

Review

Hydrogen–Natural Gas Blends in Combined Heat and Power Systems: A Comprehensive Review of Energy Performance, Emission Characteristics, and Integration Challenges

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Abstract

The decarbonization of energy systems has intensified interest in hydrogen-enriched natural gas (H₂NG) as a transitional fuel for combined heat and power (CHP) units and micro-CHP systems. This review consolidates experimental and numerical studies that explore the energy, environmental, and techno-economic implications of H₂NG blends in CHP applications. Research conducted over the last decade highlights that enriching natural gas with hydrogen extends the flammability limits, enhances combustion stability, and reduces CO₂ and CO emissions, while maintaining or improving electrical efficiency. However, these benefits are accompanied by higher NO_x formation under stoichiometric conditions, which can be mitigated by operating under lean-burn regimes. The review further examines hybrid solutions that integrate electrolyzers, photovoltaic systems, and oxygen-enriched combustion to improve system flexibility and sustainability. The findings consistently show that moderate hydrogen fractions (5–20% vol.) provide optimal trade-offs between efficiency gains and emission control, supporting the role of H₂NG as an intermediate step toward fully hydrogen-powered CHP technologies. Technical challenges related to ignition control, thermal recovery efficiency, and infrastructure adaptation are also discussed, along with emerging strategies for techno-economic optimization. This comprehensive assessment contributes to understanding how hydrogen blending can accelerate the transition to low-carbon, distributed energy systems.

Keywords: hydrogen-enriched natural gas (H₂NG); combined heat and power (CHP); micro-CHP; oxy-combustion; energy efficiency; emissions reduction; decarbonization; renewable integration; power-to-gas

Academic Editor: Antonis Peppas

Received: 6 May 2026

Revised: 16 June 2026

Accepted: 25 June 2026

Published: 28 June 2026

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1. Introduction

The global energy sector is undergoing a profound transformation toward sustainability, driven by the urgent need to reduce greenhouse gas emissions and mitigate climate change. The European Union's decarbonization roadmap targets climate neutrality by 2050, emphasizing renewable integration, efficiency improvement, and the gradual replacement of fossil fuels with low-carbon alternatives. Within this framework, hydrogen has emerged as a key energy vector due to its high specific energy content, clean combustion characteristics, and potential to store and transport renewable energy. When blended

with natural gas, hydrogen enables a gradual transition toward carbon-free energy conversion without requiring immediate large-scale infrastructure replacement.

In this review, the term hydrogen-enriched natural gas refers to hydrogen–natural gas blends with low hydrogen volumetric fractions, typically ranging from 5% to 20%, which represent realistic near-term pathways for hydrogen integration into existing CHP systems.

The utilization of hydrogen-enriched natural gas (H₂NG) in combined heat and power (CHP) systems represents one of the most practical and technically feasible routes for decarbonizing distributed energy generation. CHP systems simultaneously produce electricity and useful heat, achieving total efficiencies of up to 80–90%. By substituting part of the methane content with hydrogen, these systems can substantially reduce CO₂ emissions while maintaining or even improving operational performance. Experimental and numerical research over the last two decades has demonstrated that hydrogen blending modifies flame structure, increases burning velocity, and extends lean flammability limits, thereby improving combustion stability and efficiency [1–3].

In fact, the U.S. Environmental Protection Agency reports that a 1 MW CHP system can emit only about 4200 tons of CO₂ annually compared to approximately 8300 tons from separated electricity generation plus a conventional boiler, as shown in Figure 1 [4]. This nearly 50% reduction underscores the emission mitigation potential of CHP by increasing overall fuel utilization and eliminating transmission losses.

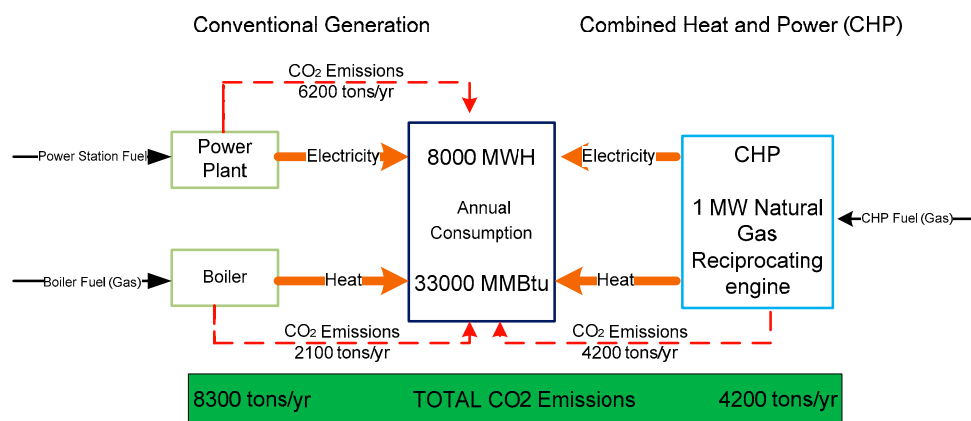


Figure 1. CO₂ emissions savings: comparison between CHP systems and conventional separate generation. Conceptual representation based on Ref. [4].

This figure compares the annual CO₂ emissions of a 1 MW combined heat and power (CHP) system versus a conventional power and heating scheme. While conventional generation emits about 8300 tons of CO₂ per year, the CHP-based system emits only ~4200 tons, representing roughly a 50% reduction thanks to efficiency gains and heat utilization.

However, these improvements come with certain challenges. Hydrogen’s high diffusivity and low ignition energy can alter flame propagation dynamics, leading to increased flame temperatures and, consequently, higher formation rates of nitrogen oxides (NO_x) under stoichiometric conditions. Controlling these effects requires careful optimization of the air–fuel ratio and ignition timing, along with advanced cooling and exhaust recirculation strategies. Studies by Lo Basso et al. [5] and Palmisano et al. [6] have shown that operating under lean-burn conditions ($\lambda > 1.3$) effectively mitigates NO_x emissions while maintaining high electrical efficiency, particularly for micro-CHP units and small-scale internal combustion engines.

In recent years, hybrid system architectures have attracted increasing attention, particularly those coupling CHP units with electrolyzers for on-site hydrogen production. This integration enables the direct conversion of surplus renewable electricity into

hydrogen, stored and later used as a supplementary fuel. Recent studies on hydrogen-enriched natural gas in combustion systems show that hydrogen addition can significantly influence engine and microturbine performance as well as emission characteristics. Investigations on microturbine CHP systems demonstrate that hydrogen blending with natural gas affects overall operational behavior and combustion performance, with implications for efficiency and emissions under different operating conditions [7].

Thermo-economic and environmental assessments of hydrogen–natural gas blends in CHP applications indicate that such mixtures can contribute to decarbonization and performance improvement; however, their effectiveness is strongly dependent on system configuration, operating conditions, and economic constraints [8].

Experimental studies focused on microturbine combustion further show that hydrogen addition has a notable impact on NO_x formation, primarily due to increased flame temperatures associated with hydrogen-enriched fuels, highlighting emissions control as an important challenge [9].

In addition, combined experimental and numerical investigations of methane–hydrogen blends in spark-ignition engines confirm that hydrogen enrichment affects combustion behavior, including flame propagation and stability, and can improve certain performance parameters, supporting its feasibility for internal combustion engine applications [10]. The combination of these technologies supports emerging concepts such as Power-to-Gas and Power-to-Heat, which aim to integrate renewable generation, heat recovery, and storage within a unified circular energy system.

A variety of experimental investigations have explored the performance of CHP systems operating with different hydrogen blending ratios. Lo Basso et al. [5,11] evaluated the impact of 5–20% hydrogen content on a microturbine-based CHP unit, reporting efficiency improvements up to 3% and reductions in CO₂ emissions exceeding 10%. De Santoli et al. [12] compared conventional natural gas CHP operation with dual-fuel hydrogen blends, demonstrating the potential to achieve near-zero carbon emissions when renewable hydrogen is utilized. Boulahlib et al. [13] extended these analyses by examining combustion stability and exhaust temperature variations across different operating regimes, confirming that H₂ addition generally enhances stability, especially at low load conditions.

From a thermodynamic standpoint, hydrogen addition alters the energy distribution between electrical and thermal outputs. While the higher flame temperature improves the electrical conversion efficiency, it may slightly decrease the amount of recoverable heat due to modified heat transfer characteristics. This shift requires re-optimization of heat exchanger design and load management strategies to fully exploit the potential benefits of H₂NG in CHP configurations [14–16].

Furthermore, research has emphasized the importance of digitalization and control optimization in managing combustion dynamics in hydrogen-enriched systems. The application of data-driven algorithms and adaptive control techniques allows real-time adjustment of operating parameters, ensuring safe and efficient operation even under fluctuating hydrogen concentrations [17]. Such approaches are aligned with the principles of Industry 4.0, enabling predictive maintenance, process optimization, and autonomous operation—features critical for the next generation of intelligent energy systems.

