

## LOWERING COSTS AND IMPROVING EFFICIENCY IN THE SAUDI HYDROGEN VALUE CHAIN: A CORE ENABLER OF SAUDI ARABIA'S HYDROGEN EXPORT AMBITIONS UNDER VISION 2030

### REDUÇÃO DE CUSTOS E MELHORIA DA EFICIÊNCIA NA CADEIA DE VALOR DO HIDROGÊNIO DA ARÁBIA SAUDITA: UM FATOR FUNDAMENTAL PARA AS AMBIÇÕES DE EXPORTAÇÃO DE HIDROGÊNIO DA ARÁBIA SAUDITA NO ÂMBITO DA VISÃO 2030

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#### Abstract

Saudi Arabia considers low-carbon and green hydrogen to be a central component of its Vision 2030 plan and its net-zero goal in the longer term. Saudi Arabia has huge advantages: plenty of sunshine and winds, already established energy infrastructure, and adequate financing. Saudi Arabia must, however, leverage its potential to be a powerhouse in hydrogen export by optimizing its hydrogen value chain, from renewable energy to feedstock gas, then to hydrogen production, conversion to blue carrier fuels such as ammonia, to hydrogen transportation, to final imports. This report examines the cost drivers and efficiency boundaries in the hydrogen value chain that are relevant for the export strategy in the case of Saudi. The report proposes an action plan on how the costs could be reduced and efficiency increased. The report first provides the context for hydrogen under Vision 2030 and the market perspective. Then the report dissects the levelized cost of hydrogen (LCOH) for green and blue hydrogen for Saudi beyond. The article further includes policy instruments that can promote scale-up and attract private sector investment, like offtake contract models with a long-term perspective, low carbon certification for hydrogen, strategic industrial clustering, and global collaboration with importing nations. It concludes with a plan for Saudi Arabia to develop and transport cost-competitive hydrogen on a large scale and emerge as a major hydrogen supplier in the international market and also achieve its domestic decarbonization targets during the period of 2030-2040.

**Keywords:** Saudi Arabia, Vision 2030, Hydrogen, Green Hydrogen, Blue Hydrogen,

#### Resumo

A Arábia Saudita considera o hidrogênio verde e de baixo carbono um componente central do seu plano Visão 2030 e da sua meta de emissões líquidas zero a longo prazo. A Arábia Saudita tem enormes vantagens: sol e ventos abundantes, infraestrutura energética já estabelecida e financiamento adequado. No entanto, a Arábia Saudita deve alavancar seu potencial para se tornar uma potência na exportação de hidrogênio, otimizando sua cadeia de valor do hidrogênio, desde a energia renovável até o gás de matéria-prima, passando pela produção de hidrogênio, conversão em combustíveis transportadores azuis, como amônia, transporte de hidrogênio e importações finais. Este relatório examina os fatores de custo e os limites de eficiência na cadeia de valor do hidrogênio que são relevantes para a estratégia de exportação no caso da Arábia Saudita. O relatório propõe um plano de ação sobre como os custos poderiam ser reduzidos e a eficiência aumentada. O relatório primeiro fornece o contexto para o hidrogênio sob a Visão 2030 e a perspectiva de mercado. Em seguida, o relatório analisa o custo nivelado do hidrogênio (LCOH) para o hidrogênio verde e azul para a Arábia Saudita no futuro. O artigo inclui ainda instrumentos de política que podem promover a expansão e atrair investimentos do setor privado, como modelos de contratos de compra com perspectiva de longo prazo, certificação de baixo carbono para hidrogênio, agrupamento industrial estratégico e colaboração global com nações importadoras. Ele conclui com um plano para a Arábia Saudita desenvolver e transportar hidrogênio com custo competitivo em grande escala e emergir como um importante



Energy Efficiency, Cost Reduction, Exports, Neom, Ammonia, Carbon Capture.

*fornecedor de hidrogênio no mercado internacional, além de atingir suas metas de descarbonização doméstica durante o período de 2030 a 2040.*

**Palavras-chave:** *Arábia Saudita. Visão 2030. Hidrogênio. Hidrogênio verde. Hidrogênio azul. Eficiência energética. Redução de custos. Exportações. Neom. Amônia. Captura de carbono.*

## 1 INTRODUCTION

**1.1** Vision 2030 focuses on moving away from dependence on crude oil, fostering high-value sectors, and turning Saudi Arabia into an investment and innovation hub for the world as a whole (Saudi Vision 2030, 2023). As for the energy transition component of Vision 2030, low-carbon and green hydrogen have arisen as key means for Saudi Arabia to realize export earnings and lower its greenhouse gas emissions (International Energy Agency, 2024).

