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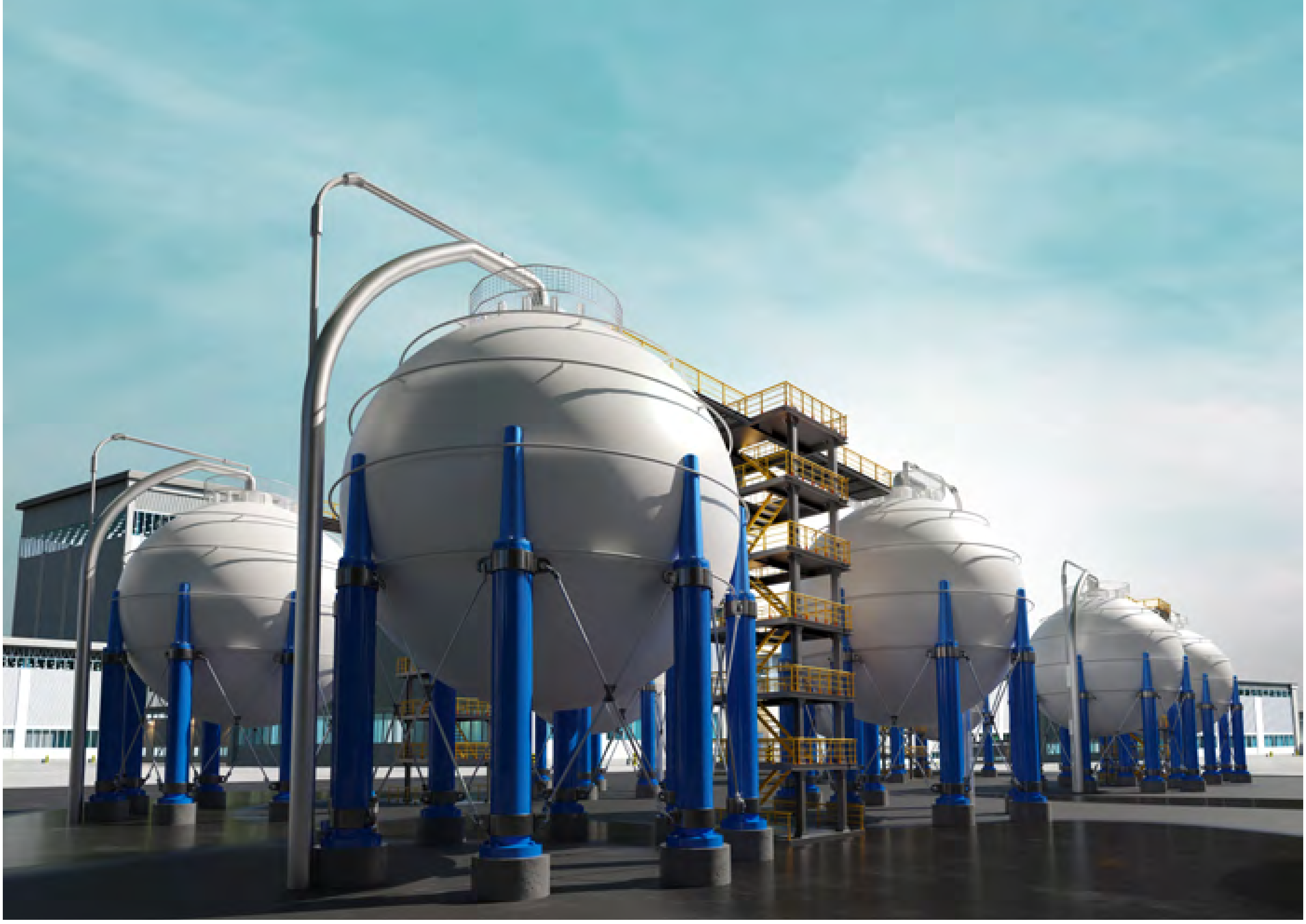
DEVELOPING A CLEAN HYDROGEN INDUSTRY IN QATAR: INVESTMENT COSTS, UNCERTAINTIES, AND CRITICAL DECISIONS

April 2025



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Report

Developing a Clean Hydrogen Industry in Qatar: Investment Costs, Uncertainties, and Critical Decisions

April 2025

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Introduction

1.1 Background

Qatar is a high-income, resource-rich country, with an economy based on the exploitation of its vast fossil fuel reserves, particularly natural gas. As a result of the development of its liquefied natural gas (LNG) and fossil fuel-intensive industries (petrochemicals, fertilisers, aluminium and steel) in the 1990s, between 2000 and 2022 Qatar's GDP grew ten-fold from $18bn to $237bn (in 2022 USD) (The World Bank, 2022). In 2008, the State of Qatar published its National Vision 2030 (QNV2030) (QNV, 2008), calling for the development of strategies to diversify Qatar's economy and transform it into a knowledge-based economy while protecting the environment. In QNV2030, the government acknowledges that it must rethink its current economic model in light of climate change and other environmental considerations.