Despite the promising outcomes reported across numerous studies, gaps remain in standardizing experimental methodologies, defining consistent performance indicators, and assessing long-term material compatibility with hydrogen blends. Moreover, the economic viability of widespread H₂NG adoption depends on the scalability of hydrogen production, transportation, and storage infrastructure. These challenges underline the need for continued interdisciplinary research, combining thermodynamic modeling, materials science, control engineering, and economic assessment to achieve robust and cost-effective decarbonization pathways.

In this context, particular attention is given to the consistency of reported performance indicators, combustion regimes, and emission metrics across different experimental and modeling approaches. This is essential because variations in engine type, hydrogen fraction definition, and efficiency reporting methodologies often limit direct comparison between studies.

The objective of this review is to provide a consolidated and critical overview of the existing literature on hydrogen-enriched natural gas utilization in CHP systems. The paper systematically examines experimental, numerical, and analytical studies published between 2013 and 2026, focusing on performance trends, emission behavior, and technological innovations. By integrating findings across multiple research domains, the review aims to identify key knowledge gaps and highlight future directions toward the development of fully decarbonized, digitally integrated, and sustainable CHP systems for the hydrogen economy.

To improve the clarity and readability of the manuscript, the overall structure and methodological workflow of the present review are summarized in Figure 2.

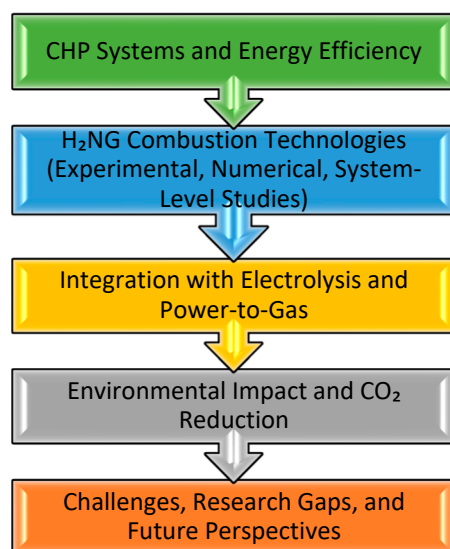


Figure 2. Structure and methodological framework of the present review.

This review systematically analyzes hydrogen-enriched natural gas (H₂NG) applications in combined heat and power (CHP) and micro-CHP systems based on experimental, numerical, and analytical studies published between 2013 and 2026. The analysis is structured into three main dimensions: (i) combustion behavior and flame dynamics, (ii) energy performance and emission characteristics with emphasis on NO_x formation mechanisms, and (iii) system-level integration including hybrid CHP configurations and digital control strategies. By explicitly linking these domains, the paper provides a critical synthesis of current findings rather than a descriptive summary, with the aim of improving comparability across studies and identifying consistent performance trends and technological limitations.

2. Methodology

The present review adopts a systematic and structured approach to analyzing the state of research on hydrogen-enriched natural gas (H₂NG) applied in combined heat and power (CHP) systems. The methodology was designed to ensure completeness, transparency, and reproducibility. The objective was to identify, classify, and evaluate relevant studies published between 2013 and 2026, focusing on experimental, numerical, and

analytical/thermodynamic investigations that explore the impact of hydrogen blending on CHP performance, combustion stability, and emissions.

The bibliographic research was conducted using major scientific databases including Scopus, ScienceDirect, MDPI, IEEE Xplore, and SpringerLink, employing a combination of keywords such as “hydrogen blending,” “H₂NG,” “CHP,” “micro-CHP,” “hydrogen combustion,” and “oxy-fuel systems”.

The initial database search yielded over 200 references, from which duplicates, conference abstracts, and unrelated studies were removed. A total of 92 peer-reviewed journal articles were retained after screening, all of which provided quantitative or qualitative data relevant to system performance, emission trends, or techno-economic aspects.

The inclusion criteria were as follows: the study analyzed CHP or micro-CHP systems operating with hydrogen–natural gas mixtures; the hydrogen content in the mixture was explicitly defined and below 50% by volume; the publication presented measurable parameters (e.g., efficiency, emissions, temperature, or fuel consumption); the study was published in a peer-reviewed journal between 2013 and 2026; exclusion criteria included studies lacking performance data, those focused exclusively on pure hydrogen systems, or papers that did not specify the mixture composition or experimental configuration. Although the primary focus of this review is on low hydrogen fractions (5–20% vol.), studies reporting hydrogen contents up to 50% were considered when they provided relevant insights into performance trends or emission mechanisms.

The selected publications were categorized into three main groups according to their research methodology: experimental studies, focused on engine or microturbine tests with varying hydrogen fractions; numerical simulations, involving CFD and thermodynamic modeling to predict combustion characteristics and efficiency trends; and analytical and theoretical analyses, evaluating system-level energy balances, exergy distributions, and emission models.

This classification allowed for a comparative evaluation of both empirical and predictive approaches. Experimental studies were prioritized when reporting performance data, while numerical analyses were used to interpret or generalize observed phenomena.

Each selected article was analyzed with respect to four key criteria: performance metrics: electrical efficiency, total efficiency, and heat-to-power ratio; combustion characteristics: flame temperature, burning velocity, stability limits, and NO_x formation; emission profiles: CO₂, CO, NO_x, and unburned hydrocarbons; economic and sustainability indicators: cost of hydrogen integration, carbon footprint, and life-cycle impact.

The comparative analysis aimed to identify consistent patterns across different experimental setups and modeling frameworks. Quantitative data were extracted and, where possible, normalized to enable comparison among studies with differing scales or configurations. In cases where direct numerical comparison was not possible, qualitative trends were synthesized based on author discussions and conclusions.

While the review follows a rigorous selection and analysis process, certain limitations must be acknowledged. First, data heterogeneity across studies makes direct numerical comparison challenging due to differences in engine types, hydrogen purity, and measurement techniques. Second, only English-language publications were included, potentially excluding relevant regional studies. Finally, techno-economic and life-cycle analyses remain underrepresented in the literature, highlighting a need for further integrative studies combining performance, cost, and sustainability evaluation.

Despite these limitations, the adopted methodology provides a comprehensive overview of the scientific landscape, ensuring that the conclusions drawn are robust, representative, and aligned with the current state of research in hydrogen-based CHP technologies.

3. State of the Art

3.1. Experimental Studies on H₂/CH₄ Blends in CHP Systems

Experimental investigations on hydrogen-enriched natural gas (H₂NG) in combined heat and power (CHP) systems generally report improvements in combustion efficiency, emission reduction, and operational stability. It should be noted that several figures presented in this section provide synthesized or conceptual representations of trends reported across multiple experimental and numerical studies, rather than direct datasets extracted from a single source. These figures are intended to support comparative interpretation and highlight general tendencies observed in the literature regarding efficiency, emissions, and operational behavior of CHP systems operating with H₂/CH₄ blends. The trends illustrated are derived from a qualitative aggregation of results reported by multiple authors and should therefore be interpreted as indicative rather than absolute.

Lo Basso et al. [18] performed extensive experimental campaigns on a microturbine-based CHP system fueled with H₂NG blends. Their results show that hydrogen addition up to 20 vol.% improves combustion completeness and enhances flame speed, leading to a measurable increase in electrical efficiency, typically in the range of 2–3%. In parallel, both CO₂ and CO emissions decrease due to the reduced carbon content of the fuel mixture.

All efficiency values shown are referenced to the lower heating value (LHV) of the fuel. Reported efficiency improvements refer to relative trends within each study, as absolute efficiency values are not always directly comparable across different CHP technologies and boundary conditions.

It should be noted that Figures 1–4 are conceptual or synthesized representations derived from multiple literature sources and do not correspond to single experimental datasets. Their purpose is to illustrate consolidated trends and system-level behaviors reported in the literature regarding efficiency variation, emission evolution, and environmental benefits of CHP systems operating with hydrogen-enriched fuels [4,19].

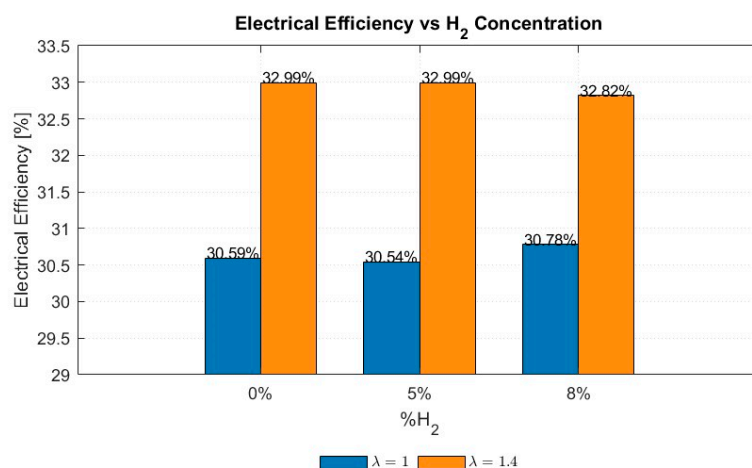


Figure 3. Variation in electrical and total efficiency as a function of hydrogen fraction in the fuel blend. Conceptual representation based on Ref. [19].

