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Review

INTEGRATED HYBRID SYSTEMS FOR RESIDENTIAL ENERGY AUTONOMY: A LITERATURE REVIEW

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Abstract

The global transition to sustainable energy systems requires innovative solutions for energy storage and the decarbonization of the energy sector. This paper presents a literature review and comparative analysis of literature in the field of hybrid energy systems integrating photovoltaic panels, a hydrogen system, and heat pumps for residential applications. While conventional battery-based systems address the issue of daily fluctuations, the analysis shows that the introduction of hydrogen enables the necessary seasonal autonomy, bridging the gap between summer energy production and winter consumption.

The key results of the review indicate that the thermal integration of components, a process known as micro-trigeneration, the overall system efficiency (thermal and electrical combined) can exceed 80% by utilizing waste heat from the electrolyzer and fuel cell for space heating and domestic hot water production. Such synergy enables a reduction in the required battery capacity by 60–75%, thereby significantly optimizing resource utilization and reducing the environmental footprint of the energy system. Additionally, the paper analyzes the impact of advanced control strategies, such as fuzzy logic, on system stability and the longevity of fuel cells. In conclusion, integrated hybrid systems represent a promising pathway for the development of net-zero energy buildings; however, further efforts to reduce capital investment costs are necessary for their broader commercialization.

Keywords: renewable energy sources, hydrogen, heat pump, trigeneration.

INTRODUCTION

The global energy transition from fossil fuels to zero-carbon energy systems has become an imperative within environmental strategies and the “Green Agenda” [1]. In this context, renewable energy sources (RES), particularly photovoltaic (PV) and PV thermal (PVT) systems, play a leading role in the decarbonization of the power sector. However, the primary challenge of PV systems remains their intermittency and seasonal variability, which requires the implementation of advanced energy storage (ES) solutions to ensure a reliable energy

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supply throughout the year [2,3]. While lithium-ion batteries (LIB) are widely used for short-term balancing of daily fluctuations, hydrogen (H_2) is emerging as a key energy vector for long-term, i.e., seasonal ES [1,4]. The integration of an electrolyzer, hydrogen storage tank, and fuel cell (FC) enables surplus solar energy generated during the summer months to be efficiently stored and utilized during the winter period, when PV production is minimal and the demand for thermal and electrical energy is at its peak [4,5]. In addition to the decarbonization of the power sector, the decarbonization of the heating sector represents one of the greatest challenges. Heat pumps (HP) are recognized as the most efficient technology for space heating and domestic hot water (DHW) production; however, their operation significantly increases grid load during winter [6]. The synergy between the hydrogen system (electrolyzer, storage tank, and FC) (HS) and HP offers an innovative solution in the form of "sector coupling". Of particular scientific interest is the possibility of utilizing waste heat (WH) generated as a byproduct in the electrolyzer and FC. Research indicates that this thermal integration can increase the overall efficiency of hybrid systems above 80%, thereby significantly improving the coefficient of performance (COP) of the HP and reducing total primary energy consumption [6,7].

Although there is extensive literature on individual components, there is a need for a comprehensive review that analyzes the interaction of these technologies within integrated residential systems. The importance of this review lies in the systematization of the latest trends in system configuration, energy management strategies, and the analysis of energy autonomy of zero-energy buildings [5,8]. The central research question is: To what extent can the synergistic integration of hydrogen storage and HP eliminate seasonal energy deficits in residential buildings while maintaining thermodynamic efficiency? To address this, the study evaluates how hydrogen-based hybrid systems can bridge the gap between summer production and winter consumption [2,4], while simultaneously increasing overall energy and exergy efficiency through the recovery of WH in trigeneration systems (CCHP) [6,7]. Furthermore, this review seeks to identify the economic and operational trade-offs that currently limit the mass adoption of these integrated solutions [9,10].

MATERIALS AND METHODS

The methodology of this paper is based on a literature review and a comparative analysis of scientific literature addressing integrated hybrid energy systems. The focus of the research is on the synergy between PV panels, battery storage, and the HS in combination with HP for residential applications.

Literature selection criteria and sources

This review is based on selected relevant scientific papers addressing hybrid systems (PV, H_2 and HP) and related hybrid energy configurations. Primary sources include papers indexed in databases such as Web of Science, Scopus, and IEEE Xplore. The selection criteria included:

- Studies analyzing hybrid systems with at least three key components: PV, storage, and HP [4,6].
- Research focused on the energy self-sufficiency of residential buildings and “zero-energy” complexes [5,8].

- Studies employing advanced simulation tools (e.g., MATLAB/Simulink, TRNSYS, HOMER) for modeling energy flows [3,11].

