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Clean Technology Assessment of Green and Grey Hydrogen Pathways: Energy–Exergy Benchmarking Against Natural Gas Power Generation

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Abstract

Hydrogen-based technologies are widely considered promising pathways for decarbonizing power generation and industrial energy systems; however, their overall sustainability depends strongly on both production routes and conversion efficiencies. This study presents a comparative energy and exergy analysis of hydrogen-based decarbonization pathways under a consistent 1 MW net electrical output boundary, including natural gas combustion (S0), grey hydrogen combustion (S1), grey hydrogen fuel cell (S2), green hydrogen combustion (S3), and green hydrogen fuel cell (S4) systems. The results indicate that combustion-based pathways (S0, S1, and S3) exhibit relatively low energy efficiencies of approximately 30–40% and exergy efficiencies of 25–40%, accompanied by high exergy destruction levels generally exceeding 60%. In contrast, fuel cell-based configurations (S2 and S4) demonstrate improved conversion-stage thermodynamic performance, achieving energy efficiencies of 50–60% and exergy efficiencies of 45–65%, while reducing exergy destruction due to electrochemical conversion and lower irreversibilities. A detailed comparison shows that the natural gas reference system reaches an exergy efficiency of 33.7%, whereas the hydrogen fuel cell system achieves 46.5%, corresponding to approximately 42% lower exergy destruction and about 36% reduced fuel input. From an environmental perspective, the simplified carbon assessment indicates that natural gas combustion generates approximately 577 kg CO_2/h. Grey hydrogen pathways remain associated with substantial upstream emissions, generating approximately 857 kg CO_2/h for grey hydrogen combustion and 545 kg CO_2/h for grey hydrogen fuel cell operation under the 1 MW net electrical output basis. In contrast, green hydrogen-based pathways are assumed to have near-zero direct/upstream operational CO_2 emissions under renewable-powered production assumptions. Overall, the findings show that hydrogen use alone does not guarantee decarbonization; rather, both the hydrogen production route and the final conversion technology must be considered to achieve thermodynamically efficient and low-carbon power generation.

Keywords: green hydrogen; grey hydrogen; natural gas benchmarking; clean technologies; decarbonization; energy analysis; exergy analysis; exergy destruction; Proton Exchange Membrane (PEM) fuel cell; low-carbon power generation

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1. Introduction

Decarbonization is the process of systematically reducing or completely eliminating carbon-based greenhouse gas emissions (especially CO_2) resulting from human activities such as energy, industry, transportation, and heating. The main goal is to create a low- or zero-carbon economy by reducing dependence on fossil fuels. Since the Industrial Revolution, the reliance on fossil fuels for energy production has led to a significant increase in the concentration of carbon dioxide (CO_2) in the atmosphere. This has resulted in problems such as global warming, climate change, and environmental degradation. In this context, decarbonization has become a fundamental strategy aimed at reducing or eliminating carbon-containing fuels from energy systems [1–4].

Hydrogen (H_2) is the first element in the periodic table and the most abundant element in nature. However, it is not found in a free state, but mostly in bonded form in water and hydrocarbon compounds. In energy systems, hydrogen is classified as an energy carrier rather than a primary energy source. Hydrogen plays a significant role in future energy systems due to its high specific energy content and lack of carbon in its use phase [5,6]. Hydrogen is expected to play a central role in the ecological transition in the coming decades due to its significant decarbonization potential. In this context, hydrogen emerges as a key energy carrier for reducing emissions in sectors where emission reduction is difficult, such as iron and steel production, glass manufacturing, oil refining, and heavy vehicle transportation [7]. However, hydrogen's contribution to decarbonization is directly related not only to its chemical structure but also to the thermodynamic efficiency of all processes from production to end use. Therefore, hydrogen-based energy systems need to be evaluated not only from the perspective of energy efficiency but also from a second-law perspective through exergy analysis. Due to its carbon-free structure, high specific energy, and flexibility in energy systems, hydrogen can be used as fuel in modified internal combustion engines or boiler systems.

To clearly position hydrogen within the broader decarbonization context, a general comparison between hydrogen and conventional fossil fuels is provided in Table 1. This comparison highlights not only the environmental advantages of hydrogen at the point of use, but also the key thermodynamic and engineering challenges that must be addressed for its large-scale deployment in energy systems.

A literature review conducted in the context of hydrogen use and decarbonization highlighted that green ammonia, as a hydrogen energy carrier, is a promising alternative for reducing carbon emissions in spark-ignition engines, but emphasizes that technical challenges such as improving combustion characteristics, engine modifications, and emission control need to be overcome [6]. The study by Ostadi [8] investigated how carbon emissions can be reduced in chemical industries through the process integration of green hydrogen. The aim was to use green hydrogen, produced from renewable energy, not only as fuel but also by integrating its energy and chemical roles into industrial processes. The study examined the production of liquid fuel from biogas processed with green hydrogen using the Fischer–Tropsch method. In this integrated system, carbon efficiency reached up to 88%.

Another study technically and systematically evaluated the use of green hydrogen, ammonia, and methanol in marine engines, along with their production and distribution chains, for rapid decarbonization in the maritime sector. A photovoltaic-photocatalytic system used on a ship reported a maximum H_2 production efficiency of ~9.82% from solar energy, producing 63 Nm^3 H_2 (~96 kWh electrical equivalent) daily and saving approximately 6.1 tons of diesel and 18.9 tons of CO_2. The study highlights that these fuels, with appropriate engine technologies and infrastructure integration, can significantly

reduce CO_2 emissions, but engineering challenges such as efficiency, safety, NOx control, and scalability are critical [9].

Table 1. General comparison of fossil fuels and hydrogen in the context of decarbonization.

Criterion	Fossil Fuels (Coal/Oil/Natural Gas)	Hydrogen (H_2)
Chemical structure	Carbon–hydrogen compounds	Carbon-free
Combustion products	CO_2, CO, NO_x, SO_x, particulates	H_2O (water vapor)
CO_2 emissions	High	Zero (at point of use)
Lower heating value (MJ/kg)	42–50 (oil), ~50 (NG)	~120
Volumetric energy density	High	Very low
Typical energy efficiency	30–45% (combustion-based systems)	50–60% (fuel cells)
Typical exergy efficiency	Low to moderate	Moderate to high
Irreversibilities	High (combustion-related)	Low (especially in fuel cells)
Emission control requirements	High (SCR, filters, CCS)	Very low
Ease of storage	High (ambient conditions)	Low (high pressure/ cryogenic)
Transportation infrastructure	Mature and widespread	Limited, under development
Renewable energy integration	Limited	High (green hydrogen)
Decarbonization potential	Low	Very high
Long-term sustainability	Limited	High

The study conducted by Akhtar [10] comparatively evaluates the use of green hydrogen and green ammonia in decarbonizing the transportation and electricity generation sectors. A techno-economic analysis was performed on the production of hydrogen from ammonia and its use in fuel cell vehicles and stationary power systems, as well as the direct use of ammonia in vehicles and energy production using Direct Ammonia Fuel Cell (DAFC) technology. According to the analysis results, in the transportation sector, hydrogen has a lower levelized cost of fuel (LCOF) than ammonia (~0.078 $/km vs. 0.133 $/km), and hydrogen is a more economical option due to its higher energy density. In the carbon reduction cost (CAC) analysis, hydrogen was found to be more suitable for decarbonizing the transportation sector (~353 $/t$CO_2$) compared to ammonia (~595 $/t$CO_2$).

