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From Hype to Fit-For-Purpose: Assessing the Viability of Hydrogen as Clean Energy

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ABSTRACT

Hydrogen is increasingly positioned as a critical energy vector for achieving global decarbonization and meeting climate neutrality targets. However, significant ambiguity exists regarding which hydrogen production pathways can deliver genuine environmental and economic benefits. This paper systematically evaluates the viability of hydrogen as a clean energy solution, examining production methodologies, technological maturity, cost economics, and implementation challenges. Through comprehensive analysis of green, blue, and grey hydrogen pathways, this study reveals a persistent ambition-implementation gap where only 7% of global capacity announcements meet scheduled timelines (Odenweller and Ueckerdt, 2024). While green hydrogen demonstrates long-term potential, particularly for hard-to-electrify sectors, near-term viability remains constrained by high production costs ($4.4/kg currently, projected to decline to $2.4/kg by 2030), renewable energy requirements, and insufficient infrastructure development. The paper identifies critical success factors including technological advancement in electrolysis, cost reduction through economies of scale, supportive policy frameworks, and demand-side coordination. The findings suggest that hydrogen's transition from hype to practical deployment requires strategic targeting of specific applications, substantial capital investment, and realistic timeline expectations aligned with technological development cycles

1. Introduction

The global energy transition represents one of the most pressing challenges of the 21st century. As nations commit to achieving net-zero emissions by 2050, the energy sector must fundamentally transform from dependency on fossil fuels to renewable and sustainable alternatives (Hassan et al., 2024). Within this transformational landscape, hydrogen emerges as a potentially transformative energy carrier, capable of addressing energy demands across multiple sectors including power generation, industry, transportation, and heating (MDPI, 2021).

The International Energy Agency and numerous national governments have positioned hydrogen as integral to climate change mitigation strategies. The European Commission's Hydrogen Strategy, China's 14th Five-Year Plan, and India's National Green Hydrogen Mission collectively represent trillions of dollars in projected investment commitments (PIB, 2024). However, behind these ambitious policy declarations lies a complex technical and economic reality that distinguishes between aspirational goals and achievable outcomes.

The motivation for this research emerges from a critical observation: while hydrogen attracts unprecedented policy support and capital investment, substantial questions persist regarding the practical viability of large-scale deployment. Market announcements frequently exceed project delivery timelines, cost economics remain unfavourable compared to incumbent energy systems, and technological pathways continue to evolve. This paper addresses these tensions by conducting a rigorous assessment of hydrogen's viability as a clean energy solution, examining both the theoretical promise and practical constraints.

This paper provides a novel synthesis by systematically analysing the 'hype-to-implementation gap' across technical, economic, and temporal dimensions, offering differentiated viability assessments for near-term (2024-2027), medium-term (2027-2035), and long-term (2035-2050) horizons.

1.1 Research Objectives:

This research aims to:

- Critically evaluate the technical feasibility and environmental credentials of different hydrogen production pathways
- Assess current and projected cost economics of green, blue, and grey hydrogen
- Identify the implementation gaps between announced capacity and actual project delivery
- Analyse barriers and enablers for hydrogen deployment at scale

Determine the realistic near-term and long-term viability of hydrogen across different end-use sectors

1.2 Scope and Limitations

This paper focuses primarily on hydrogen as a primary energy carrier and energy storage medium. Analysis concentrates on hydrogen production pathways (electrolysis, steam methane reforming, coal gasification, and biomass gasification), with particular emphasis on green hydrogen derived from renewable electrolysis. The temporal scope encompasses current status (2024-2025) and projections to 2030, with selected references to longer-term scenarios. Geographic focus includes developed economies and emerging markets, with particular attention to India's hydrogen initiatives given recent policy developments.

2. Literature Review

Recent research on hydrogen energy has concentrated on three critical areas: production pathway assessments, cost-reduction mechanisms, and deployment challenges. Hassan et al. (2024) provide comprehensive analysis of hydrogen's role in achieving net-zero transitions, emphasizing that hydrogen will play an indispensable role as both an energy vector and essential molecule in the transition to climate neutrality. Their techno-economic assessment indicates that while production costs remain elevated, systematic cost reduction through technological learning and scale economies presents viable pathways to competitiveness by 2030-2035.

