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Case study to achieve net-zero using hydrogen energy in Saudi Arabia

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Abstract
This case study argues that hydrogen produced through renewable electrolysis (green) and gas with CCUS (blue) is significant to Saudi Arabia's aim of achieving net-zero emissions by using 2060 within a round carbon financial system framework, by and large thru boom in renewables and clean hydrogen (Saudi green Initiative, 2021; KAPSARC, 2024) [23, 24 15]. It examines how hydrogen can help meet energy demands while protecting energy security and competitiveness. The evaluation encompasses policies, techno-economics, infrastructure, the NEOM Green Hydrogen Company (NGHC) venture, export capabilities, and challenges, which include price, water, CO_2 capture, and certification. The report's major argument is that Saudi Arabia's strong solar and wind sources, financial capabilities, and business base uniquely position it to lead global hydrogen and ammonia exports by the 2030s (IEA, 2022; Al-Saadi *et al*., 2023). However, recognizing that this role relies on integrating hydrogen with domestic decarbonization, accelerating renewables, enhancing CO_2 tracking and storage, and adopting transparent certification that aligns with global markets (IRENA, 2023; IEF, 2024). Review the conclusion, which includes coverage and implementation roadmaps for 2026-2035.

Keywords: Green hydrogen, carbon capture, Saudi Arabia, renewable energy, net-zero emissions

1. Introduction
Net-zero, energy security, and the Saudi context
Saudi Arabia is the world's largest exporter of crude oil and a significant producer of electricity. It holds a pivotal position in global hydrocarbon markets. The government acknowledged the urgency of addressing climate change and the shifting demand for electricity. In October 2021, it set a goal to reach net-zero emissions by 2060. This pledge was announced at the inaugural Saudi Green Initiative (SGI) forum. The goal is based on the Circular Carbon Economy (CCE) framework, which involves reducing, reusing, recycling, and eliminating carbon (Saudi Green Initiative, 2021; KAPSARC, 2024; Climate Motion Tracker, 2024) [23, 24, 15]. The CCE approach focuses on technological innovation and emissions management, not a sudden phase-out of fossil fuels. This reflects Saudi Arabia's role as a leader in hydrocarbons and its ambition to remain a cornerstone of global energy security.

Several advanced economies prioritize long-term decarbonization through swift phase-outs of fossil fuels. In contrast, Saudi Arabia uses a multi-pronged approach. It includes scaling up renewable power, improving performance across sectors, expanding carbon capture, usage, and storage (CCUS), and producing clean hydrogen on an industrial scale (Time, 2022; Weather Movement Tracker, 2024) [25]. This balanced approach enables the kingdom to maintain stable business output and export sales. At the same time, it gradually aligns its energy system with international net-zero goals.

In that framework, hydrogen becomes one of the Saudi pillars of energy transition for the future. Hydrogen is especially appealing because of its range of uses: it can decarbonize difficult-to-abate industry (e.g., steel, refining, chemicals); serve as low-carbon fuel for heavy transport, as well as shipping and aviation; and offer dispatch able energy generation if deployed as a fuel such as ammonia coffering (CSIS, 2021; NDMC, 2024; ISA-GHIC, n.d.) [10, 19, 14]. Most important, hydrogen enables the kingdom to remain a valued exporter of strength, but now in the shape of a decarbonized power vector, instead of hydrocarbons themselves.

This paper considers in an exploratory manner the role that hydrogen can play in sifting through and to sound out Saudi Arabia's prospective net-zero targets and the need to square the circle with regard to energy security, climate responsibility and economic diversification in the Vision 2030 plan. It is collaborating with industry and others to identify the capability roles of hydrogen throughout home and export markets, the enabling expertise and infrastructure, and the coverage and institutional steps needed to deliver on this vision. The discussion also looks at the milestones that will have to be met over the next 15 years for Saudi Arabia to still be taken seriously when it comes to net-zero pledges and for the country to still boast the influence it does today over the management of the world's energy resources.

Policy architecture and strategic objectives

The Circular Carbon Economy (CCE) and net-zero 2060

The Circle Carbon Economy (CCE) is the bedrock of Saudi climate policy, providing a structural mechanism to both reduce emissions and further economic growth. The CCE is based on the foundation of four adjoining pillars: Reduce (twice as much through end-use energy efficiency, fuel switching, and method response); Reuse (through CO_2 use) Recycle (returning carbon back into the economy as a feedstock), and Reject (via natural sinks, carbon capture, use, and storage [CCUS] and direct air capture). Against the linear decarburization method only for the FF sectors, CCE advocates incorporating CCUS, clean fuels, renewable energy layout and power system reform etc into a much broader route (KAPSARC, 2024; Climate Action Tracker, 2024) [15, 8].