Another study systematically evaluates the techno-economic (TEA) and environmental impacts of producing decarbonized green hydrogen with high efficiency and in an environmentally sustainable manner using biomass gasification. The study shows that a 300 MWth biomass gasification plant can produce approximately 100,000 Nm^3 (99.95% purity) of green hydrogen per hour, achieving up to 90% CO_2 capture and specific emissions reduced to approximately 60 kgCO_2/MWh thanks to integrated CO_2 capture. Energy efficiency in integrated systems is reported to be in the range of 57–59%, and the cost of hydrogen production is approximately €73/MWh [11]. In the study conducted by Franco and Rocca [12] the decarbonization potential and limitations of the blended combustion strategy using natural gas and green hydrogen in industrial heating applications (furnaces, boilers, etc.) were examined. This study indicated that it is possible to mix approximately 20–30% hydrogen by volume in existing industrial burners. A 20% hydrogen mixture resulted in approximately a 7% reduction in CO_2, while a 30% hydrogen mixture resulted in a CO_2 reduction of approximately 10–11%. In the study conducted by Juangsa [13] the thermodynamic performance of using H_2, produced through NH_3 (ammonia) storage, as an alternative fuel in cement clinker production was investigated, and its environmental advantages

compared to the existing coal-fired system were revealed. While 0.95 kg-CO_2/kg-clinker emissions were observed in the conventional coal-fired process, this value decreased to 0.51 kg-CO_2/kg-clinker with the H_2-based integrated system, and approximately 44% CO_2 reduction was achieved.

In the study conducted by Dumbrava and Cormos [11,14] hydrogen production via direct biogas conversion based on thermochemical cycling (TCL) was evaluated from a technical and economic perspective. It was reported that the energy efficiency of hydrogen production for the proposed configurations is approximately in the range of 65–75%. Thanks to integrated heat recovery and the cyclical reaction structure, a significant reduction in CO_2 emissions was achieved compared to conventional reforming processes, and a large portion of the carbon was captured within the process. According to the techno-economic analysis results, the cost of hydrogen production was calculated to be approximately 2.5–4.0 \$/kg H_2, depending on the scale and configuration, indicating an economically competitive range for low-carbon hydrogen production based on biogas. Another study investigated the cost of decarbonized hydrogen production by evaluating the thermodynamic and economic performance of a CO_2 capture system with an integrated membrane reactor. According to the analyses, integrating the CO_2 capture system into the membrane reactor reduced the cost of hydrogen production by approximately 12%, resulting in a decrease in environmental costs [15].

In addition to its role as a clean energy carrier, hydrogen is increasingly recognized as a strategic vector for enabling sector coupling and enhancing the flexibility of future low-carbon energy systems. By linking the electricity, heat, transport, and industrial sectors, hydrogen facilitates the large-scale integration of renewable energy sources and mitigates the intermittency challenges associated with wind and solar power generation. As a result, hydrogen-based systems are considered a cornerstone of long-term decarbonization strategies at both national and global levels [16–18].

However, the environmental benefits of hydrogen cannot be assessed solely based on its carbon-free end-use characteristics. The thermodynamic performance of hydrogen systems across their entire value chain encompassing production, compression, storage, transport, and final conversion play a decisive role in determining their true sustainability. In this context, first-law (energy) efficiency alone is insufficient to capture the quality degradation of energy resources and the irreversibilities inherent in hydrogen pathways. Instead, exergy analysis, grounded in the second law of thermodynamics, provides a more comprehensive framework for identifying performance losses, system inefficiencies, and improvement potentials [19,20].

Recent studies emphasize that hydrogen pathways characterized by low carbon intensity may still exhibit substantial exergy destruction, particularly during energy-intensive production processes such as electrolysis, methane reforming, or biomass conversion. These irreversibilities can significantly reduce the overall system efficiency and increase resource consumption, thereby limiting the net decarbonization benefit if not properly addressed [21,22]. Consequently, a rigorous thermodynamic assessment is essential to distinguish between hydrogen pathways that are merely low-carbon and those that are both low-carbon and thermodynamically sustainable.

Moreover, the comparative evaluation of hydrogen-based systems against conventional fossil fuel benchmarks, such as natural gas-fired power generation, remains critical for guiding technology selection and policy development. While hydrogen offers clear advantages in terms of emissions reduction, its deployment must be justified through transparent comparisons of energy efficiency, exergy efficiency, and system-level losses relative to existing technologies. Scenario-based assessments that integrate different hydrogen production routes (e.g., grey versus green hydrogen) and end-use technologies (e.g.,

combustion versus fuel cells) are therefore increasingly adopted to support evidence-based decarbonization pathways [23]. Energy and exergy analyses have been widely employed to evaluate the thermodynamic performance of complex energy systems, particularly those integrating renewable energy sources and advanced energy storage technologies. Such approaches enable the identification of inefficiencies and irreversibilities that cannot be captured through energy-based evaluations alone [24]. In the context of hydrogen-based decarbonization, exergy analysis is especially valuable for assessing the quality degradation of energy resources across production and conversion pathways.

In the study conducted by Anand et al. [25], it was noted that hydrogen production based on fossil fuels constitutes approximately 76% of the global hydrogen supply and that these methods cause 8–30 kg of CO_2 emissions per 1 kg of H_2 produced, while it was emphasized that renewable energy-supported water electrolysis is the most sustainable alternative. However, the study is primarily based on a literature review and does not directly compare the thermodynamic performances of different energy conversion technologies. In contrast, the energy and exergy analyses conducted in our study quantitatively demonstrate the impact of hydrogen use on system performance. The obtained results have shown that combustion-based systems are limited to 30–40% exergy efficiency, whereas fuel cell systems achieve energy efficiency values of 50–60% and exergy efficiency values of 45–65%.

In the study conducted by Bhuiyan and Siddique [26], it was reported that approximately 96% of global hydrogen production comes from fossil sources, the efficiency of electrolysis ranges from 55% to 80%, and the cost of green hydrogen is at the level of 1.28–7.39/kg H_2. However, the study evaluates hydrogen technologies from a general perspective. Our study, on the other hand, reveals the impact of hydrogen usage on system performance from a thermodynamic perspective. The results obtained have shown that combustion-based systems have an exergy efficiency of 30–40%, while hydrogen fuel cell systems provide an energy efficiency of 50–60% and an exergy efficiency of 45–65%. Therefore, the current study contributes to the literature by quantitatively demonstrating the superiority of hydrogen technologies through energy and exergy performance indicators.

