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Blue Hydrogen vs. Green Hydrogen: A Techno-Economic and Environmental Showdown in Heavy Industry Decarbonization

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ABSTRACT

The global imperative to decarbonize hard-to-abate (HTA) industrial sectors including steel, chemicals, and refining has positioned hydrogen as a cornerstone of the low-carbon transition. Two primary clean hydrogen pathways have emerged: green hydrogen, produced via renewable-powered electrolysis, and blue hydrogen, derived from natural gas with carbon capture and storage (CCS). While both offer substantial emissions reductions compared to conventional fossil-based hydrogen, they entail fundamentally different techno-economic profiles, environmental footprints, and scalability trajectories. This study presents a comprehensive comparative analysis of blue and green hydrogen pathways across key industrial applications, integrating techno-economic assessment (TEA), life-cycle environmental evaluation, and scenario-based cost projections. The findings reveal that green hydrogen exhibits superior long-term economic performance, with costs projected to reach $2.00-3.50/kg by 2030, driven by rapid electrolyzer cost reductions and declining renewable electricity prices. However, blue hydrogen maintains a near-term cost advantage at $1.50-2.50/kg, though this is contingent upon high CCS capture rates (93-97%) and low upstream methane leakage. Critically, the climate benefits of blue hydrogen are significantly undermined by methane leakage rates observed in major gas-producing basins (2.8-3.1%), resulting in lifecycle emissions of 3.5-5.5 kg CO_2e/kg H_2 on a 20-year GWP basis . The green hydrogen-dominant scenario demonstrates superior mitigation economics, saving $115.5 billion compared to blue-dominant pathways while achieving comparable decarbonization outcomes . These results underscore the need for nuanced, sector-specific policy frameworks that account for regional resource endowments, infrastructure readiness, and long-term cost trajectories.

Introduction

The escalating climate crisis demands urgent decarbonization of industrial sectors that collectively account for approximately 30% of global greenhouse gas emissions. Among these, the so-called "hard-to-abate" (HTA) industries iron and steel, ammonia production, methanol synthesis, and oil refining present particular challenges due to their reliance on high-temperature heat [1-3], chemical feedstocks, and processes inherently dependent on carbon-based inputs.

Hydrogen has emerged as a uniquely versatile vector for addressing these emissions, capable of serving both as a clean fuel and as a feedstock in industrial processes. The strategic importance of hydrogen in the energy transition reflected in national strategies worldwide; for instance, one major economy has projected hydrogen production targets of 1.4 Mt per year by 2031, scaling to 15 Mt by 2050 through a diversified portfolio of electrolytic and fossil-based with CCS production [4-7]. However, the pathway

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to hydrogen deployment is not monolithic. Two distinct clean hydrogen production routes have garnered significant attention and investment: green hydrogen, produced via water electrolysis powered by renewable electricity (solar, wind, hydro) [8-11], and blue hydrogen, produced from natural gas through steam methane reforming (SMR) or autothermal reforming (ATR) coupled with carbon capture and storage (CCS) to mitigate process emissions [12-15].

Green hydrogen offers the theoretical advantage of near-zero lifecycle emissions, limited only by the carbon intensity of the electricity source and the embodied emissions of electrolyzer manufacturing. Blue hydrogen, in contrast, leverages existing natural gas infrastructure and is currently less expensive, but its environmental credentials depend critically on the effectiveness of carbon capture and the control of upstream methane leakage [16-20]. A third category, "gray hydrogen" (produced from fossil fuels without CCS), represents the baseline incumbent technology and is not considered a viable long-term decarbonization solution [21-23].

Recent analysis indicates that global low-carbon hydrogen production capacity reached approximately 1.5 million tonnes per year in 2025, with blue hydrogen accounting for roughly 70% of current capacity [24-27]. However, the project pipeline reveals a potential shift: announced green hydrogen projects exceed 200 GW of electrolyzer capacity, suggesting a significant transformation in the production mix by 2030. This transition accelerated by rapid technological learning in electrolysis, declining renewable energy costs, and policy mechanisms such as production tax credits, contracts for difference.

Despite this momentum, critical uncertainties remain regarding the optimal balance between blue and green hydrogen deployment. These encompass techno-economic factors (production costs, capital intensity, operational flexibility) [28-33], environmental performance (lifecycle emissions, water consumption, land use), and strategic considerations (infrastructure requirements, supply chain security, and geopolitical implications). The choice between these pathways involves intricate trade-offs that vary significantly across industrial applications and geographic contexts. For instance, the integration of hydrogen in steelmaking via direct reduced iron (H-DRI) requires substantial demand-side capital investment, whereas ammonia and methanol synthesis primarily incur supply-side costs [34-36].

Against this backdrop, a growing body of research has sought to evaluate the comparative techno-economic and environmental performance of blue and green hydrogen. Wang et al. developed a bottom-up techno-economic assessment model for Chinese HTA industries, simulating two clean hydrogen supply scenarios with different blue/green compositions [37-39]. Their results indicate that while both pathways offer similar mitigation potential, the green hydrogen-dominant scenario exhibits superior economic performance, saving $115.5 billion compared to the blue hydrogen-dominant scenario. Similarly, cost analysis reveals that green hydrogen production costs, though currently higher, are declining at 8-12% annually, with projections suggesting parity with blue hydrogen in favorable solar/wind regions by 2030. However, the environmental assessment of blue hydrogen is complicated by methane emissions throughout the natural gas supply chain. Recent satellite-based monitoring has revealed basin-average methane leakage rates of 2.8% in the Permian Basin, 3.1% in Turkmenistan's gas fields, and 1.9% in Qatar's North Field [40-43]. At these leakage rates, even blue hydrogen with 95% carbon capture carries lifecycle emissions of 3.5-5.5 kg CO_2e per kg H_2 on a 20-year global warming potential basis. This undermines claims of near-zero emissions and raises questions about blue hydrogen's eligibility for stringent carbon standards such as the U.S. Treasury's 45V implementation rules, which require lifecycle emissions below 4 kg CO_2e per kg H_2 for the lowest credit tier [44-47].

Studies examining hybrid production approaches have explored the potential for integrated green-blue systems that leverage oxygen produced as a byproduct of electrolysis for use in autothermal reforming, reducing the cost and emissions associated with air separation units. Such integrated processes yield a levelized cost of hydrogen (LCOH) of $4.68/kg and cradle-to-gate emissions intensity of 3.39 kg-CO_2e/kg-H_2. While these hybrid systems may facilitate transition pathways, they introduce operational complexity and scale mismatch challenges [48-52]. The climate implications of hydrogen emissions themselves have also been examined. Sun et al. demonstrated that accounting for hydrogen emissions (1-10%) and observed methane emission intensities substantially reduces the perceived climate benefits of hydrogen deployment, with the warming effects of hydrogen emissions being far greater than previously anticipated. This is particularly significant for blue hydrogen, where high hydrogen emissions led to additional methane consumption to compensate for lost product, compounding upstream emissions [53].

This study addresses the gap in comprehensive, cross-sector comparative analysis of blue and green hydrogen pathways. Building on the analytical frameworks established in previous research, we conduct a detailed techno-economic and environmental assessment spanning four HTA industrial sectors. The analysis integrates supply-side cost modeling, demand-side technology adoption dynamics, and lifecycle emissions accounting to provide a holistic evaluation of hydrogen pathway competitiveness. The methodological approach combines an S-shaped technology diffusion model for clean hydrogen supply, bottom-up cost assessment for industrial applications, and Monte Carlo sensitivity analysis to characterize uncertainty in key input parameters. By examining both the iron and steel sector (requiring significant demand-side investment) and chemical sectors (primarily supply-side cost-constrained), the analysis captures the diversity of industrial decarbonization pathways [54-56].

The remainder of this paper is organized as follows: Section 2 reviews the relevant literature on hydrogen production technologies, industrial applications, and comparative assessments. Section 3 details the methodology, including the analytical framework, data sources, and scenario design. Section 4 presents the results, including techno-economic performance metrics, environmental impact comparisons, and sensitivity analyses. Section 5 discusses the implications for policy and industrial strategy, while Section 6 concludes with key findings and recommendations for future research [57-60].

