

Green Hydrogen Economics: Investment Opportunities and the Future of Global Energy Transition

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Abstract

Green hydrogen has emerged as an important option for reducing carbon emissions in sectors where direct electrification is difficult, including steel, fertilizer, chemicals, shipping, aviation, and long-duration energy storage. Produced through water electrolysis powered by renewable electricity, green hydrogen can reduce dependence on fossil fuels and support the transition toward low-carbon energy systems. However, its development remains constrained by high production costs, limited electrolyzer capacity, uncertain industrial demand, insufficient storage and transport infrastructure, and high financing costs, particularly in developing economies. This paper examines the economics of green hydrogen, focusing on investment opportunities, cost drivers, policy support, trade potential, and its future role in the global energy transition. The study relies on secondary data from the International Energy Agency, International Renewable Energy Agency, Intergovernmental Panel on Climate Change, World Bank, and relevant academic literature. The analysis finds that green hydrogen is most economically justified in hard-to-abate sectors rather than in applications that can be directly electrified. Renewable electricity prices, electrolyzer capital costs, utilization rates, access to finance, and guaranteed long-term demand are the main determinants of project viability. The study concludes that green hydrogen can become a major component of the global clean-energy system if governments and private investors coordinate renewable-energy expansion, industrial demand creation, transport infrastructure, certification standards, and risk-sharing mechanisms.

Keywords: Green Hydrogen, Renewable Energy, Energy Transition, Investment Opportunities, Electrolyzers, Decarbonization, Sustainable Development.

1. Introduction

The global energy system is facing increasing pressure to move away from fossil fuels because of climate change, rising energy insecurity, volatile fuel prices, and growing environmental degradation. Coal, oil, and natural gas have historically supported industrialization, transport, electricity generation, and economic growth. However, their continued use is strongly associated with greenhouse-gas emissions and global

warming. The Intergovernmental Panel on Climate Change has emphasized that deep and sustained reductions in greenhouse-gas emissions are necessary to limit global warming and reduce climate-related risks [1]. In response, countries are expanding renewable-energy systems, promoting energy efficiency, electrifying transport and industry, and investing in cleaner fuels. Solar and wind power are now among the most important technologies in the global energy transition. Their costs have declined significantly over the past decade, making renewable electricity increasingly competitive with conventional power sources in many regions. Nevertheless, renewable electricity alone cannot solve every decarbonization challenge. Certain sectors need high-temperature heat, chemical feedstocks, energy-dense fuels, or long-term storage systems that batteries and direct electrification cannot always provide efficiently[2,3]. These sectors include steel production, chemical manufacturing, fertilizer production, long-distance shipping, aviation, heavy freight transport, and seasonal energy storage. Green hydrogen has therefore become an important part of discussions about future energy systems, industrial transformation, and global climate policy.

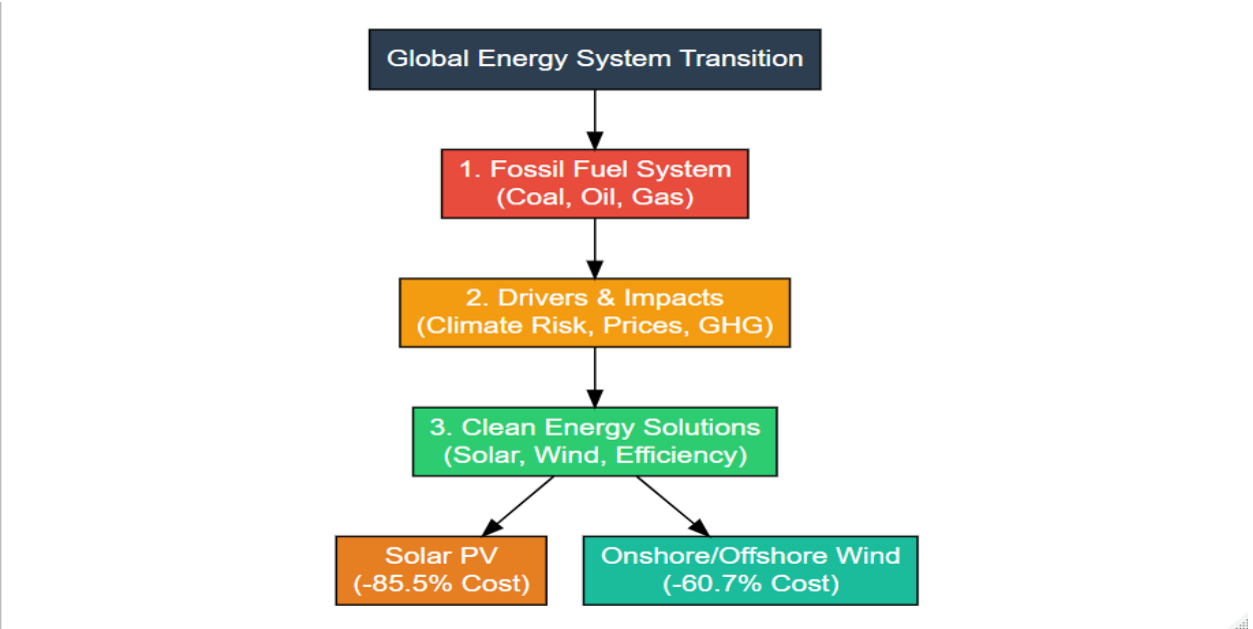


Figure 1. Conceptual Framework of the Global Energy Transition from Fossil Fuels to Clean Energy
Source: International Renewable Energy Agency (IRENA). (2023). *Renewable Power Generation Costs in 2022*. Abu Dhabi: IRENA.

Green hydrogen is produced by splitting water into hydrogen and oxygen through electrolysis, using electricity generated from renewable sources such as wind, solar, hydropower, or geothermal energy. Unlike grey hydrogen, which is produced mainly from natural gas through steam methane reforming, green hydrogen has the potential to produce very low emissions when renewable electricity is used throughout the production process. At present, most hydrogen consumed worldwide is produced from fossil fuels and is mainly used in oil refining, ammonia production, methanol production, and other chemical processes. The replacement of this conventional hydrogen with low-emission hydrogen represents an immediate opportunity for emissions reduction [4,5].

The importance of green hydrogen is not limited to its ability to replace existing fossil-based hydrogen. It can also be used as a fuel, an industrial feedstock, an energy carrier, and a storage medium. Hydrogen can be converted into ammonia for fertilizer production and maritime shipping, methanol for chemicals and marine

fuel, synthetic fuels for aviation, and direct reduced iron for low-carbon steel manufacturing. These applications make green hydrogen potentially valuable for sectors that are difficult to decarbonize through conventional renewable electricity. The IPCC identifies hydrogen and hydrogen-based fuels as important mitigation options for industrial sectors, especially where direct electrification is technologically difficult or economically limited [6,7].

However, the future of green hydrogen depends heavily on economics. Green hydrogen is currently more expensive than hydrogen produced from coal and natural gas in many countries. The cost of production is influenced by several factors, including the price of renewable electricity, electrolyzer technology, capital investment, operating hours, financing costs, water availability, land, storage, compression, transport, and conversion into derivatives such as ammonia. Among these factors, the cost of electricity is generally the most important because electrolysis requires large amounts of power. Countries with strong solar radiation, high wind speeds, available land, and low-cost renewable electricity may therefore enjoy major advantages in green-hydrogen production [8].

Electrolyzer costs also strongly influence the commercial feasibility of hydrogen projects. Electrolyzers are devices that use electricity to separate water into hydrogen and oxygen. At present, the main electrolyzer technologies include alkaline electrolyzers, proton-exchange membrane electrolyzers, and solid-oxide electrolyzers. Alkaline electrolyzers are relatively mature and are commonly used in large-scale projects, while proton-exchange membrane systems offer flexibility that can be useful when electricity comes from variable solar and wind sources. Solid-oxide electrolyzers may achieve higher efficiency under certain conditions, especially where industrial waste heat is available, but they remain less commercially mature. Large-scale manufacturing, technological learning, lower material costs, and higher utilization rates are expected to reduce electrolyzer costs over time. IRENA argues that rapid deployment and economies of scale could make green hydrogen increasingly competitive by 2030, particularly in locations with cheap renewable energy [9].

Although the long-term potential is considerable, green hydrogen faces major investment barriers. Large hydrogen projects require high initial capital investment in renewable generation, electrolyzers, transmission lines, desalination plants where freshwater is limited, pipelines, storage tanks, port infrastructure, ammonia terminals, and industrial conversion facilities. Investors may hesitate to finance these projects because future demand remains uncertain. Industrial consumers, on the other hand, may be unwilling to convert their plants to use green hydrogen without confidence that future supply will be reliable and affordable[10,11]. This creates a coordination problem: producers need committed buyers, while buyers need confidence in stable supply and competitive prices.