In the study conducted by Venizelou and Poullikkas [27], the potential of green hydrogen to serve as an alternative to natural gas combined cycle power plants was evaluated from a techno-economic perspective, and it was shown that hydrogen-fueled plants could become competitive if the carbon price exceeds \$60/tCO_2. Additionally, it has been reported that the use of hydrogen can provide approximately 340 gCO_2/kWh emission reduction in electricity generation. However, while the study primarily focuses on economic and environmental performance, our work directly demonstrates the thermodynamic superiority of hydrogen technologies. The results obtained have shown that hydrogen fuel cell systems exhibit higher performance with 50–60% energy efficiency and 45–65% exergy efficiency compared to combustion-based systems (30–40% exergy efficiency), thus quantitatively validating the advantages of hydrogen use from the perspective of energy and exergy.

In the study conducted by Sahin [28], it was determined that a 200 kW PEM electrolyzer system modeled under İzmir conditions could produce 7939 kg of green hydrogen annually, with a specific energy consumption of 59.18 kWh/kg H_2 and a hydrogen production cost of \$5.29/kg H_2. By applying a volumetric hydrogen mixture of 5–20% to natural gas, a reduction in CO_2 emissions between 1.62% and 7.25% was achieved, demonstrating that 84.6 tons of CO_2 equivalent emissions could be prevented annually. However, while the study focuses on emission reduction, our study presents the first quantitative comparison of performance under 1 MW output conditions between grey hydrogen and fossil fuel systems.

In the study conducted by Yue et al. [29], green hydrogen-based energy storage systems were evaluated in terms of energy, exergy, economic, and environmental aspects. The results show that the system's energy efficiency varies between approximately 42–52%, and the exergy efficiency between 35–48%, while significantly reducing CO_2 emissions compared to traditional storage technologies. However, while the study focuses on the energy storage potential of hydrogen, our work directly compares the thermodynamic performances of different energy conversion technologies. The results obtained have shown that hydrogen fuel cell systems exhibit superior performance with 50–60% energy efficiency and 45–65% exergy efficiency compared to combustion-based systems (30–40% exergy efficiency). In this respect, our study contributes to the literature by quantitatively demonstrating the advantages of hydrogen technologies not only in storage but also in final energy conversion processes.

Within this framework, the present study aims to contribute to the hydrogen literature by providing a systematic thermodynamic evaluation of hydrogen utilization for decarbonization, combining energy and exergy analyses with comparative case studies and scenario-based assessments. By explicitly benchmarking hydrogen-based pathways against natural gas systems and distinguishing between production and conversion options, this work seeks to clarify the conditions under which hydrogen can deliver meaningful and sustainable decarbonization benefits.

Accordingly, this study presents a thermodynamic assessment of hydrogen-based decarbonization pathways by integrating energy and exergy analyses with comparative case studies and scenario-based evaluations, explicitly benchmarking green and grey hydrogen utilization against conventional natural gas systems.

Unlike most previous studies that focus either on energy efficiency or carbon emissions, this study provides a unified thermodynamic assessment framework by integrating both energy and exergy analyses for hydrogen-based decarbonization pathways. The main novelty of this work lies in the consistent benchmarking of hydrogen systems against a natural gas reference under identical operating conditions, enabling a transparent and fair comparison of thermodynamic performance.

Furthermore, this study introduces a scenario-based approach that simultaneously considers hydrogen production routes (grey vs. green) and conversion technologies (combustion vs. fuel cells), which is rarely addressed in a single framework in the existing literature. This integrated perspective allows the identification of pathways that are not only low-carbon but also thermodynamically sustainable.

In addition, the study highlights that hydrogen utilization alone does not guarantee effective decarbonization, emphasizing the critical role of exergy destruction across the entire value chain. This insight contributes to the ongoing discussion by shifting the focus from purely carbon-based evaluations toward second-law-based sustainability assessment.

The main contributions of this study can be summarized as follows:

- A unified energy–exergy assessment framework for evaluating hydrogen-based decarbonization pathways.
- A consistent benchmarking of hydrogen systems against natural gas under identical system boundaries.
- A scenario-based comparison integrating both hydrogen production routes (grey and green) and conversion technologies (combustion and fuel cells).
- Quantification of exergy destruction as a key indicator of thermodynamic sustainability in decarbonization studies.
- Demonstration that hydrogen-based decarbonization is only effective when combined with low-exergy-loss pathways.
- Validate or challenge existing conclusions about green hydrogen's viability.

- Identify gaps in current infrastructure or cost assumptions that may hinder its adoption.
- Propose actionable insights for policymakers, engineers, and investors based on the thermodynamic and economic feasibility of each pathway.

The present study is directly aligned with the clean technology perspective because it evaluates hydrogen-based pathways as alternatives to conventional natural gas power generation. By comparing grey and green hydrogen options with combustion and PEM fuel cell conversion under an equivalent 1 MW net electrical output basis, the study identifies the conditions under which hydrogen can reduce both carbon emissions and thermodynamic irreversibilities. Therefore, the assessment provides a clean-technology basis for selecting hydrogen pathways that are not only low-carbon at the point of use but also more efficient from a second-law perspective.

2. Material and Methods

2.1. Methodological Framework

This study evaluates the effect of hydrogen utilization on decarbonization using a combined energy and exergy analysis framework. The methodology is designed to assess not only the quantity of energy converted within hydrogen-based systems but also the quality degradation of energy resources arising from irreversibilities during fuel conversion processes. The integration of first- and second-law thermodynamic analyses enables a comprehensive evaluation of hydrogen-based pathways relative to conventional fossil fuel systems.

All analyses are conducted under steady-state operating conditions using a control volume approach. The methodology focuses on system-level performance metrics, allowing transparent comparison between hydrogen-based and fossil fuel-based energy conversion systems in terms of efficiency, exergy destruction, and decarbonization potential.

2.2. System Boundaries, Assumptions and Input Parameters

To ensure a consistent and fair comparison among all evaluated pathways, the system boundary was defined on the basis of an equivalent 1 MW net electrical output. All scenarios were assessed under steady-state operating conditions using the same useful output as the functional unit. Therefore, the comparison was not based on the amount of fuel supplied, but on the amount of useful electrical energy delivered by each system.

The system boundary includes the fuel input, energy conversion process, useful electrical output, and thermodynamic losses occurring during conversion. For the natural gas reference case, the boundary covers natural gas input and combustion-based electricity generation. For hydrogen-based scenarios, the boundary covers hydrogen input and its conversion either through combustion-based systems or Proton Exchange Membrane fuel cell systems. Hydrogen production routes are considered separately as grey hydrogen and green hydrogen in order to evaluate their influence on decarbonization potential.

It should be noted that different system boundaries were adopted for the thermodynamic and environmental assessments. The energy and exergy analyses were performed at the energy conversion stage, considering only the fuel-to-electricity conversion process. In contrast, the carbon emission assessment employed a simplified well-to-wire perspective by including upstream emissions associated with fuel production and processing. Therefore, the thermodynamic performance indicators and carbon emission results should be interpreted within their respective system boundaries.