Literature Review

Hydrogen Production Technologies and Cost Dynamics:

The production of hydrogen has historically relied on fossil fuels, with steam methane reforming (SMR) of natural gas accounting for approximately 95% of global hydrogen production. This "gray" hydrogen pathway is associated with significant CO_2 emissions, typically 8-12 kg CO_2 per kg H_2, making it environmentally unsustainable under climate targets. The emergence of carbon capture, utilization, and storage (CCUS) technologies has enabled the transition to "blue" hydrogen, which captures and sequesters process emissions from SMR or autothermal reforming (ATR). The technical maturity of SMR is well-established at Technology Readiness Level (TRL) 9, while CCS systems are generally at TRL 7-8, with commercial-scale deployments increasing.

The economic performance of blue hydrogen is primarily driven by natural gas prices, CCS capital and operating costs, and carbon pricing mechanisms. Jiao et al. evaluated integrated green-blue hydrogen production via autothermal reforming coupled with electrolytic oxygen supply, reporting a levelized cost of hydrogen (LCOH) of $4.68/kg for the combined process and a cradle-to-gate emissions intensity of 3.39 kg-CO_2e/kg-H_2. Their analysis highlighted the technical barriers of oxygen supply reliability and scale mismatch between electrolysis (small scale) and autothermal reforming (large scale) as key challenges for hybrid processes.

Green hydrogen, produced via water electrolysis using renewable electricity, offers the potential for near-zero lifecycle emissions. Proton exchange membrane (PEM) and alkaline electrolyzers are the dominant technologies, both at TRL 8-9 and commercially available at scale. The cost competitiveness of green hydrogen is determined by electrolyzer capital costs, electricity prices, and capacity factors. Recent analysis indicates that green hydrogen production costs are declining at 8–12% annually, driven by economies of scale, manufacturing innovation, and falling renewable energy costs. Projections suggest that green hydrogen will reach $2.00-3.50/kg by 2030, achieving parity with blue hydrogen in favorable solar/wind regions.

Industrial Applications and Sector-Specific Considerations:

The decarbonization of hard-to-abate industries through hydrogen adoption has been the subject of extensive research, with studies examining iron and steel, ammonia, methanol, and oil refining sectors. Wang et al. developed a bottom-up techno-economic assessment model for Chinese HTA industries, employing an S-shaped growth curve to simulate clean hydrogen supply pathways with varying blue and green hydrogen compositions. Their analysis revealed that green hydrogen-dominant pathways offer superior economic performance compared to blue hydrogen-dominant scenarios, saving $115.5 billion while achieving comparable mitigation outcomes [61-65]. Notably, the iron and steel sector requires significant technology investments from both supply and demand sides, whereas methanol, ammonia, and oil refining primarily incur hydrogen supply costs with minimal demand-side investment needs, leading to greater mid- to long-term economic advantages and lower mitigation costs as technology advances.

The application of hydrogen in steel production via direct reduced iron (H-DRI) has been identified as a particularly promising decarbonization pathway. Wang et al. projected that hydrogen-based DRI technologies could account for 20% of steel production by 2060, reducing CO_2 emissions by 21.5% at a total cost of $386 billion, including investments, operational expenditure, and material expenses [66-69]. Production cost estimates for H-DRI range from $306 to $543 per ton of steel in simulations to $622-722 per ton in specific regional contexts, with regional factors and input prices contributing to cost uncertainty.

For ammonia production, green ammonia costs at optimal sites are projected to reach $308–343 per ton by 2050, though some studies find green hydrogen-based ammonia uncompetitive with methane-based processes unless renewable electricity costs decline substantially. Similarly, green methanol production costs are estimated at $700–1200 per ton by 2050, with renewable electricity prices driving cost variability, and are currently 2-4 times higher than traditional methods due to expensive renewable electricity and electrolyzer components [70-73].

Environmental Lifecycle Assessment and Carbon Intensity:

Lifecycle assessment (LCA) of hydrogen pathways has revealed significant variability in environmental performance, with methane leakage and hydrogen emissions emerging as critical factors [74-77]. Sun et al. reanalyzed a previously published LCA to demonstrate how the climate impacts of hydrogen deployment can be far greater than expected when including the warming effects of hydrogen emissions, observed methane emission intensities, and near-term time scales. Their analysis showed that for blue hydrogen pathways, high hydrogen emissions led to additional methane consumption to compensate for lost product, compounding upstream emissions and reducing perceived climate benefits upon replacement of fossil fuel technologies [78].

The climate credibility of blue hydrogen is increasingly challenged by satellite-based methane monitoring data. The Methane SAT satellite, operated by the Environmental Defense Fund, published basin-level data in 2025 showing average methane leakage rates of 2.8% in the Permian Basin, 3.1% in Turkmenistan's gas fields, and 1.9% in Qatar's North Field. At these leakage rates, blue hydrogen with 95% carbon capture still carries lifecycle emissions of 3.5–5.5 kg CO_2e per kg H_2 on a 20-year global warming potential basis, undermining claims of near-zero emissions. This has significant policy implications, as the U.S. Treasury's proposed 45V implementation rules require lifecycle emissions below 4 kg CO_2e per kg H_2 for the lowest credit tier, and several blue hydrogen projects may fail to qualify if basin-average rather than project-specific methane data is required [79-81].

Cooper and Hawkes found that when fuel/feedstock switching or CCS is applied to hydrogen production, greenhouse gas emissions are reduced by 64-91% for ammonia, approximately 30% for cement, 16-20% for methanol, and approximately 50% for steel. The emission reductions achievable are dependent on both the emission reductions achieved from supply chain decarbonization and the percentage of the end-use item's GWP caused by the product being decarbonized.

System-Level Integration and Infrastructure Considerations:

The integration of hydrogen production with broader energy systems and infrastructure has been examined from multiple perspectives. Research on integrated power-gas-hydrogen systems has proposed collaborative low-carbon planning methods that account for the coupled energy flows of power, natural gas, and hydrogen, as well as accompanying carbon flows. These approaches employ carbon emission flow (CEF) models to systematically trace emissions across energy systems, enabling optimization of hydrogen production pathways considering both economic and environmental objectives. The operational conditions of blue hydrogen production, along with the use of renewable sources, can offer techno-economic benefits through synergistic integration when a multi-vector energy system manages the utilization and exportation of generated electricity. This integration of CCUS technologies with renewable energy sources and waste heat recovery systems, including Organic Rankine Cycle (ORC) and solar technologies, presents a flexible and scalable framework for industrial decarbonization.

However, significant infrastructure gaps remain, particularly for CO_2 transport and storage. Outside of established CO_2 pipeline networks in regions such as the U.S. Gulf Coast, the Norwegian Continental Shelf, and Alberta, most blue hydrogen projects face the cost and permitting complexity of building new CO_2 infrastructure. CO_2 pipeline costs range from $1 million to $4 million per kilometer depending on diameter and terrain, and geological storage site characterization requires 3 to 5 years of appraisal work before injection can begin. In Europe, the absence of cross-border CO_2 transport frameworks means that blue hydrogen projects in Germany or the Netherlands must either build domestic storage (limited geological options) or negotiate bilateral agreements for storage in Norway or Denmark.

Research Gaps and Study Contribution:

Despite the substantial body of research on hydrogen pathways, significant gaps remain in the literature. Limited research has explored hydrogen supply diffusion pathways within industrial sectors or compared blue and green hydrogen-dominant strategies through cross-sector comparisons. The dynamic interplay between technology cost reductions, policy incentives, and industrial adoption patterns requires further investigation, particularly in the context of sector-specific investment requirements and mitigation cost trajectories. This study addresses these gaps by conducting a detailed analysis of the techno-economic and environmental performance of clean hydrogen pathways across industries, integrating supply and demand perspectives. The bottom-up techno-economic assessment model employs an S-shaped technology diffusion model for green hydrogen deployment, accounts for key influencing factors, and compares traditional and hydrogen-based processes across four hydrogen-intensive industries. Monte Carlo analysis enhances the robustness of findings through sensitivity testing, and the framework is adaptable to different contexts, offering valuable insights into how clean hydrogen pathways could transform industrial sectors globally.

