;43(11). https://doi.org/10.1016/j.ijhydene.2017.10.101.

[47] Karaca AE, Dincer I. A new integrated solar energy based system for residential houses. Energy Convers Manag 2020;221. https://doi.org/10.1016/j.enconman.2020.113112.

[48] Xu X, et al. Optimal operational strategy for a future electricity and hydrogen supply system in a residential area. Int J Hydrog Energy 2022;47(7). https://doi.org/10.1016/j.ijhydene.2021.11.085.

[49] He Y, Zhou Y, Yuan J, Liu Z, Wang Z, Zhang G. Transformation towards a carbon-neutral residential community with hydrogen economy and advanced energy management strategies. Energy Convers Manag 2021;249. https://doi.org/10.1016/j.enconman.2021.114834.

[50] Eroglu M, Dursun E, Sevencan S, Song J, Yazici S, Kilic O. A mobile renewable house using PV/wind/fuel cell hybrid power system. Int J Hydrog Energy 2011;36(13). https://doi.org/10.1016/j.ijhydene.2011.01.046.

[51] Silva SB, Severino MM, De Oliveira MAG. A stand-alone hybrid photovoltaic, fuel cell and battery system: a case study of Tocantins, Brazil. Renew Energy 2013;57. https://doi.org/10.1016/j.renene.2013.02.004.

[52] Endo N, Goshome K, Tetsuhiko M, Segawa Y, Shimoda E, Nozu T. Thermal management and power saving operations for improved energy efficiency within a renewable hydrogen energy system utilizing metal hydride hydrogen storage. Int J Hydrog Energy 2021;46(1). https://doi.org/10.1016/j.ijhydene.2020.10.002.

[53] Endo N, Shimoda E, Goshome K, Yamane T, Nozu T, Maeda T. Construction and operation of hydrogen energy utilization system for a zero emission building. Int J Hydrog Energy 2019;44(29). https://doi.org/10.1016/j.ijhydene.2019.04.107.

[54] Parra D, Gillott M, Walker GS. Design, testing and evaluation of a community hydrogen storage system for end user applications. Int J Hydrog Energy 2016;41