The Kingdom of Saudi Arabia has numerous obvious advantages:

- Strong sun and good winds present in some regions (International Renewable Energy Agency, 2024);
- Oil, Gas, and Chemical Infrastructure (existing pipelines, terminals, and ports) (Saudi Aramco, 2023);
- Large integrated energy companies with good project abilities (ACWA Power, 2024);
- Close to potential hydrogen buyers in Europe and Asia because of existing shipping routes (Hydrogen Europe, 2023).

Such aspects make Saudi Arabia a prime candidate for the production of cheap hydrogen and its derivatives, ammonia, and further export them to the global decarbonized energy markets (BloombergNEF, 2024).

## 1.2 Problem: cost as well as efficiency matter most

Despite having such great potential, the markets for hydrogen are still nascent (International Energy Agency, 2023). Importing countries are very interested in hydrogen's cost, carbon intensity, and reliability (European Commission, 2024). Australia, UAE, Oman, Chile, and North Africa are competing by developing large-scale hydrogen projects (Wood Mackenzie, 2024).

In the context of Saudi Arabia, cost reduction and optimization of efficiency along the entire value chain are imperative from three aspects:

1. Competitiveness in the world market – Saudi hydrogen has to outcompete other exporting sources and be an attractive alternative among various decarbonization alternatives (renewables with batteries, direct electrification, biofuels, and so on) (International Renewable Energy Agency, 2023)
2. Bankability - Projects of a very large size require good economic viability in a realistic pricing scenario to attract international funds (Hydrogen Council, 2024)
3. Domestic value creation – Improved efficiency releases resources (electricity, gas, water) to be used for other purposes, increasing domestic value, and high-skilled employment creation (Saudi Green Initiative, 2023)

## 1.3 Research objectives

This paper seeks to:

1. Break down the cost of exporting hydrogen from Saudi Arabia, for both green and blue hydrogen production routes using natural gas and carbon capture and storage technology, respectively (International Energy Agency, 2024)
2. Categorise and identify cost-reduction and enhancements in efficiency that can be deployed along the value chain of hydrogen, according to Saudi infrastructure and policies (BloombergNEF, 2024)
3. Recommend a roadmap strategy for Saudi Arabia to utilize such drivers in order to boost its hydrogen export strategy under Vision 2030 and up to 2040 (Saudi Vision 2030, 2023).

## 1.4 Scope and methodology

The study is conceptual and analytic and not empirical alone. The study includes:

- International research on cost and learning curves for hydrogen technology (International Renewable Energy Agency, 2023)
- Public data regarding Saudi energy or hydrogen schemes (major green hydrogen projects such as NEOM, blue hydrogen or ammonia production initiatives connected to gas resources, more general renewable energy proposals) (NEOM, 2024)
- Exports by route/path (liquefied hydrogen vs. ammonia or other alternatives) (Hydrogen Council, 2023)

It looks at the entire chain of values from the input of energy to the delivery of the final molecule and indicates which actions would be the best fits in the Saudi context (BloombergNEF, 2024).

### 1. International Scene and the Rising Role of Saudi Arabia

#### 2.1 Types of Hydrogen and Their Effects with Regard to Exports

Hydrogen is normally categorized depending on its production process (International Energy Agency, 2024):

- Grey hydrogen - Produced from fossil fuels, particularly natural gas, without carbon capture; high CO<sub>2</sub> emissions
- Blue hydrogen - Produced from fossil fuels with carbon capture and storage (CCS); assumes emissions dependent on the level of carbon capture and methane leaks (Global CCS Institute, 2023)
- Green Hydrogen – Produced through electrolyzing water with renewable electricity (from sunlight, wind, or water); near-zero emissions when in operation (International Renewable Energy Agency, 2024)

Export markets are closing in on stricter requirements concerning carbon intensity (European Commission, 2024). Therefore, blue hydrogen needs high rates of capture and low levels of upstream emissions, and green hydrogen needs an association with additional renewable energy and high certification standards (CertifHy, 2023).

Saudi Arabia has strong potential for blue and green hydrogen:

- Plenty of natural gas resources and growing gas projects, with CO<sub>2</sub> stored in old reservoirs or in saline aquifers, can enable blue hydrogen (Saudi Aramco, 2023)
- High solar power resource and availability of land make Saudi Arabia an area where cheap solar power and wind energy can be used for the generation of green hydrogen (International Renewable Energy Agency, 2024).