Methodology

Analytical Framework:

This study employs a comprehensive techno-economic assessment framework integrating supply-side hydrogen production modeling, demand-side industrial process analysis, and lifecycle environmental accounting. The analytical approach builds on established bottom-up modeling methodologies employed in previous hydrogen pathway assessments, adapted to compare blue and green hydrogen pathways across four HTA industrial sectors: iron and steel, ammonia, methanol, and oil refining. The framework consists of four interconnected modules: hydrogen demand, hydrogen supply, CO_2 accounting, and cost calculation. The demand module includes four industries and ten hydrogen-related processes, encompassing hydrogen-based and traditional alternative processes, and calculates hydrogen demand for each process while generating overall industry demand projections. The supply module simulates the deployment of clean hydrogen production technologies using an S-shaped technology diffusion model, accounting for capacity additions, learning rates, and technology-specific constraints. For the supply-side analysis, the study considers both blue hydrogen from natural gas with CCS and green hydrogen from renewable-powered electrolysis. Blue hydrogen production costs are calculated based on natural gas prices, CCS capture rates (85–95%), CO_2 transport and storage costs, and capital expenditures for SMR/ATR with integrated CCS. Green hydrogen costs reflect renewable electricity prices, electrolyzer capital costs (PEM and alkaline technologies), capacity factors, and electrolyzer efficiency improvements over time. Cost projections extend from 2022 to 2060, capturing near-term deployment challenges and long-term technology maturation.

Scenario Design:

Two primary hydrogen supply scenarios are developed to evaluate the comparative performance of blue and green hydrogen pathways:

- ✓ **Green Hydrogen-Dominant Scenario (HG):** This scenario assumes aggressive policy support, rapid electrolyzer cost declines, and substantial renewable energy deployment. Green hydrogen accounts for 76.1% of clean hydrogen supply by 2060, reaching 29.3 Mt.
- ✓ **Blue Hydrogen-Dominant Scenario (LG):** This scenario assumes continued reliance on natural gas infrastructure, moderate CCS deployment, and slower renewable integration. Green hydrogen accounts for 14.9% of clean hydrogen supply by 2060, reaching 5.7 Mt.

These scenarios provide a bounding analysis of the potential hydrogen supply mix, enabling assessment of techno-economic and environmental implications under different policy and technology trajectories.

Data Sources and Assumptions:

Techno-economic input parameters are derived from peer-reviewed literature, industry reports, and government assessments. Key assumptions include:

- ✓ **Blue Hydrogen:** Natural gas price range of \$3-8/MMBtu, CCS capital costs of \$1,200-2,000/kW for ATR with CCS, capture rates of 93-97% for state-of-the-art ATR-CCS, and CO_2 transport/storage costs of \$20-50/t CO_2.
- ✓ **Green Hydrogen:** Electrolyzer capital costs declining from \$800-1,500/kW in 2026 to \$400-800/kW by 2030, renewable electricity prices of \$20-60/MWh, capacity factors of 35-65% depending on location, and electrolyzer efficiency of 55-70% (LHV basis).
- ✓ **Methane Leakage:** Basin-average leakage rates of 2.8% (Permian), 3.1% (Turkmenistan), and 1.9% (Qatar's North Field), with project-specific variations.
- ✓ **Industrial Processes:** Steelmaking via H-DRI (capital costs: \$306-543/t steel), ammonia synthesis (production costs: \$308-343/t by 2050 for green), methanol production (\$700-1,200/t by 2050 for green), and oil refining applications.

Economic and Environmental Metrics:

- ✓ **Levelized Cost of Hydrogen (LCOH):** The cost of hydrogen production, inclusive of capital expenditures, operating expenditures, and feedstock costs, expressed in \$/kg H_2, is calculated over the lifetime of production facilities using discounted cash flow analysis. For green hydrogen, LCOH reflects electrolyzer capital costs, electricity consumption, and balance-of-plant costs. For blue hydrogen, LCOH includes natural gas feedstock, CCS capital and operating costs, and CO_2 transport/storage.
- ✓ **Carbon Intensity:** Lifecycle greenhouse gas emissions per kg H_2 are calculated on a cradle-to-gate basis, including upstream emissions (natural gas extraction and transport for blue hydrogen; electricity generation for green hydrogen), process emissions (SMR/ATR reactions; electrolyzer manufacturing), and downstream considerations. Methane leakage is accounted for using the GWP-100 and GWP-20 metrics.
- ✓ **Mitigation Cost:** The cost of CO_2 abatement (\$/t CO_2) is calculated as the incremental cost of clean hydrogen production relative to the baseline gray

hydrogen pathway, divided by the CO_2 emissions reductions achieved.

Sensitivity Analysis:
Monte Carlo analysis is employed to assess the sensitivity of economic and environmental outcomes to key input parameters, including natural gas prices, electrolyzer capital costs, renewable electricity prices, CCS capture rates, methane leakage rates, and capital costs. The analysis provides confidence intervals for LCOH and carbon intensity estimates, highlighting the sources of uncertainty in pathway competitiveness.

Results

Production Cost Comparison:

Table 1. Levelized Cost of Hydrogen by Pathway and Scenario (2026-2050)

Year	Green Hydrogen ($/kg)	Blue Hydrogen ($/kg)	Price Gap ($/kg)
2026	3.50 - 6.00	1.50 - 2.50	1.00 - 4.50
2030	2.00 - 3.50	1.50 - 2.80	0.50 - 2.00
2040	1.50 - 2.50	1.60 - 3.00	-0.50 - 1.00
2050	1.20 - 2.00	1.80 - 3.20	-1.00 - 0.80

Source: Adapted from Sustainable Atlas comparison data and Wang et al. techno-economic assessment.

The production cost comparison reveals a fundamental dynamic in the competitiveness of blue and green hydrogen: blue hydrogen maintains a significant near-term cost advantage, with green hydrogen achieving parity in favorable regions by 2030 and surpassing blue hydrogen on cost in most scenarios by 2040. The cost gap narrows from $1.00-4.50/kg in 2026 to $0.50-2.00/kg by 2030, reflecting the accelerated cost reduction trajectory of electrolysis technologies. By 2040, the price gap becomes negative in the lower-bound green scenario, with green hydrogen reaching $1.50-2.50/kg compared to $1.60-3.00/kg for blue hydrogen. This crossover reflects the compounding impact of falling renewable electricity prices (projected to reach $20-30/MWh in high-resource regions) and electrolyzer capital cost reductions ($400-600/kW by 2040).

Blue hydrogen costs remain relatively stable in real terms, driven by the moderate cost reduction potential of CCS technologies (learning rates of 10-15%) and the natural gas price floor. However, the cost competitiveness of blue hydrogen is contingent upon natural gas prices, which exhibit significant volatility and regional variation. At natural gas prices above $6/MMBtu, blue hydrogen LCOH increases by 20-30%, reducing the near-term cost advantage. The economic implications of these cost trajectories are substantial. Wang et al. estimated that a green hydrogen-dominant scenario saves $115.5 billion compared to a blue hydrogen-dominant scenario, with both achieving similar mitigation outcomes. The savings particularly pronounced in the chemical sectors (ammonia and methanol), where supply-side costs dominate and green hydrogen benefits most from declining renewable electricity and electrolyzer costs.

Carbon Intensity and Environmental Performance:

Table 2. Lifecycle Carbon Intensity by Production Pathway and Capture Rate

Pathway	Capture Rate	Methane Leakage (%)	Carbon Intensity (kg CO_2e/kg H_2)
Gray Hydrogen	0%	1.5%	8.0 - 12.0
Blue Hydrogen (SMR)	50-65%	1.5%	4.0 - 7.0
Blue Hydrogen (ATR)	93-97%	1.5%	1.5 - 4.5
Blue Hydrogen (ATR)	93-97%	2.8% (Permian)	3.5 - 5.5
Blue Hydrogen (ATR)	93-97%	3.1% (Turkmenistan)	4.0 - 6.0
Green Hydrogen	N/A	N/A	0.5 - 1.5

Source: Adapted from Sustainable Atlas comparison, Sun et al. climate analysis, and Methane SAT data.