Since then, however, despite the substantial efforts made to diversify away from hydrocarbon exports and fossil fuel-intensive industries, Qatar's economy has remained highly reliant on both. In particular, the oil and gas sector accounts for more than 50% of GDP, 85% of export earnings, and 70% of government revenues (MOFA, 2021). This makes Qatar's economy vulnerable to fossil fuel price fluctuations in the short term and, in the longer term, to growing international pressure to transition away from using fossil fuels (IEA, 2022; United Nations, 2023). Moreover, increasingly stringent requirements are being placed on the embodied carbon content of fuels and commodities. These new requirements are driven by regulations, such as the EU Carbon Border Adjustment Mechanism (CBAM, 2023), and other initiatives promoted during COP28, such as the Oil and Gas Decarbonization Charter and the Industrial Transition Accelerator that aim to decarbonize the upstream sector and heavy emitting industries, respectively (United Nations, 2023).

Therefore, in an increasingly carbon-constrained world, clean hydrogen[1] provides an opportunity for Qatar to continue to exploit its natural gas resources. This can be achieved by directly exporting clean hydrogen and by using it domestically to reduce embodied carbon in export commodities, such as fertilisers and steel. To develop a clean hydrogen and low-carbon commodity export industry, Qatar can leverage its existing industry know-how and commercial relations. However, the substantial uncertainties that affect the future of both LNG and clean hydrogen markets make developing a hydrogen strategy and roadmap for Qatar a complex exercise. The complexities around the development of a hydrogen strategy for Qatar are yet to be explored.[2] In this report, we seek to characterize uncertainties around future clean hydrogen markets and conduct an initial assessment of possible investment risks and critical decisions involved in developing a clean hydrogen industry in Qatar.

[1] In this report, we use the term "clean hydrogen" to indicate hydrogen the production of which results in very low emissions of CO_2, methane and other GHGs being released into the atmosphere, irrespective of the feedstock and production methods used.

[2] For a discussion of previous relevant studies, roadmaps and strategies, please refer to Appendix I.

1.2 Aim and scope of study

Qatar, like other GCC countries, faces different options in relation to clean hydrogen. This report constitutes an initial step in characterising them. It provides a scenario-based assessment of the investment costs, main uncertainties and critical decisions associated with the different strategies that Qatar could adopt in developing a clean hydrogen industry. This study acknowledges that some of the uncertainties in the scenarios could be further explored using statistical methods, that the risks and rewards could be investigated using financial methods, and possible critical decisions could be studied using various modelling approaches. However, the aim of the study is to gain initial insight into the problem and determine whether it warrants further research.

This report is structured as follows.
Section 2 characterises the existing production and use of hydrogen as industrial feedstock in Qatar, its carbon footprint and the international regulatory drivers for reducing it.

Section 3 provides a comparison of projected international hydrogen trade routes and volumes based on current policies and announcements, with the current LNG trade routes and volumes, from Qatar.

Section 4 provides a discussion of Qatar's current clean hydrogen policy compared with that of the other countries of the Gulf Cooperation Council (GCC).

Building on the options outlined in Section 1.1, **Section 5** presents a set of possible strategies for developing a clean hydrogen industry in Qatar and estimates of the infrastructure investment costs associated with them.

Section 6 presents a comparison of the different strategies and highlights the possible risks and critical decisions associated with them, and

Section 7 provides concluding remarks and ways forward.

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Use of hydrogen in Qatar's industrial sector and decarbonisation drivers

2.1 Current use of hydrogen as industrial feedstock in Qatar and its carbon footprint

A substantial amount of hydrogen is already being produced in Qatar for various industrial uses. The hydrogen is produced from unabated steam reforming of natural gas (SMR), classified as "grey hydrogen". Hydrogen in Qatar is used in the production of naphtha, diesel, jet fuel, LPG, ammonia (NH_3), methanol (CH_3OH), and steel, for a total demand of roughly 1.20 MTPA per year (see Table 1).

This is equivalent to approximately 1.3% of global hydrogen demand. Moreover, driven by the Gas to Liquids (GTL) industry, Qatar produces around 8.3 MTPA of hydrogen-rich syngas, which is converted into hydrocarbons through the Fischer-Tropsch process. The hydrogen in syngas will not be included in the analysis.