The literature was selected based on relevance to residential-scale hybrid renewable systems, explicit inclusion of hydrogen-based storage, and the presence of either HP integration, energy management optimization, or thermal recovery analysis. Papers dealing exclusively with transport applications, industrial-scale hydrogen production, or isolated component-level analyses without system integration were excluded.

Classification of analyzed systems

The methodological approach includes the classification of the analyzed systems into two main categories for easier comparison:

1. **Systems with separated energy flows:** where the hydrogen subsystem is used exclusively for the storage and regeneration of electrical energy.
2. **Integrated trigeneration systems:** where WH from the electrolysis process and FC operation is utilized to improve the performance of the HP [6,9].

Key performance indicators

For the purpose of objective evaluation of different solutions, the following key parameters are defined and analyzed:

- Energy autonomy rate: the ability of the system to meet the building’s energy demand without relying on the electrical grid throughout the year [4].
- HP COP: analysis of the impact of thermal integration on heating efficiency, particularly at low outdoor temperatures [6,7].
- Overall system efficiency: comparison of energy losses across different conversion stages (electrolysis, storage, regeneration) [9,12].
- Energy management optimization**:** analysis of control algorithms, ranging from rule-based strategies to advanced fuzzy logic and Model Predictive Control (MPC), used to balance energy flows between the battery and hydrogen storage [3,11,13,14]. This indicator evaluates the system's ability to maintain power balance while reducing energy consumption by up to 17.9% compared to conventional methods [14].
- System stability and component longevity: A critical parameter that evaluates how control strategies impact the operational lifespan of the FC stack and electrolyzer membrane [5]. It focuses on the reduction of damaging start-stop cycles and the mitigation of efficiency degradation, which can otherwise lead to a 13.4% to 15.1% increase in fuel consumption over a 10-year period due to hardware aging [15].

This methodological structure enables a systematic insight into the current state of the art and the identification of critical factors for the future development of hybrid hydrogen systems in the residential sector.

RESULTS AND DISCUSSION

The analysis of the collected literature indicates that the integration of the HS with HP and PV systems addresses the critical shortcomings of conventional solutions based exclusively on battery storage.

Energy autonomy and the role of hydrogen in seasonal balancing

One of the most significant findings of the research is the advantage of hybrid storage configurations in achieving seasonal autonomy. While battery systems demonstrate high efficiency in charge–discharge cycles on a daily basis, they are not economically viable for long-term ES due to self-discharge and high capital costs per unit of capacity [2,3].

The synthesis of data shows that the introduction of a hydrogen storage tank enables bridging the gap between peak summer production and peak winter consumption [4,5]. Studies indicate that, in hybrid configurations, battery capacity can be drastically reduced (in some cases from 115 kWh to as little as 27 kWh), as hydrogen serves as a seasonal buffer. This approach not only increases the level of energy independence of the building, but also significantly reduces the environmental footprint associated with the production of LIB [6].

Thermal integration and efficiency improvement

A critical point of discussion in recent studies is the thermal coupling between hydrogen components and HP. In conventional systems, heat generated during electrolysis and FC operation is often considered a loss. However, modern trigeneration concepts utilize this “waste” heat for preheating fluids or directly for the heating system [6,7].

The key findings in this area include:

- Improvement of COP: The use of WH from the FC enables the HP to operate under more favorable temperature conditions, thereby directly increasing its COP, particularly at low outdoor temperatures [6,7].
- Overall system efficiency: While the electrical efficiency of individual components may be relatively low (e.g., around 40–50%), complete thermal integration enables the system to achieve an overall system efficiency of over 80% [1,6].
- Coverage of DHW demand**:** It has been established that WH can cover up to 80% of the annual DHW demand in the residential sector [6].

Advanced energy management strategies

The overall efficiency of the system largely depends on the applied control algorithm. The literature review identifies a transition from simple rule-based algorithms to advanced optimization methods.

Systems employing fuzzy logic or dynamic programming demonstrate significantly better performance in balancing energy flows between PV panels, the battery, and the electrolyzer [3,11]. These algorithms not only minimize operational costs but also extend the lifespan of FC by avoiding abrupt power fluctuations and frequent on/off cycling [3]. The results suggest that intelligent control can reduce component degradation, which is one of the main challenges for the commercialization of hydrogen technologies [11].

Comparison with traditional systems

Compared to conventional micro-cogeneration systems (e.g., those based on internal combustion engines), the integrated hybruid system offers the complete elimination of local greenhouse gas emissions and silent operation, which is crucial for urban residential environments [12]. Although initial investment costs remain higher, exergy analysis shows that FC offer better efficiency under partial load compared to internal combustion engines, making them well suited for the variable energy demands of households [9,12].