The implementation gap between policy ambitions and project delivery constitutes a critical research theme. Odenweller and Ueckerdt (2024) quantify this gap through longitudinal tracking of 190 hydrogen projects globally, revealing that only 7% of announced capacity achieved on-schedule commissioning. This persistent implementation gap reflects technical complexities, financing challenges, regulatory uncertainties, and supply chain constraints that extend project timelines substantially beyond initial expectations. The authors conclude that the hydrogen sector would need to grow at an unprecedented compound annual growth rate exceeding 90% from 2024 to 2030 to meet announced targets—well above growth rates experienced by solar photovoltaics during its fastest expansion phases.

Lifecycle assessments of blue hydrogen production present contested conclusions within the academic literature. Howarth and Jacobson (2021) argue that blue hydrogen's fugitive methane emissions and energy-intensive carbon capture processes undermine its environmental credentials, potentially generating greater lifecycle emissions than continued use of natural gas in specific applications. Their analysis emphasizes that even with optimistic assumptions about carbon capture rates (90%), upstream methane leakage during extraction and transmission creates substantial unaccounted emissions. Schlissel and Juhn (2024) further conclude that blue hydrogen cannot serve as a long-term decarbonization solution, recommending policy emphasis shift toward green hydrogen pathways rather than blue hydrogen infrastructure commitments.

Cost reduction trajectories for green hydrogen represent another substantial research focus. Li et al. (2024) analyse three sustainable hydrogen production technologies with emphasis on technology readiness levels, production costs, and lifecycle environmental impacts. Their perspective identifies alkaline electrolysis at Technology Readiness Level (TRL) 8-9 with current costs of $3.50-6.00/kg, while emerging Solid Oxide Electrolysis Cell (SOEC) technology remains at TRL 5-6 but promises future costs below $2.50/kg through efficiency improvements exceeding 90%. Maka et al. (2024) highlight that green hydrogen production, which depends on renewable energy resources, has become increasingly attractive due to decreased expenditures in solar and wind generation, with potential to mitigate environmental issues while promoting economic expansion.

Infrastructure development and sector-specific applications constitute emerging research priorities. Bataille et al. (2023) examine the role of energy services demand reduction in net-zero transitions, identifying hydrogen's strongest viability in hard-to-electrify sectors including high-temperature industrial heat (steel, cement, chemicals) where direct electrification proves technically unfeasible. Their analysis concludes that hydrogen demonstrates genuine comparative advantages in sectors representing approximately 28% of industrial final energy consumption, while facing competitive disadvantages in applications where battery electric alternatives or direct electrification offer superior efficiency.

Policy frameworks and demand stimulation represent critical enablers for hydrogen deployment at scale. The International Energy Agency's Global Hydrogen Review 2024 emphasizes that government support on the supply side is 50% larger than on the demand side, concluding that stronger government action is needed to stimulate demand for low-emissions hydrogen as an essential requirement to underpin supply-side investments. Industrial hubs, where low-emissions hydrogen could replace existing large-scale hydrogen demand currently met by unabated fossil fuels, remain an important untapped opportunity for governments to coordinate demand creation with infrastructure development.

This literature review establishes the foundation for assessing hydrogen's viability by highlighting persistent gaps between technological potential and practical deployment, emphasizing the necessity of differentiated assessments across production pathways, temporal horizons, and sectoral applications.

3. Hydrogen Production Pathways: Technical Overview

Hydrogen production globally employs diverse methodologies, each with distinct environmental, economic, and technical characteristics. Understanding these pathways is essential for assessing viability claims.

3.1 Grey Hydrogen

Grey hydrogen, derived primarily from natural gas through steam methane reforming (SMR), currently represents approximately 96% of global hydrogen production (Li et al., 2024). Steam methane reforming involves the reaction of natural gas with high-temperature steam over a nickel catalyst, producing hydrogen, carbon dioxide, and carbon monoxide. While this pathway benefits from mature technology and established infrastructure, it generates substantial CO_2 emissions approximately 9-12 tonnes of CO_2 per tonne of hydrogen produced (O'Shea & Lin, 2024).