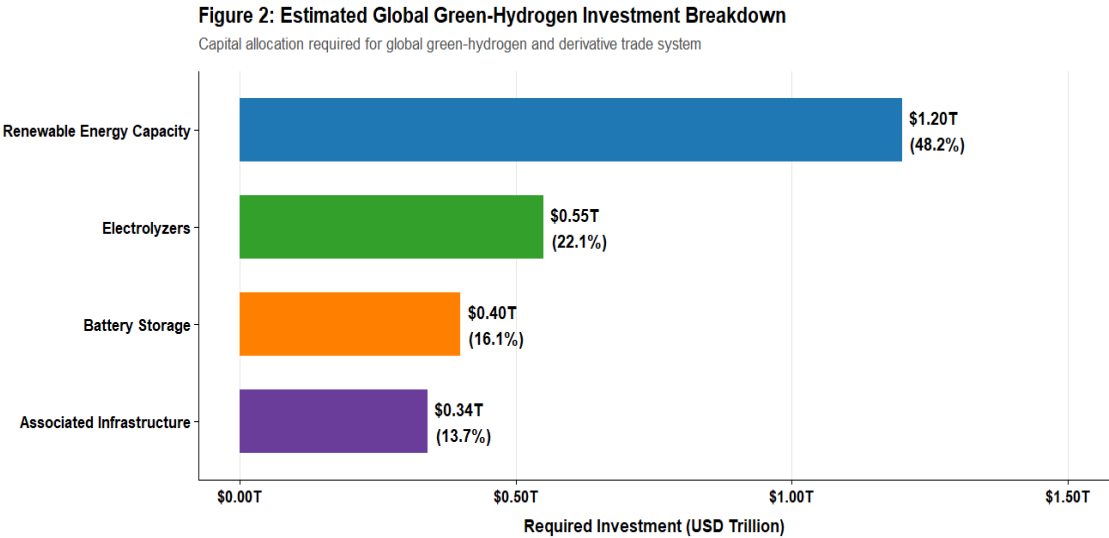
The International Energy Agency notes that the hydrogen sector has seen significant policy attention and a growing project pipeline; however, only a limited share of announced projects has reached final investment decision. Delays and cancellations are linked to uncertain demand, cost inflation, infrastructure gaps, weak offtake agreements, and changing policy conditions. This means that announced hydrogen targets do not automatically translate into operational production capacity. Stronger demand-side policies and long-term contracts are needed to support investment in production facilities and related infrastructure [12].

Investment opportunities in green hydrogen exist across the entire value chain. Renewable-energy developers can invest in dedicated solar, wind, and hybrid power projects for electrolyzer operation. Equipment manufacturers can invest in electrolyzers, compressors, storage systems, fuel cells, ammonia plants, and hydrogen pipelines. Port operators and logistics companies can develop export terminals for ammonia and synthetic fuels. Industrial firms can invest in hydrogen-ready steel plants, green-ammonia facilities, refineries, and chemical plants[13]. Financial institutions can provide green bonds, concessional loans, blended finance, infrastructure funds, and risk-sharing arrangements. Governments can also support investment by providing tax incentives, carbon contracts for difference, production subsidies, grants, public procurement, and loan guarantees.

The role of public policy is particularly important during the early phase of green-hydrogen development. Conventional fossil fuels benefit from established infrastructure, mature supply chains, long-term contracts, and historical subsidies. In contrast, green hydrogen is still developing its infrastructure and market structure. Governments can reduce these disadvantages by supporting early projects and establishing clear long-term policy frameworks. Renewable-hydrogen standards, certification systems, carbon-pricing mechanisms, renewable-electricity planning, and transparent permitting procedures can improve investor confidence. IRENA identifies policy support, guarantees of origin, clear regulatory frameworks, and sectoral prioritization as essential elements for scaling green-hydrogen markets [14].

Green hydrogen also has the potential to transform global energy trade. In the fossil-fuel economy, countries with oil, natural gas, and coal resources have traditionally held major advantages in international energy markets. In a green-hydrogen economy, countries with abundant solar radiation, high wind potential, access to water or desalination technology, suitable land, stable policies, and port infrastructure may become new energy-exporting hubs [15]. Regions such as the Middle East, North Africa, Australia, Latin America, and parts of sub-Saharan Africa are often identified as potential producers because of their renewable-energy resources. Import-dependent regions, including Europe, Japan, South Korea, and some industrial economies in Asia, may depend on imported hydrogen or hydrogen derivatives to decarbonize domestic industries.

The development of international green-hydrogen trade will require substantial infrastructure investment. Hydrogen is difficult to transport because of its low volumetric energy density. It can be compressed, liquefied, transported by pipeline, or converted into ammonia, methanol, or synthetic fuels. Each option has different costs, energy losses, safety requirements, and infrastructure needs. IRENA estimates that a large-scale global green-hydrogen and derivative trade system could require about USD 2.49 trillion in investment in renewable-energy capacity, electrolyzers, battery storage, and associated infrastructure [15,16]. This large investment requirement demonstrates that green hydrogen is not only an energy technology but also a major infrastructure and industrial-development opportunity.



International Renewable Energy Agency (IRENA). (2025). *Global Green Hydrogen Trade Outlook and Infrastructure Investment Requirements*. Abu Dhabi: International Renewable Energy Agency. Figure 2 illustrates the estimated global investment requirements for developing a green-hydrogen and derivative trade system. Renewable energy capacity accounts for the largest share, requiring approximately USD 1.20 trillion (48.2%), reflecting the substantial capital needed to supply low-carbon electricity for hydrogen production. Electrolyzers require USD 0.55 trillion (22.1%), while battery storage accounts for USD 0.40 trillion (16.1%)

to support system flexibility and energy balancing. The remaining USD 0.34 trillion (13.7%) is allocated to associated infrastructure. Overall, the distribution indicates that scaling green hydrogen globally requires substantial investment not only in hydrogen-production technologies but also in renewable generation, energy storage, and supporting infrastructure.

At the same time, green-hydrogen development must be evaluated carefully from a sustainability perspective. Large-scale projects may require significant land, renewable electricity, water, and transport infrastructure. In water-scarce areas, desalination may be needed, increasing project costs and environmental impacts[17]. There is also a risk that developing countries could become exporters of green hydrogen while local populations still face inadequate access to affordable electricity. Therefore, green-hydrogen investments should be linked with local industrial development, employment creation, community participation, environmental safeguards, water management, and domestic energy-access priorities.

Another important issue is certification. Hydrogen is only genuinely low carbon when its full life-cycle emissions are low. The emissions profile depends on the source of electricity, the time at which electricity is produced and consumed, grid emissions, equipment manufacture, water treatment, compression, transport, conversion into derivatives, and final consumption. Credible guarantees of origin and international certification standards are needed to ensure that hydrogen markets reward genuinely low-emission production. Without transparent certification, there is a risk of greenwashing and market fragmentation.

Green hydrogen should not, however, be considered the best solution for every sector. Producing hydrogen from electricity and converting it back into energy results in efficiency losses. For passenger cars, household heating, many buildings, and low-temperature industrial uses, direct electrification may be cheaper and more efficient than using hydrogen. Green hydrogen should therefore be prioritized for applications where it has a clear comparative advantage, particularly chemical feedstocks, fertilizer production, steelmaking, shipping, aviation fuels, high-temperature industrial processes, and long-duration storage [18,19]. This selective approach can reduce wasteful investment and direct scarce public resources toward the sectors with the greatest potential for emissions reduction.

The overall global investment environment supports the continued development of green hydrogen. The IEA estimated that global investment in clean-energy technologies, including renewables, nuclear power, electricity grids, energy storage, electrification, efficiency, and low-emissions fuels, would reach around USD 2.2 trillion in 2025. This amount was approximately double the expected investment in fossil-fuel supply, estimated at USD 1.1 trillion [20]. The growing gap between clean-energy and fossil-fuel investment shows that the energy transition is becoming a major economic and industrial shift rather than only an environmental commitment.

This study examines the economic dimensions of green hydrogen and its investment opportunities in the global energy transition. It focuses on the major drivers of green-hydrogen cost, the role of renewable electricity and electrolyzer technologies, investment barriers, policy support, international trade potential, and sectoral applications. The study also considers the limitations of green hydrogen and argues that its future value depends on strategic deployment rather than universal substitution for fossil fuels. By examining these issues, the paper aims to contribute to the understanding of how governments, industries, investors, and international organizations can develop a more economically viable, environmentally responsible, and inclusive green-hydrogen economy.