## 2.2 Major Saudi hydrogen projects

Public statements convey that Saudi Arabia aims to be a leading exporter worldwide for hydrogen and hydrogen-related products (Saudi Ministry of Energy, 2023). Some examples include:

- An enormous project for the production of green hydrogen and ammonia, associated with the NEOM region in the northwest, combining solar energy, wind energy, desalination, and electrolysis to produce ammonia to be exported abroad (NEOM, 2024).
- Blue hydrogen/blue ammonia pilot shipments to partners in Japan and South Korea, enabling Saudi enterprises to break into export markets with a desire to decarbonise their power and industrial sectors (Saudi Aramco, 2023).
- Discusses national plans for hydrogen, low-carbon fuels, certification requirements, and geographic clusters for industry surrounding export hubs, for example, industrial cities along coastlines (Saudi Green Initiative, 2023).

This is an attempt by Saudi Arabia to rapidly progress from pilot schemes to large-scale integrated hydrogen export hubs, and at the same time emphasise the need to reduce costs and increase efficiency (BloombergNEF, 2024).

## 3 COST STRUCTURE OF HYDROGEN EXPORT VALUE CHAIN

### 3.1 Levelized cost of hydrogen (LCOH): green

The LCOH is the average life cycle cost of producing one kilogram of hydrogen, including (International Renewable Energy Agency, 2023):

- CAPEX for electrolyzers, power electronics, and plant Balance of System
- OPEX for Maintenance, Labour, and Water

- Electricity input cost (renewables or grid)
- Plant lifetime and capacity factor
- Financing costs (weighted-average cost of capital)

**For green hydrogen, these are the two main components of cost:**

1. Cost of Electricity - typically 50-70% of LCOH (BloombergNEF, 2024). Lower costs of renewables and higher consumption are essential.
2. Electrolyzers CAPEX and Efficiency - at present, highly costly, but likely to reduce with experience, scale, and technological developments (International Renewable Energy Agency, 2024).

In Saudi Arabia, low solar PV Levelized Cost of Electricity (LCOE) is very helpful as there is intense sunlight and large installations (International Renewable Energy Agency, 2024). Low LCOH, however, requires:

- High electrolyzer capacity factor (to spread CAPEX over more hours)
- Good sizing and integration between generation and electrolysis
- Economies of scale, regionalisation, and learning-based reductions in the cost of electrolysis (Hydrogen Council, 2023)

### 3.2 Blue hydrogen, LCOH

Principal cost components of blue hydrogen (International Energy Agency, 2024):

- Natural Gas Price (Upstream Production & Processing)
- CAPEX and OPEX for Steam Methane Reformers (SMRs) or Auto-Thermal Reformers (ATRs)
- CAPEX and OPEX costs associated with carbon capture, compression, and transport
- Storage and monitoring systems
- Carbon pricing or emissions standards in export markets (Global CCS Institute, 2023)

Low costs of Saudi Arabian natural gas, resources, and potentially low-priced CO<sub>2</sub> storage will make blue hydrogen more competitive—primarily during the transition phase when the cost of electrolyzers and renewables will continue to rise (Saudi Aramco, 2023).

Long-term competitiveness will rely on:

- Very high CO<sub>2</sub> capture rates

- Very low methane leaks along the gas distribution lines
- How blue hydrogen is perceived relative to fully renewable green hydrogen (European Commission, 2024)

### 3.3 Conversion, storage, and shipping costs

Most export destinations won't accept gas at low pressure because gas diffuses easily (Hydrogen Council, 2023). To overcome this problem, there are three major export forms in which hydrogen is converted. They are:

1. Ammonia (NH<sub>3</sub>) – hydrogen with nitrogen via the Haber-Bosch process; more transportable utilizing current infrastructure for ammonia tankers and ports (International Energy Agency, 2024).
2. Liquefied hydrogen (LH<sub>2</sub>) - hydrogen cooled to cryogenic temperatures; requires special tanks and ships (Kawasaki Heavy Industries, 2023).
3. Liquid Organic Hydrogen Carriers (LOHCs) - hydrogen that is bonded to a liquid carrier, and then delivered and released (Hydrogenious LOHC Technologies, 2023).

Each option involves incremental CAPEX and OPEX costs (BloombergNEF, 2024):

- Conversion plants (ammonia production plants, liquefaction plants, hydrogenation or dehydrogenation facilities)
- Storage tanks, port, and handling systems
- Transport costs: this involves special transport vessels and energy costs

For Saudi export options, the most fully developed technology currently appears to be ammonia due to the expertise in the fertilizer industry and the existing maritime transport of ammonia worldwide, although further cost reductions and improvements in these steps are encouraged (International Energy Agency, 2023).