In all cases, the useful output was fixed at 1 MW net electrical power. The required fuel energy input was then calculated according to the energy efficiency of each system. This approach enables a direct comparison of natural gas combustion, hydrogen combustion, and hydrogen fuel cell pathways under identical output conditions. The same functional

unit, namely 1 MW net electrical output, was used for all scenarios; however, thermodynamic and carbon-emission indicators were evaluated under explicitly defined but different assessment boundaries.

The following assumptions were used in the analysis:

- The useful output of all systems was fixed at 1 MW net electrical output.
- All systems were evaluated under steady-state operating conditions.
- Natural gas was used as the fossil-fuel reference case.
- Grey hydrogen was assumed to be produced through conventional fossil-based pathways.
- Green hydrogen was assumed to be produced using renewable electricity.
- Hydrogen was evaluated in two end-use pathways: combustion-based conversion and PEM fuel cell conversion.
- Storage and transport losses were acknowledged but not explicitly modeled in the base-case calculations.
- Lower heating value values were used consistently for fuel energy input calculations.
- Chemical exergy input was calculated using fuel-specific exergy coefficients.
- A natural gas-fired power generation system serving as the reference fossil fuel benchmark.
- Hydrogen combustion-based systems, representing retrofitted or modified combustion applications.
- Hydrogen fuel cell-based systems, representing electrochemical energy conversion pathways.

The thermodynamic and environmental analyses were conducted using representative performance parameters reported in the literature. The electrical efficiency of the natural gas-fired power generation system was assumed to be 35%, while the PEM fuel cell system was assigned an electrical efficiency of 55%. Chemical exergy correction factors (β) of 1.04 for natural gas and 1.18 for hydrogen were adopted to determine the corresponding fuel exergy inputs. For the simplified carbon emission assessment, a carbon emission factor of 0.202 kg CO_2/kWh was used for natural gas combustion, whereas grey hydrogen production via steam methane reforming (SMR) was characterized by an emission factor of 10 kg CO_2/kg H_2. Green hydrogen produced from renewable-powered electrolysis was assumed to have negligible direct carbon emissions. All scenarios were evaluated under a common net electrical output of 1 MW to ensure a consistent comparison of thermodynamic and environmental performance.

2.3. Energy Analysis Parameters

The energy analysis is performed in accordance with the first law of thermodynamics. Energy efficiency is defined as the ratio of useful electrical output to fuel energy input. The lower heating value (LHV) of fuels is used consistently throughout the analysis to ensure uniform comparison across different energy carriers.

The energy performance of the evaluated systems is determined based on the first law of thermodynamics. Under steady-state conditions, the energy balance for the control volume is expressed as

$$\sum \dot{E}_{in} = \sum \dot{E}_{out} \quad (1)$$

For a control volume operating under steady-state conditions, the general energy balance is expressed as

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \quad (2)$$

The required fuel energy input is calculated as

$$\dot{E}_{fuel} = \frac{\dot{E}_{el}}{\eta_{en}} \tag{3}$$

where $\dot{E}_{fuel}$ is the fuel energy input (MW), $\dot{E}_{el}$ is the net electrical output (MW), and η_{en} is the energy efficiency of the system.

The energy efficiency is defined as

$$\eta_{en} = \frac{\dot{E}_{el}}{\dot{E}_{fuel}} \tag{4}$$

The total energy loss within the system is given by

$$\dot{E}_{loss} = \dot{E}_{fuel} - \dot{E}_{el} \tag{5}$$

For each system, the required fuel input is determined based on the specified net electrical output and the corresponding conversion efficiency. Energy losses are calculated as the difference between the total fuel energy input and the useful electrical output. This approach provides a quantitative basis for evaluating the relative energy performance of hydrogen-based and fossil fuel-based systems.

2.4. Exergy Analysis Parameters

To capture the quality of energy conversion and identify irreversibilities, an exergy analysis based on the second law of thermodynamics is employed. The chemical exergy of fuels is calculated using fuel-specific exergy coefficients, enabling the quantification of the maximum useful work potential of each energy carrier.

Exergy analysis provides a rigorous second-law-based framework for quantifying irreversibilities in energy conversion systems and has been successfully applied to hydrogen-related processes, including hydrogen liquefaction and processing systems. Previous studies have demonstrated that advanced exergy-based approaches are essential for identifying the true sources of inefficiency in hydrogen systems beyond conventional energy efficiency metrics [30]. Accordingly, the present study adopts a combined energy and exergy analysis framework to evaluate hydrogen utilization pathways for decarbonization.

Exergy efficiency is defined as the ratio of useful electrical output to the chemical exergy input of the fuel. The total exergy destruction within each system is determined as the difference between the fuel exergy input and the useful electrical output. This metric serves as a direct indicator of thermodynamic irreversibility and resource degradation.

To evaluate the quality of energy conversion and system irreversibilities, an exergy analysis based on the second law of thermodynamics is conducted. The general exergy balance for a steady-state control volume is expressed as

$$\sum \dot{E}x_{in} = \sum \dot{E}x_{out} + \dot{E}x_{dest} \tag{6}$$

where $\dot{E}x_{dest}$ represents the total exergy destruction rate due to irreversibilities.

The steady-state exergy balance is given by

$$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \dot{E}x_{dest} \tag{7}$$

where $\dot{E}x_{dest}$ represents exergy destruction due to irreversibilities and is directly related to entropy generation:

$$\dot{E}x_{dest} = T_0 \dot{S}_{gen} \tag{8}$$

The chemical exergy of the fuel is calculated using fuel-specific exergy coefficients:

$$\dot{E}x_{fuel} = \beta \cdot \dot{E}_{fuel} \tag{9}$$

where β is the chemical exergy factor of the fuel.

The exergy efficiency of the system is defined as

$$\eta_{ex} = \frac{\dot{E}_{el}}{\dot{E}x_{fuel}} \tag{10}$$

For chemical fuels, the chemical exergy can be approximated as

$$E_{xch} \approx \beta \, \mathrm{LHV} \tag{11}$$

where β is a fuel-specific coefficient (≈1.04 for hydrocarbons and ≈1.18 for hydrogen). Figure 1 shows comparison of total exergy destruction rates of a fossil fuel-based energy system and a hydrogen fuel cell system.