The economic advantage of grey hydrogen historically has been significant, with production costs below USD 1/kg when accounting for natural gas costs, operational expenditure, and capital expenditure. However, this cost advantage incorporates significant externalities not reflected in market pricing namely, unpriced carbon emissions and climate impacts (Li et al., 2024).

3.2 Blue Hydrogen

Blue hydrogen represents grey hydrogen production combined with carbon capture, utilization, and storage (CCUS) technologies. This pathway aims to reduce CO_2 emissions by approximately 90% through post-combustion or pre-combustion carbon capture, subsequently storing CO_2 in geological formations or utilizing it in industrial processes (Govindan et al., 2023).

However, recent lifecycle assessments challenge blue hydrogen's environmental credentials. Howarth and Jacobson (2021) argue that blue hydrogen remains environmentally unviable due to fugitive methane emissions during natural gas extraction and transmission, methane leakage during the production process, and energy-intensive carbon capture requirements. The assessment concludes that blue hydrogen cannot satisfy strict climate goals if deployment targets exceed specific thresholds. Crucially, the research suggests that blue hydrogen will become economically and environmentally unviable by 2025-2035 as renewable electricity costs continue declining and electrolysis technology matures.

3.3 Green Hydrogen

Green hydrogen, produced through water electrolysis powered by renewable electricity sources (solar, wind, hydroelectric), represents the pathway aligned with deep decarbonisation objectives. Electrolysis involves splitting water molecules into hydrogen and oxygen through application of electrical current, producing zero direct greenhouse gas emissions when powered by renewable sources.

Electrolysis technologies include:

- **Alkaline Electrolysis (AEL)**: Mature commercial technology utilizing alkaline electrolytes, proven at scale with lower capital costs but moderate efficiency (~60-70%)
- **Proton Exchange Membrane (PEM) Electrolysis**: More advanced technology with higher current density and efficiency potential (~75-80%), improved response to variable renewable input
- **Solid Oxide Electrolysis Cells (SOEC)**: Emerging technology operating at high temperatures, potentially achieving efficiencies exceeding 90%, currently in demonstration phase (Li et al., 2024)

Green hydrogen's environmental advantage is substantial when powered by renewable energy with low carbon footprint. However, the pathway faces critical constraints related to energy availability, production costs, and infrastructure requirements.

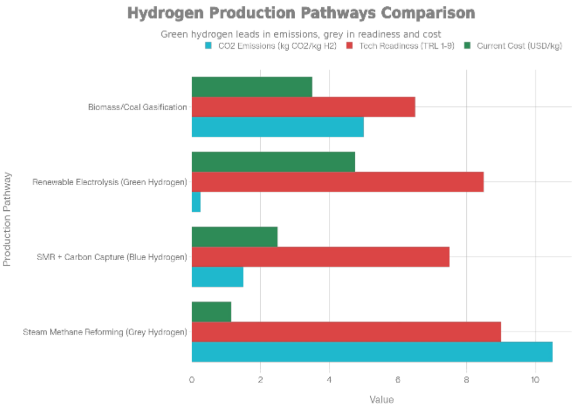

Figure 1: Hydrogen Production Pathways Comparison

A comprehensive flowchart displaying the four primary hydrogen production pathways (steam methane reforming, electrolysis, coal gasification, and biomass gasification) with their respective CO_2 emission profiles, current technology readiness levels, and cost structure positioning.

3.4 Other Production Pathways

Coal gasification and biomass gasification represent alternative hydrogen production routes. Coal gasification produces syngas (mixture of hydrogen and carbon monoxide) from coal conversion, with potential integration of CCUS for emission reduction. Biomass gasification employs similar processes using organic feedstock, offering potential carbon neutrality if feedstock sourcing is sustainable and regenerative. Both pathways face challenges including high capital costs, technical complexity, feedstock quality management, and incomplete decarbonization without CCUS integration (Govindan et al., 2023).