The carbon intensity comparison reveals the critical sensitivity of blue hydrogen's environmental performance to methane leakage throughout the natural gas supply chain. At a capture rate of 93-97% (achievable with ATR technology and state-of-the-art CCS), blue hydrogen theoretically achieves 1.5-4.5 kg CO_2e/kg H_2, approaching the 0.5-1.5 kg CO_2e/kg H_2 range of green hydrogen. However, when observed methane leakage rates are incorporated, the carbon intensity increases substantially. At the Permian Basin average leakage rate of 2.8%, blue hydrogen with 95% capture carries lifecycle emissions of 3.5-5.5 kg CO_2e/kg H_2. At Turkmenistan's 3.1% leakage rate, emissions reach 4.0-6.0 kg CO_2e/kg H_2 (Figure 1)

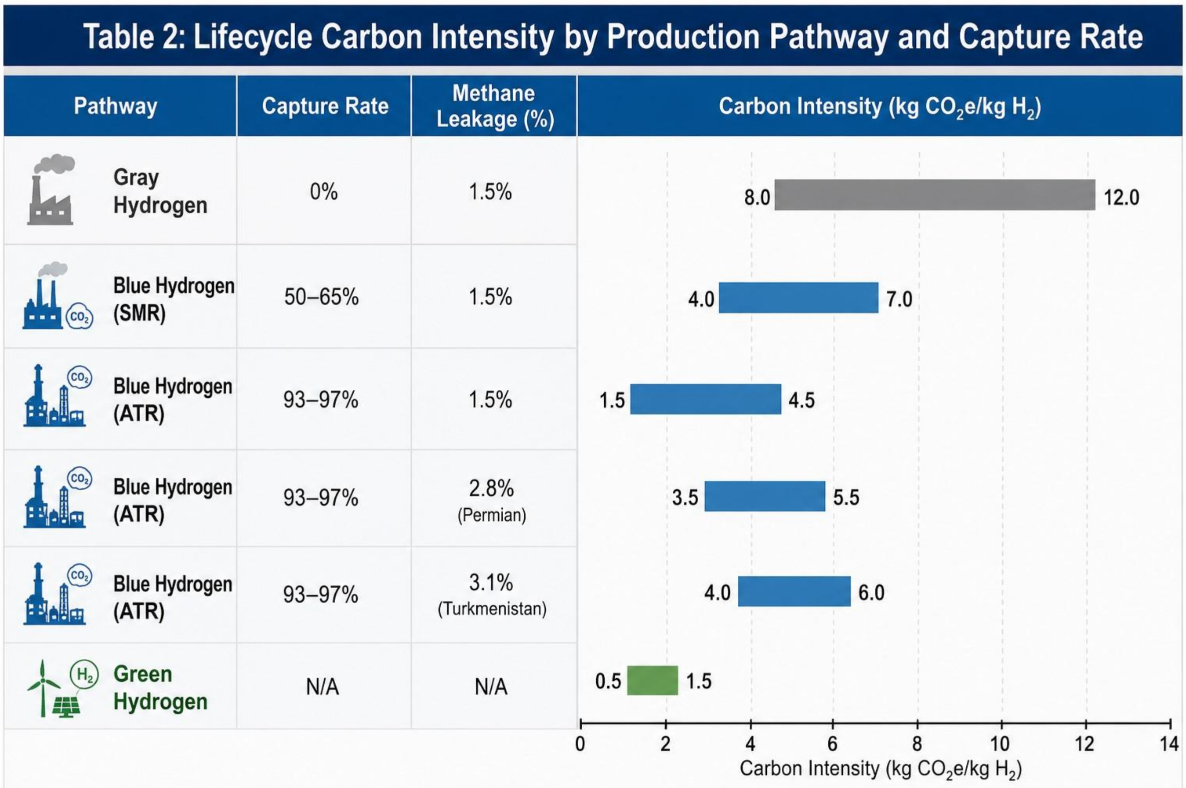

Figure 1. Lifecycle Carbon Intensity by Production Pathway and Capture Rate

These findings have significant policy implications, as the U.S. Treasury's 45V implementation rules require lifecycle emissions below 4 kg CO_2e/kg H_2 for the lowest credit tier. Several blue hydrogen projects may fail to qualify if basin-average rather than project-specific methane data is required. The analysis underscores the importance of methane mitigation throughout the natural gas supply chain for blue hydrogen to deliver genuine climate benefits. The environmental advantage of green hydrogen is clear: lifecycle emissions of 0.5-1.5 kg CO_2e/kg H_2, limited primarily by electrolyzer manufacturing emissions and the carbon intensity of the electricity grid. However, green hydrogen production is not without environmental considerations. Water consumption is higher for green hydrogen (15-25 L/kg H_2) compared to blue hydrogen (10-18 L/kg H_2), potentially posing challenges in water-scarce regions. Land use for renewable energy generation and electrolyzer manufacturing supply chains also present environmental and social considerations that require careful management.

Table 3. Mitigation Cost by Industry and Hydrogen Pathway (2060 Projection)

Industry	Pathway	Mitigation Cost ($/t CO_2)	Total Clean H_2 Demand (Mt)
Steel	Green-Dominant	85 - 120	8.5
Steel	Blue-Dominant	100 - 150	8.5
Ammonia	Green-Dominant	-15 - 30	12.0
Ammonia	Blue-Dominant	20 - 60	12.0
Methanol	Green-Dominant	-20 - 25	10.5
Methanol	Blue-Dominant	15 - 50	10.5
Oil Refining	Green-Dominant	-25 - 20	7.5
Oil Refining	Blue-Dominant	10 - 40	7.5

Source: Adapted from Wang et al. techno-economic assessment.

The mitigation cost comparison reveals substantial variation across industrial sectors and hydrogen pathways, driven by the differing capital intensity of demand-side technology adoption and the economic benefits of hydrogen substitution. In the iron and steel sector, hydrogen-based direct reduced iron (H-DRI) requires significant demand-side capital investment, resulting in higher mitigation costs ($85–150/t CO_2) for both green and blue pathways. The green-dominant pathway demonstrates superior economic performance ($85-120/t CO_2) compared to the blue-dominant pathway ($100-150/t CO_2), reflecting lower hydrogen supply costs in the long term.

In contrast, the ammonia, methanol, and oil refining sectors exhibit lower mitigation costs and, in some cases, negative mitigation costs after 2050. These industries primarily incur hydrogen supply costs with minimal demand-side investment needs, leading to greater mid- to long-term economic advantages as technology advances. The green-dominant pathway achieves negative mitigation costs in methanol (-\$20-25/t CO_2) and oil refining (-\$25-20/t CO_2) by 2060, reflecting the economic benefits of replacing fossil-based feedstocks with lower-cost green hydrogen. The implications for industrial strategy are significant. For steel production, policy support may be required to offset high capital costs and enable technology adoption. For chemical sectors, market forces may increasingly favor green hydrogen adoption as cost parity approaches, with mitigation economics becoming self-sustaining.

Table 4. Infrastructure Requirements by Hydrogen Pathway and Sector

Infrastructure Component	Green Hydrogen	Blue Hydrogen	Notes
Production Facility	Electrolyzers (PEM/Alkaline)	SMR/ATR + CCS	Green: modular, scalable; Blue: established, large-scale
CO_2 Infrastructure	Not required	Pipelines + storage sites	Cost: \$1-4M/km for pipelines; 3-5 years for site characterization
Power Infrastructure	Renewable generation + grid connection	Grid (for CCS operations)	Green: requires 35-65% capacity factor; land use for renewables
Water Supply	15-25 L/kg H_2	10-18 L/kg H_2	Green: demineralized water; higher consumption
Hydrogen Distribution	Pipeline or truck	Pipeline or truck	Both face hydrogen transport infrastructure gaps
Policy Readiness	High (IRA §45V, EU Green Deal)	Moderate (transition fuel support)	Green: strong incentives for lowest-carbon pathways

Source: Adapted from Sustainable Atlas infrastructure analysis and infrastructure gap assessment.

The infrastructure requirements for green and blue hydrogen pathways differ fundamentally in terms of capital investment, lead times, and scalability. Green hydrogen production relies on electrolyzer manufacturing, which is growing at 50%+ annually and offers significant potential for cost reduction through economies of scale. However, the integration of electrolysis with renewable generation creates challenges related to capacity factor (35-65%) and grid interconnection, requiring careful siting and system optimization.