## 4 LEVERS TO LOWER COSTS AND IMPROVE EFFICIENCY

### 4.1 Lowering renewable power cost and increasing use

Saudi Arabia tends to bid low for large solar projects already, but there is room for additional cost reduction and performance improvement (International Renewable Energy Agency, 2024):

- Hybrid solar-wind systems for levelling the output and increasing load factor in the power plant and electrolyzer (BloombergNEF, 2024)
- Grid connection versus islanded mode for utilization of grid balancing capacities with added renewable resources for low carbon intensity
- Colocation and clustering to lower transmission losses and avoid duplication of infrastructure (ACWA Power, 2024)
- Advanced forecasting and dispatch by machine learning models to forecast sun, wind, and prices, thus improving dispatch of electrolyzers, storage, and back-ups (Siemens Energy, 2023)

To ensure maximal hours per year for the electrolyser, it is necessary not to adversely affect renewables (International Renewable Energy Agency, 2023). This can considerably reduce [the LCOH].

### 4.2 Reducing electrolyser & CCS Costs

The learning curve of electrolyzer tech (alkaline, PEM, and new solid oxide tech) seems to be quite steep, with price reductions happening due to economies of scale (Hydrogen Council, 2024). Saudi Arabia could help quicken this by:

- Facilitating the local assembly or production of the electrolyser stack and other balance of plant components close to the NEOM or any other energy hub location (NEOM, 2024)
- Standardized and module-based approaches towards volume procurement and quick deployment
- Assisting R&D in the use of worldwide equipment suppliers and universities to adjust electrolyser systems to desert conditions (temperature, dust, salinity) and

integrate with desalination and renewable energy (King Abdullah University of Science and Technology, 2023)

For Blue Hydrogen, attaining reduced costs of Carbon Capture and Storage involves (Global CCS Institute, 2023):

- Creation of large CCS nodes with collection points for CO<sub>2</sub> from multiple sources, such as power plants and industries
- Saudi Arabia the Kingdom's Geological Capability for Carbon Dioxide Sequestration in Abandoned Oil/Gas Fields and Saline Formations (Saudi Aramco, 2023)
- Standardization of capture technology and project configuration to reduce transaction and engineering costs (International Energy Agency, 2024).

### **4.3 Increasing system-level effectiveness**

The combining of systems is an important tool that goes beyond the costs related to individual assets (International Renewable Energy Agency, 2024):

Integration in power, hydrogen, along with water preheating water or powering extra equipment with waste heat from electrolysis or ammonia synthesis; link electrolyzers to desalination plants, where seawater is desalinated to reduce water quality for electrolysis and energy flows between units are maximised (ThyssenKrupp, 2023).

#### *4.3.1 Green-blue hybrid configurations*

Early on, Saudi efforts might combine green and blue hydrogen through a single cluster, sharing export infrastructure and gradually raising the green share as costs decrease to facilitate the transition (BloombergNEF, 2024).

#### *4.3.2 Buffering and storage*

Separating variable renewable generation from perpetual export obligations through intermediate hydrogen storage (such as compressed storage tanks or subterranean

salt mines where geology approvals are required) increases the use of expensive downstream infrastructure (Hydrogen Council, 2023).

#### *4.3.3 Water efficiency*

To decrease general water consumption, high-efficiency desalination processes and water reclamation programs should be put in place (International Desalination Association, 2023). This is fundamental from an economic and environmental standpoint.

All of these actions reduce the actual price per supplied unit of hydrogen or ammonia and increase the system's overall energy efficiency (International Energy Agency, 2024).

### **4.4 Export, storage, and logistics optimisation**

Logistics may make in an important part of the total delivered cost for hydrogen that is being prepared for export (Bloomberg NEF, 2024). Saudi Arabia has an array of possibilities for action:

#### *4.4.1 Port and terminal optimization*

Is the development of combined shipping terminals, which minimize between-terminal transportation journeys and pump energy through integration of energy from renewable sources, manufacturing of hydrogen, nitrogen synthesis, tanks for storage, and transportation facilities (Saudi Ports Authority, 2023).

#### *4.4.2 Shipping economies of scale*

Include lowering unit shipping costs by chartering or cooperating on enormous chemical transporters and specialized hydrogen vessels (Kawasaki Heavy Industries, 2023).

#### 4.4.3 *Optimizing routes and arranging them between Saudi ports and significant importing hubs*

(which include Europe's northwest, Japan, Korea, and Singapore) with the goal of decreasing transit times and port congestion is referred to as strategic import choice (Hydrogen Council, 2023).