4. Economic Viability Assessment

Economic viability constitutes a fundamental determinant of hydrogen deployment at scale. Despite policy support, market economics currently favor incumbent energy systems in most applications.

4.1 Current Cost Structure

Table 1: Hydrogen production costs across pathways (2024-2030 Projection)

Production Pathway	Current Cost (USD/kg)	2030 Projection (USD/kg)	Key Cost Driver
Grey Hydrogen (SMR)	0.80-1.50	0.75-1.40	Natural gas price, plant capacity
Blue Hydrogen (SMR + CCUS)	1.50-3.50	1.20-2.80	CCUS capital and operating costs
Green Hydrogen (Alkaline PEM)	3.50-6.00	2.40-4.00	Renewable electricity, electrolyzer capital
Green Hydrogen (SOEC emerging)	4.00-7.50	2.00-3.50	Technology maturation, scale development

Current green hydrogen production costs of $4.4/kg substantially exceed grey hydrogen costs, creating a competitiveness gap that persists despite renewable energy cost reductions. The pathway to cost reduction depends on multiple factors operating simultaneously: decline in renewable electricity costs (continuing at approximately 5-7% annually), improvement in electrolyzer efficiency through materials science advancement, and achievement of scale economies as cumulative production increases.

Research indicates that achieving competitiveness with grey hydrogen requires both cost reduction and carbon pricing mechanisms. At current renewable electricity prices ($30-50/MWh in favourable jurisdictions), green hydrogen approaches competitiveness with blue hydrogen rather than grey hydrogen. Achieving parity with grey hydrogen (USD 1/kg) requires either renewable electricity costs declining to approximately $15-25/MWh or implementation of carbon pricing mechanisms creating USD 100-150/tonne CO_2 equivalent pricing (Reuß et al., 2024).

4.2 Cost Reduction Trajectories

India's Green Hydrogen Mission provides an instructive case for cost reduction dynamics. Analysis of ISTS-connected projects reveals production cost reductions of 20-30% through subsidy mechanisms and optimal renewable energy co-location compared to state-level alternatives. Projections for 2024-2030 indicate average cost reductions of 46%, with green hydrogen production costs declining from $4.4/kg to approximately $2.4/kg through combined effects of renewable energy cost reduction, electrolyzer cost decline, and infrastructure maturation (RMI, 2024).

Achieving these cost reduction targets requires sustained investment in:

1. Electrolyzer manufacturing scale-up and technology development
2. Renewable energy deployment expansion
3. Hydrogen transmission and storage infrastructure
4. Carbon capture technology advancement (for blue hydrogen pathway)

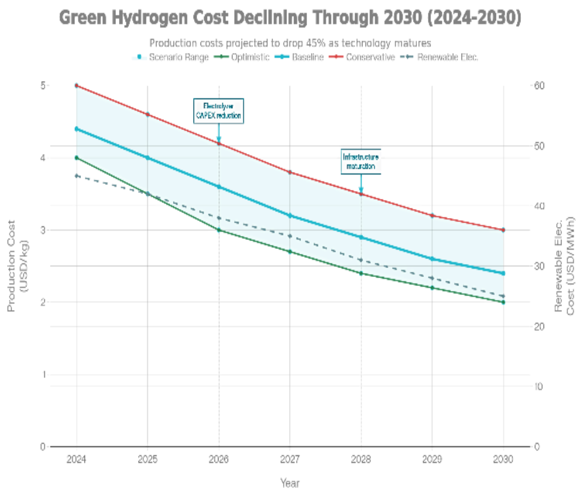

Figure 2: Green hydrogen cost reduction trajectory (2024-30)

A dual-axis line graph displaying the projected decline in green hydrogen production costs from $4.4/kg (2024) to $2.4/kg (2030), alongside concurrent renewable energy cost reduction and electrolyzer efficiency improvements.