Figure 3 is a conceptual representation based on Ref. [19], illustrating the variation in electrical efficiency with increasing hydrogen fraction in the fuel blend under different operating conditions. The trend confirms that moderate hydrogen enrichment (approximately 10–20%) provides the most favorable efficiency improvement, particularly under lean combustion regimes. The representation reflects aggregated experimental tendencies rather than a single dataset.

De Santoli et al. [19] further confirmed that small hydrogen fractions (5–10%) can already provide measurable gains in total CHP efficiency, especially under lean-burn operation, reporting values up to 88% overall efficiency and significant reductions in specific CO₂ emissions.

Palmisano et al. [6] demonstrated stable operation of micro-CHP internal combustion engines fueled with H₂NG blends up to 15% hydrogen content, with improved thermal efficiency and no significant degradation in mechanical performance.

NO_x formation in hydrogen-enriched methane combustion is governed by multiple coupled mechanisms rather than flame temperature alone. The dominant pathway is thermal NO_x (Zeldovich mechanism), which is strongly temperature dependent. However, prompt NO_x (Fenimore mechanism) contributes significantly to fuel-rich or near-stoichiometric regions due to hydrocarbon radicals, while N₂O-intermediate pathways may appear under specific low-temperature or transient conditions.

NO_x formation is also strongly influenced by local residence time, oxygen availability, flame speed, dilution level, exhaust gas recirculation (EGR), wall heat losses, and flame stabilization position. Hydrogen addition modifies flame structure and shifts reaction zones, which can either increase or decrease NO_x depending on operating conditions such as equivalence ratio (λ) and combustor geometry.

Therefore, NO_x trends reported in the literature are not universally monotonic with hydrogen content and must be interpreted in relation to system-specific operating regimes [9,14].

Figure 4 is a conceptual emission trend diagram based on Ref. [19], synthesizing experimental observations from multiple studies on hydrogen-enriched methane combustion in CHP systems. The reduction in CO₂ emissions follows an almost linear trend due to progressive fuel decarbonization. In contrast, NO_x emissions exhibit a non-monotonic and system-dependent behavior resulting from the combined effects of flame temperature, residence time, oxygen availability, flame speed, dilution level, and heat losses. Hydrogen enrichment alters flame structure and stabilization, which may either enhance or mitigate NO_x formation depending on the combustion regime and operating conditions. The figure therefore represents aggregated experimental tendencies rather than a single experimental dataset.

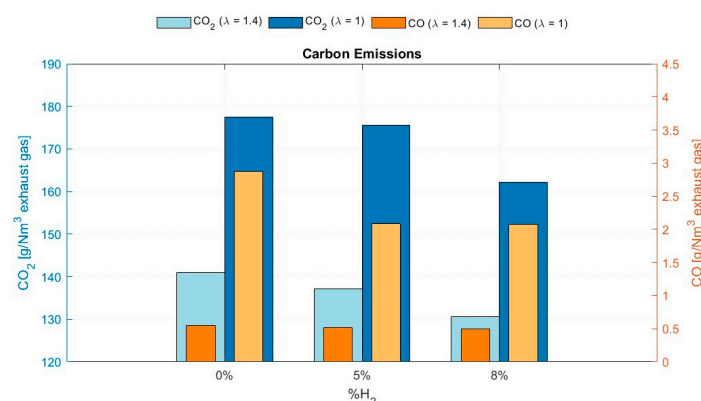


Figure 4. Experimental trends of NO_x and CO₂ emissions with increasing hydrogen content in CHP combustion systems. Conceptual representation based on Ref. [19].

Additional studies [10,14] confirm that hydrogen addition improves ignition stability, reduces combustion delay, and lowers cycle-to-cycle variability, making H₂NG suitable for flexible distributed energy systems. Overall, the experimental evidence indicates that hydrogen additions in the range of 5–20 vol.% represent a robust compromise between efficiency improvement and emission control across a wide range of CHP

configurations. Higher hydrogen fractions, while technically feasible, require advanced combustion management strategies due to the increased sensitivity of NO_x formation mechanisms to operating conditions.

3.2. Hybrid Systems and Oxy-Combustion Concepts

Recent research has explored both experimentally investigated subsystems and conceptually proposed hybrid CHP configurations integrating electrolyzers and oxygen-enriched combustion concepts. Lo Basso et al. [5] and Palmisano et al. [6] analyzed systems combining PEM electrolysis with microturbine CHP units. Hydrogen produced on-site is injected into the fuel stream, while oxygen is partially reused in combustion enhancement strategies. These configurations improve flame stability and enable flexible operation under variable renewable input.

Figure 5 is a schematic conceptual representation based on Ref. [20], showing integration of PEM electrolyzers with a CHP system and optional oxygen-enriched combustion pathway. The diagram does not represent measured data but rather system architecture and energy flows. Its purpose is to illustrate coupling between Power-to-Gas and CHP subsystems. It should be noted that oxygen reuse levels are typically limited in practical systems due to material constraints and safety considerations.

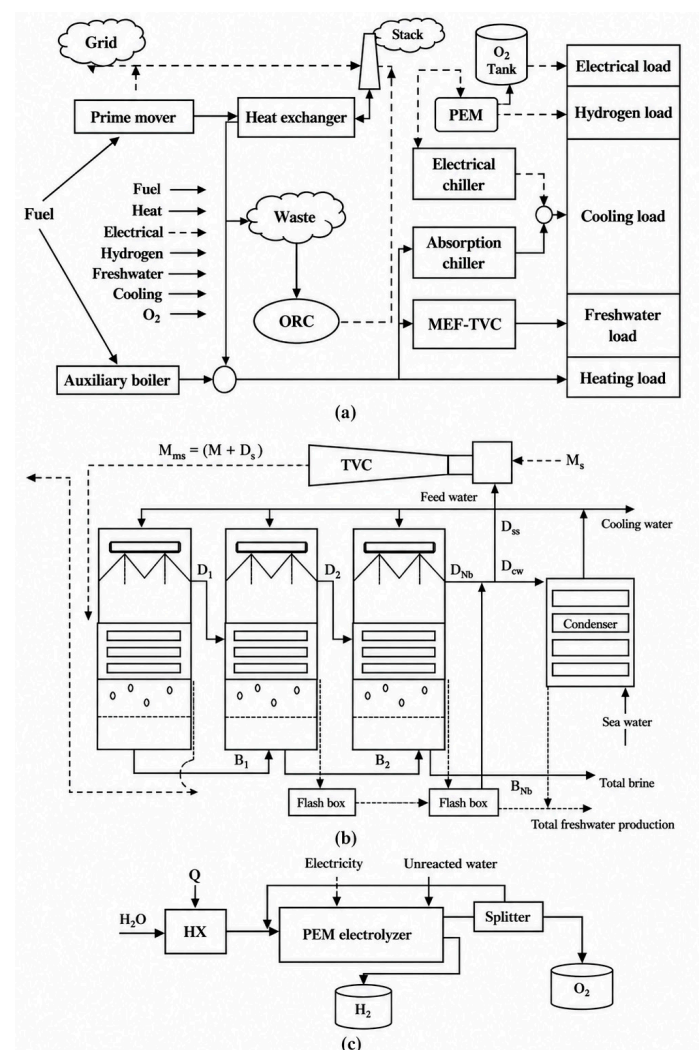


Figure 5. Schematic representation of a hybrid CHP system integrating electrolyzers and oxy-combustion subsystems. (a) Conceptual layout of the cogeneration system; (b) multi-effect evaporation with thermal vapor compression unit; (c) proton exchange membrane electrolyzer. Conceptual representation based on Ref. [20].

De Santoli et al. [8] showed that partial oxy-combustion stabilizes lean flames and reduces unburned hydrocarbons, while hydrogen blending extends flammability limits and improves controllability of combustion processes.

Campanari et al. [15] and Caposciutti et al. [16] demonstrated that integration of hydrogen production into distributed CHP systems can reduce CO₂ emissions by more than 40%, depending on renewable penetration and system configuration.

All efficiency values shown are referenced to the lower heating value (LHV) of the fuel.

Figure 6 is a conceptual performance trend based on Ref. [19], illustrating system behavior under variable hydrogen production rates in hybrid CHP operation. Figure 6 does not represent a single experimental dataset but a qualitative synthesis of performance trends derived from the experimental observations reported in Ref. [19]. The figure is intended to highlight the relative system response to variable hydrogen production rates rather than to provide absolute efficiency values for direct quantitative comparison across different CHP configurations.