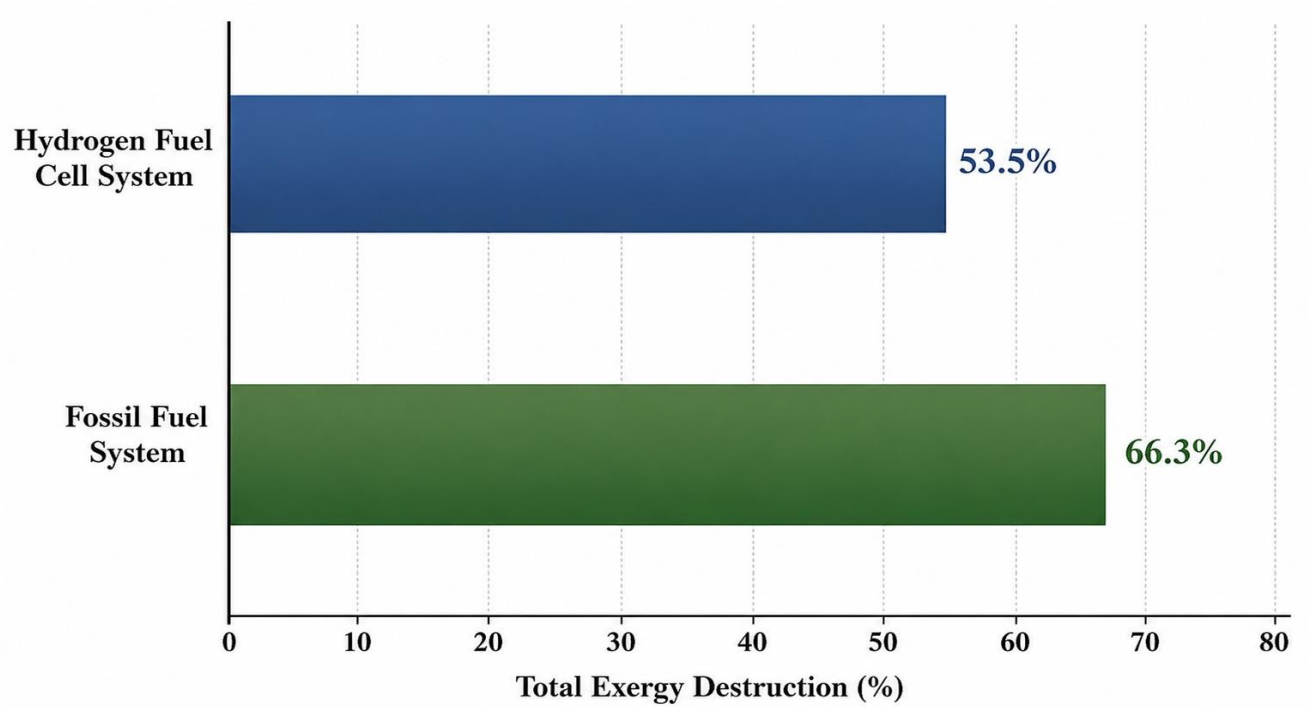


Figure 1. Comparison of total exergy destruction rates of a fossil fuel-based energy system and a hydrogen fuel cell system.

The total exergy destruction within the system is calculated as

$$\dot{E}x_{dest} = \dot{E}x_{fuel} - \dot{E}_{el} \tag{12}$$

This formulation allows the direct quantification of irreversibilities associated with fuel conversion and provides a second-law-based indicator of thermodynamic sustainability.

$$\varepsilon_{dest} = \frac{\dot{E}x_{dest}}{\dot{E}_{el}} \tag{13}$$

By integrating exergy analysis with energy-based metrics, the methodology allows the identification of pathways that are not only low-carbon but also thermodynamically sustainable.

2.5. Scenario Definition and Comparative Approach

A scenario-based methodology is adopted to evaluate the combined effects of hydrogen production routes and conversion technologies on decarbonization performance. Five representative scenarios are defined:

- S0: Natural gas combustion-based power generation (reference case)
- S1: Grey hydrogen combustion-based power generation
- S2: Grey hydrogen utilization in fuel cell systems
- S3: Green hydrogen combustion-based power generation
- **S4:** Green hydrogen utilization in fuel cell systems

Grey hydrogen is assumed to be produced via conventional fossil-based pathways, while green hydrogen is assumed to be produced using renewable energy sources with negligible direct carbon emissions. All scenarios are evaluated using identical system boundaries and thermodynamic metrics to ensure fair comparison.

2.6. Comparative Performance Metrics

The comparative assessment of scenarios is based on the following key performance indicators:

- Energy efficiency
- Exergy efficiency
- Exergy destruction rate
- Carbon emission characteristics at the point of use
- Qualitative assessment of decarbonization potential

These metrics enable a systematic evaluation of the trade-offs between thermodynamic performance and environmental benefits across hydrogen-based and fossil fuel-based pathways.

For comparative evaluation of hydrogen-based and fossil fuel-based systems, the following dimensionless indicators are used:

- Energy efficiency: η_{en}
- Exergy efficiency: η_{ex}
- Specific exergy destruction:

These indicators enable consistent comparison across different scenarios operating at an equivalent net electrical output.

2.7. Visualization and Interpretation

To enhance the interpretability of the results, Sankey diagrams are employed to visualize energy and exergy flow structures within the evaluated systems. These diagrams provide a clear representation of fuel input requirements, useful output, and irreversibilities, facilitating intuitive comparison between scenarios.

3. Results and Discussion

The effectiveness of decarbonization strategies is determined not only by the reduction of carbon emissions but also by the thermodynamic quality of energy conversion processes. In this context, energy analysis reveals the performance of systems from a first-law perspective, while exergy analysis evaluates irreversibilities, quality losses, and the actual amount of usable energy based on the second law.

For an accurate comparison of the decarbonization potential of fossil fuel and hydrogen-based systems, both analysis methods must be considered together.

3.1. Hydrogen and Fossil Fuels from an Energy Analysis Perspective

Energy analysis is based on the principle of conservation of energy entering and leaving systems. In this analysis, the amount of energy is conserved, and reductions in energy quality are not taken into account.

Hydrogen is a highly advantageous fuel in terms of mass due to its high specific energy content (≈120 MJ/kg, LHV). However, its low volumetric energy density requires additional energy inputs for storage and transportation. Fossil fuels, on the other hand, offer practical advantages due to their high volumetric energy density despite having a lower specific energy content.

Hydrogen exhibits a clear advantage in terms of specific energy content and can achieve higher conversion efficiencies when utilized through electrochemical processes rather than conventional combustion systems.

3.2. Hydrogen and Fossil Fuels from an Exergy Analysis Perspective

Exergy analysis reveals the true performance of systems by considering the irreversibilities and entropy production that occur in energy conversion processes. This analysis is critically important for decarbonization because high exergy destruction indirectly means greater resource consumption and environmental burden.

As shown in Figure 1, the calculated exergy destruction was 66.3% for the natural gas-fired power generation system and 53.5% for the hydrogen fuel cell system. The lower exergy destruction observed in the hydrogen pathway is mainly attributed to electrochemical energy conversion, which avoids many of the irreversibilities associated with conventional combustion processes. Table 2 shows an energy and exergy-based comparison of fossil fuels and hydrogen in the context of decarbonization. Values represent typical literature ranges and are not directly calculated in the present study.

Table 2. Energy and Exergy-Based Comparison of Fossil Fuels and Hydrogen in the Context of Decarbonization.