5.Implementation Gap and Project Delivery Challenges

Significant disparity exists between hydrogen project announcements and actual capacity commissioning. This implementation gap represents a critical viability constraint with profound implications for deployment timelines and investment risk assessment.

5.1 The Ambition-Implementation Gap

Tracking analysis of 190 hydrogen projects over three-year periods (2021-2024) reveals that only 7% of announced capacity achieved on-schedule completion (Odenweller and Ueckerdt, 2024). This represents a dramatic implementation gap between policy ambitions and project delivery reality. Typical project delays range from 18-36 months beyond initial timelines, with causative factors including:

- Regulatory uncertainty and evolving policy frameworks

- Grid connection delays and renewable energy supply constraints
- Supply chain constraints for electrolyzer equipment and materials
- Financing challenges and investment risk perception
- Technical and engineering complexities
- Permitting and environmental assessment timelines

5.2 2030 Ambition Gap

Paradoxically, while implementation gaps in the near-term remain substantial, the 2030 ambition gap discrepancy between hydrogen deployment targets and 1.5°C climate scenarios gradually narrow (Odenweller and Ueckerdt, 2024). This reflects both increasing project maturation and accelerating policy support. However, this pattern suggests that near-term deployment will substantially underperform stated objectives, creating short-to-medium term market gaps and investment risks.

6. Technological Readiness and Development Priorities

Hydrogen production technology readiness varies substantially across pathways, with implications for near-term versus longer-term deployment prospects.

6.1 Technology Readiness Levels (TRL)

Steam methane reforming represents mature technology at TRL 9 (commercial deployment), with extensive industrial infrastructure and operational experience. Alkaline electrolysis similarly achieves TRL 8-9 status, with commercial installations operational globally at multi-MW scales. PEM electrolysis occupies TRL 7-8 status (demonstration to early commercial), with commercial pilots emerging and manufacturing scale-up commencing. SOEC technology remains at TRL 5-6 (technology demonstration), requiring substantial additional development before commercial viability (Li et al., 2024).

6.2 Critical Research and Development Priorities

Table 2: Hydrogen technology development priorities and expected outcomes

Technology Area	Current Challenge	R	D Priority (Expected Outcome)
Electrolysis Efficiency	System losses 20-30%	Catalyst and membrane development	Efficiency improvement to 85-90%
Capital Cost Reduction	Electrolyzer CAPEX $1000-2000/kW	Manufacturing scale-up	CAPEX reduction to 300-500/kW
Catalyst Materials	Platinum-based catalysts costly and scarce	Alternative non-precious metal catalysts	50% cost reduction with equivalent performance
Water Requirements	Freshwater constraints in arid regions	Seawater and wastewater electrolysis	Infrastructure flexibility and geographic diversification
Carbon Capture	High energy intensity, limited deployment	Advanced sorbent materials, process integration	30% efficiency improvement, cost reduction

7. Applications and Sector-Specific Viability

Hydrogen's viability varies substantially across end-use sectors, reflecting differences in technical requirements, competitive alternatives, and economic drivers.

7.1 Hard-to-Electrify Sectors

Hydrogen demonstrates strongest viability in sectors resistant to direct electrification:

High-Temperature Industrial Heat (steel, cement, chemicals): Hydrogen combustion provides high-temperature heat (~850°C) unachievable through conventional electrification. Sector represents approximately 28% of industrial final energy consumption. Green hydrogen viability in this sector depends on achieving cost competitiveness with coal-based alternatives currently requiring carbon pricing or subsidy mechanisms (Bataille et al., 2023).

Chemical Industry Feedstock: Hydrogen serves as essential feedstock for ammonia synthesis, methanol production, and petroleum refining. Conventional sourcing from natural gas creates strong incentive to transition to low-carbon hydrogen. This sector demonstrates relatively strong near-term transition prospects given established conversion infrastructure (Reuß et al., 2024).

Transportation (Heavy Duty): Hydrogen fuel cell electric vehicles (FCEVs) for heavy-duty transport face competition from battery electric vehicles and electrified rail/shipping options. Nevertheless, hydrogen FCEVs offer advantages in specific applications: long-range truck transport (>400km daily), rapid refuelling requirements, and specific operational profiles. European deployment targets envision approximately 95,000 fuel cell trucks on roads by 2030, though substantial infrastructure development remains essential (Hydrogen Council, 2024).