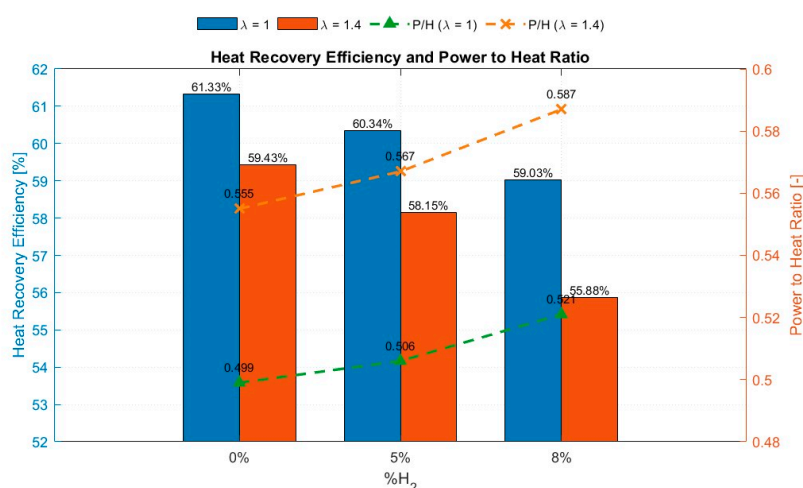


Figure 6. Conceptual performance trends of hybrid H₂NG-CHP systems under variable hydrogen production rates, derived from experimental observations reported in Ref. [19].

The figure represents aggregated experimental tendencies, showing that electrical and thermal performance remain stable across dynamic hydrogen supply conditions. It should be interpreted as a system-level qualitative validation rather than a direct experimental time series.

However, hybrid systems introduce challenges, including transient hydrogen control, thermal management between subsystems, and material compatibility issues such as hydrogen-induced embrittlement. These issues require advanced monitoring and adaptive control strategies.

Overall, hybrid CHP systems represent a promising pathway for sector coupling and increased renewable integration. However, their real-world performance strongly depends on dynamic control strategies, thermal integration maturity, and component-level durability. While laboratory-scale experiments and pilot installations demonstrate technical feasibility, large-scale deployment of integrated electrolysis-CHP and oxy-combustion concepts remains predominantly conceptual. Comprehensive validation of system-wide efficiency, long-term reliability, and economic viability under realistic operating conditions is still required.

3.3. Thermodynamic and Economic Analyses

In combined heat and power (CHP) systems, different efficiency indicators are used depending on the chosen system boundaries and performance objectives. Electrical efficiency (η_e) is defined as the ratio between net electrical power output and the fuel input expressed on a lower heating value (LHV) basis. Thermal efficiency (η_t) represents the fraction of useful recovered heat relative to the same fuel energy input. The total CHP efficiency (η_{tot}) is calculated as the sum of electrical and thermal outputs divided by the fuel input on an LHV basis. Heat recovery efficiency refers specifically to the effectiveness of extracting usable thermal energy from exhaust gases and cooling circuits and may differ from total efficiency depending on the adopted system boundary. Exergy efficiency accounts for both the quantity and quality of energy flows and is defined as the ratio between useful exergy output and the chemical exergy of the fuel.

The majority of thermodynamic, exergy-based, and techno-economic studies rely on steady-state modeling or scenario-based projections. As such, reported performance improvements and cost reductions should be interpreted as indicative trends rather than directly transferable results to real-world CHP installations.

Thermodynamic and exergy-based analyses provide deeper insight into the efficiency and irreversibility mechanisms of H₂NG-fueled CHP systems. In this context, all exergy efficiencies refer to second-law performance indicators derived from the ratio of useful exergy output to the chemical exergy of the fuel, while energy-based efficiencies reported elsewhere in the manuscript are not directly comparable unless explicitly stated. This distinction is particularly relevant when assessing hydrogen-enriched systems, where changes in fuel composition significantly affect chemical exergy content.

Several studies [21–23] demonstrate that hydrogen enrichment improves second-law efficiency by increasing chemical exergy utilization and reducing entropy generation, particularly under lean combustion conditions.

Lo Basso et al. [24] reported a 3.5% increase in electrical exergy efficiency when hydrogen content increases from 0 to 20%, with combustion irreversibility identified as the dominant source of exergy destruction.

From an economic perspective, techno-economic studies [25,26] indicate that hydrogen blending becomes viable for micro-CHP applications when hydrogen prices are within 3–4 €/kg, particularly under carbon taxation or renewable incentive schemes. These cost thresholds are typically derived under assumptions of low-carbon electricity supply, moderate electrolyzer utilization factors, and supportive policy frameworks. It should be noted that the reported efficiency improvements across different studies are discussed on a qualitative basis, as variations in system boundaries, reference conditions, and performance definitions may prevent direct numerical comparison.

Figure 7 is a combined thermodynamic and heat-recovery performance representation based on Ref. [27], showing variations in electrical efficiency, thermal efficiency, and heat recovery ratio with increasing hydrogen fraction. Consistent with its conceptual nature, Figure 7 does not represent a single experimental dataset but a synthesized thermodynamic framework derived from the trends reported in Ref. [27]. The individual performance indicators (electrical efficiency, thermal efficiency, and heat-recovery performance) originate from different operating points and are unified here to illustrate their coupled evolution with increasing hydrogen fraction. Accordingly, the figure should be interpreted as an analytical representation of system behavior rather than as a direct quantitative comparison of experimentally measured values.

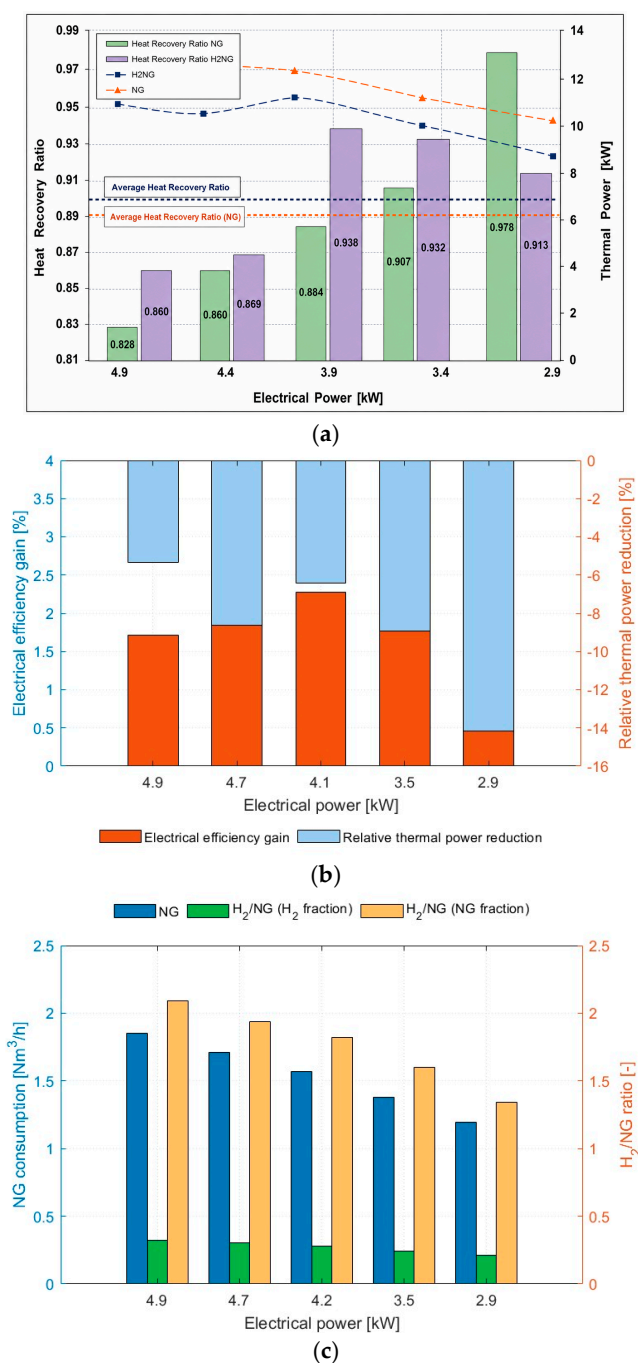


Figure 7. Combined thermodynamic and heat-recovery performance of the CHP system fueled by H₂NG mixtures. Conceptual representation based on Ref. [27]. **(a)** Thermal power output and heat release rate as functions of electrical power output for natural gas and H₂NG fueling. **(b)** Electrical efficiency gain and relative reduction in thermal power for H₂NG with a 15% volumetric fraction. **(c)** Blend consumption as a function of electrical power output.

The figure also includes fuel consumption trends under different load conditions. It is a reconstructed analytical synthesis derived from experimental datasets rather than a single direct measurement.

Figure 8 is a conceptual cost–efficiency and system performance comparison based on Ref. [28], illustrating trade-offs between hydrogen blending ratio, system efficiency, and economic performance. Although originally described inconsistently in the previous version, this figure is now aligned with a thermodynamic–economic interpretation rather than a pure exergy breakdown. The figure does not represent a fully leveled cost

analysis but rather a comparative techno-economic trend intended to highlight relative trade-offs.