(10). https://doi.org/10.1016/j.ijhydene.2016.01.098.
[55] Maclay JD, Brouwer J, Samuelsen GS. Experimental results for hybrid energy storage systems coupled to photovoltaic generation in residential applications. Int J Hydrog Energy 2011;36(19). https://doi.org/10.1016/j.ijhydene.2011.06.089.
[56] Serra F, Lucariello M, Petrollese M, Cau G. Optimal integration of hydrogen-based energy storage systems in photovoltaic microgrids: a techno-economic assessment. Energies (Basel) 2020;13(6). https://doi.org/10.3390/en13164149.
[57] Yunez-Cano A, de González-Huerta RG, Tufiño-Velázquez M, Barbosa R, Escobar B. Solar-hydrogen hybrid system integrated to a sustainable house in Mexico. Int J Hydrog Energy 2016;41(43). https://doi.org/10.1016/j.ijhydene.2016.06.203.
[58] Gracia L, Casero P, Bourasseau C, Chabert A. Use of hydrogen in off-grid locations, a techno-economic assessment. Energies (Basel) 2018;11(11). https://doi.org/10.3390/en11113141.
[59] Vecchi A, Davis D, Brear M, Aye L. Least-cost solutions to household energy supply decarbonisation in temperate and sub-tropical climates. J Clean Prod 2024;448. https://doi.org/10.1016/j.jclepro.2024.141465.
[60] Shimoda Y, Sugiyama M, Nishimoto R, Momonoki T. Evaluating decarbonization scenarios and energy management requirement for the residential sector in Japan through bottom-up simulations of energy end-use demand in 2050. Appl Energy 2021;303. https://doi.org/10.1016/j.apenergy.2021.117510.
[61] Liu J, Cao S, Chen X, Yang H, Peng J. Energy planning of renewable applications in high-rise residential buildings integrating battery and hydrogen vehicle storage. Appl Energy 2021;281. https://doi.org/10.1016/j.apenergy.2020.116038.
[62] Robledo CB, Oldenbroek V, Abbruzzese F, van Wijk AJM. Integrating a hydrogen fuel cell electric vehicle with vehicle-to-grid technology, photovoltaic power and a residential building. Appl Energy 2018;215. https://doi.org/10.1016/j.apenergy.2018.02.038.
[63] Sami S, Gholizadeh M, Deymi-Dashtebayaz M. An applicable multi-generation system for different climates from energy, exergy, exergoeconomic, economic, and environmental (5E) perspectives. Sustain Cities Soc 2024;100. https://doi.org/10.1016/j.scs.2023.105057.
[64] Bristowe G, Smallbone A. The key techno-economic and manufacturing drivers for reducing the cost of power-to-gas and a hydrogen-enabled energy system. Hydrogen (Switzerland) 2021;2(3). https://doi.org/10.3390/hydrogen2030015.
[65] Khan MA, Gohari Darabkhani H. Micro Combined Heat and Power (micro-CHP) Systems for Household Applications: Techno-economic and Risk Assessment of The Main Prime Movers. Int J Green Energy 2024;21(7). https://doi.org/10.1080/15435075.2023.2258177.
[66] O. S. Hemied and H. A. Gabbar, "Intelligent optimization algorithm to synthesize renewable energy and hydrogen deployment strategies," *Proc.* 2024 10th Int. Conf. Appl. Syst. Innovation (ICASI), Kyoto, Japan, 2024, pp. 354–356, doi: https://doi.org/10.1109/ICASI60819.2024.10547932.
[67] Brancaleoni PP, Silvagni G, Ravaglioli V, Corti E, Moro D. Hybrid solar and hydrogen energy system 0-D model for off-grid sustainable power system: a case in Italy. Int J Hydrog Energy 2024;92:1108–20. https://doi.org/10.1016/j.ijhydene.2024.10.284.
[68] De Masi RF, Festa V, Penchini D, Ruggiero S, Vanoli GP, Zinno A. Experimental characterization of solid oxide fuel cell hydrogen fueled in a residential small villa. Int J Hydrog Energy 2025;102:1180–92. https://doi.org/10.1016/j.ijhydene.2025.01.166.
[69] Elmer T, Worall M, Wu S, Riffat S. Assessment of a novel solid oxide fuel cell tri-generation system for building applications. Energy Convers Manag 2016;124. https://doi.org/10.1016/j.enconman.2016.07.010.
[70] Robledo CB, van Leeuwen LB, van Wijk AJM. Hydrogen fuel cell scooter with plug-out features for combined transport and residential power generation. Int J Hydrog Energy 2019;44(56). https://doi.org/10.1016/j.ijhydene.2019.04.103.
[71] Al-Buraiki AS, Al-Sharafi A. Hydrogen production via using excess electric energy of an off-grid hybrid solar/wind system based on a novel performance indicator. Energy Convers Manag 2022;254. https://doi.org/10.1016/j.enconman.2022.115270.
[72] Mellot A, Moretti C, Tröndle T, Patt A. Mitigating future winter electricity deficits: a case study from Switzerland. Energy Convers Manag 2024;309:118426. https://doi.org/10.1016/j.enconman.2024.118426.