Inside this framework, hydrogen emerges as a strategic decarbonized power provider and a CCE enabler. It enables a reduction in emissions by substituting fossil fuels in power-intensive sectors. Alternatively, when coupled with CCUS or used to synthesize low-carbon chemicals, hydrogen supports the recycling and removal dimensions of the CCE. This reinforces its role as a cornerstone of Saudi Arabia's net-zero ambition by 2060.

Renewable targets and power-mix transition

Saudi Arabia's energy-mix trajectory to 2030 suggests an increasing number of formidable diversification techniques. The Ministry of Power has set a target for 45-50% of the united huge power technology to be sourced from renewables by 2030, with the remaining 50-55% to return from thermal technology (Ministry of Power, 2025) [17]. This shift suggests a decisive shift away from a heavy reliance on oil and gas for domestic energy manufacturing, aligning with broader efforts to diversify the economy and weather-related risks.

Consistent with the Saudi Green Initiative, the kingdom currently has 6.2 GW of renewable capacity already connected to the grid, with 44.2 GW under active development and an additional 100-130 GW scheduled to be tendered by 2030 (Saudi Green Initiative, n.d.) [23, 24]. Reaching those milestones might not only drastically reduce the carbon footprint of home electricity generation but also provide the low-carbon power necessary for large-scale electrolytic hydrogen production. Furthermore, the transition should unlock significant volumes of oil and natural gas for higher-fee downstream uses or export markets, reinforcing the kingdom's approach of maximizing the monetary returns from its hydrocarbon sources at the same time as progressing toward net-zero.

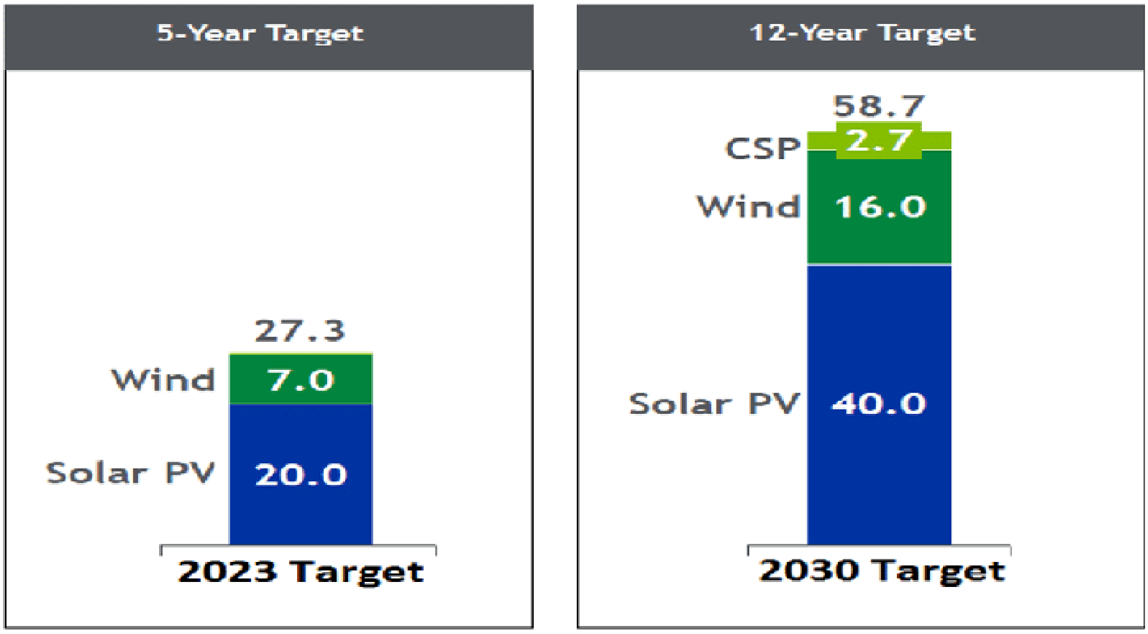

Fig 1: Saudi Arabia Electricity Generation Mix Target for 2030 (Ministry of Energy, 2025) [17].