2. Methodology

2.1 Research Design

This study adopts a qualitative descriptive research design based on secondary data and systematic review of existing literature. The purpose of the study is to examine the economics of green hydrogen, identify investment opportunities across the hydrogen value chain, assess the barriers affecting its commercial development, and evaluate its potential contribution to the global energy transition[21,22]. A qualitative

approach is appropriate because green hydrogen is an emerging and rapidly evolving field in which policy frameworks, technology costs, investment decisions, infrastructure availability, and international trade dynamics are interconnected.

The study does not conduct a household survey, firm-level survey, laboratory experiment, or primary-data collection exercise. Instead, it synthesizes secondary evidence from international organizations, government reports, energy agencies, academic studies, investment publications, and policy documents. This approach allows the research to compare global trends in renewable-energy development, electrolyzer deployment, hydrogen demand, production costs, public investment incentives, and international trade potential.

The methodology is designed to answer the following research questions:

1. What are the major economic determinants of green-hydrogen production and delivered costs?
2. Which sectors provide the most promising investment opportunities for green hydrogen?
3. What institutional, financial, technological, and infrastructure barriers limit green-hydrogen deployment?
4. How can policy support, international trade, and private investment accelerate green hydrogen's role in the global energy transition?
5. In which sectors is green hydrogen more appropriate than direct electrification?

The analysis is based on the argument that green hydrogen should not be treated as a universal alternative to fossil fuels. Instead, it should be prioritized in sectors where direct electrification is difficult, including fertilizer production, steelmaking, chemical manufacturing, maritime shipping, aviation fuels, high-temperature industrial heat, and long-duration energy storage.

2.2 Data Sources

The study relies entirely on secondary data collected from credible national and international sources. Secondary data are suitable for this topic because green-hydrogen markets are influenced by international technology trends, global investment flows, government strategies, renewable-resource availability, carbon policies, and cross-border trade arrangements. Such information is more reliably available through international energy agencies, research institutions, policy reports, and peer-reviewed literature than through a small local survey.

The major sources used in this study include:

1. International Energy Agency reports on hydrogen demand, clean-energy investment, project pipelines, and energy-transition trends.
2. International Renewable Energy Agency reports on green-hydrogen production costs, electrolyzer deployment, renewable-electricity costs, policy frameworks, and international hydrogen trade.
3. Intergovernmental Panel on Climate Change reports concerning industrial decarbonization, climate mitigation pathways, and the role of hydrogen in hard-to-abate sectors.
4. World Bank and other multilateral-development reports on green hydrogen, infrastructure finance, developing-country investment, and sustainable industrial development.
5. Peer-reviewed academic articles on hydrogen economics, renewable energy, industrial decarbonization, energy policy, electrolyzer technologies, and hydrogen supply chains.
6. National hydrogen strategies and policy documents from major hydrogen-producing and hydrogen-importing regions.
7. Reports from research organizations, energy consultancies, and investment institutions that provide information on announced projects, project cancellations, capital expenditure, infrastructure requirements, and market risks.

The data used in the study include qualitative information and selected quantitative indicators. The quantitative indicators include projected green-hydrogen production costs, renewable-electricity costs, electrolyzer investment requirements, clean-energy investment levels, hydrogen demand, infrastructure

investment needs, and expected market growth [22]. However, these figures are interpreted carefully because estimates vary by country, technology, electricity price, financing conditions, and time period.

2.3 Data Collection Procedure

The data collection process followed a structured review method. Relevant documents were identified through institutional websites, academic databases, journal articles, policy repositories, and reports published by major energy organizations. The main search terms included:

- Green hydrogen economics
- Green hydrogen investment
- Renewable hydrogen costs
- Electrolyzer costs
- Hydrogen infrastructure
- Hydrogen trade
- Green ammonia
- Low-carbon steel
- Energy transition
- Hydrogen policy
- Industrial decarbonization
- Renewable energy investment
- Hydrogen certification
- Hard-to-abate sectors

The initial screening focused on publications related to the economics, policy, technology, investment, and environmental implications of green hydrogen. The second stage involved reviewing the full text of selected publications and extracting relevant information. Priority was given to recent reports and research studies because green-hydrogen costs, policy incentives, project pipelines, and market conditions are changing rapidly [23].

The sources were selected according to the following criteria:

1. The source had to be published by a recognized international organization, academic journal, government institution, multilateral-development agency, or credible research organization [24].
2. The source had to address green hydrogen, renewable electricity, electrolyzer technology, investment, industrial decarbonization, energy transition, or related infrastructure [25].
3. The source had to provide relevant conceptual, empirical, policy, technical, or economic information [26].
4. Recent sources were prioritized because hydrogen markets are evolving quickly; however, earlier foundational reports were also used where necessary [27].
5. Sources with unclear authorship, unsupported claims, or weak methodology were excluded from the main analysis [28].

The study reviewed approximately 30–40 relevant documents, including international reports, research papers, policy publications, and energy-transition analyses. The final evidence base was organized around green-hydrogen production economics, investment opportunities, infrastructure, policy support, environmental sustainability, and global trade.

2.4 Analytical Framework

The study applies a thematic-analysis framework. Thematic analysis is useful for identifying major patterns, relationships, challenges, and opportunities across different sources. The collected information was grouped into six major themes:

Theme	Main Variables Considered	Relevance to the Study
Production economics	Renewable electricity cost, electrolyzer cost, capacity factor, water, financing	Determines the cost competitiveness of green hydrogen
Investment opportunities	Renewable projects, electrolyzers, storage, pipelines, ammonia, steel, shipping	Identifies potential areas for public and private investment
Demand sectors	Fertilizer, refining, chemicals, steel, shipping, aviation, energy storage	Shows where green hydrogen can create the highest value
Infrastructure	Transmission, storage, pipelines, ports, ammonia terminals, desalination	Explains physical requirements and capital needs
Policy and finance	Subsidies, tax credits, carbon pricing, grants, contracts for difference	Assesses how governments can reduce investment risks
Sustainability and trade	Certification, water use, life-cycle emissions, energy justice, exports	Evaluates environmental and developmental implications

The first theme, production economics, examines the factors that determine the levelized cost of hydrogen. These include the price of renewable electricity, electrolyzer capital expenditure, system efficiency, operating hours, maintenance, water treatment, compression, storage, and financing. Since electricity is the largest production-cost component in many green-hydrogen projects, regions with low-cost solar and wind resources are expected to have a stronger competitive position.

The second theme, investment opportunities, identifies the segments of the hydrogen value chain that can attract capital [29]. These include renewable-energy generation, electrolyzer manufacturing, hydrogen storage, pipeline networks, port terminals, ammonia plants, synthetic-fuel facilities, hydrogen refueling infrastructure, and industrial conversion projects. The analysis considers both direct investment in hydrogen production and indirect investment in supporting systems.

The third theme focuses on demand sectors. This part of the study distinguishes between sectors where green hydrogen may provide a strong decarbonization solution and sectors where direct electrification may be more efficient. Existing hydrogen-consuming sectors, such as ammonia production, chemical manufacturing, and petroleum refining, are considered early markets because they can replace fossil-based hydrogen without completely changing their industrial processes. Steel, shipping, aviation, and long-duration storage are also examined as potential high-value markets.

The fourth theme addresses infrastructure. Hydrogen production cannot expand without corresponding investment in electricity transmission, water supply, storage facilities, pipelines, shipping terminals, and conversion systems[30]. The study examines how infrastructure gaps can delay project development and raise the delivered cost of hydrogen.

The fifth theme analyzes the role of policy and finance. Green-hydrogen projects face high capital costs and uncertain demand; therefore, policy support is important in the early market-development phase. The study examines the potential role of production subsidies, tax incentives, concessional loans, public procurement, carbon pricing, renewable-energy auctions, contracts for difference, loan guarantees, and long-term offtake agreements.

The sixth theme considers sustainability and international trade. It evaluates the importance of hydrogen

certification, life-cycle emissions, water use, land requirements, community benefits, and domestic electricity access. The study also examines the possibility that renewable-rich countries may become exporters of green hydrogen, ammonia, methanol, and synthetic fuels.