7.2 Lower Priority Sectors

Direct hydrogen use in light-duty transportation faces competitive disadvantages versus battery electric vehicles, which demonstrate superior energy efficiency (~77% vs 40% for hydrogen FCEVs) and favourable cost economics. Hydrogen's potential role in light-duty transport likely concentrates on specific applications (commercial fleet vehicles, long-range scenarios) rather than mass-market deployment.

Hydrogen for power generation (electricity) competes unfavourably with direct renewable deployment and battery energy storage, except in specific contexts requiring seasonal energy storage or dispatchable carbon-free generation with hydrogen import or domestic production capability.

8. Infrastructure and Enabling Conditions

Beyond technology and economics, hydrogen viability requires substantial infrastructure development and supportive enabling conditions.

8.1 Hydrogen Infrastructure Requirements

Viable hydrogen deployment requires:

- **Production Capacity**: Electrolyzer manufacturing and deployment infrastructure operating at gigawatt scales
- **Transmission Infrastructure**: Dedicated hydrogen pipelines or repurposed natural gas infrastructure (requires materials compatibility research and development)
- **Storage**: Large-scale salt cavern storage, compressed gas storage, or liquid hydrogen storage for seasonal requirements
- **Distribution and Refuelling**: Localized distribution networks and retail refuelling stations for transportation applications
- **End-Use Equipment**: Hydrogen-compatible industrial processes, fuel cell systems, and combustion equipment

Current infrastructure development proceeds slowly relative to policy timelines. Europe's hydrogen backbone initiative targets 53,000 km of transmission pipeline by 2050 (currently ~1,600 km operational), while similar infrastructure development lags in Asia and other regions (Hydrogen Council, 2024).

8.2 Policy and Financing Enablers

Successful hydrogen deployment requires:

- **Carbon Pricing Mechanisms**: Establishing price floor for carbon emissions, improving hydrogen cost competitiveness
- **Investment Support**: Grants, risk-sharing mechanisms, and capital subsidies reducing investment barriers
- **Regulatory Frameworks**: Clear standards, safety protocols, and permitting processes accelerating project development
- **Demand Guarantees**: Government procurement commitments and industrial off-take agreements
- **Research Funding**: Sustained investment in technology development and demonstration projects

India's National Green Hydrogen Mission exemplifies integrated policy approach, combining production incentives (USD 2.27/kg support), renewable energy co-location benefits, and industrial deployment pathways. Early results demonstrate effectiveness of coordinated policy frameworks in accelerating project development and cost reduction (PIB, 2024).

9. Risk Factors and Constraints

Multiple factors present material constraints on near-to-medium term hydrogen viability.

9.1 Technical Risks

Catalyst Degradation and Durability: Electrolyzer catalysts (particularly platinum-based PEM catalysts) require extended operational lifetimes (40,000+ hours) with minimal degradation. Achieving these durability standards while reducing catalyst cost remains challenging (Li et al., 2024).

System Integration Complexity: Hydrogen production systems require integration with variable renewable energy sources, creating control and optimization complexity. Managing production variability with downstream demand patterns presents engineering and economic challenges.

Materials Compatibility: Hydrogen's reactivity with metallic materials (particularly hydrogen embrittlement phenomena) creates infrastructure challenges. Material standards require development and validation across diverse operational conditions.

9.2 Economic and Market Risks

Cost Reduction Uncertainty: Projected cost reductions depend on assumptions regarding renewable electricity prices, electrolyzer manufacturing learning curves, and technology development. Failure to achieve cost reduction targets would substantially extend viability timelines.

Demand Uncertainty: Hydrogen demand depends on complementary technology development (fuel cells, industrial processes), carbon pricing evolution, and policy commitment sustainability. Premature policy reversal or technology shifts could reduce hydrogen demand expectations significantly.