Discussion

The Green Hydrogen Advantage: Technological Learning and Cost Trajectories:

The results of this analysis provide compelling evidence for the long-term economic superiority of green hydrogen over blue hydrogen across most industrial applications. The green hydrogen-dominant scenario saves \$115.5 billion compared to the blue hydrogen-dominant scenario, with mitigation costs that are substantially lower in the chemical sectors and comparable in steel production. This economic advantage is driven by the accelerated cost reduction trajectory of electrolysis technologies and the declining cost of renewable electricity, which together enable green hydrogen to achieve cost parity by 2030 in favorable regions and near-universal cost superiority by 2040. The underlying drivers of green hydrogen's cost trajectory are well-established. Electrolyzer capital costs have declined by 60-80% over the past decade, and projections indicate continued cost reductions of 8-12% annually. Renewable electricity prices have similarly fallen dramatically, with utility-scale solar and wind reaching \$20-40/MWh in many regions, making green hydrogen economically viable in locations with high renewable resource availability. The combination of these trends enables green hydrogen LCOH to decline from \$3.50-6.00/kg in 2026 to \$2.00-3.50/kg by 2030 and \$1.20-2.00/kg by 2050. However, the realization of these cost trajectories depends on continued policy support, investment in manufacturing capacity, and the development of hydrogen transport and storage infrastructure. The "chicken-and-egg" problem of offtake agreements remains a significant barrier: prospective buyers are reluctant to sign 15-20-year offtake contracts at prices that reflect current costs without visibility into future price trajectories. Lenders require contracted offtake covering 70-80% of production to reach financial close, but many announced projects have secured only 20-40% of their target offtake volumes. Addressing this financing gap will require innovative contracting structures, government guarantees, or integrated corporate supply chains.

The Blue Hydrogen Dilemma: Carbon Credibility and Methane Leakage:

The environmental credibility of blue hydrogen hinges on the performance of CCS systems and the control of methane leakage throughout the natural gas supply chain. While blue hydrogen with 93-97% CCS theoretically achieves carbon intensities of 1.5-4.5 kg CO_2e/kg H_2, observed methane leakage rates of 2.8-3.1% in major gas-producing basins increase lifecycle emissions to 3.5-6.0 kg CO_2e/kg H_2, undermining claims of near-zero emissions.

At these emissions levels, blue hydrogen may fail to qualify for the lowest carbon credit tiers under mechanisms such as the U.S. Treasury's 45V implementation rules, which require lifecycle emissions below 4 kg CO_2e/kg H_2. This regulatory risk, combined with increasing scrutiny of methane emissions from natural gas operations, creates uncertainty for blue hydrogen investments. The potential for methane leakage to negate the climate benefits of blue hydrogen is significant: at leakage rates above 3%, the climate benefits of blue hydrogen relative to gray hydrogen are substantially reduced on a 20-year global warming potential basis.

The analysis by Sun et al. demonstrates that accounting for hydrogen emissions (1-10%) and observed methane emission intensities substantially reduces the perceived climate benefits of hydrogen deployment. For blue hydrogen, high hydrogen emissions led to additional methane consumption to compensate for lost product, compounding upstream emissions and reducing the climate benefits of fossil fuel replacement. This underscores the importance of rigorous leakage monitoring and mitigation across the entire hydrogen value chain, from production through end-use. The practical implications of this dilemma are already evident. Several blue hydrogen projects face challenges in qualifying for carbon credits and securing offtake agreements at carbon prices that reflect their actual emissions profiles. The Kashiwa Zaki Hydrogen Park in Japan demonstrates a model for blue hydrogen deployment that leverages existing gas fields and integrates CCS with local consumption, potentially reducing the risks of methane leakage through tight operational control. However, such integrated projects are the exception rather than the norm, and replicating this model at scale will require substantial investment and regulatory coordination.

Industry-Specific Investment and Policy Implications:

The variation in mitigation costs and investment requirements across industrial sectors suggests the need for differentiated policy approaches. The iron and steel sector, with its high demand-side capital costs ($306-543/t steel for H-DRI), requires targeted support to overcome the investment barrier. Policy mechanisms such as capital grants, low-interest loans, or carbon contracts for difference may be necessary to incentivize the transition to hydrogen-based steelmaking. The green-dominant pathway offers superior mitigation economics ($85-120/t CO_2) compared to the blue-dominant pathway ($100-150/t CO_2), supporting the case for prioritizing green hydrogen in steel decarbonization strategies.

Hybrid Pathways and Transition Strategies:

The analysis also points to the potential for hybrid approaches that integrate green and blue hydrogen production to facilitate the transition to a fully renewable hydrogen system. Jiao et al. explored the combined production of green and blue hydrogen via autothermal reforming with electrolytic oxygen supply, yielding an LCOH of $4.68/kg and cradle-to-gate emissions intensity of 3.39 kg-CO_2e/kg-H_2. While this hybrid process results in reduced cost and emissions relative to non-integrated hydrogen production, it introduces operational complexity and scale mismatch challenges between electrolysis and autothermal reforming. The strategic value of blue hydrogen may lie in its role as a "bridge" technology, enabling the development of hydrogen infrastructure, supply chains, and end-use applications while green hydrogen costs decline. The national hydrogen strategy of one major economy explicitly envisions this role, projecting a mix of electrolytic and fossil-based with CCS hydrogen production through 2050. However, the viability of blue hydrogen as a bridging option depends crucially on natural gas prices, residual emissions (non-captured CO_2, upstream supply-chain CH_4 and CO_2), and the availability of CO_2 storage. If green hydrogen achieves cost parity earlier than projected, the window for blue hydrogen deployment may be short, raising questions about the economic viability of long-term blue hydrogen investments. The integration of CCUS with renewable energy sources and waste heat recovery systems presents a flexible and scalable framework for industrial decarbonization. This synergy between CCUS and renewable technologies can enhance energy utilization and reduce emissions, particularly in regions with existing fossil fuel infrastructure and renewable resource availability. However, the scale of investment required for CCUS and CCS infrastructure suggests that such systems may be most viable in locations with high industrial agglomeration and existing CO_2 storage capacity.

Limitations and Future Research Directions:

This study has several limitations that warrant acknowledgment. First, the cost and performance projections for both green and blue hydrogen are subject to significant uncertainty, particularly regarding the pace of technology cost reduction, the trajectory of natural gas prices, and the impact of policy interventions. The sensitivity analysis provides some insight into the robustness of the results but cannot capture all sources of uncertainty. Second, the analysis focuses on production costs and carbon intensities, but does not fully account for the broader social, environmental, and geopolitical implications of hydrogen pathways, including land use, water consumption, and energy security. Third, the study does not address the potential for other decarbonization technologies, such as direct electrification or bioenergy with CCS, to compete with hydrogen in certain applications.

Future research should address these gaps by expanding the analysis to include a wider range of decarbonization options, integrating social and environmental considerations into the assessment framework, and examining the distributional impacts of hydrogen pathways on different regions and communities. Research into novel hydrogen production technologies, such as methane pyrolysis or photoelectrochemical water splitting, may also provide alternative pathways that offer economic or environmental advantages over current approaches. Finally, more detailed analysis of the regulatory, financial, and institutional barriers to hydrogen deployment is needed to inform policy design and investment decisions.

Conclusion

This study presents a comprehensive comparative analysis of blue and green hydrogen pathways across key hard-to-abate industrial sectors, integrating techno-economic assessment, lifecycle environmental accounting, and scenario-based cost projections. The findings provide several important conclusions:

- ✓ First, green hydrogen demonstrates superior long-term economic performance. The green hydrogen-dominant scenario achieves comparable decarbonization outcomes while saving $115.5 billion compared to the blue hydrogen-dominant scenario. Green hydrogen costs projected to reach parity with blue hydrogen by 2030 in favorable regions and achieve near-universal cost superiority by 2040, driven by rapid electrolyzer cost reductions and declining renewable electricity prices.
- ✓ Second, the environmental credibility of blue hydrogen is contingent upon methane leakage control. Observed methane leakage rates of 2.8-3.1% in major gas-producing basins increase blue hydrogen's lifecycle carbon intensity to 3.5-6.0 kg CO_2e/kg H_2, potentially disqualifying projects from stringent carbon credit mechanisms. The climate benefits of blue hydrogen significantly reduced when accounting for hydrogen emissions and near-term time scales.
- ✓ Third, sector-specific policy approaches warranted. The iron and steel sector requires targeted support to overcome high demand-side capital costs for H-DRI deployment, with the green-dominant pathway offering superior mitigation economics ($85-120/t CO_2) compared to the blue-dominant pathway ($100-150/t CO_2). The chemical sectors and oil refining exhibit lower mitigation costs and, in some cases, negative mitigation costs after 2050, suggesting that market forces may increasingly favor green hydrogen adoption as cost parity approaches.
- ✓ Fourth, infrastructure requirements differ fundamentally across pathways. Green hydrogen requires investment in renewable generation and electrolyzer manufacturing, while blue hydrogen depends on CO_2 transport and storage infrastructure, the absence of which in many regions creates significant deployment barriers. The absence of cross-border CO_2 transport frameworks in Europe, for example, constrains blue hydrogen deployment in countries without domestic storage capacity.