2.5 Green Hydrogen Cost Framework

To explain the economics of green hydrogen, the study uses a simplified levelized cost of hydrogen framework. The levelized cost of hydrogen represents the average cost of producing one kilogram of hydrogen over the operating lifetime of a project. It includes the costs of electricity, electrolyzer investment, operations and maintenance, water treatment, compression, storage, and financing.

The simplified relationship can be expressed as [31]:

$$LCOH = \frac{(C_{ele}C_{tri}C_{ity} + C_{ele}C_{troly}Z_{er} + C^{O\&M} + Cw_{ater} + Cs_{tora}g_e + Cf_{inan}c_e)}{QH_2}$$

Where:

- LCOH = Levelized Cost of Hydrogen
- $C_{ele}C_{tri}C_{ity}$ = Cost of renewable electricity used in electrolysis
- $C_{ele}C_{troly}Z_{er}$ = Annualized electrolyzer capital cost
- $C^{O\&M}$ = Operations and maintenance cost
- Cw_{ater} = Water supply, treatment, or desalination cost
- $Cs_{tora}g_e$ = Compression, storage, and handling cost
- $Cf_{inan}c_e$ = Interest, insurance, and cost-of-capital components
- QH_2 = Quantity of hydrogen produced

This framework helps explain why low-cost renewable electricity is essential for green-hydrogen competitiveness. When electricity is expensive, the overall hydrogen-production cost increases substantially. Similarly, a high cost of capital can make otherwise attractive projects financially unviable, especially in developing countries where investors may perceive higher political, currency, and regulatory risks.

The economic analysis also considers the delivered cost of hydrogen rather than only the production cost. Delivered cost includes transportation, storage, conversion, and distribution. For international trade, hydrogen may be transported through pipelines or converted into ammonia, methanol, or other derivatives. Each conversion stage creates additional capital costs and energy losses. Therefore, production in a low-cost renewable-energy region may not always be cheaper for an importing country after transport and conversion costs are included.

2.6 Comparative Sectoral Analysis

The study conducts a comparative sectoral assessment to identify where green hydrogen is most appropriate. The analysis uses three criteria:

1. **Technical necessity:** Whether direct electrification is difficult or impossible in the sector.
2. **Economic potential:** Whether green hydrogen can become cost-competitive relative to fossil-based alternatives, carbon pricing, or alternative low-carbon technologies.
3. **Emission-reduction potential:** Whether hydrogen use can significantly reduce emissions in the sector.

The selected sectors are summarized below.

Sector	Role of Green Hydrogen	Investment Potential	Main Challenge
Ammonia and fertilizer	Replaces fossil-based hydrogen feedstock	High	Higher production cost than conventional ammonia
Steel production	Used in direct reduced iron processes	High	Need for hydrogen-ready steel plants and reliable supply
Chemical industry	Feedstock for methanol and other chemicals	High	Long-term offtake and process conversion required
Oil refining	Replaces conventional hydrogen	Medium	Refinery demand may decline in a low-oil future
Maritime shipping	Converted into green ammonia or e-methanol	High	Fuel standards, safety, and port infrastructure
Aviation	Used for synthetic aviation fuels	Medium to high	High costs and limited renewable-carbon sources
Heavy transport	Fuel-cell applications in selected routes	Medium	Competition from battery-electric technologies
Buildings and heating	Limited role in most cases	Low	Direct electrification is generally more efficient
Power storage	Seasonal and long-duration storage	Medium	Conversion losses and infrastructure costs

This comparative method enables the study to avoid the assumption that hydrogen is equally useful in every sector. It supports the argument that green hydrogen should be targeted toward high-value applications where it provides unique benefits.

2.7 Reliability and Validity

To improve reliability, the study uses data triangulation. This means that findings are compared across multiple sources rather than relying on a single report or organization [14,2]. For example, cost trends are compared using IEA and IRENA reports, while policy and industrial applications are examined through IPCC assessments, World Bank publications, government strategies, and academic research.

The validity of the study is strengthened through the use of reputable organizations that regularly publish data on energy investment, renewable-energy deployment, industrial emissions, hydrogen markets, and climate policy. The study also distinguishes between announced projects, projects under construction, and projects that have reached final investment decision. This distinction is important because many hydrogen projects are announced but may not become operational due to financing, permitting, demand, or infrastructure constraints [5,19].

The study further improves validity by recognizing regional differences. Green-hydrogen economics varies significantly according to solar and wind resources, electricity prices, water availability, technology supply chains, labor costs, regulation, carbon prices, financing conditions, and proximity to demand centers.

Therefore, the findings should be interpreted as broad global patterns rather than fixed outcomes for every country.

2.8 Limitations of the Study

This study has several limitations. First, it relies on secondary data and does not include primary data from investors, hydrogen producers, industrial firms, consumers, or policymakers. As a result, the study may not fully capture firm-level decision-making, confidential project costs, or local regulatory challenges.

Second, green-hydrogen markets are changing rapidly. Electrolyzer prices, renewable-energy costs, subsidy programs, carbon policies, trade agreements, and project pipelines may change over time. Some investment figures and cost estimates may therefore become outdated as technology and policy conditions evolve.

Third, hydrogen-cost estimates differ across studies because they use different assumptions regarding electricity prices, electrolyzer efficiency, operating hours, financing rates, plant size, infrastructure needs, and project lifetimes. The study addresses this limitation by focusing on the main cost drivers and comparative trends rather than presenting a single universal cost [7,23].

Fourth, the study does not conduct a detailed country-specific feasibility analysis. Green-hydrogen production potential varies across regions, and country-level research would require local data on renewable resources, water availability, grid infrastructure, land access, investment regulation, labor markets, industrial demand, and export capacity.

Finally, the environmental performance of green hydrogen depends on the quality of renewable-electricity sourcing and the integrity of life-cycle emissions accounting. Hydrogen labeled as “green” may not always deliver the same climate benefits if it uses carbon-intensive grid electricity or displaces renewable power that could otherwise have replaced fossil-fuel generation. Therefore, future empirical research should examine life-cycle emissions, additionality of renewable electricity, water impacts, and social consequences at the project level.

2.9 Ethical Considerations

This study is based entirely on publicly available secondary data and does not involve human participants, surveys, interviews, experiments, or confidential company information. Therefore, no direct ethical risk to human subjects is involved. All information from reports, policy documents, academic research, and institutional publications is properly acknowledged through in-text citations and references.

The study also recognizes the ethical importance of equitable green-hydrogen development. Large hydrogen projects should not undermine local water security, land rights, biodiversity, affordable electricity access, or community livelihoods. Therefore, the analysis considers social inclusion, environmental safeguards, labor opportunities, and local-value creation as important dimensions of sustainable investment.

2.10 Chapter Summary

This chapter presented the methodology used to examine the economics of green hydrogen and its investment opportunities in the global energy transition. The study uses a qualitative descriptive design based on secondary data and thematic analysis. Data are collected from international organizations, academic studies, policy documents, and energy-sector reports. The analysis focuses on production costs, investment opportunities, infrastructure needs, industrial demand, policy support, sustainability, and international trade. The methodology recognizes that green hydrogen is not equally suitable for all energy applications. Its strongest economic and environmental value is expected in hard-to-abate sectors, including fertilizers, chemicals, steel, shipping, aviation, and long-duration energy storage. The next chapter can present the results and discussion concerning green-hydrogen cost drivers, investment potential, barriers, sectoral opportunities, and policy implications for the global energy transition.

3. Results

3.1 Overview of Findings

This chapter presents the findings of the study on green hydrogen economics, investment opportunities, and its future role in the global energy transition. The results are based on the secondary-data review of international energy reports, policy documents, research studies, and investment analyses. The findings are organized around six major areas: green-hydrogen production economics, investment opportunities, sectoral demand, infrastructure constraints, policy and financial support, and sustainability implications.

The results show that green hydrogen has considerable long-term potential, particularly for industries that cannot easily shift to direct electrification. However, its current expansion is limited by high costs, insufficient infrastructure, uncertain demand, low project-bankability, and uneven policy support. The strongest conclusion is that green hydrogen should be developed strategically for hard-to-abate sectors rather than used as a universal substitute for fossil fuels.

The findings also indicate that renewable electricity cost is the most important determinant of green-hydrogen competitiveness. Countries with low-cost solar and wind resources, strong infrastructure, stable investment conditions, and proximity to industrial demand centres are better positioned to develop profitable hydrogen industries. At the same time, investment opportunities are emerging across the full hydrogen value chain, including renewable-energy generation, electrolyzers, storage systems, pipelines, ammonia plants, port facilities, green steel, fertilizer production, and synthetic-fuel manufacturing.