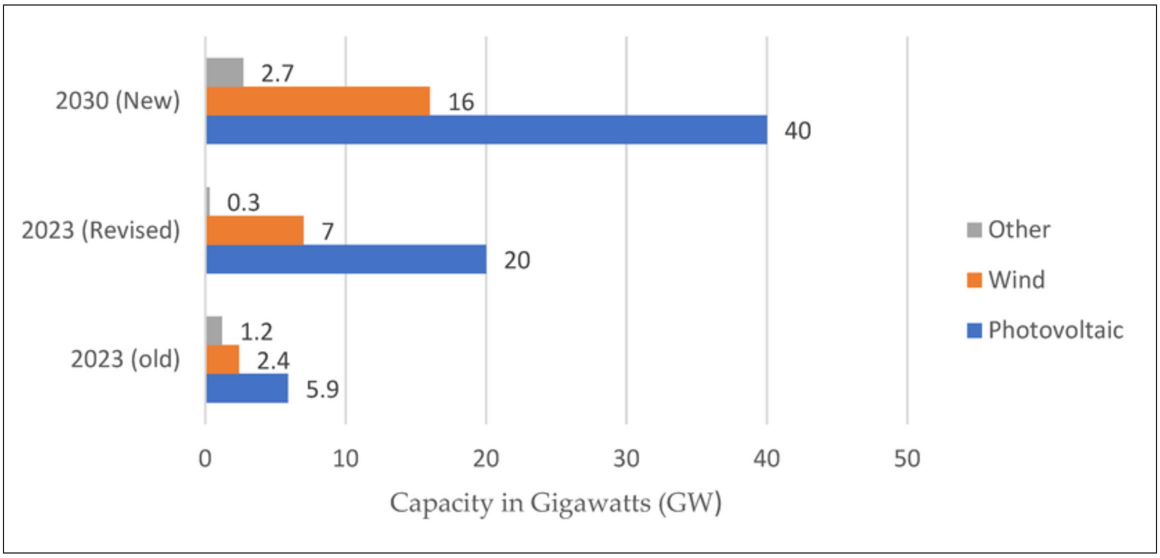

Fig 2: Revised renewable targets of KSA's Vision 2030

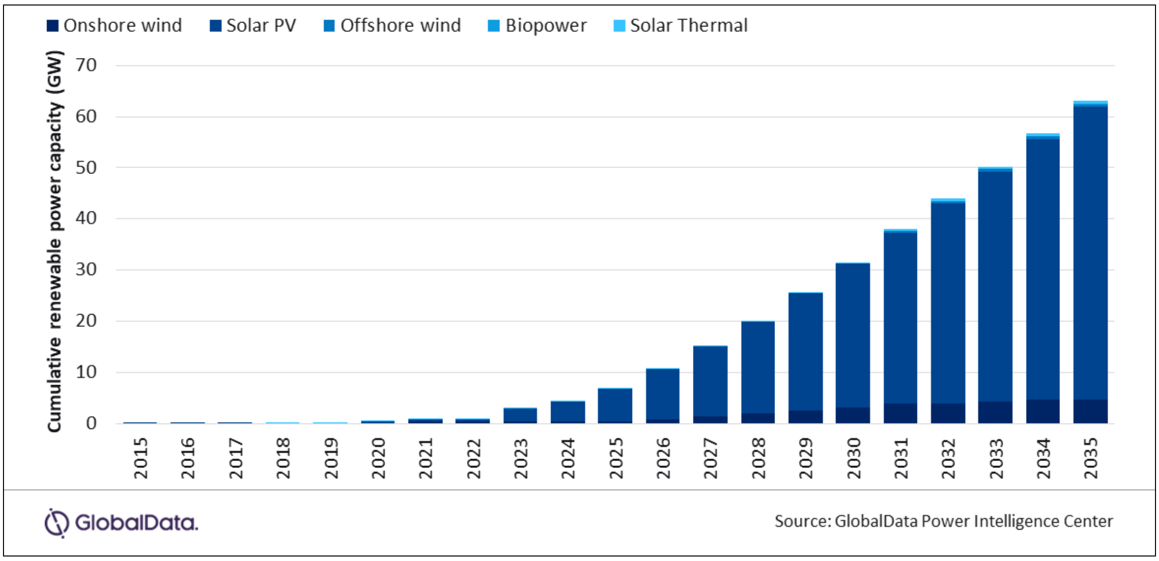

Fig 3: Cumulative renewable power capacity, Saudi Arabia, 2015-2035

National Hydrogen Strategy (in development) and quantified ambitions: Saudi Arabia is finalizing a national Hydrogen approach to manual production (hands-on, non-automated methods), domestic use, and exports throughout two pathways: Green (hydrogen produced using renewable energy) and blue (hydrogen produced from natural gas with carbon capture) (NDMC, 2024; German-Saudi electricity talk, n.d.) [19]. Outside trackers assignment provisional objectives of ~2.9 million tonnes per year (Mt/12 months) are set for 2030 and around 4 Mt/12 months through 2035 for easy hydrogen output, positioning the country among the world's leading suppliers (ISA-GHIC, n.d.) [14]. This aligns with policy statements that Saudi Arabia objectives are to be a leading global dealer of hydrogen, leveraging its superior sun/wind sources, as well as its CCUS (carbon capture, utilization, and storage) capabilities (CSIS, 2021; My.gov.sa, 2024) [10, 18].

Resource endowment and infrastructure advantages

Saudi Arabia's comparative blessings for easy hydrogen consist of (i) international-magnificence sun irradiance and sturdy wind regimes in choose areas (driving low Levelized value of strength, LCOE—meaning the average cost of electricity generation over the lifetime of a project), (ii) huge land availability for gigawatt-scale initiatives, (iii) mature petrochemical and export infrastructure, (iv) geological CO_2 garage potential, drastically in the Rub' al Khali basin and depleted gas reservoirs, and (v) nation-subsidized builders and long-term finance from the public investment Fund and countrywide champions (KAPSARC, 2024; CATF, 2023) [15, 7].