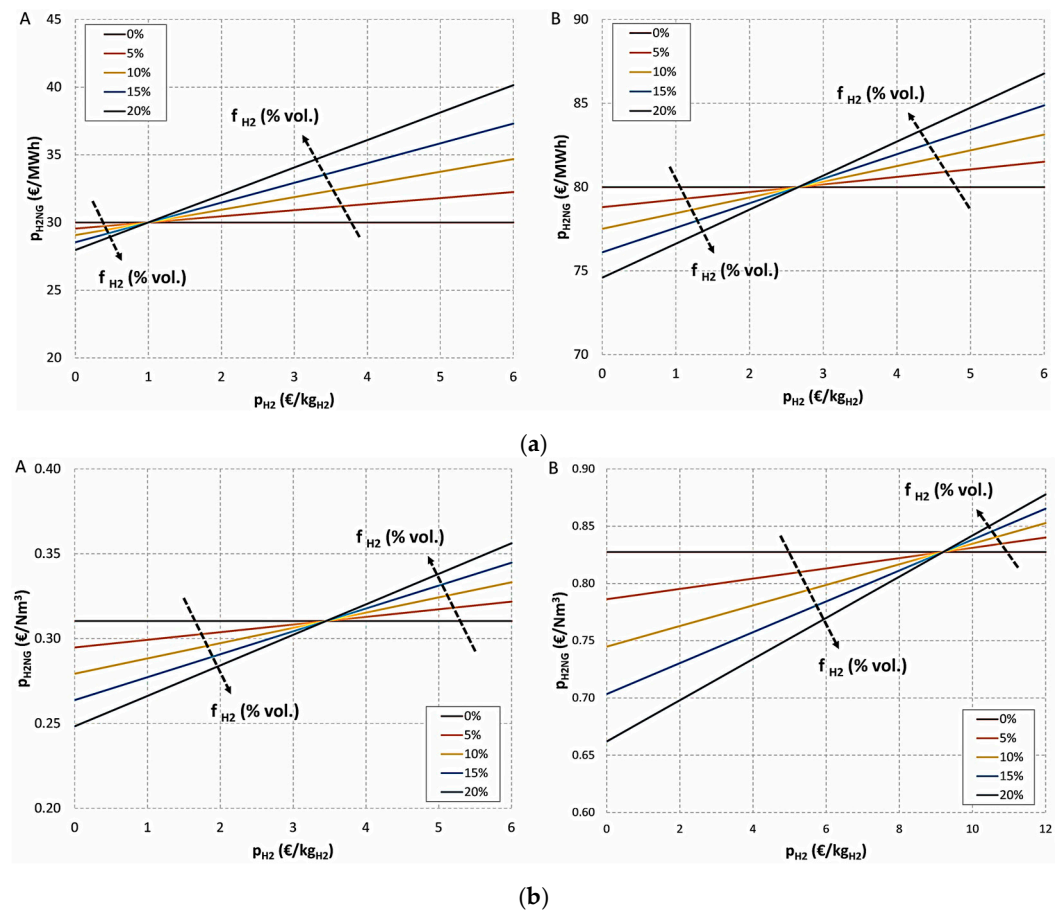


Figure 8. Comparative cost–efficiency analysis for hydrogen blending ratios between 0% and 30% rates. Conceptual representation based on Ref. [28]. (a) Energy price of the H₂NG blend as a function of hydrogen price and volumetric fraction: (A) natural gas price of 30 €/MWh; (B) natural gas price of 80 €/MWh. (b) Volumetric price of the H₂NG blend as a function of hydrogen price and volumetric fraction: (A) natural gas price of 30 €/MWh; (B) natural gas price of 80 €/MWh.

Life-cycle assessment studies [29,30] indicate that replacing up to 20% of natural gas with hydrogen can reduce life-cycle CO₂ emissions by approximately 20–25%, depending on hydrogen production pathways and system boundaries.

It should be emphasized that NO_x emission data reported in hydrogen-enriched combustion studies are not directly comparable unless normalized, as different works use different metrics such as ppm, ppm corrected to a reference oxygen level, g/kWh, g/MJ, or emission index (g/kg fuel). This inconsistency in reporting can lead to misinterpretation when comparing results across studies and highlights the need for standardized emission reporting in future research.

Recent research published between 2024 and 2026 has significantly advanced the understanding of hydrogen-enriched natural gas (H₂NG) applications in combined heat and power (CHP) systems, particularly in terms of combustion behavior, system integration, emission impacts, and techno-economic performance.

Recent research published between 2024 and 2026 has significantly advanced the understanding of hydrogen-enriched natural gas (H₂NG) applications in combined heat and power (CHP) systems, combining numerical modeling, experimental validation, and system-level analysis. Nosek investigated in [31] the combustion intensity and emission behavior of hydrogen-enriched natural gas through numerical simulations, highlighting the

need for advanced combustion control to manage reduced net heat output under high hydrogen fractions. Ref. [32] coupled numerical and experimental approaches to evaluate hydrogen blending in industrial boilers, reporting improved flame propagation accompanied by increased NO_x sensitivity under sub-optimal control. Fichtner demonstrated in [33] that lean-burn CHP engines operating with hydrogen blends can achieve lower NO_x emissions and enhanced combustion stability without major hardware modifications when equivalence ratios are optimized.

Broader system-level implications have been addressed by Ref. [34], who reviewed in the hydrogen injection practices in natural gas networks with emphasis on material compatibility and safety requirements, and by Sîrbu [35] who analyzed the combustion behavior in residential appliances, identifying flashback and NO_x control as key design challenges. Ref. [36] further showed that optimized blends of natural gas, hydrogen, and biogas in gas-turbine-based CHP systems can substantially reduce greenhouse gas emissions.

Integrated energy system modeling and optimization studies further underline the importance of coordinated control of electricity, heat, and hydrogen flows in H_2NG -based CHP systems. Liu [37] demonstrated that dynamic multi-energy optimization can mitigate supply–demand imbalances and improve overall system efficiency, while Lozano-Martín highlighted in [38] the limitations of conventional equations of state in predicting density variations of hydrogen-enriched natural gas mixtures, with implications for transport and storage design. Liu [39] reviewed optimization and control technologies for hydrogen-blended gas–electricity systems, emphasizing the role of advanced scheduling and digital tools.

Regional and techno-economic aspects have been examined by [40], who discussed infrastructure and regulatory challenges for hydrogen blending in Romanian gas networks, as well as by [41] and [42], who analyzed the co-combustion of natural gas with hydrogen in low-power-output condensing boilers (second and third generation) with hydrogen content of up to 50% by volume. Techno-economic assessments indicate that environmental benefits can outweigh additional costs under supportive policy frameworks, as shown in [43,44]. Recent studies on hydrogen-enriched natural gas in CHP and integrated energy systems report increasing interest in modeling, optimization, digitalization, and lifecycle-based assessment. Studies on micro-CHP systems based on internal combustion engines operating with methane–hydrogen blends indicate that fuel composition can influence system behavior under variable operating conditions, particularly in terms of performance and control-oriented analysis [45].

Literature on digital twin and artificial intelligence applications in energy systems indicates their use for monitoring, prediction, and optimization tasks. However, studies consistently report that most implementations remain at simulation or pilot scale due to limitations related to data availability, model validation, and real-time deployment [46].

Research on hydrogen blending in natural gas networks indicates potential contributions to decarbonization pathways while also reporting technical, economic, and infrastructure-related constraints that may limit large-scale implementation [47].

Studies on artificial intelligence and digital twin applications in energy systems further indicate their role in supporting complex energy system management, including prediction and optimization tasks, although industrial-scale deployment is still limited [48].

Machine learning-based studies on internal combustion engines operating with hydrogen–natural gas blends report improvements in performance prediction and combustion analysis capabilities while also indicating an increase in NO_x emissions tendency at higher hydrogen fractions [49].

Lifecycle assessment and process-oriented studies indicate that environmental performance of hydrogen-based systems strongly depends on system boundaries and upstream processes, which must be considered in sustainability evaluations [50].

Broader digital twin reviews report potential benefits for energy system optimization and decision support while also highlighting a gap between conceptual frameworks and large-scale implementation [51].

Studies focused on hydrogen utilization in CHP systems report improved operational flexibility and performance potential while also identifying technical and regional constraints affecting practical application [52].

When hydrogen is blended with methane, discrepancies between these efficiency metrics may increase, as hydrogen affects combustion temperature, exhaust heat availability, and system irreversibility. Therefore, direct comparison between studies is only meaningful when efficiency definitions and reference bases are explicitly stated, particularly in thermodynamic and exergetic assessments of CHP systems [52,53].

In the reviewed literature, different efficiency indicators are employed depending on system boundaries and performance objectives. Electrical efficiency refers strictly to the ratio between net electrical output and the chemical energy input of the fuel, while thermal efficiency accounts for the useful recovered heat. Total efficiency represents the combined utilization of electrical and thermal outputs and is commonly used as a primary performance indicator in CHP applications [52]. In contrast, exergy efficiency evaluates system performance from a second-law perspective by accounting for irreversibilities and reference environmental conditions [53].

Finally, system-level analyses of hydrogen-based CHP decarbonization report that feasibility depends on infrastructure readiness, economic conditions, and sector-specific energy demand, which remain key limiting factors for deployment [53].

Overall, thermodynamic and economic analyses confirm that hydrogen enrichment improves exergy utilization and offers tangible environmental benefits in CHP systems, while economic viability remains highly sensitive to hydrogen cost, policy incentives, and system boundary definitions. Although recent studies demonstrate significant progress in combustion understanding, system optimization, and hybrid integration, most advanced control and digitalization strategies should be regarded as prospective developments rather than fully validated large-scale solutions.