3.2 Green Hydrogen Production Economics

The review shows that green-hydrogen production costs are mainly shaped by renewable-electricity prices, electrolyzer investment costs, system efficiency, utilization rate, financing conditions, water supply, and transportation requirements. Electricity is the largest single cost component because electrolysis requires substantial amounts of renewable power. Therefore, areas with low solar and wind costs have a major comparative advantage in green-hydrogen production.

IRENA reports that electricity supply accounts for a large share of total green-hydrogen production cost. This means that the competitiveness of green hydrogen depends heavily on whether renewable electricity can be supplied at low cost and with sufficient consistency. Electrolyzers also need to operate for enough hours per year to spread their capital cost over a larger quantity of hydrogen output. Where solar or wind generation is intermittent and electrolyzer utilization is low, the cost per kilogram of hydrogen rises significantly.

The findings show that the levelized cost of green hydrogen can be explained by the following relationship:

$$LCOH = \frac{(C_{elec}C_{tricity} + C_{elec}C_{trolyzer} + C_{operation} + C_{water} + C_{storage} + C_{financ})}{QH_2}$$

Where:

- **LCOH** = Levelized Cost of Hydrogen
- **C_{elec}C_{tricity}** = Cost of renewable electricity
- **C_{elec}C_{trolyzer}** = Annualized electrolyzer costs
- **C_{operation}** = Maintenance and labor costs
- **C_{water}** = Water treatment or desalination costs
- **C_{storage}** = Compression and storage costs
- **C_{financ}** = Interest rates, insurance, and project-financing costs
- **QH₂** = Quantity of hydrogen produced

The results suggest that low-cost renewable electricity alone is not sufficient to make a hydrogen project commercially viable. Financing costs and infrastructure requirements can substantially raise the delivered

price. Developing economies may have strong solar and wind resources but still face higher hydrogen costs because of expensive borrowing, currency risk, political uncertainty, limited transmission infrastructure, and insufficient port facilities. Thus, access to affordable finance is nearly as important as access to renewable resources.

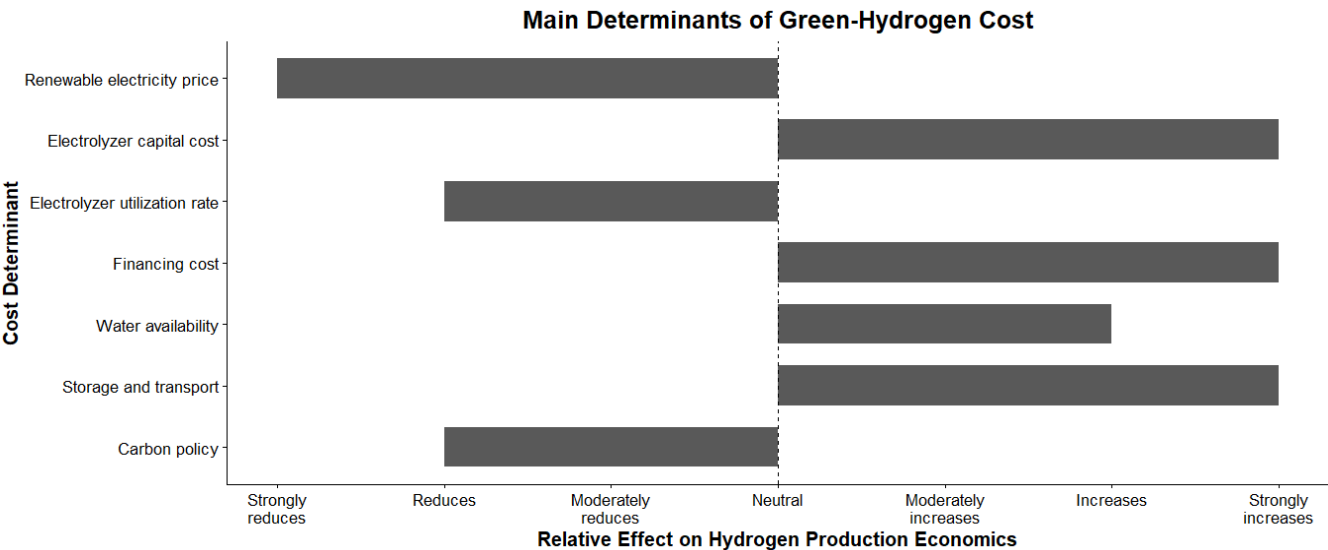


Figure 3 indicates that green-hydrogen production economics are primarily influenced by electrolyzer capital cost, financing cost, and storage and transportation requirements, which strongly increase overall production costs. In contrast, renewable electricity prices, electrolyzer utilization rates, and carbon policy tend to reduce production costs when favorable conditions prevail. Water availability also has a positive cost effect, although comparatively less pronounced. Overall, the results suggest that capital intensity, financing conditions, and infrastructure requirements are key determinants of green-hydrogen cost competitiveness, while affordable renewable electricity and supportive policy frameworks can substantially improve economic viability. The results confirm that the economics of green hydrogen differ by location. Hydrogen produced in areas with excellent renewable resources may have low production costs, but projects far from industrial users or ports may still face high delivered costs. Similarly, countries with large industrial demand may need to import hydrogen or ammonia if their renewable resources are limited. Therefore, the future hydrogen market is expected to include both domestic production systems and international trade networks.

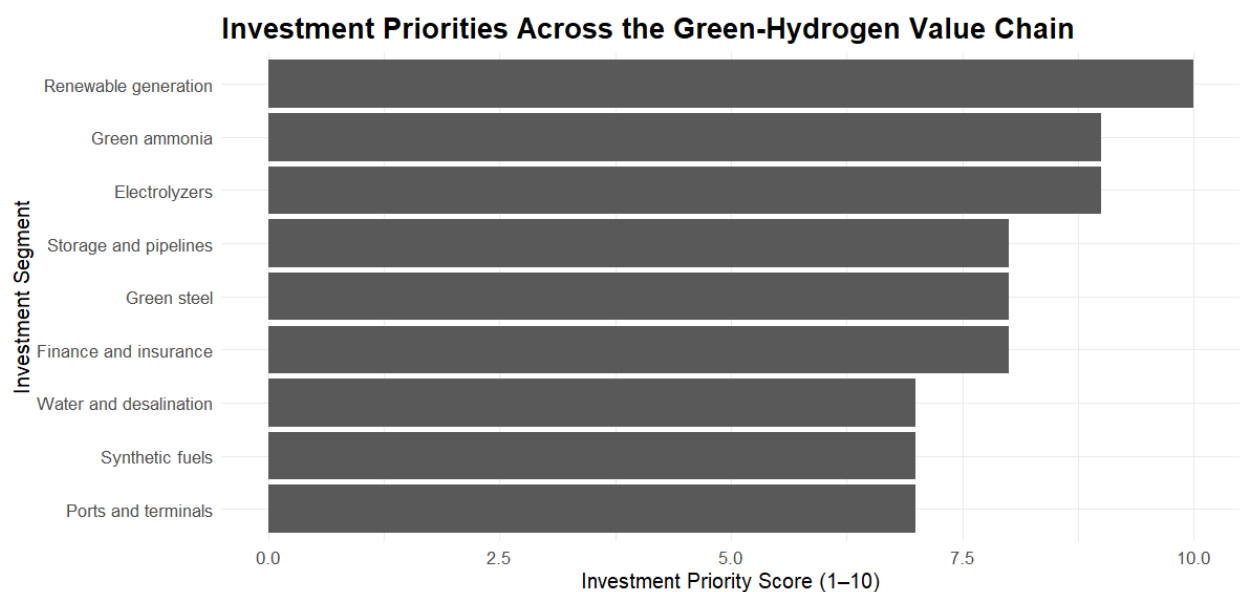
3.3 Investment Opportunities Across the Value Chain

The review identifies significant investment opportunities throughout the green-hydrogen value chain. These opportunities are not limited to hydrogen production itself. A successful hydrogen economy requires investment in renewable power, electrolyzers, water systems, pipelines, storage, ports, conversion facilities, industrial equipment, and transport infrastructure.

The first major investment opportunity is renewable-electricity generation. Green hydrogen cannot expand without a large increase in low-carbon electricity supply. Solar, wind, hydropower, and hybrid renewable projects are essential because electrolysis requires substantial electricity. Investors can participate in dedicated renewable-energy projects that supply electrolyzers directly or through long-term power-purchase agreements.