CCUS (carbon capture, utilization, and storage) is not hypothetical: the Uthmaniyah mission has captured ~0.8 $MtCO_2$/12 months (million tonnes of carbon dioxide per year) from natural fuel processing since 2015, transported through an ~ 85 km pipeline for EOR (enhanced oil recovery) injection—providing operational facts on capture, transport, and storage tracking (OGCI, 2021; U.S. DOE CSLF archive, n.d.; SCCS, n.d.) [22].

The flagship: NEOM Green Hydrogen Company (NGHC): NEOM Green Hydrogen Corporation (NGHC) has secured financial close on the first ever US$ 8.4 billion transaction for its flagship project being constructed in Oxygen (NEOM, 2023) [12]. The project makes use of a total of around 4 GW of renewable electricity through electrolysis to produce up to 600 tones of carbon-free hydrogen per day. This hydrogen is to be produced as green ammonia for worldwide shipment (Air Merchandise, n.d., Green Car Congress, 2023). The NGHC aims to open its first phase of operations from 2026 and 2027 (NGHC, n.d.; ACWA Power, n.d.).

In annual terms, 600 t/day is about 0.219 Mt/yr. of hydrogen - a significant milestone for a first export project. Most importantly, NGHC is a key "bankability" proof point for global lenders and deep pocketed commercial purchasers considering the financial viability of large-scale Green fuel projects in the Middle East.