#### 4.4.4 *Comparison of pipeline vs. shipping*

While feasible, consider distant pipeline options to neighboring countries or within the GCC, which can prove more effective than freight for local trade (International Energy Agency, 2024).

### 4.5 AI, digitalization, and sophisticated analytics

Digital technologies are an efficient cross-cutting lever that boosts productivity while lowering costs (Siemens Energy, 2023):

**Predictive maintenance** - reduces service expenses as well as downtime by using detectors and artificial intelligence models to foresee breakdowns in pumps, air compressors, and electrolytes (McKinsey & Company, 2024).

**Optimal dispatch and planning:** Based on market prices, storage levels, and current renewable output, algorithms can continually schedule the creation of hydrogen (Bloomberg NEF, 2024).

**Supply chain optimization:** The digital twin models of the entire hydrogen export chain, from clean energy sources to foreign ports, have the ability to identify obstacles, test different scenarios, and evaluate economics under various demand and price circumstances (Accenture, 2023).

**Measurement, reporting, and verification (MRV):** To be able to certify the sustainability profile of sent hydrogen, which will have a significant impact on its value and acceptance in nations that impose demanding carbon emissions regulations, digital MRV systems are crucial (CertifHy, 2023).

## 5 REGULATORY ENABLERS AND POLICY TOOLS

### 5.1 Industrial clusters and investment incentives

Policy encouragement is essential for early deployment, given the financial intensity of hydrogen projects (Clean Energy Ministerial, 2024):

**Special economic regions and industrial clusters** - Setting up hydrogen and ammonia clusters in new areas (such as the Red Sea and Arabian Gulf coasts, or the area surrounding NEOM) with suitable land, infrastructure, and regulatory conditions (NEOM, 2024).

**Low-cost land, rebates on taxes, and exemptions from customs** lower project costs up front and encourage local production (e.g., electrolysers, tanks for storage, specialised valves) (Saudi Arabian General Investment Authority, 2023).

**Public-private agreements (PPPs)** are co-investment agreements wherein private firms and foreign partners contract risk with government organizations (like national oil companies or public investment funds) (Saudi Public Investment Fund, 2023).

### 5.2 Long-term pricing and offtake strategies

Reliable income streams are required for builders and lenders to back up their substantial expenditures (Hydrogen Council, 2024). Saudi policy may assist with this by:

**long-term purchase contracts**, often in stable exchange rates, with foreign dealers, industrial clients, and utilities (European Commission, 2024).

**Contracts for difference (CfDs)** minimize volatility in the market by guaranteeing an initial cost for hydrogen that is low in carbon in relation to a fossil base (International Energy Agency, 2023).

**Assistance with pilot projects that generate domestic anchor interest**, like the co-generation of ammonium in power plants, the use of gas in petroleum products and refinement, and the decarbonization of local steel (Saudi Green Initiative, 2023).

## 6 CASE STUDIES AND APPLICATIONS

### 6.1 NEOM Green Hydrogen Project

Co-location of renewables, electrolysis, desalination, and ammonia synthesis, minimizing electricity and water transportation losses (NEOM, 2024); A carefully constructed blended renewable lineup improving electrolyser utilization; Use of modern electrolysers with high effectiveness and flexible design (Air Products, 2023); Digital control mechanisms that maximise energy flows, upkeep, and shipment schedules (Siemens Energy, 2023).

This effort acts rather than just as an export hub yet also as a growing platform that offering data and expertise to reduce expenses for succeeding operations (BloombergNEF, 2024).

### 6.2 Blue hydrogen from gas developments with CCS

In the eastern section of the nation, massive natural gas expansions and current industrial structures present a possibility for blue hydrogen communities (Saudi Aramco, 2023).

Here, fossil-based gas power plants connect with:

- High-catch-rate CO<sub>2</sub> collection systems (Global CCS Institute, 2023);
- CO<sub>2</sub> pipelines to neighbouring preservation sites or better oil recovery operations (Saudi Aramco, 2023);
- Ammonia plants as well as shipping terminals (International Energy Agency, 2024).

#### 6.2.1 Cost and Efficiency Levers are comprised of the following

- Infrastructure of joint CO<sub>2</sub> transport and storage by various emitters;
- Established methane management practices for upstream and midstream activities (International Energy Agency, 2024);

- Integration of steam and heat between plants, CCS plants, and other industrial collaborators (BloombergNEF, 2024).

There should be coordination between all stakeholders to ensure there's [optimal integration]. These clusters may be capable of offering low-carbon hydrogen and ammonia on a short-to-medium term basis, supporting export plans while scalable "green" hydrogen volumes expand (Hydrogen Council, 2023).