Criterion	Fossil Fuels	Hydrogen (H_2)
Primary energy carrier	Coal, oil, natural gas	Energy carrier
Carbon content	High	None
Main conversion mechanism	Combustion	Combustion/Electrochemical
Lower heating value (MJ/kg)	42–50	~120
Volumetric energy density	High	Very low
Typical energy efficiency (%)	30–45	50–60 (fuel cells)
Typical exergy efficiency (%)	25–40	45–65
Exergy destruction (%)	40–65	20–40
Dominant irreversibility source	Combustion and heat transfer	Electrochemical losses, compression
CO_2 emissions	High	Zero at point of use
NO_x formation	Significant	Low/negligible
Storage-related exergy losses (%)	2–5	10–30
System-level decarbonization potential	Low	Very high
Long-term thermodynamic sustainability	Limited	High

The exergy-destruction values reported in Table 2 represent typical ranges found in the literature. The calculated values obtained in the present study are 66.3% for the natural gas system and 53.5% for the hydrogen fuel cell system and are reported separately in the Results section. Figure 2 presents a normalized and illustrative energy–exergy flow diagram based on 100 units of renewable electricity input. Therefore, the reported values are intended to show the relative distribution of energy losses and exergy destruction across the main stages, rather than to represent a specific experimental system.

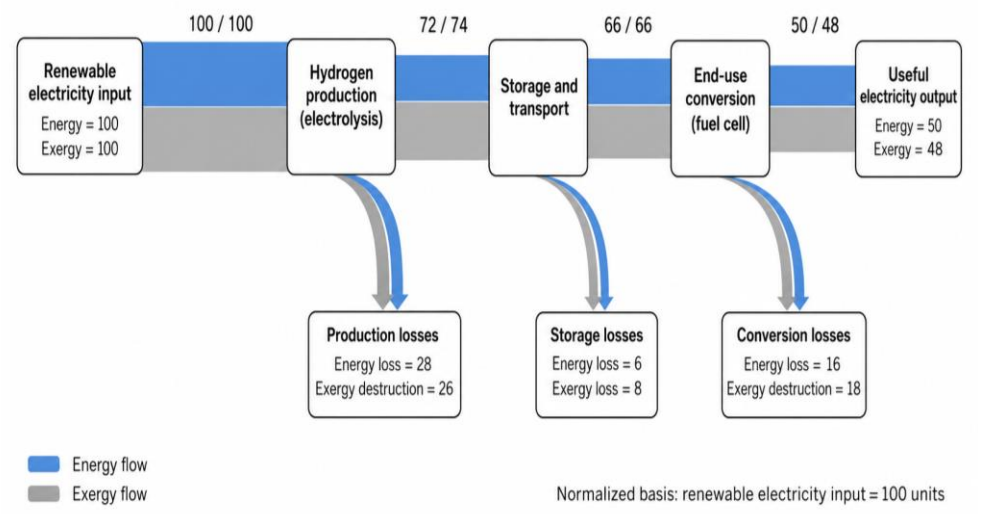


Figure 2. Normalized and illustrative energy and exergy flow diagram for a hydrogen-based energy pathway.

As shown in Figure 2, a significant portion of the input energy is lost due to irreversibilities during the hydrogen production phase (e.g., electrolysis), followed by additional losses during the storage and transport phases. The figure is intended for conceptual visualization and does not represent a specific operating condition. Ultimately, the usable energy flow represents approximately half of the total input energy. The Sankey diagram clearly shows that exergy destruction is concentrated particularly during the production phase, even when decarbonization is achieved in hydrogen systems.

3.3. Case Study: Thermodynamic Evaluation of Green Hydrogen vs. Natural Gas for Power Generation

To quantitatively demonstrate the thermodynamic and decarbonization advantages of hydrogen utilization, a simplified case study is conducted comparing a green hydrogen-based fuel cell system with a natural gas-fired power generation system. The assessment is performed on an equivalent 1 MW net electrical output basis under steady-state operating conditions.

3.3.1. System Description and Assumptions

Two representative energy conversion systems are considered:

- System A: Natural Gas-Fired Power Generation System
- System B: Proton Exchange Membrane (PEM) fuel cell powered by green hydrogen produced via renewable-based electrolysis

The main thermodynamic and operational assumptions are summarized as follows:

- The lower heating value (LHV) of hydrogen is taken as 120 MJ/kg, while the LHV of natural gas is assumed to be 48–50 MJ/kg, consistent with standard thermodynamic references [31,32].

- The electrical efficiency of natural gas power generation systems typically ranges between 30–40%, depending on system configuration and operating conditions; in this study, a representative value of 35% is adopted [16,33].
- PEM fuel cell systems exhibit higher electrical efficiencies due to electrochemical conversion, generally in the range of 50–60%; a conservative efficiency of 55% is assumed here [17,34].
- The chemical exergy of fuels is estimated using fuel-specific exergy coefficients (β), taken as 1.04 for natural gas and 1.18 for hydrogen, in accordance with classical exergy theory [20].
- Hydrogen is assumed to be produced using renewable electricity, resulting in negligible direct CO_2 emissions during the power generation phase.

3.3.2. Energy Analysis

For a net electrical output of 1 MW, the corresponding fuel energy inputs are obtained as follows. The required fuel energy input is defined at Equation (3):

For the natural gas-based system:

$$\dot{E}_{fuel,NG} = \frac{1}{0.35} = 2.86 \text{ MW}$$

For the hydrogen fuel cell system:

$$\dot{E}_{fuel,H_2} = \frac{1}{0.55} = 1.82 \text{ MW}$$

These results indicate that the hydrogen-based system requires approximately 36% less fuel energy input than the natural gas system to deliver the same electrical output, reflecting the higher conversion efficiency of electrochemical processes [16,33].

3.3.3. Exergy Analysis

To evaluate system performance from a second-law perspective, the chemical exergy input of each fuel is calculated using Equation (9):

- Natural gas system:

$$\dot{Ex}_{fuel,NG} = 1.04 \times 2.86 = 2.97 \text{ MW}$$

- Hydrogen system:

$$\dot{Ex}_{fuel,H_2} = 1.18 \times 1.82 = 2.15 \text{ MW}$$

The exergy efficiency is defined at Equation (10):

which yields:

$$\text{Natural gas system : } \eta_{ex,NG} = 33.7\%$$

$$\text{Hydrogen fuel cell system : } \eta_{ex,H_2} = 46.5\%$$

The significantly higher exergy efficiency of the hydrogen-based system highlights the reduced irreversibility of electrochemical conversion compared to high-temperature combustion processes [19,21].

3.3.4. Exergy Destruction and Decarbonization Implications

The total exergy destruction rate for each system is determined from Equation (12):

The calculated exergy destruction rates are:

$$\text{Natural gas system}: \dot{E}x_{dest,NG} = 1.97 \text{ MW}$$

$$\text{Hydrogen system}: \dot{E}x_{dest,H_2} = 1.15 \text{ MW}$$

This corresponds to an approximate 42% reduction in exergy destruction when hydrogen is used instead of natural gas. Since exergy destruction is directly related to entropy generation and resource degradation, this reduction indicates a substantially improved thermodynamic sustainability [19,20].

From an environmental perspective, natural gas-based electricity generation emits approximately 0.18–0.20 kg CO_2/kWh, corresponding to nearly 180–200 kg CO_2 per hour for a 1 MW system [35]. In contrast, the hydrogen fuel cell system achieves near-zero direct CO_2 emissions when green hydrogen is employed.