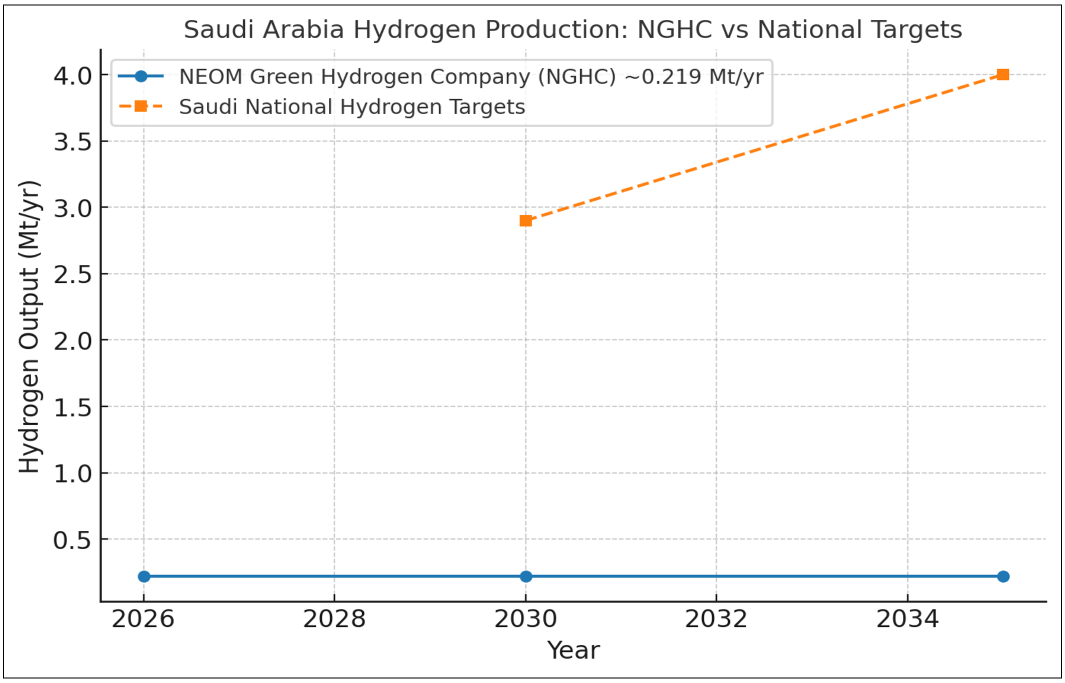

Fig 4: Chart 3. Clean Hydrogen Production Milestones: NGHC vs. indicative national targets (ISA-GHIC, n.d.; NGHC, n.d.) [14].

NGHC's fulfillment will de-chance supply-chain bottlenecks (e.g., huge-format electrolyze shipping, integration of variable renewables, water deliver and treatment, ammonia managing, and offtake contracts), thereby catalyzing a second wave of initiatives within the late 2020s and early 2030s.

Blue hydrogen as a bridge: Aramco's role and CCUS scale-up: Saudi Aramco is growing blue hydrogen and blue ammonia pathways to supplement green production. In 2020, Aramco and SABIC shipped a pilot batch of 40 tonnes of blue ammonia to Japan for power generation assessments—a global first (Aramco, 2020; Ammonia power, 2020) [4]. Blue ammonia and blue hydrogen are produced using fossil fuels but incorporate carbon capture to reduce emissions, whereas green production utilizes renewable energy. More recently, Aramco agreed to acquire 50% of the Blue Hydrogen Industrial Gases enterprise (BHIG) in Jubail from Air Products Qudra to supply hydrogen at scale within the Eastern Province, including lower-carbon versions (Reuters, 2024; Aramco, 2025) [4, 27]. Aramco has also announced a programme of CCUS (carbon capture, utilization and storage) expansion, including a ~9 $MtCO_2$/yr capture and storage hub near Jubail by 2027, and pilots in direct air capture (removing CO_2 directly from the air) to enhance the CCE (circular carbon economy) "remove" pillar (Reuters, 2025) [28]. While critics point out that blue hydrogen depends on sustained high capture rates and verifiable storage permanence, the Kingdom's geology and CCUS operational experience make it one of the few regions capable of delivering this at scale if regulatory and MRV (measurement, reporting, verification) frameworks are strong (CATF, 2023; KAPSARC, 2024) [15, 7].

Techno-economics: costs, water, and system integration

Green hydrogen costs and renewable build-out

In high-irradiance markets like Saudi Arabia, solar PV LCOE is among the world's lowest. Onshore wind sources are also competitive. Both are crucial for reducing the Levelized Cost of Hydrogen (LCOH) via electrolysis. The Ministry of Energy's power mix target—45-50% renewables by 2030—is a foundational enabler (Ministry of Energy, 2025) [17]. Stakeholders should accelerate investment and policy implementation to realize these renewable targets and unlock hydrogen's full potential.
However, green hydrogen LCOH remains highly sensitive to electrolyser CAPEX/OPEX, capacity factors, and financing costs. The NGHC financial close demonstrates lenders' increasing comfort with the risk profile when long-term offtake is secured and policy support is credible (NEOM, 2023) [12].

Blue hydrogen costs and capture rates

Blue hydrogen charges are ruled through fuel feedstock prices, capture plant CAPEX, power consequences, and CO_2 transport and storage. Saudi Arabia's access to low-cost gasoline and the ability to establish commercial clusters can make blue hydrogen cost-effective in the near term. However, climate integrity requires excessive seize costs (≥ 90-95%) and minimized methane leakage throughout the gas supply chain. And on the supply side, it is straightforward requirements and fair verification that will decide market attractiveness-particularly within the EU and in Japan-where "easy hydrogen" definitions are increasingly premised on lifecycle emissions benchmarks (CATF, 2023; Climate Movement Tracker, 2024) [7, 8].