In conclusion, the evidence suggests that green hydrogen is the long-term winner on both economic and environmental grounds, with costs projected to reach $2/kg by 2030 in favorable regions. Blue hydrogen offers lower costs today and can serve as a bridge, but faces risks from methane leakage, CCS underperformance, and tightening carbon standards. Organizations and policymakers should evaluate hydrogen pathways based on timeline, geography, and end-use requirements, prioritizing investments that align with long-term decarbonization goals and avoiding lock-in to technologies that may become economically or environmentally obsolete.

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Authors' Contributions

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References

[1] Wang, K., Liu, F., & Liu, J. (**2025**). Techno-economic assessment of different clean hydrogen

development pathways across industries in China. Applied Energy, 382, 125244.
[2] Fazlinezhad, A., Karimi, B., & Hasanpour, A. (**2026**). Energy analysis of simultaneous polygeneration of green dimethyl ether, clean electricity, hot steam and fresh water using geothermal energy and seawater. Iranian Journal of Chemistry and Chemical Engineering, *44*(4), 125–145.
[3] Hasanpour, A., Tabazadeh, A., & Bouteldja, M. (**2025**). Theoretical investigation and modeling of hydrocarbon sediment formation in distillation towers of monomer styrene production process. Advanced Journal of Chemistry, Section B: Natural Products and Medical Chemistry, *7*(3), 209–220.
[4] Hasanpour, A., Hoseinzadeh, M., Gholian Mohamdi, P., & Taheri, H. (**2025**). Hydrogen production from biogas: Simulation and pinch analysis. Advanced Journal of Chemistry, Section B: Natural Products and Medical Chemistry, *7*(4), 298–314.
[5] Hasanpour, A., Fazlinezhad, A., & Tabazadeh, A. (**2025**). Physicochemical characteristics, process optimization, and energy efficiency of hydrogen production from methanol, ethanol, and glycerol: A comparative review. Advanced Journal of Chemistry, Section B: Natural Products and Medical Chemistry, *7*(3), 250–271.
[6] Eslampoor, Y and Abedini, N. (**2026**). Hemodynamic Effects and Complications of Bone Cement Utilization in Orthopedic Operations. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(4), 317-328.
[1] Ranjbar, R., Dehkordi, F. S., & Heiat, M. (**2020**). The frequency of resistance genes in Salmonella enteritidis strains isolated from cattle. *Iranian Journal of Public Health*, *49*(5), 968.
[2] Abdolmaleki, Z., Mashak, Z., & Safarpoor, D. F. (**2019**). Molecular and virulence characteristics of methicillin-resistant Staphylococcus aureus bacteria recovered from hospital cockroaches. 2019;12(12):e98564.
[3] Dehkordi, F. S., Yahaghi, E., & Darian, E. K. (**2014**). Prevalence of antibiotic resistance in Escherichia coli isolated from poultry meat supply in Isfahan. *Iran J Med Microbiol: 8*(2), 41-7.
[4] Rostami, F., Rahimi, E., Yahaghi, E., Khodaverdi Darian, E., & Bagheri Moghadam, M. (**2014).** Isolation and evaluation virulence factors of Salmonella typhimurium and Salmonella enteritidis in milk and dairy products. *Iranian Journal of Medical Microbiology*, *8*(1), 54-61.
[5] Mashak, Z., Banisharif, F., Banisharif, G., Reza Pourian, M., Eskandari, S., Seif, A., …., & Alavi, I. (**2021**). Prevalence of listeria species and serotyping of Listeria monocytogenes bacteria isolated from seafood samples. *Egyptian Journal of Veterinary Sciences*, *52*(1), 1-9.
[6] Nayebpoor, F., Momeni, M., & Dehkordi, F. S. (**2013**). Incidence of Ochratoxin A in raw and salted dried fruits using High Performance Liquid Chromatography. *American-Eurasian Journal of Toxicological Sciences*. 2013; 5 (1): 01-06.
[7] Ranjbar, R., Mahmoodzadeh Hosseini, H., & Safarpoor Dehkordi, F. (**2020**). A review on biochemical and immunological biomarkers used for laboratory diagnosis of SARS-CoV-2 (COVID-19). *The Open Microbiology Journal*, *14*(1).
[8] Dehkordi, F. S., & Rafsanjani, M. S. (**2012**). Prevalence study of Coxiella urnetiid in aborted fetuses of small ruminants in various partum and seasons in Iran. *African Journal of Microbiology Research*, *6*(27), 5594-5600.
[9] Safarpour dehkordi, F., Hosseini, S., Rahimi, E., Yahaghi, E., & Momeni, M. (**2026**). Investigate the frequency of virulence genes Vibrio parahaemolyticus isolated from fish, lobsters and crabs caught from Persian Gulf. *Iranian Journal of Medical Microbiology*, *8*(2), 1-7.
[10] Safarpourdehkourdi, F., Momtaz, H., Esmailzade, S., Khayyat Khameneie, M., & Yahaghi, E. (**2026**). Detection of virulence factors of Uropathogenic Escherichia coli isolates from infertile women high vaginal swabs. *Iranian Journal of Medical Microbiology*, *7*(4), 1-8.
[11] Momeni Shahraki, M., Shakerian, A., Rahimi, E., & Safarpoor DEHKORDI, F.. (**2020**). Study the frequency of enterotoxin encoding genes and antibiotic resistance pattern of methicillin-resistant Staphylococcus aureus isolated from vegetable and salad samples in Chaharmahal Va Bakhtiari province. Journal of food microbiology, 7(2), 55-69.
[12] Dormanesh, B., Mirnejad, R., Khodaverdi Dariyan, E., Momtaz, H., Yahaghi, E., Safarpour Dehkordi, F., & Pilevarzadeh, M. (**2026**). Characterization and study the antibiotic resistance of Uropathogenic Escherichia coli isolated from pediatrics with pyelonephritis and cystitis in Iran. *Iranian Journal of Medical Microbiology*, *7*(2), 27-39.
[13] Mousavi, S., SAFARPOOR, D. F., & Valizadeh, Y. (**2017**). Genotyping of Helicobacter pylori strains isolated from raw milk and dairy products. 4(3):41-53.
[14] Rashidiani, J., Eskandari, K., Ranjbar, R., Kooshki, H., Afshar, D., & SAFARPOOR, D. F. (**2021**). Application of gold core-shell magnetic nanoparticles immunosensor for detection of vibrio cholera. 8(1):71-75.
[15] Madahi, H., Rostami, F., Rahimi, E., SAFARPOOR, D. F., & Jalali, M. (**2013**). Detection of classical enterotoxins of Staphylococcus aureus isolates from chicken nugget and ready to eat foods in Esfahan province by ELISA technique. 3(3): 9.
[16] Shahreza, M., Dehkordi, F., Kurbanova, S. K. S., & Sapayev, V. S. V. (**2025**). Occurrence of Staphylococcus aureus, Campylobacter jejuni, Listeria monocytogenes and Arcobacter butzleri in

poultry meat. *International Journal of Health and Medical Innovation (IJHMI)*, *2*(1), 10-17.

[17] Shahreza, M. S., Jafariaskari, S., Al-Aouadi, R. F. A., & Dehkordi, F. S. (**2024**). Molecular genotyping and antimicrobial resistance characters of Helicobacter pylori isolates from raw milk of naturally infected animal species. *International Invention of Scientific Journal*, *8*(4), 793-803.