Figure 3 presents a Sankey diagram comparing the energy and exergy flow structures of the natural gas-based and hydrogen-based systems. The visual comparison clearly indicates that the hydrogen fuel cell system requires a substantially lower fuel input while exhibiting markedly reduced exergy destruction. In contrast, the natural gas system shows significant irreversibilities associated with combustion and heat transfer processes. These results further confirm that hydrogen utilization enables a more efficient and thermodynamically sustainable pathway for decarbonized power generation.

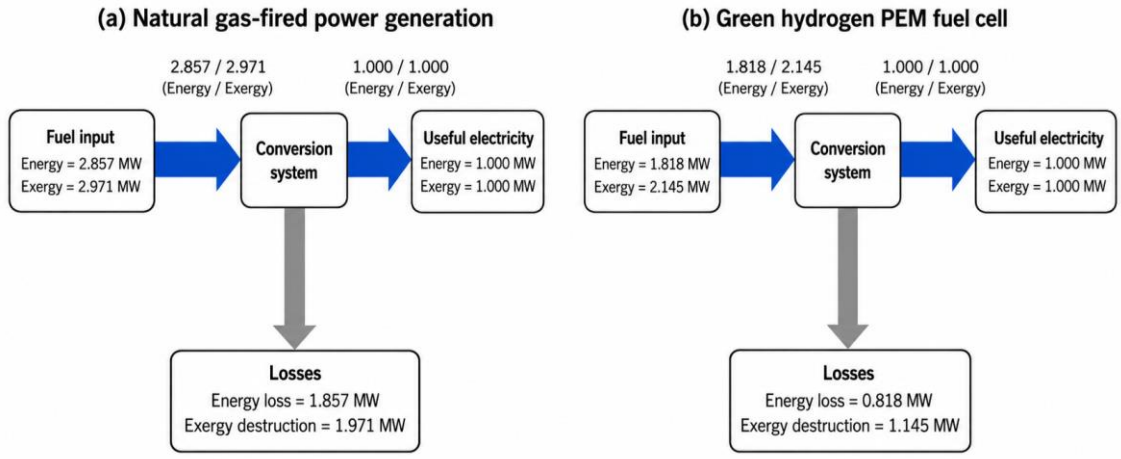


Figure 3. Sankey diagram illustrating the energy and exergy flows for (**a**) a natural gas-fired power generation system and (**b**) a green hydrogen-based PEM fuel cell system operating at a net electrical output of 1 MW.

The diagram highlights the significantly lower fuel input requirement and reduced exergy destruction associated with hydrogen utilization, emphasizing its thermodynamic superiority and decarbonization potential. Values are normalized to facilitate comparison among the investigated pathways and do not represent detailed plant-scale simulations.

The presented case study clearly demonstrates that hydrogen utilization, particularly in combination with fuel cell technology, provides substantial advantages in terms of both energy and exergy performance. While hydrogen production involves upstream energy and exergy losses, the elimination of combustion-related irreversibilities and the higher efficiency of electrochemical conversion significantly improve overall system performance.

These results confirm that hydrogen is not only a carbon-free energy carrier at the point of use but also a thermodynamically superior alternative to conventional fossil fuel-based power generation systems when evaluated from a second-law perspective, thereby reinforcing its strategic role in deep decarbonization pathways.

3.4. Extended Scenario Analysis Including Natural Gas Benchmark

To provide a comprehensive benchmark for hydrogen-based decarbonization pathways, the previously analyzed natural gas-fired power generation system is incorporated into the scenario framework. This extended comparison enables a consistent evaluation of fossil fuel and hydrogen-based systems under identical operating conditions.

3.4.1. Definition of Scenarios

Five representative scenarios are defined on a 1 MW net electrical output basis:

- S0: Natural gas combustion-based power generation (reference case)
- S1: Grey hydrogen + combustion-based power generation
- S2: Grey hydrogen + PEM fuel cell system
- S3: Green hydrogen + combustion-based power generation
- S4: Green hydrogen + PEM fuel cell system

The natural gas system (S0) corresponds to the case study presented in Section 3.3 and serves as the baseline for thermodynamic and environmental comparison.

3.4.2. Simplified Carbon Emission Assessment

For the natural gas reference system (S0), a carbon emission factor of 0.202 kg CO_2/kWh of fuel energy was adopted. Based on a representative electrical conversion efficiency of 35%, the fuel input required to produce 1 MW of net electrical output is approximately 2.86 MW, resulting in an estimated end-use CO_2 emission of approximately 577 kg CO_2/h.

Grey hydrogen production via steam methane reforming without carbon capture results in 9–11 kg CO_2 per kg H_2, leading to substantial upstream emissions even when hydrogen is used in high-efficiency conversion systems.

Green hydrogen, produced via renewable electricity-driven electrolysis, enables near-zero lifecycle CO_2 emissions, assuming a fully renewable electricity supply.

Accordingly:

- S0 and S1 exhibit high CO_2 emissions.
- S2 shows reduced emissions compared to S1 due to higher conversion efficiency, but remains carbon-intensive upstream.
- S3 eliminates upstream CO_2 emissions but suffers from combustion-related inefficiencies and NO_x formation.
- S4 achieves the lowest overall carbon footprint.

For a simplified carbon assessment, both upstream and end-use emissions were considered. The calculations were performed on the basis of 1 MW net electrical output.

The carbon intensity of natural gas combustion was assumed as

$$EF_{NG} = 0.202\ \mathrm{kgCO_2/kW\ h_{fuel}}$$

For grey hydrogen production via steam methane reforming (SMR), an average emission factor of

$$EF_{GreyH2} = 10\ \mathrm{kgCO_2/kgH_2}$$

was adopted from the literature.

Green hydrogen produced via renewable-powered electrolysis was assumed to have negligible direct carbon emissions.

Based on the calculated fuel energy requirements:

$$E_{fuel,NG} = 2.86\ \mathrm{MW}$$

$$E_{fuel,H2} = 1.82 \text{ MW}$$

The corresponding carbon emissions were estimated through calculation.

Table 3 shows simplified carbon emission comparison for 1 MW net electrical output.

Table 3. Simplified carbon emission comparison for 1 MW net electrical output.

Scenario	Representative Conversion Efficiency (%)	Fuel Input (MW)	H_2 Consumption (kg/h)	Upstream CO_2 (kg/h)	End-Use CO_2 (kg/h)	Total CO_2 (kg/h)
S0: Natural gas combustion	35	2.86	0	0	577	577
S1: Grey H_2 + combustion	35	2.86	85.7	857	0	857
S2: Grey H_2 + PEM fuel cell	55	1.82	54.5	545	0	545
S3: Green H_2 + combustion	35	2.86	85.7	≈0	0	≈0
S4: Green H_2 + PEM fuel cell	55	1.82	54.5	≈0	0	≈0

Table 3 presents a simplified carbon emission assessment for the investigated scenarios based on a net electrical output of 1 MW. The results show that the natural gas combustion pathway (S0) generates approximately 577 kg CO_2/h at the end-use stage. Grey hydrogen pathways remain associated with substantial upstream emissions due to steam methane reforming. However, the total emissions differ depending on the conversion technology: grey hydrogen combustion (S1) results in approximately 857 kg CO_2/h, whereas the grey hydrogen PEM fuel cell pathway (S2) decreases this value to approximately 545 kg CO_2/h because of its higher conversion efficiency and lower hydrogen consumption. In contrast, green hydrogen pathways (S3 and S4) exhibit near-zero carbon emissions under the assumption of renewable-powered hydrogen production. These results indicate that hydrogen use alone does not guarantee decarbonization; the production route and conversion efficiency must be considered together.