3.4. Added Value of the Present Review and Quantitative System Classification

Previous studies have clearly demonstrated that hydrogen enrichment generally increases flame speed, extends lean operability, reduces CO₂ emissions, and may lead to higher NO_x formation depending on operating conditions. These effects have been extensively reported for laboratory burners, internal combustion engines, gas turbines, and residential appliances [1–3,10,14,31–35]. Recent reviews further confirm that these combustion trends are well established and broadly reproducible across different natural gas compositions and hydrogen blending levels [54–56].

However, most existing reviews focus primarily on combustion fundamentals or gas network compatibility without providing a CHP-oriented system classification that simultaneously addresses electrical performance, heat recovery, emissions, and system integration constraints [54,55]. As a result, the practical implications of hydrogen blending for combined heat and power applications are often discussed only qualitatively.

To address this gap, the present review introduces a structured classification of H₂NG-fueled CHP systems, explicitly distinguishing between experimentally validated CHP units, numerically investigated system extensions, and conceptual multi-energy and smart CHP architectures. This classification approach aligns with recent contributions

emphasizing the need to separate demonstrated performance from system-level projections in hydrogen-integrated energy systems [57,58].

From a quantitative perspective, experimental and numerical studies consistently indicate that hydrogen blending below 15–20 vol.% represents a robust operating window for existing CHP technologies, ensuring stable combustion and efficiency gains while limiting NO_x escalation [5–7,9,33]. Numerical investigations further confirm that NO_x formation in hydrogen-enriched CHP systems is governed not only by peak flame temperature but also by flame speed, local equivalence ratio, residence time, and dilution effects, particularly under lean-burn conditions [56,57]. Consequently, moderate hydrogen enrichment does not inherently lead to excessive NO_x emissions, provided that combustion phasing and air–fuel management are properly controlled.

Beyond combustion-level analysis, recent studies highlight that hydrogen blending alters the energy–exergy balance of CHP systems, affecting the distribution between electrical output and recoverable heat. Exergy-based system analyses show that moderate hydrogen enrichment can reduce combustion irreversibility, while higher hydrogen fractions may shift losses toward exhaust heat and emission formation zones if not properly controlled [23,24,58].

Finally, this review clearly distinguishes experimentally demonstrated results from numerical optimization studies and future-oriented concepts, such as AI-assisted control, digital twins, and sector-coupled CHP–hydrogen hubs. While studies report promising results for predictive control and integrated multi-energy optimization, these approaches remain largely validated at simulation or pilot scale and should not yet be interpreted as mature industrial solutions [57,58].

Unlike previous reviews, the present work explicitly combines quantitative performance trends with a maturity-based system classification, enabling a clearer distinction between experimentally demonstrated results and forward-looking CHP–hydrogen integration concepts.

Overall, the added value of the present review lies in its quantitative synthesis, maturity-based system classification, and critical comparison framework, which together move beyond a descriptive summary of known combustion trends and provide a structured assessment of H₂NG-fueled CHP systems from laboratory validation to emerging smart energy concepts.

4. Discussion and Research Gaps

The comparative analysis of the reviewed literature reveals both convergence and divergence in the reported effects of hydrogen enrichment on combined heat and power (CHP) systems. Despite the growing number of experimental and numerical studies, significant gaps remain regarding the systematic interpretation of NO_x formation pathways under varying hydrogen blending ratios and operating conditions, as well as the consistent use of efficiency indicators across thermodynamic analyses [45,47].

While nearly all studies confirm that hydrogen blending improves combustion efficiency and reduces carbon-based emissions, the magnitude and consistency of these benefits depend strongly on the operating regime, hydrogen fraction, and system configuration. In contrast to a statistical meta-analysis, the present discussion provides a qualitative–quantitative synthesis of experimental, numerical, and system-level results, emphasizing performance trends, technological maturity, and remaining research gaps.

Table 1 summarizes representative experimental and system-level studies on hydrogen-enriched natural gas (H₂NG) in CHP and micro-CHP applications, highlighting key performance indicators and operating conditions.

Table 1. Comparative performance of H₂NG in CHP and micro-CHP systems (literature synthesis).

Study/System	H ₂ Fraction (vol.%)	Electrical Efficiency	Total Efficiency	CO ₂ Emissions	NO _x Emissions	Key Operating Condition
Lo Basso et al. [5,7,18] (microturbine CHP)	5–20%	↑ 2–3%	↑ up to +3%	↓ ~8–15%	↑ slight increase	Lean-burn optimized
Palmisano et al. [6] (micro-CHP ICE)	5–15%	↑ slight	↑ stable (~85–88%)	↓ proportional	↔/slight ↑	Stable combustion regime
De Santoli et al. [8,19] (CHP dual-fuel)	0–20%	↑ moderate	up to ~88%	↓ up to 15–20%	↑ at stoichiometric	Fuel flexibility mode
Boulahlib et al. [9,13] (microturbine combustion)	10–30%	↑ slight	variable	↓ significant	↑ noticeable (>20% H ₂)	High temperature region
Battista et al. [14] (lean-burn engine)	0–20%	↑ stable	↑ slight	↓ linear trend	↓ or stable under lean ($\lambda > 1.3$)	Lean-burn operation
Kovacs et al. [10] (SI engine H ₂ NG)	5–20%	↑ moderate	not reported	↓ moderate	↔/slightly ↑	Transient load operation
Campanari et al. [15] (system-level CHP)	0–20%	↑ system-level gain	↑ overall system efficiency	↓ 10–25%	not primary focus	Hybrid integration
Caposciutti et al. [16] (district CHP systems)	10–20%	↑ slight	↑ optimized	↓ significant	↔	Energy system coupling
Ficarella et al. [26] (LCA-based CHP)	0–20%	not primary metric	not primary	↓ life-cycle up to 25%	not primary metric	Sustainability focus

The comparative synthesis presented in Table 1 highlights consistent trends across different experimental platforms and system scales. In particular, moderate hydrogen enrichment (5–20 vol.%) generally leads to improved electrical efficiency and significant CO₂ emission reduction. However, nitrogen oxides (NO_x) emissions exhibit a non-linear behavior that is strongly dependent on combustion regime, equivalence ratio, and hydrogen fraction, confirming the importance of lean-burn operation and advanced control strategies. Quantitative discrepancies between studies arise from differences in system configuration, measurement methodology, and efficiency definitions, underlining the need for harmonized assessment protocols.

One of the most consistent findings across experimental investigations [1–4] is the increase in electrical efficiency and flame stability at moderate hydrogen levels (5–20 vol.%). This improvement is primarily attributed to hydrogen's higher laminar flame speed and wider flammability limits, which enhance combustion completeness and reduce cycle-to-cycle variability. Lo Basso et al. [5] demonstrated that hydrogen addition enables stable operation at leaner air–fuel ratios, resulting in reduced CO and CO₂ emissions. Nevertheless, improved combustion quality is often accompanied by higher adiabatic flame temperatures, which may promote thermal NO_x formation. This effect was confirmed by Boulahlib et al. [9], who reported sharp NO_x increases near stoichiometric conditions, while showing that lean-burn operation ($\lambda > 1.3$) or exhaust gas recirculation (EGR) can effectively mitigate this penalty.

A major challenge in cross-study comparison is the lack of methodological standardization. Experimental configurations range from internal combustion engines and micro-turbines to hybrid CHP systems, making direct comparison of efficiency values and emission indices difficult. Some studies include mechanical and thermal losses in reported efficiencies, whereas others focus solely on electrical conversion efficiency. Similarly, emission indicators are not consistently normalized to useful energy output, which contributes to apparent inconsistencies between datasets. These issues clearly indicate the need for unified testing procedures and standardized performance indicators for H₂NG-based CHP systems.

From a thermodynamic perspective, hydrogen enrichment generally leads to an increase in system exergy efficiency due to more complete oxidation reactions and reduced entropy generation during combustion. However, hydrogen blending also alters the distribution between electrical output and recoverable thermal energy. Several studies [7,8] report that while electrical efficiency increases, thermal output may slightly decrease at higher hydrogen fractions, necessitating a careful balance between power generation and heat recovery depending on the intended CHP application.

Another important dimension concerns combustion control and operational stability. Hydrogen's low ignition energy and fast flame propagation introduce challenges related to knock, flashback, and transient instability under variable load conditions. Experimental studies by Palmisano et al. [6] and Kovacs et al. [10] indicate that adaptive control strategies—such as closed-loop air–fuel ratio control and predictive algorithms—can compensate for these nonlinear effects, ensuring stable operation and limited emission fluctuations. Despite promising results, real-time intelligent control strategies remain only partially implemented in experimental test benches, indicating a clear opportunity for further research.