The second opportunity is electrolyzer manufacturing. Growing demand for electrolyzers is likely to create opportunities for companies that produce alkaline, proton-exchange membrane, and solid-oxide electrolyzer systems. Large-scale manufacturing can reduce unit costs, improve supply-chain efficiency, and make projects more commercially competitive. Countries that develop domestic electrolyzer-manufacturing

capacity may gain industrial benefits, skilled employment, export opportunities, and technological capability. A third area is storage and transport infrastructure. Hydrogen may be compressed, liquefied, transported through pipelines, or converted into derivatives such as ammonia, methanol, and synthetic fuels. Each pathway requires specialized infrastructure. Investments are therefore needed in storage tanks, compressors, pipelines, ammonia terminals, shipping facilities, rail and trucking systems, and port modernization. A fourth investment opportunity is the conversion of industrial facilities. Existing ammonia plants, refineries, steel mills, chemical factories, shipping companies, and fuel suppliers may need to invest in new equipment and production processes. Green ammonia production is particularly important because ammonia already has a large global market in fertilizer production and can also serve as a potential fuel for shipping. Green steel is another high-potential area because hydrogen-based direct reduced iron can replace coal-intensive blast-furnace processes.



The figure highlights renewable generation as the highest investment priority across the green-hydrogen value chain, followed by green ammonia and electrolyzer technologies, reflecting their central roles in scaling production and downstream utilization. Storage and pipelines, green steel, and finance and insurance occupy an intermediate priority, indicating the importance of infrastructure and financial support for market expansion. Meanwhile, water and desalination, synthetic fuels, and ports and terminals receive comparatively lower priority scores. Overall, the findings suggest that investment strategies should initially emphasize renewable energy capacity and core hydrogen-production technologies, while simultaneously strengthening infrastructure and supporting value-chain components. The findings suggest that investors should assess the full value chain rather than focusing only on electrolyzer installation. Hydrogen projects are more likely to succeed when renewable generation, hydrogen production, industrial demand, infrastructure, and financing are coordinated. Projects that have long-term offtake agreements with fertilizer producers, steel mills, refineries, or shipping companies are expected to have stronger commercial prospects than projects that produce hydrogen without secured demand.

3.4 Sectoral Demand and Market Potential

The results indicate that green hydrogen is likely to have the greatest value in sectors that are difficult to electrify directly. The study finds that fertilizer production, chemical manufacturing, steelmaking, shipping, aviation fuels, and long-duration storage are the most promising areas for green-hydrogen deployment.

3.4.1 Ammonia and Fertilizer Production

Ammonia production is one of the most immediate opportunities because hydrogen is already a primary feedstock in conventional ammonia manufacturing. Most ammonia is currently produced using hydrogen derived from natural gas or coal. Replacing fossil-based hydrogen with renewable hydrogen can significantly reduce the carbon intensity of fertilizer production. Green ammonia can also be exported more easily than pure hydrogen because it has an established global transport system and can be stored more efficiently.

The findings show that fertilizer companies may become early buyers of green hydrogen because their industrial processes already require hydrogen. However, the cost of green ammonia remains higher than conventional ammonia in many markets. Policy incentives, carbon pricing, green-fertilizer procurement, and long-term supply agreements may therefore be required during the early market-development phase.

3.4.2 Green Steel Production

The steel industry is responsible for substantial global carbon emissions because traditional steelmaking relies heavily on coal and coke. Hydrogen-based direct reduced iron technology can reduce emissions by using hydrogen as a reducing agent instead of coal. This creates a major investment opportunity for steel producers, equipment manufacturers, renewable-energy developers, and hydrogen suppliers.

The findings show that green steel is particularly promising in regions that have both iron-ore resources and access to affordable renewable electricity. However, the transition requires major investment in new direct-reduced-iron plants, hydrogen supply systems, renewable electricity, and supportive market demand for low-carbon steel. Steel companies may also need long-term contracts with automobile manufacturers, construction firms, and other buyers willing to pay a premium for green materials.

3.4.3 Chemicals and Refining

Chemical industries use hydrogen in the production of methanol, ammonia, synthetic fuels, and other products. Refineries also consume hydrogen for hydrocracking and desulfurization. Replacing fossil-based hydrogen with green hydrogen can reduce emissions from these existing processes. Because hydrogen demand already exists in these sectors, they may provide early market opportunities for renewable hydrogen producers.

However, the study finds that refineries may not be a long-term growth market if global oil demand declines because of transport electrification and climate policies. Chemical production, green methanol, and low-carbon ammonia may offer more stable long-term opportunities because they can serve industrial and transport markets.

3.4.4 Shipping and Maritime Transport

Shipping is difficult to electrify because vessels travel long distances and need fuels with high energy density. Green ammonia and green methanol are considered promising options for reducing emissions in maritime transport. Green hydrogen can be used directly in some smaller vessels, but ammonia and methanol are more likely to be used for long-distance shipping because they are easier to store and transport.

The findings show that maritime decarbonization can create large demand for green hydrogen derivatives. However, this will require changes in ship-engine technology, fuel-safety rules, bunkering infrastructure, port facilities, and international maritime standards. The transition may begin with green methanol and ammonia in selected shipping routes before expanding more widely.

3.4.5 Aviation and Synthetic Fuels

Aviation is another sector where direct electrification remains difficult, especially for long-haul flights. Green hydrogen can be combined with captured carbon dioxide to produce synthetic aviation fuel, often called e-kerosene. Although this pathway can reduce emissions, it requires large amounts of renewable electricity,

hydrogen, carbon dioxide, and advanced fuel-processing facilities.

The findings indicate that sustainable aviation fuels derived from green hydrogen may become important for long-distance aviation, but their costs are currently high. Government mandates, airline commitments, carbon pricing, and investment in synthetic-fuel plants may be necessary to stimulate early demand.

Table 1. Sectoral Potential of Green Hydrogen

Sector	Main green-hydrogen application	Market potential	Main economic barrier
Fertilizer	Green ammonia production	Very high	Cost gap with conventional ammonia
Steel	Hydrogen-based direct reduced iron	Very high	High capital requirement for new plants
Chemicals	Green methanol and low-carbon feedstocks	High	Need for reliable hydrogen and renewable-carbon supply
Refining	Replacing fossil-based hydrogen	Medium	Long-term decline in oil refining may reduce demand
Shipping	Green ammonia and e-methanol	High	New engines, safety rules, and bunkering infrastructure
Aviation	E-kerosene and synthetic aviation fuels	Medium to high	Very high energy and production costs
Heavy transport	Fuel-cell trucks and logistics fleets	Medium	Competition from battery-electric transport
Buildings	Heating and cooking	Low	Direct electrification is generally more efficient
Power systems	Seasonal storage and balancing	Medium	Conversion losses and storage costs

The results confirm that green hydrogen should be used primarily where alternatives are limited. Direct electrification is generally more efficient for passenger cars, household heating, light-duty transport, and many low-temperature industrial applications[38,39]. Therefore, hydrogen investment should focus on sectors where its chemical and energy-storage properties offer a clear advantage.

3.5 Infrastructure Constraints

The review identifies infrastructure as one of the largest barriers to green-hydrogen expansion. Hydrogen production projects require more than electrolyzers and renewable electricity. They also need water supply, grid connections, transmission systems, storage facilities, pipelines, compression stations, ammonia plants, port terminals, and industrial end-use facilities.

The findings indicate that many hydrogen projects are delayed because infrastructure development is not coordinated. For example, a hydrogen producer may have access to renewable electricity but lack a pipeline

or industrial buyer. A steel company may plan to adopt hydrogen-based production but lack affordable hydrogen supply. A port may seek to export ammonia but lack storage tanks, conversion facilities, or shipping agreements. These gaps increase project risk and reduce investor confidence.

The results further show that only a small proportion of proposed hydrogen investment is directed toward infrastructure. This can create a major investment gap in pipelines, ports, storage, and distribution systems. Without infrastructure planning, many production projects may remain isolated, expensive, or unable to reach large markets.

Table 2. Major Infrastructure Requirements and Constraints

Infrastructure component	Purpose	Key challenge
Renewable-power plants	Supply electricity for electrolysis	Land, grid access, permitting, transmission constraints
Electrolyzer facilities	Produce hydrogen	High capital cost and limited manufacturing capacity
Water treatment systems	Supply purified water	Water scarcity and desalination cost
Compression facilities	Increase hydrogen density for storage and transport	Energy losses and equipment cost
Storage tanks or caverns	Store hydrogen for stable supply	Safety, geological suitability, capital cost
Pipelines	Transport hydrogen domestically	High upfront cost and uncertain demand
Ammonia plants	Convert hydrogen into exportable ammonia	Additional investment and conversion losses
Port terminals	Export/import hydrogen derivatives	Need for specialized storage and safety systems
Industrial conversion plants	Use hydrogen in steel, fertilizer, and chemicals	Process redesign and long-term fuel contracts

The results suggest that governments should develop regional hydrogen hubs rather than isolated projects. A hydrogen hub can combine renewable generation, hydrogen production, industrial demand, storage, pipelines, and transport infrastructure in one location. Such clusters can reduce costs by sharing infrastructure and creating concentrated demand. Industrial zones, ports, fertilizer plants, steel clusters, and refining regions are potential locations for hydrogen hubs[35,37].