### **6.3 Export corridors to Europe and Asia**

Saudi Arabia is also strategically located to serve either the European or the Asian market through shipping routes passing through either the Red Sea or the Arabian Gulf (Hydrogen Europe, 2023). The Kingdom can:

- Establish standard export routes with guaranteed quantities, periodicity of shipment, and uniform certification (CertifHy, 2023);
- Coordinate importations to co-optimize receiving terminals, reconversion units, and power/industrial use (European Commission, 2024);
- Apply digital technologies to simulate end-to-end logistics networks, including renewable energy sources and hydrogen-producing facilities, all the way to the destination ports in other countries (McKinsey & Company, 2024).

These case studies illustrate that cost-cutting is a means not only at a plant level but at a system level and international level as well (International Energy Agency, 2024).

## **7 ROAD MAP TO REDUCING COSTS AND INCREASING EFFICIENCY THROUGH 2030 AND BEYOND**

It can be implemented through a phased roadmap (Saudi Vision 2030, 2023).

### **7.1 Phase 1 (2024–2027): Demonstration and capability**

- Finish and operate first-of-kind large-scale green and blue hydrogen plants, which will provide real-world operating experience (NEOM, 2024).
- Development of hydrogen governing structures, standards, and certification (Saudi Standards, Metrology and Quality Organization, 2023).

- Activate industrial clusters and start the localization of main components (such as mounting structures, cables, and some electrolyser parts) (Saudi Arabian General Investment Authority, 2023).
- Establish digital twin and advanced analytics pilots in chosen projects (Siemens Energy, 2023).

## **7.2 Phase 2 (2027-2030): Scaling & Cost Optimization**

- Increase capacity for generating hydrogen using renewable energy and upgrade designs for hybrid power plants (International Renewable Energy Agency, 2024).
- Apply Phase 1 learnings to implement standardized designs, minimize engineering and procurement expenses, and enhance construction schedules (BloombergNEF, 2024).
- Use CCS hubs and CO<sub>2</sub> transportation and storage infrastructures on a larger scale in those places where blue hydrogen can still be viable (Global CCS Institute, 2023).
- Enter into long-term offtake agreements and CfDs with major importers (European Commission, 2024). This step would have the effect of making projects more bankable and reducing the cost [risks].
- Accelerate skills development programs to have an adequate local technical workforce (Saudi Green Initiative, 2023).

## **7.3 Phase 3 (2030-2040): global cost leadership and system integration**

- Continue with technological advancements: next-generation electrolysers, better catalysts, and membranes (Hydrogen Council, 2024).
- Assess and potentially use alternative means of transport (e.g., LOHCs or liquefied hydrogen) when these alternatives become economical (Hydrogenious LOHC Technologies, 2023).
- Increased use of hydrogen in the energy mix (power, industry, transport), thereby reducing emissions and developing flexible demand that can stabilize the level of exports (Saudi Green Initiative, 2023).

- Raise the profile of Saudi Arabia as an innovation centre for hydrogen knowledge and technology, and an exporter not only of molecules but also of engineering and digital solutions (Saudi Vision 2030, 2023).

#### **7.4 Implications for Saudi hydrogen export ambitions**

Applying the cost levers and efficiency levers as presented in this paper will enable Saudi Arabia to (BloombergNEF, 2024):

1. LCOH can be lowered significantly to a [competitive level] – primarily due to low-cost renewables, decreasing electrolysis costs, efficient CCS, and optimal logistics (International Renewable Energy Agency, 2024).
2. Provide certified low-carbon hydrogen and ammonia – Satisfying tough import conditions in Europe and East Asia, and possibly enjoying market power because of trustworthy and low-carbon supply (European Commission, 2024).
3. Attract large-scale private & International investment - Through the creation of easy regulatory environments and risk-sharing structures, among other aspects (Hydrogen Council, 2024).
4. Develop domestic [industries and capabilities] - New industries such as equipment manufacturing and engineering services, high-value jobs, and more resilient energy systems in the Kingdom (Saudi Green Initiative, 2023).
5. Strengthen geopolitical and economic [position] - Harnessing hydrogen exports as an energy diplomacy tool, solidifying Saudi Arabia's role as an important energy source in a decarbonised world (Saudi Ministry of Energy, 2023).

## **8 CONCLUSION**

Hydrogen is at the forefront of Saudi Arabian plans to ensure the country retains superpower status in the energy sector within the globally decarbonised economy (Saudi Vision 2030, 2023). Although the competitive scene is changing rapidly, the future viability of hydrogen exports from Saudi Arabia would depend on the country's ability to make its hydrogen industry more cost-effective (International Energy Agency, 2024).