3.4.3. Energy and Exergy Performance Comparison

From a thermodynamic perspective, combustion-based systems (S0, S1, S3) exhibit relatively low exergy efficiencies (30–40%) due to high irreversibilities associated with chemical reactions and heat transfer.

Fuel cell-based systems (S2, S4) benefit from electrochemical conversion, achieving higher energy efficiencies (50–60%) and exergy efficiencies (45–65%), with substantially reduced exergy destruction.

Compared to the natural gas benchmark:

- Switching from natural gas combustion (S0) to grey hydrogen combustion (S1) does not improve thermodynamic performance and increases upstream emissions.
- Replacing combustion with fuel cell technology (S2) significantly improves exergy efficiency but does not eliminate upstream CO_2 emissions.
- The combination of green hydrogen and fuel cell technology (S4) provides both thermodynamic superiority and deep decarbonization.

3.4.4. Integrated Scenario Comparison

The extended scenario analysis clearly demonstrates that natural gas remains an inadequate long-term solution for decarbonization due to high carbon emissions and thermodynamic irreversibilities. Furthermore, simply replacing natural gas with grey hydrogen

does not yield meaningful environmental benefits and may even worsen lifecycle emissions. Table 4 shows quantitative comparison of the investigated decarbonization pathways.

Table 4. Quantitative Comparison of the Investigated Decarbonization Pathways.

Scenario	Energy Efficiency (%)	Exergy Efficiency (%)	Exergy Destruction (%)	Carbon Intensity (kg CO_2/MWh)
S0: NG Combustion	35	33.7	66.3	550–650
S1: Grey H_2 + Combustion	30–35	25–35	65–75	700–900
S2: Grey H_2 + Fuel Cell	50–55	45–50	50–55	450–650
S3: Green H_2 + Combustion	30–35	30–40	60–70	~0
S4: Green H_2 + Fuel Cell	55–60	50–65	35–50	~0

The results reported in Table 4 confirm that combustion-based pathways (S0, S1, and S3) generally exhibit lower energy efficiencies (approximately 30–40%) and exergy efficiencies (approximately 25–40%), resulting in higher exergy destruction levels (typically exceeding 60%). In contrast, fuel cell-based pathways (S2 and S4) achieve higher energy efficiencies (50–60%) and exergy efficiencies (45–65%), with substantially lower exergy destruction. The quantitative comparison further demonstrates that grey hydrogen pathways (S1 and S2) remain associated with significant upstream carbon emissions due to natural-gas-based hydrogen production. Although S2 benefits from the higher efficiency of fuel cell conversion, its overall carbon intensity remains considerably higher than that of green hydrogen pathways. Conversely, green hydrogen scenarios (S3 and S4) eliminate upstream CO_2 emissions and provide significantly greater decarbonization potential, with S4 (Green H_2 + Fuel Cell) achieving the highest overall thermodynamic performance and the lowest carbon footprint among all investigated cases. In particular, hydrogen-related processes exhibit significant potential for improvement when exergy-based performance indicators are used to guide system design and optimization [30]. Similarly, system-level energy and exergy assessments of renewable-based energy systems have shown that integrated thermodynamic analyses are critical for identifying realistic efficiency limits and decarbonization potentials [24].

3.4.5. Sensitivity Analysis

To assess the robustness of the conclusions, a simple sensitivity analysis was conducted by varying the assumed energy efficiencies of the natural gas and PEM fuel cell systems. The efficiency of the natural gas system was varied between 30% and 40%, while the PEM fuel cell efficiency was varied between 50% and 60%, covering typical operating ranges reported in the literature. Tables 5 and 6 show the sensitivity ranges and efficiency percentages of the system, respectively.

Table 5. Sensitivity range of the systems.

System	Base Case	Sensitivity Range
Natural Gas	35%	30–40%
PEM Fuel Cell	55%	50–60%

Table 6. Sensitivity results for system efficiency and fuel input.

Scenario	Efficiency (%)	Fuel Input (MW)
NG (Low)	30	3.33
NG (Base)	35	2.86
NG (High)	40	2.50
PEMFC (Low)	50	2.00
PEMFC (Base)	55	1.82
PEMFC (High)	60	1.67

For 1 MW of net electricity production:

$$E_{fuel} = \frac{1}{\eta} \tag{14}$$

The results indicate that the hydrogen fuel cell pathway consistently requires lower fuel input than the natural gas system across the investigated efficiency range. For a net electrical output of 1 MW, the fuel requirement varies between 1.67 and 2.00 MW for the PEM fuel cell system, compared to 2.50–3.33 MW for the natural gas system.

Therefore, the main conclusions regarding the superior thermodynamic performance and decarbonization potential of hydrogen fuel cell systems remain unchanged despite reasonable variations in system efficiency assumptions.

4. Conclusions

Energy analysis highlights hydrogen's high theoretical potential as an energy carrier, while exergy analysis provides deeper insight into its strategic role in decarbonization by explicitly accounting for irreversibilities and energy quality degradation. Although fossil fuel-based systems remain competitive in terms of energy quantity, their long-term sustainability is fundamentally constrained by high exergy destruction and carbon emissions.

In this study, the impact of hydrogen utilization on decarbonization was evaluated using a comprehensive thermodynamic framework based on combined energy and exergy analyses. Hydrogen-based systems were systematically compared with conventional fossil fuel-based systems using a consistent natural gas benchmark. System efficiencies, energy flows, and exergy destruction rates were quantified and visualized through scenario-based and graphical analyses, enabling a transparent comparison of different fuel pathways and conversion technologies. The results indicate that hydrogen fuel cell systems exhibit superior thermodynamic performance at the conversion stage, characterized by higher energy and exergy efficiencies and lower exergy destruction. However, the overall environmental benefit depends on the hydrogen production pathway, as upstream emissions may significantly influence the life-cycle carbon footprint.

However, the findings clearly show that hydrogen utilization alone does not guarantee effective decarbonization. The overall sustainability of hydrogen pathways strongly depends on minimizing exergy losses across the entire value chain, including production, storage, and conversion processes. Therefore, energy-based evaluations alone are insufficient, and exergy analysis emerges as a critical tool for identifying efficiency limits and realistic improvement potentials.

These findings provide clear guidance for energy system design and policy development, indicating that future decarbonization strategies should prioritize not only low-carbon fuels but also pathways that minimize exergy destruction across the entire energy chain. Future research should extend this framework through integrated exergoeco-

nomic and life cycle assessment approaches to enable a more comprehensive evaluation of hydrogen-based energy systems.

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