Stranded Assets: Investment in hydrogen infrastructure and production creates path dependencies and stranded asset risks if technology trajectories shift or policy support changes.

9.3 Environmental and Resource Constraints

Renewable Energy Requirements: Scaling green hydrogen production to meet ambitious targets (10+ million tonnes annually by 2030) requires substantial renewable energy deployment. Competing demands for renewable energy (direct electrification of buildings, transport, industry) may constrain hydrogen energy availability.

Water Availability: Green hydrogen production requires significant freshwater approximately 9 litres per kilogramme of hydrogen produced. Geographic constraints on freshwater availability (particularly in arid regions) may limit hydrogen production feasibility in specific locations despite adequate renewable energy resources.

Supply Chain Constraints: Global electrolyzer manufacturing capacity currently operates at approximately 15-20 GW annually with substantial supply chain dependencies (rare earth elements, specialized materials). Meeting 2030 deployment targets requires tripling or quadrupling of manufacturing capacity within 5 years.

10. Viability Assessment: From Hype To Fit-For-Purpose

The comprehensive assessment presented above enables differentiated conclusions regarding hydrogen viability across temporal, sectoral, and geographic dimensions.

10.1 Near-Term Viability (2024-2027)

Near-term hydrogen deployment concentrates on:

1. **Chemical Industry Transition**: Refinery hydrogen replacement and ammonia synthesis represent highest near-term viability given established infrastructure and strong transition incentives
2. **Niche Transportation Applications**: Heavy-duty commercial vehicles in specific geographies with supportive policy frameworks (Northern Europe, selected Asian regions)
3. **Industrial Heat in Targeted Applications**: Specific high-temperature processes where alternative decarbonisation options are limited
4. **Pilot and Demonstration Projects:** Technology validation and learning curve acceleration Near-term deployment is constrained by: cost economics requiring policy support, infrastructure limitations, relatively small market volumes despite significant policy attention, and continued implementation gaps. Realistic near-term expectations indicate that announced deployment targets will substantially underperform, with actual deployment typically 50-80% below policy statements (Odenweller and Ueckerdt, 2024).

10.2 Medium-Term Viability (2027-2035*)*

Medium-term outlook depends on achievement of critical development milestones:

- Cost reduction targets (green hydrogen approaching $2-3/kg): essential for competitiveness expansion
- Infrastructure development (especially hydrogen transmission networks): enabling economies of scale
- Technology maturation (SOEC and advanced catalysts): expanding efficiency and capability
- Demand development in industrial sectors: creating market pull complementing policy push

If development milestones achieve targets, medium-term viability expands substantially. Hydrogen becomes competitive with fossil alternatives in selected sectors without policy support, deployment accelerates, and infrastructure investment demonstrates economic returns. Conversely, failure to achieve cost reduction targets or persistent infrastructure development delays would substantially constrain medium-term viability.

10.3 Long-Term Viability (2035-2050)

Long-term hydrogen viability (post-2035) reflects achievement of mature technology and scaled infrastructure. By 2050, hydrogen represents integral component of decarbonised energy system, particularly concentrated in:

- Industrial decarbonisation (steel, cement, chemicals)
- Long-range transportation (aviation, shipping, heavy-duty)
- Seasonal energy storage
- International energy trade and supply

However, long-term viability should not be assumed inevitable. Continued competitive evolution of battery technology, direct electrification progress, and alternative fuels development (sustainable aviation fuels, synthetic fuels) may substantially reduce hydrogen's long-term role compared to current expectations.

10.4 Sector-Specific Viability Matrix

High Viability (Strong Case):

- Ammonia and methanol synthesis
- Steel production (direct reduction with hydrogen)
- Cement industry high-temperature heat
- Heavy-duty long-range transport (with infrastructure development)

Moderate Viability (Conditional):

- Petroleum refinery conversion
- Chemical feedstock applications
- Light-duty commercial vehicles (specific use cases)
- Power generation (in specific contexts)

Low Viability (Challenging):

- Light-duty passenger vehicles (versus battery electric)
- Space heating (versus heat pumps and electrification)
- Power generation (competing with renewable + battery storage)
- Seasonal storage (competing with alternative storage methods)

11. Conclusions and Recommendations

The assessment presented in this paper reveals hydrogen as promising yet complex clean energy solution with substantial viability constraints limiting near-to-medium term deployment.