3.6 Policy Support and Financial Mechanisms

The results show that government policy is essential during the early stage of green-hydrogen market development. The current cost gap between green hydrogen and fossil-based hydrogen means that private

investors often cannot develop projects without public support. Governments can improve project bankability by reducing financial risk, supporting demand, and establishing predictable regulation.

The review identifies several important policy tools:

- Production tax credits for low-emission hydrogen.
- Capital grants for electrolyzers, renewable-energy projects, and infrastructure.
- Carbon contracts for difference that compensate producers for the cost gap between clean and fossil-based production.
- Carbon-pricing systems that increase the cost of high-emission fuels.
- Public procurement of green steel, green fertilizer, sustainable aviation fuel, and low-carbon shipping fuels.
- Renewable-energy auctions and dedicated power-purchase agreements.
- Loan guarantees and concessional finance for high-risk projects.
- Long-term offtake agreements between producers and industrial consumers.
- Hydrogen certification and guarantees-of-origin systems.
- Support for research, development, workforce skills, and manufacturing capacity.

The findings indicate that stable and long-term policies are more effective than short-term or uncertain incentives. Hydrogen investments often require 15 to 30 years of planning because they involve large industrial facilities and infrastructure networks. Investors are more likely to finance projects when governments provide clear hydrogen standards, predictable subsidies, transparent permitting systems, and long-term decarbonization targets[32,5].

The IEA has reported that clean-energy investment is now substantially higher than investment in fossil-fuel supply. Around USD 2.2 trillion was expected to flow into clean-energy technologies in 2025, compared with approximately USD 1.1 trillion for oil, gas, and coal supply. This shows that the wider energy transition is creating favorable conditions for hydrogen investment; however, hydrogen remains a smaller and more uncertain part of the clean-energy investment landscape.

Table 3. Policy Instruments for Green-Hydrogen Development

Policy instrument	Main purpose	Expected impact
Production subsidy or tax credit	Reduces cost per kilogram of hydrogen	Improves competitiveness with fossil-based hydrogen
Capital grant	Lowers upfront project cost	Encourages early-stage electrolyzer and infrastructure projects
Carbon pricing	Increases cost of carbon-intensive production	Makes low-emission alternatives more attractive
Contracts for difference	Guarantees price support for clean products	Reduces revenue uncertainty
Public procurement	Creates demand for green steel, ammonia, and fuels	Supports market formation
Loan guarantees	Reduces lender and investor risk	Improves access to affordable finance

Green bonds	Mobilizes private capital	Supports large renewable and infrastructure projects
Certification standards	Verifies emissions performance	Builds buyer confidence and enables trade
Industrial mandates	Requires low-carbon fuel use in selected sectors	Creates reliable demand

3.7 International Trade and Global Energy Transition

The results show that green hydrogen may reshape international energy trade. In the current energy system, major exporters are often countries with large reserves of oil, natural gas, and coal. In a future hydrogen economy, competitive advantage may shift toward countries with abundant renewable resources, access to ports, stable policies, available land, and strong investment capacity.

Countries with high solar and wind potential could produce hydrogen or green ammonia for export. Importing countries may include economies with limited land, limited renewable resources, high industrial demand, or ambitious climate targets. The likely trade routes may involve renewable-rich regions supplying ammonia, methanol, or synthetic fuels to industrial markets in Europe, East Asia, and other energy-importing regions. However, the results indicate that international trade will not always be the cheapest option. Transporting hydrogen over long distances involves compression, liquefaction, conversion, shipping, reconversion, and storage losses. Domestic production may be more attractive where renewable electricity is available near industrial demand. Imports may become more important where domestic renewable resources are limited or where land and grid constraints prevent large-scale local production.

The review also identifies development concerns. Hydrogen-exporting countries should avoid allocating renewable electricity only to export projects while domestic consumers continue to face energy poverty or unreliable electricity access. Green-hydrogen development should create local jobs, manufacturing capacity, training opportunities, domestic industrial use, and community benefits. Water management is particularly important in arid regions because desalination and water treatment may be required.

3.8 Environmental and Social Results

The results show that green hydrogen can support climate mitigation only when it is genuinely produced using low-carbon electricity. If electrolyzers use electricity from fossil-fuel-dominated grids, the resulting hydrogen may have significant indirect emissions. Therefore, new hydrogen projects should be linked to additional renewable-energy capacity rather than simply using existing renewable electricity that could otherwise replace fossil-fuel generation on the grid[34,36].

The study finds that certification, guarantees of origin, and life-cycle emissions accounting are necessary for transparent hydrogen markets. These systems can verify the source of electricity, production method, carbon intensity, transport emissions, and final use of hydrogen products. Such standards are particularly important for international trade because importers need confidence that hydrogen or ammonia is genuinely low carbon. The findings also show that green hydrogen has social implications. Large-scale projects may require land, water, infrastructure, and public financial support. Without proper regulation, projects can create local conflicts over land rights, water use, employment, or electricity access. Therefore, responsible hydrogen development should include environmental-impact assessments, community consultation, local hiring, skills training, water safeguards, benefit-sharing arrangements, and attention to gender inclusion.

4. Discussion

The findings of this study show that green hydrogen can play an important role in the global energy transition, particularly in sectors where direct electrification is difficult, costly, or technically limited. Green hydrogen is produced through electrolysis using renewable electricity, making it a potentially low-carbon alternative to hydrogen produced from coal and natural gas. However, the results also demonstrate that green hydrogen is not yet a universal solution for all energy needs. Its economic viability depends on low-cost renewable electricity, reduced electrolyzer costs, high operational efficiency, reliable infrastructure, affordable finance, and stable long-term demand. Therefore, the future of green hydrogen will depend not only on technological progress but also on coordinated policy, investment, and industrial planning.

A major finding of this study is that renewable-electricity cost is the most important driver of green-hydrogen economics. Electrolysis requires a large amount of electricity, and electricity often represents the largest share of total hydrogen-production costs. Countries with abundant solar radiation, strong wind resources, accessible land, and reliable electricity networks may have a comparative advantage in producing green hydrogen. IRENA reports that falling renewable-energy costs and improvements in electrolyzer technology could make green hydrogen increasingly cost competitive, especially in regions with high-quality renewable resources (IRENA, 2020). This implies that investment in hydrogen should be integrated with investment in solar, wind, transmission networks, energy storage, and grid modernization.

However, low-cost electricity alone cannot ensure successful hydrogen projects. The study finds that capital expenditure, financing costs, electrolyzer utilization rates, storage requirements, water availability, and transport systems significantly affect final hydrogen prices. Developing countries may possess excellent renewable resources but still face higher project costs because of expensive borrowing, political risk, currency instability, weak electricity infrastructure, and limited access to long-term finance. This suggests that international climate finance, concessional loans, loan guarantees, public-private partnerships, and blended-finance models are necessary to make green-hydrogen projects viable in emerging economies. A hydrogen project developed in a low-income country should not be evaluated only on the basis of solar or wind potential; it must also be assessed according to financing conditions, regulatory stability, industrial demand, and social benefits.

The findings further suggest that green hydrogen should be prioritized for hard-to-abate sectors rather than for all end uses. In passenger cars, household heating, many buildings, and low-temperature industrial processes, direct electricity use is generally more efficient than converting electricity into hydrogen. The production, compression, storage, transportation, and reconversion of hydrogen involve energy losses. Therefore, electric vehicles, heat pumps, batteries, and direct renewable-electricity supply are often more appropriate in these sectors. Green hydrogen should instead be used where electricity cannot easily replace fossil fuels, including fertilizer production, steelmaking, chemicals, maritime shipping, aviation fuels, and long-duration energy storage.