[18] Jafariaskari S, Shahreza MS, Al-Aouadi RFA, Dehkordi FS. (**2020**), Hydroxychloroquine Therapeutic effects on COVID19: a systematic review and meta-analysis. International Invention of Scientific Journal 8 (4), 804–817

[19] Alijani, H. Q., Fathi, A., Amin, H. I. M., Lima Nobre, M. A., Akbarizadeh, M. R., Khatami, M., … & Shafiee, A. (**2024**). Biosynthesis of core–shell α-Fe2O3@ Au nanotruffles and their biomedical applications. *Biomass Conversion and Biorefinery*, *14*(14), 15785-15799.

[20] Rezaei-Tazangi, F., Mirhosseini, A. F., Fathi, A., Roghani-Shahraki, H., Arefnezhad, R., & Vasei, F. (**2024**). Herbal and nano-based herbal medicine: New insights into their therapeutic aspects against periodontitis. *Avicenna Journal of Phytomedicine*, *14*(4), 430.

[21] Mirzaei, K., Fathi, A., Asadinejad, S. M., & Moghadam, N. C. (**2022**). Study the antimicrobial effects of Zataria multiflora-based mouthwash on the microbial community of dental plaques isolated from children: A candidate of novel plant-based mouthwash. *Acad J Health Sci*, *37*, 58-63.

[22] Mohammad, W. T., Alijani, H., Faris, P., Salarkia, E., Naderifar, M., Akbarizadeh, M. R., … & Khatami, M. (**2023**). Plant-mediated synthesis of sphalerite (ZnS) quantum dots, Th1-Th2 genes expression and their biomedical applications. *South African Journal of Botany*, *155*, 127-139.

[23] Mehrabanian, M., Ahari, U. Z., Fathi, A., & Parizi, M. M. (**2021**). Comparison of Dental Health Status in Schizophrenic Patients with Healthy Individuals: A Case Study in Iran. *Clinical Schizophrenia & Related Psychoses* 15 (2).

[24] Zadeh, S. M. M., Elyaskhil, M., Fathi, A., & Asadinejad, S. M. (**2021**). Evaluate Risk Markers For Periodontal Disease In Children With Type 1 Diabetes: A Systematic Review And Meta-Analysis. *Turkish Online Journal of Qualitative Inquiry*, *12*(8).

[25] Barjoee, S. S., & Fathi, A. (**2020**), A Systematic Review on the Applications of Nanoparticles in Dentistry. *International Journal of Health Sciences*, *6*(S6), 4864-4876.

[26] Fathi, A., Rahnama, S., Alesaeidi, S., Mousavi, E., Bagherboum, N., Gholami, M., & Fotovat, F. (**2023**). Comparing knowledge and opinions of medical and dental students in the field of pediatric anesthesia. *Journal of Family Medicine and Primary Care*, *12*(4), 632-636.

[27] Fathi, A., Natanzian, Y., Ghorbani, M., & Mosharraf, R. (**2024**). Evaluation of the Bonding Shear Strength between Enamel and Dentin Feldspathic Porcelain and Two Different Monolithic Zirconia with Low and High Translucency. *International Journal of Dentistry*, *2024*(1), 5921637.

[28] Makiya, A., Moghaddam, M. A., Faghihinia, F., Anzabi, R. M., Asadi, H., & Fathi, A. (**2024**). Pro-inflammatory Cytokines may Associate Periodontitis with Pregnancy Complications: A Short Review. *New Emirates Medical Journal*, *5*(1), e02506882262319.

[29] Ghasemi, E., Fathi, A., Mohammadi, D., & Salehi, S. (**2025**). Stress distribution analysis in bone adjacent to implant in various abutment-implant connection designs using finite element analysis. *Journal of Oral Implantology*, *51*(2), 134-141.

[30] Mosharraf, R., Fathi, A., Rismanchian, M., Ghasemi, E., & Givehchian, P. (**2025**). Customized versus titanium healing abutments for preimplant tissue healing in fresh socket implants: A systematic review. *Dental Research Journal*, *22*(1), 10-4103.

[31] Moazzam, M., Fathi, A., Ghorbani, M., & Mosharraf, R. (**2025**). Comparison of Vertical Marginal Discrepancy in High and Low Translucent Monolithic Zirconia Crowns in Repeated Firing Cycles. *European Journal of Dentistry*, *19*(03), 843-850.

[32] Fathi, A., Borhani, S., Salehi, S., Mosharraf, R., & Atash, R. (**2025**). Effect of Thermodynamic Cyclic Loading on Screw Loosening of Tightened Versus New Abutment Screw in Bone Level and Tissue Level Implants in DIO Implant Company (In-Vitro Study). *Clinical and Experimental Dental Research*, *11*(4), e70162.

[33] Ebadian, B., Fathi, A., & Beiranvand, N. (**2022**). Investigation of the effect of bonding factors on strength of porcelain bond to soft metal alloys after application of thermal cycle. *Dental research journal*, *19*(1), 91.

[34] Fathi, A., Nadian, F., Ghorbani, M., Razavi, P., Mosharraf, R., & Ebadian, B. (**2024**). Enhancing oral function: a case report on mandibular overdenture utilization with custom-made subperiosteal implant. *Journal of Prosthodontics*, *33*(9), 835-840.

[35] Secundar, B., Fathi, A., Baghaei, K., & Atash, R. (**2024**). Effect of ceramic thickness on the polymerization quality and film thickness of dual-polymerizing versus heated light-polymerizing adhesive cement. *The Journal of Prosthetic Dentistry*, *132*(6), 1328-e1.

[36] Hatami, M., Jalali, E., Kamran, M. H. L., Kazemi, A. D., & Fathi, A. (**2025**). Evaluating the Effect of High-Translucent Zirconia Thickness and Substrate Shade on the Final Color of the Restoration. *Clinical and Experimental Dental Research*, *11*(1), e70091.

[37] Fathpour, K., Astaraki, E., Zandian, A., Fathi, A., & Mirmohammadi, H. (**2023**). Shear bond

strength of composite resins to lithium disilicate ceramics using universal bonding and different methods of surface preparation. *Dental research journal*, *20*(1), 82.

[38] Atash, R., Fathi, A., Salehi, H., Abedian, Y., Bottenberg, P., & Baghaei, K. (**2024**). Evaluation of the effectiveness of four composite Polishing systems: an in vitro study. *International Journal of Prosthodontics and Restorative Dentistry*, *14*(1), 16-22.

[39] Fathi, A., Mosharraf, R., Ghorbani, M., & Saberipour, S. (**2024**). Effect of shape and design of the internal connection of tissue-level and bone-level implants on detorque values and removal forces: An in vitro study. *The Journal of Prosthetic Dentistry*, *131*(6), 1135-e1.

[40] Shahreza MH, Rahimi E, Momtaz H. (**2017**), Antibiotic resistance pattern of Shiga-toxigenic Escherichia coli isolated from ready-to-eat food stuffs. Bioscience Biotechnology Research Communications; 10(2): 155-9.

[41] Shahreza MS, Jafariaskari S, Al-Aouadi RF, Dehkordi FS. (2024), Molecular genotyping and antimicrobial resistance characters of Helicobacter pylori isolates from raw milk of naturally infected animal species. *International Invention of Scientific Journal.* 2024; 8(04): 793-803.

[42] Jafariaskari S, Sakhaei Shahreza M, Aboqader Al-Aouadi RF, Safarpoor Dehkordi F. (**2024**), Hydroxychloroquine Therapeutic effects on COVID19: a systematic review and meta- analysis. *International Invention of Scientific Journal*. 2024; 8(04): 804-817.

[43] Sakhaei Shahreza M, Zendehdelmoghadam H, Rafiee Jelodar N, Safarpoor dehkordi F. (**2024**), Autoimmune disease, its general features and treatment. *Scholars' press*.:96.

[44] Badjadi, M. A., Zhu, H., Zhang, C., & Safdar, M. (**2023**). A Bayesian network model for risk management during hydraulic fracturing process. *Water*, 15(23), 4159.

[45] Badjadi, M. A., Zhu, H., Zhang, C., & Naseem, M. H. (**2023**). Enhancing water management in shale gas extraction through rectangular pulse hydraulic fracturing. *Sustainability*, 15(14), 10795.

[46] Badjadi, M. A., Zhu, H., Zhao, P., Zhang, F., Hou, D., Huang, L., & Micheal, M. (**2025**). Hybrid CNN-LSTM Model for predicting wettability alterations in shale reservoir based on experimental techniques. *Geoenergy Science and Engineering*, 214217.