11.1 Key Findings

1. **Fundamental Ambition-Implementation Gap**: Market delivery substantially lags policy statements, with only 7% of announced projects achieving on-schedule completion. Realistic deployment timelines extend beyond current policy expectations.
2. **Cost Economics Remain Challenging**: Despite consistent cost reduction trajectories, green hydrogen ($4.4/kg currently) substantially exceeds grey hydrogen ($0.8-1.5/kg). Achieving competitiveness requires combined effects of renewable cost reduction, electrolyzer cost decline, carbon pricing, and/or sustained policy support.
3. **Blue Hydrogen Faces Environmental Challenges**: Recent lifecycle assessments question blue hydrogen's environmental credentials, suggesting limited viability beyond transitional timeframes (2025-2035). Policy emphasis should focus on long-term green hydrogen rather than blue hydrogen infrastructure development.
4. **Significant Infrastructure Development Requirements**: Viable hydrogen deployment requires substantial investment in production capacity, transmission infrastructure, storage systems, and distribution networks. Current infrastructure development proceeds substantially slower than policy timelines suggest.
5. **Sector-Specific Approaches Essential**: Hydrogen viability varies substantially across applications. Strategic deployment targeting hard-to-electrify sectors (industrial chemistry, high-temperature heat, specific heavy-duty transport applications) represents more viable approach than attempts at comprehensive hydrogen economy.
6. **Policy and Market Coordination Critical**: Hydrogen deployment requires coordinated policy frameworks combining carbon pricing, investment support, regulatory clarity, demand guarantees, and research funding. Individual policy instruments alone demonstrate insufficient effectiveness.

11.2 Recommendations

For Policy Makers:

1. Establish clear hydrogen roles targeting hard-to-electrify sectors rather than pursuing comprehensive hydrogen economy
2. Implement integrated policy packages combining production incentives, carbon pricing, infrastructure investment, and demand support
3. Set realistic deployment timelines reflecting technology readiness and infrastructure development requirements
4. Prioritize green hydrogen pathways; reconsider blue hydrogen infrastructure development
5. Coordinate hydrogen policy with competing decarbonization strategies (electrification, alternative fuels) to optimize resource allocation

For Investors and Industry:

1. Conduct rigorous due diligence on hydrogen project timelines, reflecting historical implementation delays.
2. Target near-term deployment in chemical industry applications and selected industrial heat applications
3. Pursue technology partnerships and cost reduction through scale-up and learning curve effects
4. Develop business models aligned with evolving policy and market conditions
5. Consider hydrogen investments as longer-duration plays with realistic returns materializing post-2030

For Researchers and Technology Developers:

1. Prioritize electrolyzer cost reduction through manufacturing innovation and catalyst material development
2. Advance alternative catalyst research reducing precious metal dependencies
3. Develop hydrogen compatibility solutions for existing infrastructure utilization
4. Research water availability solutions (seawater and wastewater electrolysis) for geographic diversification

11.3 Final Assessment

Hydrogen's transition from hype to fit-for-purpose solutions requires managing expectations, targeting applications with strong viability cases, and investing in technology and infrastructure development aligned with realistic deployment timelines. Near-term expectations should concentrate on industrial and chemical applications with established infrastructure rather than comprehensive energy system transformation. Medium-term viability depends on achieving critical cost reduction and technology development milestones. Long-term viability reflects potential but should not be assumed inevitable given continued competitive evolution of alternative technologies.

The pathway from hype to viability exists, but requires current political rhetoric suggests concentrated in applications where it delivers genuine comparative advantages over alternatives rather than serving as universal replacement for fossil fuels. disciplined targeting, sustained investment, and realistic timeline expectations reflecting technological development realities. Hydrogen's role in the clean energy transition is significant but likely narrower than

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