Table 1 *Overview of key studies on integrated hybrid systems*

Authors	**System configuration**	**Primary focus / Methodology**	**Key findings and results**
Rutnik *et al.*	PV + Battery + H_2 loop	Seasonal autonomy of residential buildings	Enables bridging the winter energy deficit to achieve 100% energy autonomy
Cikatić Šanić & Barbir	PV + electrolyzer + FC + HP	Thermal integration and trigeneration	Overall system efficiency exceeds 80%, while WH recovery covers 78.42% of thermal demand
Zidane & Belaid	PV + H_2 subsystem / MPC	Control strategies and operational stability	Advanced management reduces energy consumption by 3.9% to 17.9% compared to base strategies
Patin *et al.*	H_2 multi-energy system	Multi-objective optimization	Optimized systems cover 63% of building demand and achieve a 23% reduction in total costs
Mobayen *et al.*	Integrated solar system	Dynamic analysis of zero-energy complexes	Annual generation of 29,145.8 kWh achieved with a thermal comfort index of only 6.8%.
Sun *et al.*	PVT + HP + PEM electrolyzer	Thermodynamic analysis of trigeneration	Synergy between PVT and HP maximizes COP and significantly improves exergy efficiency
Jafari & Malekjamshidi	Hybrid renewable system	2D dynamic programming	Real-time optimization enables 100% utilization of available surplus PV energy for hydrogen generation
Vivas *et al.*	Hybrid systems with H_2	Review of control strategies	Confirms hydrogen as a superior solution for long-term storage due to high energy density (33.3 kWh/kg)
Ceran *et al.*	PV system with hydrogen storage	Analysis of the effects of aging	Component degradation over 10 years lead to a 13.4% to 15.1% increase in fuel consumption
Jia *et al.*	CCHP system with biomass and SOFC	3E evaluation	System reaches 83% energy efficiency and approximately 41% exergetic efficiency
Kurses *et al.*	PV + HP + H_2	Economic and environmental analysis	Project payback periods range from 4.6 to 8.9 years, depending on local climatic conditions

This analysis reveals several clear trends in literature that directly address the central research question regarding seasonal energy autonomy and efficiency:

- Dominance of hybrid storage: The reviewed studies, particularly [2] and [4], confirm that while batteries are efficient for daily cycles, hydrogen is the only viable solution for seasonal balancing. This hybrid approach allows for a 60% to 75% reduction in required battery capacity, which is crucial for the physical and economic feasibility of zero-energy buildings.

- Thermodynamic synergy through sector coupling: The integration of HP with the HS significantly alters the efficiency landscape. Analysis shows that utilizing WH from electrolysis and FC operation for water preheating can elevate the overall system efficiency to above 80% [6], with some configurations reaching 83% energy and 41% exergy efficiency [9]. This confirms that trigeneration is not just an addition, but a necessity for maximizing the COP of HP in winter conditions [7].
- System intelligence and longevity: A critical finding is the shift toward advanced algorithms. While simple rule-based strategies suffice for basic operation, MPC and fuzzy logic are essential for mitigating the 13.4% to 15.1% efficiency degradation caused by component aging over a 10-year [15]. Furthermore, these intelligent systems can reduce overall energy consumption by up to 17.9% [14], directly answering the need for operational stability mentioned in this study's objectives.

CONCLUSION

The analysis conducted in this review paper confirms that the synergistic integration of PV panels, the HS, and HP effectively eliminates seasonal energy deficits in residential buildings while significantly enhancing thermodynamic efficiency.

The main conclusions of the study, which provide a comprehensive answer to the research questions, are summarized as follows:

1. Effective bridging of seasonal gaps: Hydrogen storage represents a superior solution for long-term energy autonomy compared to standalone battery systems. By converting summer surplus PV energy into H_2, buildings can achieve 100% energy independence during winter months, while simultaneously optimizing the system's environmental footprint through reduced reliance on lithium-ion storage.
2. Achievement of high-efficiency trigeneration: The integration of thermal and electrical flows is the key to surpassing the limitations of individual components. The recovery of WH for residential thermal demand enables the system to meet up to 78.42% of heating and hot water needs, maintaining a total efficiency level above 80%.
3. Critical role of intelligent management: To ensure the commercial viability and equipment longevity of these systems, advanced control strategies are indispensable. They not only maximize the utilization of surplus PV energy in real-time but also protect sensitive components from damaging start-stop cycles, thereby preserving efficiency over long operational horizons.
4. Economic and environmental feasibility: While capital costs remain a challenge, the analyzed systems show a promising payback period of 4.6 to 8.9 years under favorable conditions. This makes them a key pillar for achieving the "Green Agenda" goals and transitioning toward a truly net-zero residential sector.

In conclusion, integrated hybrid systems are not only technologically feasible but are currently the most robust answer to the challenge of year-round energy autonomy in sustainable architecture.

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