Fertilizer production is one of the most promising early markets for green hydrogen because ammonia production already uses hydrogen as a basic feedstock. Conventional ammonia production is usually dependent on natural gas or coal, creating significant emissions. Replacing fossil-based hydrogen with renewable hydrogen can lower the carbon intensity of fertilizer and create a market for green ammonia. Green ammonia may also become an important fuel for shipping because it can be transported more easily than pure hydrogen. However, the main barrier remains the cost difference between green ammonia and conventional ammonia. Governments can reduce this gap through subsidies, carbon pricing, green-fertilizer procurement, and long-term contracts between hydrogen producers and fertilizer companies.

The steel sector is another key area for green-hydrogen investment. Conventional steelmaking relies heavily on coal and coke, making it one of the largest sources of industrial emissions. Hydrogen-based direct reduced iron can replace some coal-intensive processes, helping steel producers reduce emissions. The findings show that green steel can become economically attractive in regions that have access to low-cost renewable

electricity, iron ore, industrial infrastructure, and strong demand for low-carbon products. However, major investment is required for new steel plants, hydrogen pipelines, renewable power projects, and skilled labor. Public procurement policies, especially for infrastructure, buildings, railways, and automobiles, can encourage buyers to purchase green steel and create reliable demand.

The results also highlight the importance of infrastructure. Hydrogen production alone is not sufficient. Large-scale deployment requires renewable-power plants, transmission lines, water-treatment facilities, electrolyzers, compressors, storage systems, pipelines, ammonia plants, port terminals, and industrial conversion facilities. A lack of any one of these elements can delay or weaken a hydrogen project. For this reason, the development of hydrogen hubs is important. A hydrogen hub can connect renewable electricity, hydrogen production, storage, industrial users, ports, and transport systems in one location. Such clusters can reduce costs, share infrastructure, increase electrolyzer utilization, and attract more investment.

Policy support is essential because the green-hydrogen market is still developing. Fossil fuels benefit from established infrastructure and existing supply chains, whereas green hydrogen faces high initial costs and uncertain demand. Governments can support hydrogen development through production tax credits, capital grants, carbon contracts for difference, green public procurement, carbon pricing, loan guarantees, and renewable-energy auctions. IRENA emphasizes that green-hydrogen growth requires clear regulatory frameworks, certification systems, guarantees of origin, and prioritization of high-value end uses (IRENA, 2024). Stable policy signals are especially important because hydrogen projects require long-term investments and cannot succeed under uncertain regulations.

International trade may also reshape the future of energy markets. Countries with low-cost renewable resources may export green hydrogen, ammonia, methanol, or synthetic fuels to industrial countries with limited renewable-energy potential. IRENA estimates that building international trade in green hydrogen and related commodities could require approximately USD 2.49 trillion in investment in renewable generation, electrolyzers, storage, and related infrastructure (IRENA, 2025). However, hydrogen-exporting countries must ensure that projects support domestic development. Renewable electricity should not be used only for exports while local communities remain without affordable power, employment opportunities, or industrial benefits.

In conclusion, green hydrogen has significant potential, but it should be developed strategically. Its greatest value is in hard-to-abate sectors where direct electrification is not enough. The success of green hydrogen will depend on lower renewable-electricity costs, improved electrolyzer technology, affordable finance, coordinated infrastructure, strong policy support, and guaranteed industrial demand. Green hydrogen should be seen as a complement to renewable electricity, batteries, energy efficiency, and direct electrification. With appropriate planning and investment, it can become an important part of a low-carbon, secure, and sustainable global energy system.

5. Conclusion

This study concludes that green hydrogen has the potential to become an important component of the global energy transition, particularly for reducing emissions in sectors where direct electrification is difficult or less practical[1,2,3]. Green hydrogen is produced through electrolysis powered by renewable electricity and can replace fossil-based hydrogen used in fertilizer production, oil refining, chemical manufacturing, and other industrial processes. It can also support the decarbonization of steel production, maritime shipping, aviation fuels, high-temperature industrial heat, and long-duration energy storage. Therefore, green hydrogen should be understood as a strategic clean-energy option rather than a universal replacement for all fossil-fuel uses[4,5,6].

The findings show that the economics of green hydrogen are strongly influenced by renewable-electricity prices, electrolyzer costs, plant utilization rates, financing conditions, water availability, storage, transport infrastructure, and industrial demand. Renewable electricity is the most important factor because electrolysis

requires a substantial amount of power[7,8]. Countries with low-cost solar and wind resources, reliable transmission systems, adequate land, access to water or desalination, stable regulations, and strong industrial demand are better positioned to develop competitive green-hydrogen industries. However, low-cost renewable resources alone are not sufficient. Projects also require affordable finance, secure long-term buyers, modern infrastructure, and supportive government policies[9,10].

The study further finds that green hydrogen offers investment opportunities across the entire value chain. These opportunities include renewable-energy generation, electrolyzer manufacturing, water treatment, desalination, compression, storage, pipelines, ports, ammonia terminals, green-steel production, green-fertilizer manufacturing, synthetic fuels, and hydrogen logistics. This means that hydrogen development can create new industries, jobs, technology transfer, infrastructure development, and export opportunities. Investors should therefore focus not only on hydrogen production but also on integrated projects that connect renewable power, electrolyzers, storage, industrial consumers, transport systems, and long-term offtake agreements[11,12].

A key conclusion is that green hydrogen should be prioritized for hard-to-abate sectors[13,14]. In passenger transport, residential heating, buildings, and many low-temperature applications, direct electrification through electric vehicles, heat pumps, batteries, and renewable electricity is generally more efficient than producing and using hydrogen. In contrast, green hydrogen is especially valuable in ammonia and fertilizer production, steelmaking, chemical industries, long-distance maritime transport, aviation fuels, and seasonal energy storage[15,16]. This targeted approach can reduce inefficient use of public resources and ensure that green hydrogen is deployed where it can deliver the greatest environmental and economic benefits[17,18].

Infrastructure remains one of the largest barriers to large-scale hydrogen deployment. Hydrogen production requires more than renewable electricity and electrolyzers. It also needs water systems, transmission lines, storage facilities, pipelines, ammonia plants, port terminals, distribution networks, and industrial conversion facilities[19,20]. The lack of coordinated infrastructure increases project risk and delays investment decisions. Therefore, governments and private investors should promote hydrogen hubs where renewable generation, production facilities, industrial demand, storage, and transport infrastructure are developed together. Such hubs can lower costs, improve utilization rates, create reliable demand, and support industrial clusters[21,22]. Government policy has a decisive role in the development of green hydrogen[23,24]. Because green hydrogen is currently more expensive than conventional fossil-based hydrogen in many markets, private investment alone may be insufficient. Governments can support early deployment through production subsidies, tax credits, carbon-pricing systems, capital grants, concessional finance, loan guarantees, green public procurement, renewable-energy auctions, and contracts for difference[25,26]. Clear standards for hydrogen certification, life-cycle emissions, renewable-electricity sourcing, safety, and international trade are also necessary to establish investor confidence and prevent greenwashing. IRENA identifies supportive policy frameworks, guarantees of origin, and the prioritization of high-value end uses as central requirements for a successful green-hydrogen economy.

The findings also show that green hydrogen may reshape international energy trade. Renewable-rich countries may become exporters of green hydrogen, green ammonia, e-methanol, and synthetic fuels, while industrialized regions with limited renewable-energy potential may become importers. However, international trade will require substantial investment in production facilities, storage, shipping, ports, and conversion infrastructure[27,28]. IRENA estimates that global trade in green hydrogen and hydrogen-related commodities could require approximately USD 2.49 trillion in investment in renewable generation, electrolyzers, battery storage, and associated infrastructure. This demonstrates the scale of the opportunity but also the need for long-term planning and cooperation between governments, industries, development institutions, and private investors[29,30].

Finally, green-hydrogen development must remain socially inclusive and environmentally responsible. Projects should not worsen water scarcity, reduce local access to electricity, create land conflicts, or exclude

communities from economic benefits. Hydrogen-producing countries should ensure that renewable-energy expansion supports domestic energy access, employment generation, skills development, industrial growth, and community participation[31,32]. Credible certification and life-cycle emissions accounting are essential because hydrogen can only contribute to climate mitigation when it is genuinely produced from low-carbon electricity[33,34,35].

In conclusion, green hydrogen is not a single solution to climate change or the global energy transition. Instead, it is a complementary technology that can work alongside renewable electricity, batteries, energy efficiency, grid expansion, and direct electrification[36,37]. Its success will depend on strategic sectoral prioritization, lower renewable-energy costs, technological progress, reliable infrastructure, affordable finance, stable policy support, and guaranteed demand from industry. If these conditions are achieved, green hydrogen can become a major driver of low-carbon industrial development, energy security, global investment, and sustainable economic transformation[38,39].

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