Water requirements and circularity

"Electrolysis relies on pure water and in dry regions, that adds extra stages of desalination and processing, which adds to cost and environmental impact such as brine spread and power consumption. The location on the coast is key in solving water logistics for NEOM. (KAPSARC, 2024) [15].

Grid integration, storage, and flexibility

For large-scale hydrogen production, electrolysis do provide location-side flexibility, these contraptions that use power to split water into hydrogen and oxygen can be dialed back to absorb surplus solar and wind power. This reduces curtailment (reduction in delivery of renewable power when output exceeds supply) and stabilizes the grid. Hydrogen/ammonia mills and gas cells that might be able to generate electricity in response to demand, as appropriately stored and converted stored hydrogen or ammonia are expected to do (see Chapter 10 on batteries). Saudi grid planners priorities the issue of how to deal with the practical (intermittent) nature of renewables, including better grid infrastructure and power storage solutions (KAPSARC Futures, 2024) [15]. Co-optimized hydrogen production + grid balancing services can then go from the former-winner-takes-all-'math'-that-adds-revenue-arbitrage-across-two-industries, to both industrial AND market sector 'wins.'

Markets and off take

Export vectors: Ammonia first

Within the 2020s, ammonia is expected to stand out as the most bankable export vector for hydrogen, primarily due to the existing global shipping and storage infrastructure and established commodity markets. Importantly, ammonia can be utilized without delay—such as for co-firing in energy applications or as a delivery fuel—or it can be cracked to hydrogen at its destination. While Japan and South Korea are early adopters, Europe could capture significant market opportunities if it aligns certification and develops supporting infrastructure (Aramco, 2020; Hydrogen Perception, 2022) [4].

Domestic demand: refining, chemicals, steel, and heavy transport

Locally, low-carbon hydrogen can decarbonize refining (desulfurization), ammonia/methanol manufacturing, and steel production through DRI (direct reduced iron). In transport, hydrogen or ammonia could be used as fuel for heavy trucks, buses, and potentially rail vehicles, while e-fuels produced from hydrogen represent an important longer-term opportunity for decarbonizing aviation. Aramco's 2019 hydrogen fueling station pilot with Air Products suggests a nascent mobility atmosphere (Aramco, n.d.).

Risks, critiques, and credibility tests

Enthusiasm for and skepticism of Saudi Arabia's plan are both nature rational for any such grand design. Its proponents praise a mix of assets, financial strength and business acumen; sceptics fear this gale of advocacy. If American oil output builds per domestic decarburization policy is held up in Congress (Time, 2022; Weather Movement Tracker, 2024) [25], shouldn't that means Saudi Arabia's green electricity campaign is going to go down the tubes a bit?

Three credibility checkpoints are outstanding

1. Renewables rate: Entirely meeting the ambitious goals in the 45-50% of renewables in electricity the government targets for 2030 requires a huge expansion of the system, plus a plan of grid reinforcement and storage (Ministry of Power, 2025; SGI, n.d.) [17] \ 45%. Green hydrogen prices are higher still if renewables deployment lags, and the power system emissions begetting them will struggle to catch my heels on the net-zero path.

2. CCUS integrity: Admission of blue hydrogen contingent on high, proven capture rates and low methane leakage. Saudi geology is favorable an example is provided by Saudi geology (though, as equally importantly, we need to replicate around the world ever larger multinational $MtCO_2$/yr hubs fully MRV-recognized (OGCI, 2021; CATF, 2023; Reuters, 2025) [22, 28, 7].

3. Harmonization of certification: Export markets are lowering the levels of lifecycle emissions thresholds and increasing proof of origin. To not strand belongings, KSA producers must comply with the buyer-market rules (i.e., inexperienced power tempo matching for blue hydrogen also, as well as methane standards).