[47] Mokhtari Torshizi, H., Salehnia, N., & Ahmadi Shadmehri, M. T. (**2026**). Are the Different Dimensions of Globalisation Necessary and Sufficient for Human Development?(A Worldwide Study). *Journal of Human Development and Capabilities*, 1-31.

[48] Mokhtari Torshizi, H., Salehnia, N., & Ahmadi Shadmehri, M. T. (**2026**). Are the Different Dimensions of Globalisation Necessary and Sufficient for Human Development? (A Worldwide Study). *Journal of Human Development and Capabilities*, 1–31.

[49] Zarini, M. K., & Amouzad Mahdiraji, E. (**2024**). Examining the secure communication network for the reliable use of micro-grids in the power system. *Journal of Engineering in Industrial Research*, *5*(2), 101–115.

[50] Mahdiraji,E. A. and Zarini,M. K. (**2025**). Integration of Smart Materials in Loss of Excitation Protection Schemes for Synchronous Generators in Renewable Energy Systems. *Journal of Chemical Engineering and Energy Materials*, *1*(2), 78-87.

[51] Mahdiraji, E. A., & Zarini, M. K. (**2025**). Integration of smart materials in loss of excitation protection schemes for synchronous generators in renewable energy systems. *Journal of Chemical Engineering and Energy Materials*, *1*(2), 78–87.

[52] Khodadadi Zarini, M., & Amouzad Mahdiraji, E. (2024). Review of energy management in micro grid in power engineering. *Journal of Engineering in Industrial Research*, *5*(2), 90–99.

[53] Amouzad Mahdiraji, E., & Sedghi Amiri, M. (**2020**). Locating, sizing, and optimal planning of the distribution substations using vanadium flow battery storage to improve the efficiency of the power distribution network. *International Journal of Smart Electrical Engineering*, *9*(1), 13–21.

[54] Amouzad Mahdiraji, E., & Khodadadi Zarini, M. (**2025**). Advanced material-based cooling and insulation strategies for enhanced protection of synchronous generators under fault conditions. *Journal of Chemical Engineering and Energy Materials*, 1(3), 119–125.

[55] Amouzad Mahdiraji, E., & Khodadadi Zarini, M. (**2024**). Smart frequency control in multi-carrier micro-grid with the presence of V2G electric vehicles. *Journal of Artificial Intelligence in Electrical Engineering*, *12*(45), 53–69.

[56] Amouzad Mahdiraji, E., & Amiri, M. S. (**2021**). Adaptive control of network frequency by doubly-fed induction generators using a data-driven method. *Eurasian Journal of Science and Technology*, *1*(2).

[57] Amouzad Mahdiraji, E. (**2022**). Multi-Objective Optimization of Distributed Generation Despite Energy Storage Systems for Optimal Management. *International Journal of Engineering and Innovative Research*, *4*(1), 44-59.

[58] Amouzad Mahdiraji, E. (**2022**). Microgrid control to ensure stability and increase flexibility in storage applications. *Journal of Engineering in Industrial Research*, *3*(2), 69–76.

[59] Fakhari, S, Bilehjani, A and Bilehjani, E. (**2026**). Effect of Intraoperative Intravenous Dexmedetomidine on Oxidative Stress in Patients Undergoing Cardiac Surgery: A Systematic Review.

Medicinal, Psychological, and Health Research Journal (MPHRJ), *2*(5), 351-359.
[60] Fakhari, S, Bilehjani, A and Bilehjani, E. (**2026**). Intravenous Dexmedetomidine in Cardiomyocyte Biology: A Systematic Review. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 360-371.
[61] Hussam Elddin Nabeih Khasawneh, AA., et al., (**2025**), A Novel Thiazole-Sulfonamide Hybrid Molecule as a promising Dual Tubulin/Carbonic Anhydrase IX Inhibitor with Anticancer Activity, Frontiers in Chemistry 13 (13), 13
[62] Lotfi, A R and Nouri Bayat, L. (**2026**). Incidence of Postoperative Complications Following Nasal Fracture Surgery in Adults. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 175-182.
[63] Moghadam, A M. (**2025**). Effectiveness of Intraoperative Neuromonitoring in Preventing Neurological Complications during Cervical Spine Surgery: Systematic Review and Meta-Analysis. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *1*(11), 378-386.
[64] Moghadam, A M. (**2025**). Effectiveness of Intraoperative Neuromonitoring in Preventing Neurological Complications during Cervical Spine Surgery: Systematic Review and Meta-Analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *1*(11), 403-411.
[65] Rezaei, M and Owaysee Osquee, H. (**2026**). Prevalence of Deep Vein Thrombosis in Patients with COVID 19 Admitted to the Intensive Care Unit. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(4), 267-275.
[66] Sadeghzadeh, A. (**2026**). Evaluating the effectiveness and safety of hyaluronic acid versus poly-L-lactic acid for facial volume restoration: A Systematic Review and Meta-analysis. *Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research (JAMPBR)*, *2*(2), 102-113.
[67] Samimi, A. Zarinabadi, S. (**2011**), Reduction of greenhouse gases emission and effect on environment, Aust. j. basic appl. sci., 5(12), 752-756
[68] Samimi, A., Zarinabadi S., Shahbazi Kootenaei AH., Azimi A., Mirzaei M., (**2019**), Use of data mining in the corrosion classification of pipelines in catalytic reforming units (CRU), *Eura. Chem. Commu.*, 1(6), 571–581
[69] Samimi, A., Zarinabadi, S. (**2012**), Application solid polyurethane as coating in oil and gas pipelines, *Chisa*, 20th International Congress of Chemical and Process Engineering and 15th Conference Pres, 2012
[70] Samimi,A. (**2025**). Investigating the Effect of Temperature and Pressure Changes in CCR Unit Reactors on Catalyst Wear and Black Dust Increase. *Iranian Journal of Chemistry and Chemical Engineering*, *44*(12), 3039-3051.
[71] Shiri, H and Ashrafi, N. (**2026**). Enhanced Recovery After Thoracotomy in the Intensive Care Unit: Current Evidence, Clinical Strategies, and Future Perspectives. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 372-382.
[72] Shiri, H and Ashrafi, N. (**2026**). Post Esophageal Surgery Dysphagia and Nutritional Support in the Intensive Care Unit. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(5), 339-350.
[73] Zbuzant, M. (**2026**). Dental Implants vs. Traditional Bridges: A Comparative Clinical Review. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 189-198.
[74] Zbuzant, M. (**2026**). Minimally Invasive Techniques in Modern Restorative Dentistry. *Medicinal, Psychological, and Health Research Journal (MPHRJ)*, *2*(3), 177-188.
[75] Hashemloo, A., Milanifard, M. (**2025**). Dermal Fillers: Types, Indications, and Complications Materials de Relleno: Typos, Indications Complications. Journal of Advanced in Medicinal, Pharmaceutical and Biomedical Research, 1(6), 161-170
[76] Hashemloo, A., Milanifard, M. (**2025**), Contouring Plus: A Comprehensive Approach of the Lower Third of the Face with Calcium Hydroxylapatite and Hyaluronic Acid, Medicinal, Psychological, and Health Research Journal, 1(5), 143-150
[77] Sunder Raj, K. S. (**2004**). Multi-Pressure Surface Condenser Performance Evaluation: A Case Study. *Proceedings of the ASME Power Conference.*
[78] Samimi,A. (**2025**). Investigating the Effect of Temperature and Pressure Changes in CCR Unit Reactors on Catalyst Wear and Black Dust Increase. *Iranian Journal of Chemistry and Chemical Engineering*, *44*(12), 3039-3051.
[79] Hedayati, A. Almasinia, B. Samimi, A. (**2014**), Optimize pictures of industrial radiography in corrosion and sediment recognizing in oil or gas transmit pipe lines, *International Journal of Chemistry*, 5, 20-29
[80] Samimi, A. Dokhani, S. Neshat, N. Almasinia, B. Setoudeh, M. (**2012**), The application and new mechanism of universal produce the 3-layer polyethylene coating, *International Journal of Advanced Scientific and Technical Research*, 465-473
[81] Samimi, A. Samimi, M. (**2020**), Investigation of Risk Management in Food Industry, *Int. J. Adv. Stu. Hum. Soc. Sci.*, 9 (3), 195-204