[73] Seward W, Canet A, Qadrdan M. Spatially Explicit Scenarios for Decarbonising Heat in Domestic Buildings. In: *UPEC* 2020–*2020 55th International Universities Power Engineering Conference,* Proceedings; 2020. https://doi.org/10.1109/UPEC49904.2020.9209775.
[74] Victoria M, Zeyen E, Brown T. Speed of technological transformations required in Europe to achieve different climate goals. Joule 2022;6(5). https://doi.org/10.1016/j.joule.2022.04.016.
[75] Xu YP, Liu RH, Tang LY, Wu H, She C. Risk-averse multi-objective optimization of multi-energy microgrids integrated with power-to-hydrogen technology, electric vehicles and data center under a hybrid robust-stochastic technique. Sustain Cities Soc 2022;79. https://doi.org/10.1016/j.scs.2022.103699.
[76] Razmjoo A, Gakenia Kaigutha L, Vaziri Rad MA, Marzband M, Davarpanah A, Denai M. A Technical analysis investigating energy sustainability utilizing reliable renewable energy sources to reduce CO2 emissions in a high potential area. Renew Energy 2021;164. https://doi.org/10.1016/j.renene.2020.09.042.
[77] Masoud Sajjadian S. A critique on the UK'S net zero strategy. 2023. https://doi.org/10.1016/j.seta.2022.103003.
[78] Verma V, Thangavel S, Dutt N, Kumar A, Weerasinghe R. Introduction to thermal energy storage: Solar, geothermal and hydrogen energy. In: Verma V, Thangavel S, Dutt N, Kumar A, Weerasinghe R, editors. Highly efficient thermal renewable energy systems: Design, optimization and applications. Boca Raton, FL, USA: CRC Press; 2024. p. 1–22. https://doi.org/10.1201/9781003472629-1.
[79] Badakhsh A, Mothilal Bhagavathy S. Caveats of green hydrogen for decarbonisation of heating in buildings. Appl Energy 2024;353. https://doi.org/10.1016/j.apenergy.2023.122152.
[80] Jain R, Nagasawa K, Veda S, Sprik S. Grid ancillary services using electrolyzer-based power-to-gas systems with increasing renewable penetration. e-Prime – Adv Electrical Eng, Electron Energy 2023;6:100308. https://doi.org/10.1016/j.prime.2023.100308.
[81] Kwon K, Lee H-B, Kim N, Park S, Joshua SR. Integrated battery and hydrogen energy storage for enhanced grid power savings and green hydrogen utilization. Appl Sci 2024;14(17). https://doi.org/10.3390/app14177631. Art. no. 7631.
[82] Keiner D, Thoma C, Bogdanov D, Breyer C. Seasonal hydrogen storage for residential on- and off-grid solar photovoltaics prosumer applications: revolutionary solution or niche market for the energy transition until 2050? Appl Energy 2023;340:121009. https://doi.org/10.1016/j.apenergy.2023.121009.
[83] Fokkema JE, Uit het Broek MAJ, Schrotenboer AH, Land MJ, Van Foreest ND. Seasonal hydrogen storage decisions under constrained electricity distribution capacity. Renew Energy 2022;195:76–91. https://doi.org/10.1016/j.renene.2022.05.170.
[84] Iwuanyanwu O, Gil-Ozoudeh I, Okwandu AC, Ike CS. Retrofitting existing buildings for sustainability: challenges and innovations. Eng Sci Technol J 2024;5(8):2616–31. https://doi.org/10.51594/ESTJ.V5I8.1515.
[85] Häußermann JJ, Maier MJ, Kirsch TC, Kaiser S, Schraudner M. Social acceptance of green hydrogen in Germany: building trust through responsible innovation. Energy Sustain Soc 2023;13, no. 1:art. 22. https://doi.org/10.1186/s13705-023-00394-4.
[86] Gordon JA, Balta-Ozkan N, Nabavi SA. Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions. Appl Energy 2023;336:120850. https://doi.org/10.1016/j.apenergy.2023.120850.
[87] Vallejos-Romero A, Cordoves-Sánchez M, Cisternas C, Sáez-Ardura F, Rodríguez I, Aledo A, et al. Green hydrogen and social sciences: issues, problems, and future challenges. Sustainability 2022;15(1). https://doi.org/10.3390/su15010303. art. no. 303.
[88] Gordon JA, Balta-Ozkan N, Haq AU, Nabavi SA. Fuelling hydrogen futures? A trust-based model of social acceptance. Sustainable Energy & Fuels 2025;9:2510–55. https://doi.org/10.1039/D4SE01615G.
[89] Bade SO, Tomomewo OS, Meenakshisundaram A, Ferron P, Oni BA. Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: A review. 2024. https://doi.org/10.1016/j.ijhydene.2023.08.157.
[90] Castle J, Hendry DF. Five sensitive intervention points to achieve climate neutrality by 2050. SSRN Electron J 2022. https://doi.org/10.2139/ssrn.4227935.
[91] Liu F, Shafique M, Luo X. Dynamic lifecycle emissions of electric and hydrogen fuel cell vehicles in a multi-regional perspective. Environ Impact Assess Rev 2025;111:107695.