Material compatibility and long-term durability represent additional critical gaps. Only a limited number of studies address hydrogen-induced embrittlement, corrosion, or accelerated aging of components exposed to H₂NG mixtures. Hydrogen's high diffusivity may increase seal leakage and exacerbate metal fatigue, particularly in high-temperature regions of CHP systems. Long-term experimental campaigns and accelerated aging tests

are therefore required to validate the reliability of hydrogen-enriched operation before large-scale deployment.

Economic and environmental assessments constitute another underdeveloped area. While most studies demonstrate technical feasibility, few integrate comprehensive techno-economic or life-cycle assessment (LCA) models. Hydrogen production, storage, and integration costs are often treated as fixed assumptions, despite their strong dependence on electricity prices, renewable penetration, and carbon pricing schemes. Incorporating these dynamic factors is essential for assessing the real competitiveness of H₂NG-based CHP systems across different regional and market contexts.

Hybrid system concepts, particularly those combining electrolysis, hydrogen blending, and oxy-combustion—remain relatively scarce and are predominantly analyzed under steady-state conditions. The dynamic behavior of such systems under fluctuating renewable input and part-load operation is still poorly understood, although it is crucial for grid-interactive and renewable-integrated energy systems.

Energy performance remains a core evaluation dimension for hydrogen-enriched CHP applications. Across the reviewed studies, electrical efficiency, thermal efficiency, and total CHP efficiency are consistently reported as key indicators. Most experimental investigations confirm that hydrogen blending in the range of 5–20 vol.% allows maintaining or slightly improving electrical efficiency, mainly due to enhanced combustion stability and faster flame propagation. Energy and exergy analyses further indicate a reduction in combustion irreversibilities and improved heat recovery under optimized operating conditions, although the magnitude of these gains remains system-specific.

Emission characteristics represent a parallel critical dimension. Hydrogen enrichment directly reduces CO₂ emissions due to the lower carbon content of the fuel blend, with reported reductions increasing approximately proportionally with hydrogen fraction. This effect constitutes one of the primary environmental drivers for H₂NG deployment in CHP systems.

In contrast, the impact on NO_x emissions is more complex. Experimental and numerical studies consistently show that hydrogen enrichment can increase thermal NO_x formation under stoichiometric or high-temperature conditions. However, lean-burn operation, EGR, oxy-combustion concepts, and advanced control strategies have been demonstrated to effectively mitigate NO_x emissions. Detailed experiments and CFD simulations indicate that hydrogen modifies flame structure and reaction zones, leading to NO_x trends that depend strongly on equivalence ratio and residence time [59,60]. Ref. [61] demonstrated simultaneous reductions in NO_x emissions, combustion instability, and efficiency loss in lean-burn CHP engines fueled with hydrogen-enriched natural gas through optimized air–fuel ratio control. Similar trends of stable or reduced NO_x emissions at low hydrogen fractions (0–5 vol.%) have been reported for heavy-duty natural gas engines operated under lean conditions [62]. These findings confirm that hydrogen enrichment does not inherently lead to higher NO_x emissions when appropriate combustion and control strategies are applied.

In hydrogen-enriched methane combustion, NO_x formation mechanisms differ significantly from those encountered in conventional natural gas operation. Three dominant pathways can be identified. Thermal NO_x, described by the extended Zeldovich mechanism, becomes predominant at elevated flame temperatures promoted by hydrogen addition and is strongly dependent on peak temperature and residence time [45]. Prompt NO_x (Fenimore mechanism) is associated with hydrocarbon radicals in locally fuel-rich zones and may remain relevant at moderate hydrogen blending ratios, particularly in spark-ignition engines [46]. At lean conditions and lower combustion temperatures, especially in premixed systems, the N₂O-intermediate mechanism can contribute to overall NO_x formation, particularly under high excess air ratios and long residence times [47].

Experimental studies consistently report that increasing hydrogen content leads to higher flame temperatures and accelerated reaction kinetics, which enhance thermal NO_x formation unless mitigation strategies such as exhaust gas recirculation, lean combustion, or dilution are applied [45,47]. The strong sensitivity of NO_x emissions to equivalence ratio, dilution level, and combustion phasing highlights the need for optimized control strategies in CHP systems operating with H₂/CH₄ blends [46].

Future research on H₂NG-based CHP systems is expected to focus on three main directions: (i) scaling hydrogen blending beyond pilot-scale demonstrations, (ii) advanced emission control under higher hydrogen fractions, and (iii) system-level integration within smart and low-carbon energy infrastructures. Recent studies on hydrogen-enriched combustion systems cover a wide range of approaches, from detailed numerical modeling to system-level assessments and burner design investigations. Advanced CFD-based work introduces improved chemical kinetic mechanisms for simulating RCCI combustion involving hydrogen-enriched natural gas and diesel mixtures, highlighting the importance of accurate reaction modeling in predicting combustion behavior [59].

At a broader level, meta-analytical studies evaluate the role of hydrogen in residential heat decarbonization, focusing on its potential contribution to emission reduction and energy transition pathways [60].

Research on natural gas engines emphasizes lean combustion enhancement techniques and decarbonization strategies, showing that hydrogen addition can influence combustion stability and emission formation in internal combustion engines [61].

In addition, numerical studies on methane–hydrogen co-fired radiant tube burners demonstrate that burner geometry and fuel mixing significantly affect flame characteristics, heat transfer, and combustion performance, underlining the importance of hydrogen-compatible burner design [62].

From a system integration perspective, future CHP units are increasingly envisioned as multi-energy hubs interacting dynamically with renewable electricity sources, electrolyzers, hydrogen storage, and thermal networks. Sector coupling and Power-to-Gas concepts position CHP systems as flexible assets capable of providing grid support and resilience in hydrogen-integrated energy systems [63,64]. In this context, hydrogen-enriched CHP units evolve from standalone generators toward integral components of smart energy ecosystems.

Safety, material compatibility, and infrastructure readiness are also gaining prominence in recent research. Studies published after 2024 highlight the need for long-term experimental validation of hydrogen effects on components, sealing systems, and distribution networks under cyclic and transient conditions [65,66]. Furthermore, harmonized standards and testing protocols for hydrogen–natural gas blends are increasingly recognized as prerequisites for regulatory acceptance and large-scale deployment [67].

To systematize these findings, Table 2 presents a comparative overview of experimental and system-level studies on H₂NG-based CHP systems, focusing on hydrogen blending ranges, operating regimes, validation status, and reported limitations.

To complement the experimental comparison, Table 3 summarizes modeling-based, hybrid integration, and techno-economic investigations, highlighting system configurations, performance metrics, and key limitations.

Tables 2 and 3 operationalize the maturity-based classification introduced in Section 3.4, clearly distinguishing experimentally validated results from numerical optimization studies and future-oriented concepts.

Table 2. Comparative overview of experimental and system-level studies on H₂NG-based CHP systems.

Reference	System Type	H ₂ Blending Range (vol.%)	Load Range	λ /Equivalence Ratio	Main Measured Outputs	Modeling Approach	Validation Status	Reported Limitations
Lo Basso et al. [5,7,18]	Microturbine CHP	5–20	Partial–nominal	Lean ($\lambda > 1.3$)	η_e , NO _x , CO ₂ , stability	Energy–exergy model	Experimental validation	Short-term tests, limited load dynamics
Palmisano et al. [6]	ICE micro-CHP	5–15	30–100%	Near-stoichiometric to lean	η_e , CO, NO _x	Experimental + control model	Bench-scale validated	No long-term durability
De Santoli et al. [8,19]	Dual-fuel CHP	0–20	Nominal	Variable	η_e , η_t , emissions	System-level modeling	Partially validated	Simplified combustion
Boulahlib et al. [9,13]	Microturbine combustor	10–30	Constant	Near stoichiometric	NO _x , flame T	CFD (ANSYS Fluent ANSYS 14.0)	Numerical validation	No system efficiency
Battista et al. [14]	Lean-burn SI engine	0–20	Variable	$\lambda > 1.3$	η_e , NO _x	Experimental	Fully validated	Narrow H ₂ range

Table 3. Comparative overview of modeling, hybrid integration, and techno-economic studies on H₂NG-based CHP systems.

Reference	System Configuration	H ₂ Blending Range (vol.%)	Operating Regime	Main Performance Metrics	Modeling Approach	Validation Status	Key Limitations
[21–23]	CHP system	0–30	Steady-state	η_e , η_{ex} , entropy generation	Energy–exergy modeling	Numerical	No transient or control dynamics
[24]	Micro-CHP	0–20	Nominal load	Electrical exergy efficiency	Detailed exergy analysis	Experimentally validated	Simplified combustion irreversibility
[15,16]	Hybrid CHP–electrolyzer	0–20	Variable	η_e , CO ₂ reduction	System-level modeling	Partially validated	Simplified electrolyzer dynamics
[25,26]	Micro-CHP	0–20	Scenario-based	LCOE, payback time	Techno-economic modeling	Scenario analysis	Hydrogen price uncertainty
[28]	CHP system	0–30	Steady-state	Cost–exergy efficiency	Thermoeconomic analysis	Numerical	No dynamic load modeling
[47]	Decarbonized CHP plant	0–20	Optimized dispatch	Cost–efficiency trade-off	ANN-based optimization	Numerical	Requires large training datasets

The comparative framework of Tables 1–3 is explicitly structured to support cross-study comparison in terms of hydrogen blending ranges, system configurations, operating regimes, performance indicators (including electrical and total efficiency), emissions behavior (including NO_x), modeling approaches, and validation status. By reporting these parameters in a standardized manner, these tables enable meaningful juxtaposition of experimental, numerical, and techno-economic studies, facilitating the identification of consistent trends and research gaps across the reviewed literature.