This paper has discussed how, on the basis of its special strengths, such as abundant solar and wind energy, gas reserves, infrastructure, and project execution

capacity, Saudi Arabia can aggressively pursue a strategy of cost-cutting and removal of inefficiencies by means of (BloombergNEF, 2024):

- Continuous reduction in cost and improved use of renewable energy sources (International Renewable Energy Agency, 2024)
- Localisation and learning on electrolyser production and CCS technology (Hydrogen Council, 2024);
- Unified plant design integrating power, water, hydrogen, and export functions (International Energy Agency, 2024)
- Optimisation of infrastructure and logistics for long-distance exports (Hydrogen Council, 2023); and
- Digitalisation and analytics to drive maximum asset performance and enable sound carbon accounting (McKinsey & Company, 2024).

With the support of focused policy tools, industry clustering, partnerships, as well as investments in human capital and innovation, such policies can possibly make Saudi hydrogen financially efficient as well as a low-carbon option (Clean Energy Ministerial, 2024). Through this, hydrogen would finally have the potential to be one of the integral parts of Saudi Arabia's plan for the year 2030 (Saudi Vision 2030, 2023).

**Table 1**

*Contrastive Study of Green vs. Blue Hydrogen Production Pathways in Saudi Arabia*

Parameter	Green Hydrogen (Electrolysis)	Blue Hydrogen (SMR/ATR + CCS)
Primary Energy Source	Solar PV, Wind	Natural Gas
Current LCOH (2024)	\$4.0-6.0/kg	\$2.5-4.0/kg
Target LCOH (2030)	\$1.5-2.5/kg	\$1.0-2.0/kg
CO <sub>2</sub> Emissions	Near-zero (operational)	0.5-2.0 kg CO <sub>2</sub> /kg H <sub>2</sub> (depending on capture rate)
Water Requirement	9-10 kg H <sub>2</sub> O/kg H <sub>2</sub>	2-3 kg H <sub>2</sub> O/kg H <sub>2</sub> (cooling)
Key Cost Driver	Renewable electricity (50-70%)	Natural gas feedstock (30-40%)
Technology Maturity	Commercially proven, scaling up	Mature, CCS integration developing
CAPEX Intensity	High (electrolyzer + renewables)	Moderate (reformer + CCS)
Carbon Certification	Easier (near-zero emissions)	Requires rigorous monitoring
Saudi Advantage	High solar irradiance, land availability	Abundant gas reserves, existing infrastructure
Export Market Preference	Premium pricing, strict EU standards	Transitional solution, price competitive
Scale-up Timeline	2025-2035 (large-scale deployment)	2024-2030 (early mover advantage)

**Table 2**

*Key Policy Instruments and Investment Incentives for the Saudi Hydrogen Sector*

<i>Policy Tool</i>	<i>Description</i>	<i>Target Outcome</i>	<i>Implementation Phase</i>
<i>Special Economic Zones</i>	Dedicated hydrogen/ammonia clusters with streamlined regulations	Attract investment, reduce bureaucratic costs	Phase 1 (2024-2027)
<i>Tax Rebates &amp; Customs Exemptions</i>	Reduced tariffs on imported equipment, tax holidays for first 5-10 years	Lower upfront CAPEX, encourage local manufacturing	Phase 1-2 (2024-2030)
<i>Long-term Offtake Agreements</i>	10-20 year purchase contracts with fixed/indexed pricing	Revenue certainty, project bankability	Phase 2 (2027-2030)
<i>Contracts for Difference (CfDs)</i>	Government guarantees minimum hydrogen price vs. fossil baseline	Risk mitigation for investors	Phase 2 (2027-2030)
<i>Low-Carbon Certification</i>	National certification scheme aligned with EU/ISO standards	Market access, premium pricing	Phase 1-2 (2024-2030)
<i>Public-Private Partnerships</i>	Co-investment with PIF, Saudi Aramco, ACWA Power	Risk sharing, technology transfer	Phase 1-3 (2024-2040)
<i>R&amp;D Grants &amp; Innovation Funds</i>	Funding for electrolyzer localization, CCS optimization, digital solutions	Technology advancement, cost reduction	Phase 1-3 (2024-2040)
<i>Skills Development Programs</i>	Training initiatives for hydrogen technicians, engineers, operators	Local workforce capacity, employment creation	Phase 2-3 (2027-2040)
<i>Domestic Anchor Demand</i>	Mandates for hydrogen use in refineries, steel, ammonia production	Guaranteed domestic offtake, market stimulus	Phase 2-3 (2027-2040)