Execution roadmap (2026-2035)

The operation of NEOM's green hydrogen plant, which will produce approximately 0.219 million tons per year of green hydrogen, will be reviewed, particularly between 2026 and 2027. To validate several electrolysis frameworks, as well as water desalination and logistics (NGHC, n.d.; NEOM, 2023) [12], hydrogen will be used as ammonia. Meanwhile, the carbon capture, utilization, and storage facility in Jubail will grow to a massive capacity of approximately 9 million tons of CO2 per year, supporting blue hydrogen and global commercial decarburization (Reuters, 2025) [28].

From 2028 to 2030, attention shifts to scaling. Renewables' potential will extend to forty-four.2 GW below improvement to over 100 GW tendered (SGI, n.d.), enabling less expensive, Green hydrogen. Locally, grey hydrogen in refineries and ammonia plants will be replaced by blue and green options, while pilots in shipping fuels-which include ammonia bunkering and co-firing-will examine international adoption.

By 2031-2035, the roadmap targets commercial transformation. Hydrogen-based steelmaking and extended green/blue ammonia and methanol production will serve each other's exports and nearby markets. Additional multi-GW electrolysis tasks will be constructed at lower generation fees and through neighborhood delivery chains, while robust tracking and reporting (MRV) will ensure lifecycle emissions transparency to maintain competitiveness and coverage backing.

Case study synthesis

Saudi Arabia's hydrogen strategy appears credible for three structural reasons. First, cost arbitrage: low renewable Levelized Cost of Energy (LCOE)-the average net present cost of electricity generation over a plant's lifetime-and competitively priced gas with carbon capture, utilization, and storage (CCUS) can yield cost-effective green and blue hydrogen, hedging market risks (Ministry of Energy, 2025; SGI, n.d.; CATF, 2023) [17, 7]. Second, mission finance and national capacity: the NGHC's USD 8.4 billion transaction signals international lender confidence in Saudi megaprojects (NEOM, 2023) [12]. Third, export infrastructure and industrial clusters: extensive experience in hydrocarbon logistics, petrochemicals, and CCUS hubs accelerates time-to-market relative to new entrants (OGCI, 2021; Reuters, 2024, 2025) [22, 27, 28].

But, achievement depends on three "ifs"

1. If renewables build-out fits targets,
2. If CCUS is scaled with strong MRV and methane manipulation, and
3. If certification aligns with client rules to release the top rate off take

Recommendations

Saudi Arabia should formalize its national Hydrogen strategy, with explicit 2030 and 2035 waypoints, such as the capacity, lifecycle emissions, and water standards, fully integrated with strength-place planning and power grid investments (e.g., NDMC, 2024; German-Saudi electricity agreement, n.d.) [19]. This would require an acceleration of tenders of renewable and integration in the grid to over 100 GW with the support of 2030 to reduce the price of green hydrogen and increase the load factors of the electrolyzes (Saudi Green Initiative, n.d.; KAPSARC Futures, 2024) [15, 23, 24]. Moreover, a national hydrogen certification scheme which aligns with European, Japanese and Korean systems-implementing hourly renewable performance matching for Green hydrogen and 95 percent capture with strict methane intensity limits for blue hydrogen-might enable fungible export. Moreover, expansion of CCUS hubs beyond Uthmaniyah into multi-$MtCO_2$/12-month Jubail and Yanbu clusters, and third-birthday celebration proven performance records in the public domain, will further contribute to worldwide acceptance (OGCI, 2021; CATF, 2023; Reuters, 2025) [22, 28, 7]. On the other, hydrogen use must focus on decarbonizing homes in refining, chemicals and metals to support nationwide zero-emission targets, not just exports. In terms of water stewardship, it would have to require renewable-powered desalination, and fine brine management, and circular water structures in every single coastal hydrogen venture. Confidence building - Demand side-pilots these include ammonia bunkering and H2-DRI metallic demonstrations and need to be financed to create reference flows which are the basis for near-term adoption across the MENA region.

Conclusion

Hydrogen is a very useful cop as anybody knows who trying to keep Saudi Arabia at the same time both electricity superpower and. It could all change, however. For instance, if the kingdom can rapidly boost renewables; develop "exhaustive" CCS that is both practical and able to last generations; and bring hydrogen and its derivatives into period of low CO 2 production - this decade might pan out differently. The tail-to-tail transformation is also eliminated. But NGHC's pilot for the first wave of wave one shows that it pays. In the next wave, we will play around with integration and provide our own insurance. Even Vietnamese foreign investment in full Lunch Restaurants around the world may be less carbon-productive than what our Saudi hydrogen can achieve.

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