Addressing the identified gaps will require coordinated research efforts that integrate experimental validation, dynamic modeling, digital twin development, and sustainability assessment. Such an integrated approach is essential for the reliable deployment of hydrogen-enriched CHP systems within decarbonized, intelligent, and resilient energy infrastructures.

Figure 9 synthesizes the main research gaps and proposed future directions identified across the reviewed literature, including the need for standardized testing procedures, long-term durability data, integrated life-cycle assessments, and advanced control strategies.

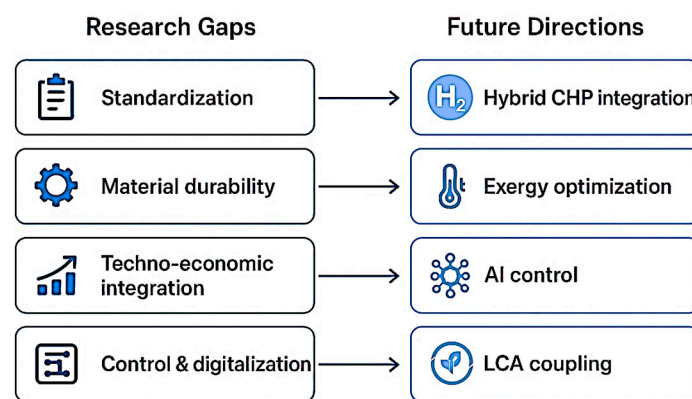


Figure 9. Synthesis of identified research gaps and proposed directions for future investigation in H₂NG-based CHP systems.

The figure summarizes the main research gaps identified across the reviewed studies, including the need for standardized testing procedures, long-term material durability data, integrated life-cycle assessments, and advanced control algorithms. It also highlights priority areas for future research: hybrid CHP integration, exergy optimization, and digitalized operational management.

5. Future Perspectives

Hydrogen-enriched natural gas (H₂NG) is increasingly recognized as a transitional solution for the decarbonization of distributed combined heat and power (CHP) systems. Large-scale demonstration projects further indicate that hydrogen blending levels up to approximately 20 vol.% are technically feasible when appropriate mixing strategies, monitoring systems, and safety protocols are implemented [67,68]. Nevertheless, harmonized standards, long-term material compatibility, and regulatory alignment remain critical challenges for widespread deployment [69]. Recent studies on integrated energy systems highlight coordinated operation of electricity, hydrogen, and natural gas networks, emphasizing optimization under economic and carbon constraints [70,71].

System-level analyses and demonstration projects further confirm the feasibility of hydrogen integration into existing gas infrastructures while also identifying technical and safety-related challenges [72,73].

At the application level, studies on CHP decarbonization underline that regional conditions, infrastructure readiness, and economic factors play a decisive role in hydrogen deployment [74].

Comprehensive review studies further emphasize that optimal planning and coordination of electric–hydrogen integrated systems represent a key direction for future decarbonization strategies [75]. A key future direction concerns the direct integration of renewable-powered electrolysis into CHP installations. On-site hydrogen production enables Power-to-Gas and Power-to-Heat coupling, mitigates renewable intermittency, and reduces dependence on external hydrogen supply.

As illustrated in Figure 10, future H₂NG-based CHP systems are expected to operate within smart, sector-coupled energy networks in which hydrogen serves both as a low-carbon fuel and as a flexibility vector. Surplus renewable electricity is converted into hydrogen via electrolysis, stored or blended into the gas network, and subsequently utilized in CHP units for low-carbon electricity and heat generation. Digital monitoring and control layers enable real-time optimization of fuel composition, load matching, efficiency, and emissions [76].

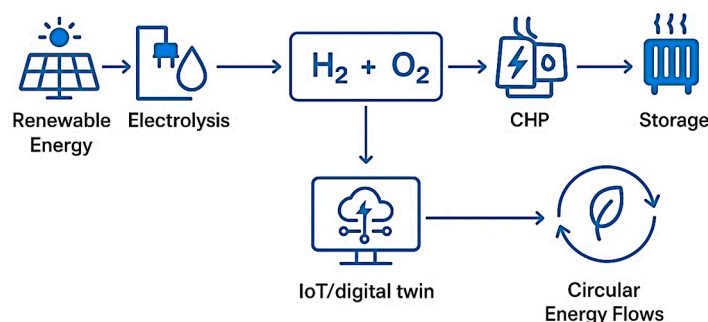


Figure 10. Conceptual framework illustrating future development pathways for hydrogen-enriched CHP systems integrating electrolysis, digital control, and circular energy flows.

Further advances in intelligent combustion control, including model predictive control, artificial intelligence, and digital twins, are expected to play a central role in managing variable hydrogen fractions and dynamic operating conditions. In parallel, materials research must address hydrogen-induced degradation mechanisms through advanced alloys, coatings, and accelerated durability testing under realistic CHP operating conditions [77].

Overall, the evolution of hydrogen-enriched CHP technology will rely on a holistic, multidisciplinary approach combining combustion optimization, renewable integration, digitalization, and sustainability assessment. Bridging the gap between laboratory-scale validation, pilot demonstrations, and real-world implementation remains the key challenge for positioning H₂NG-based CHP systems as a cornerstone of future low-carbon and intelligent energy systems [77].

Recent advances in modeling, control, and system integration have broadened the understanding of hydrogen-enriched natural gas applications beyond combustion fundamentals. Sirbu et al. provide a comprehensive review of combustion characteristics in residential appliances, covering flame stability, flashback tendency, and pollutant formation under varied hydrogen contents [78]. AI-driven control frameworks have been proposed for adaptive fuel quality management in hydrogen–natural gas networks, enabling smart blending and operational optimization [79]. Robust operational strategies for electric–heat–gas integrated energy systems with hydrogen heat recovery address uncertainties in renewable generation and coordinated dispatch [80]. Moreover, comparative thermodynamic assessments of hydrogen-enriched gas turbines operating in CHP mode illustrate

environmental advantages and system efficiency trade-offs at realistic blend levels [81]. Thermoeconomic modeling combined with artificial neural network-based optimization reveals multi-objective cost–efficiency landscapes for hydrogen-integrated CHP plants, highlighting pathways to techno-economic viability [82].

6. Conclusions

This review has provided a comprehensive synthesis of current knowledge on hydrogen-enriched natural gas (H₂NG) utilization in combined heat and power (CHP) systems, with a focus on thermodynamic performance, environmental impacts, and system-level integration aspects. Across experimental and numerical studies, hydrogen addition in the range of 5–20 vol.% is shown to improve combustion efficiency, enhance flame stability, and reduce CO₂ and CO emissions. These benefits can be achieved with limited performance penalties when lean-burn operation and appropriately optimized control strategies are applied to mitigate NO_x formation.

Hybrid CHP configurations integrating renewable-powered electrolyzers and oxygen-enriched combustion concepts demonstrate additional potential by coupling hydrogen production, heat recovery, and emission reduction within a unified low-carbon framework. Nevertheless, several challenges remain insufficiently addressed, including the lack of standardized testing methodologies, limited long-term durability data, and the scarcity of comprehensive techno-economic and life-cycle assessments. Overcoming these barriers will require coordinated advances in combustion control, materials engineering, and digitalized monitoring and optimization strategies.

Overall, hydrogen-enriched cogeneration represents a promising transitional pathway toward more flexible, resilient, and progressively decarbonized distributed energy systems. The evidence consolidated in this review supports the technical feasibility of H₂NG-based CHP under controlled conditions and provides a structured basis for guiding future research directions, system design choices, and policy-oriented assessments.

Throughout this review, a clear distinction has been maintained between experimentally validated results, model-based analyses, and forward-looking system concepts. While hydrogen blending in CHP systems has been demonstrated at laboratory and pilot scales, advanced hybrid architectures and AI-assisted control strategies should be regarded as prospective developments that require further experimental validation before large-scale implementation.

Author Contributions: Conceptualization, C.D. and M.C.; methodology, C.D.; software, C.D. and M.C.; validation, C.D. and M.C.; formal analysis, M.C.; investigation, C.D.; resources, M.C.; data curation, C.D.; writing—original draft preparation, C.D.; writing—review and editing, M.C.; visualization, C.D.; supervision, C.D.; project administration, M.C.; funding acquisition, C.D. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed at the corresponding authors.

Acknowledgments: During the preparation of this manuscript, the authors used ChatGPT, GPT-5.3 (OpenAI) solely for language-related assistance, including proofreading, grammar checking, and minor stylistic editing to improve clarity and readability. The tool was not used for generating scientific content, data, interpretations, or conclusions. The authors have carefully reviewed and edited the text and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

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