**Table 3**

*Major Saudi Hydrogen Export Corridors and Target Markets*

<i>Export Route</i>	<i>Carrier Type</i>	<i>Target Markets</i>	<i>Distance (approx.)</i>	<i>Key Infrastructure Requirements</i>	<i>Estimated Timeline</i>
<i>Red Sea Route</i>	Ammonia (NH <sub>3</sub> )	Northwest Europe (Rotterdam, Hamburg)	6,000-7,000 km	NEOM production hub, Yanbu port expansion, ammonia carriers	2026-2030
<i>Arabian Gulf Route</i>	Ammonia (NH <sub>3</sub> )	East Asia (Japan, South Korea, Singapore)	7,000-9,000 km	Eastern Province CCS clusters, Ras Tanura/Jubail terminals	2025-2028
<i>GCC Pipeline Network</i>	Compressed H <sub>2</sub>	UAE, Qatar, Oman, Kuwait	500-1,500 km	Regional hydrogen pipeline grid, cross-border agreements	2028-2035
<i>Suez Canal Route</i>	Liquefied H <sub>2</sub> (LH <sub>2</sub> )	Mediterranean Europe (Italy, Greece)	4,000-5,000 km	Cryogenic storage facilities, specialized LH <sub>2</sub> carriers	2030-2040
<i>Direct Asia Route</i>	Ammonia/LOHC	India, China	8,000-10,000 km	Multiple loading terminals, strategic partnerships	2030-2040

**Table 4***Technology Learning Curves and Cost Reduction Projections*

Technology Component	Current Cost (2024)	Projected Cost (2030)	Learning Rate	Key Drivers
PEM Electrolyzer	\$800-1,200/kW	\$300-500/kW	15-20% per doubling	Manufacturing scale, stack improvements
Alkaline Electrolyzer	\$400-700/kW	\$200-350/kW	12-18% per doubling	Standardization, bulk procurement
Solar PV (utility-scale)	\$0.015-0.020/kWh	\$0.010-0.015/kWh	20-25% per doubling	Efficiency gains, module costs
Wind Power (onshore)	\$0.020-0.030/kWh	\$0.015-0.025/kWh	10-15% per doubling	Turbine size, capacity factors
Carbon Capture (post-combustion)	\$50-80/tonne CO <sub>2</sub>	\$30-50/tonne CO <sub>2</sub>	10-15% per doubling	Modular designs, solvent improvements
Ammonia Synthesis	\$300-500/tonne NH <sub>3</sub>	\$250-400/tonne NH <sub>3</sub>	8-12% per doubling	Energy integration, catalyst efficiency
Desalination (RO)	\$0.50-0.80/m <sup>3</sup>	\$0.30-0.50/m <sup>3</sup>	15-20% per doubling	Membrane technology, energy recovery
Hydrogen Storage (compressed)	\$500-800/kg capacity	\$300-500/kg capacity	12-18% per doubling	Tank materials, composite structures

**Table 5***System Integration Opportunities and Efficiency Gains*

Integration Type	Description	Efficiency Improvement	Cost Reduction	Implementation Complexity
Power-Water-Hydrogen	Co-locate renewable generation, desalination, and electrolysis	10-15% overall system	\$0.3-0.5/kg H <sub>2</sub>	Medium
Waste Heat Recovery	Utilize heat from electrolysis for desalination pre-heating	5-8% energy efficiency	\$0.2-0.3/kg H <sub>2</sub>	Low-Medium
Green-Blue Hybrid	Shared export infrastructure, gradual green transition	15-20% CAPEX reduction	\$0.4-0.6/kg H <sub>2</sub>	High
Renewable Hybridization	Solar-wind combination for higher capacity factor	20-30% electrolyzer utilization	\$0.5-0.8/kg H <sub>2</sub>	Medium
Grid Integration	Balance renewable variability with grid connection	10-15% capacity factor	\$0.3-0.4/kg H <sub>2</sub>	Medium-High
Hydrogen Buffering	Intermediate storage decoupling production and export	25-35% infrastructure use	\$0.2-0.4/kg H <sub>2</sub>	Medium
Industrial Clustering	Multiple users sharing pipelines, storage, terminals	20-30% logistics cost	\$0.4-0.7/kg H <sub>2</sub>	High
Digital Twin Optimization	Real-time optimization of entire value chain	8-12% operational efficiency	\$0.2-0.3/kg H <sub>2</sub>	Medium

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### **Authors' Contribution**

All authors contributed equally to the development of this article.

### **Data availability**

All datasets relevant to this study's findings are fully available within the article.

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