Table 1. Demand for hydrogen in Qatar's industry

Industry	Product	Demand	Related Companies	CO_2 Emissions by Grey H_2 (Mt)	Assumptions
Oil Refining	Gasoline (Naphtha) Diesel Jet Fuel Kerosene	225,593 tons of H_2 for 34.675 million of barrels of refined products in 2022[a]	Qatar Energy	2.26	An average value of 0.0065 tons of H_2 per barrel was used[b]
Chemical	Ammonia	678,600 tons of H_2 for 3.77 million tons of Ammonia production in 2021[c]	QAFCO	6.79	180 kg of H_2 is required per ton of produced NH_3[d]
	Methanol	206,454 tons H_2 for 1,101,086 tons of Methanol production in 2022[e]	QAFAC	2.06	0.1875 kg of H_2 is required per kg of CH_3OH produced[f]
Steel	Steel	88,637 tons H_2 for 1,410,254 tons of DRI production in 2022[g]	Qatar Steel	0.89	30% of the reducing gas is assumed to be hydrogen[h]

[a] As per the Sustainability Report (QatarEnergy, 2023a)

[b] Values obtained from literature and corroborated with industry experts (Argonne National Laboratory, 2019)

[c] As per the Sustainability Report (QAFCO, 2022)

[d] Values obtained from literature and corroborated with industry experts (Chehade and Dincer, 2021; North West Hydrogen Alliance, 2022; Rivarolo et al., 2019)

[e] As per the Sustainability Report (Qatar Fuel Additives Company Limited (QAFAC), 2021)

[f] Values obtained from literature and corroborated with industry experts (Boretti, 2013)

[g] As per the Sustainability Report (Qatar Steel, 2023, 2019)

[h] Value indicated by the technology manufacturer (Astoria et al., 2022)

QatarEnergy (Qatar's national oil and gas company), Qatar Fertiliser Company (QAFCO), and Qatar Steel currently produce their own hydrogen for use as a production input. QAFCO supplies Qatar Fuel Additives Company (QAFAC) with hydrogen for plant start-up. Qatar Vinyl Company (QVC), a subsidiary of Qatar Petrochemical Company (QAPCO), produces a relatively low volume of electrolytic hydrogen (not included in Table 1) as a by-product in the manufacture of Caustic Soda (NaOH) and Chlorine (Cl_2) through brine electrolysis. QVC produced 9.9 kilo tons of electrolytic hydrogen in 2020.

Qatar's current hydrogen production has a high carbon footprint: roughly 12 million tons of CO_2 are emitted per year to satisfy the hydrogen requirements of steel and ammonia production and oil refining (see Table 1). This carbon footprint could be substantially reduced by retrofitting current SMR infrastructure with CCS technology, thereby making the hydrogen "blue". This would also reduce the carbon footprint of downstream industrial products, the demand for which is growing as a result of new government policy and voluntary industry commitments. The most significant of such policies is the EU's Carbon Border Adjustment Mechanism (CBAM).

2.2 Drivers for international trade of cleaner commodities: the case of CBAM

The European Union's Carbon Border Adjustment Mechanism (CBAM) is a carbon tariff that covers embodied emissions of commodities imported into the EU in high-emitting sectors, including electricity, hydrogen, cement, aluminium, iron, steel and fertilisers (CBAM, 2023).[3] CBAM has two main goals: 1) to create a level playing field for EU firms subject to EU environmental regulations that are relatively more strict than in other jurisdictions; (2) and to incentivise firms exporting to the EU to accelerate their efforts in combating climate change through reducing embodied GHG emissions in their export commodities.

For the State of Qatar, the EU is a major export market; in Q2 and Q3 of 2024 it accounted for around 25% of total export value (Qatar Chamber, 2024a, 2024b). CBAM could have an impact on the competitiveness of the Qatari companies, both directly when exporting to the EU and indirectly by contributing to strengthening environmental standards in other export markets, such as the USA, Turkey, and South Korea, where most of Qatar's unwrought aluminum is exported to (Qatar Development Bank, 2022).

Figure 1 illustrates the shares of the different commodities exported from to the EU. Fuels and lubricants dominate the picture while chemicals, fertilisers, iron and steel account for a smaller but not insignificant share (Trading Economics, 2022).

[3] Similarly to the case of the EU-ETS, importers must purchase CBAM certificates to offset the embodied emissions of imported products, with each CBAM certificate equaling one ton of emissions. In October 2023, a three-year transitional period started, during which importers into the EU of all commodities that fall within the scope of CBAM are obliged to declare their embodied GHG emissions on a quarterly basis without paying a financial adjustment. From 2026 onwards, CBAM certificates will be required, and their price will be linked to the carbon price of the EU Emissions Trading Scheme (EU-ETS)

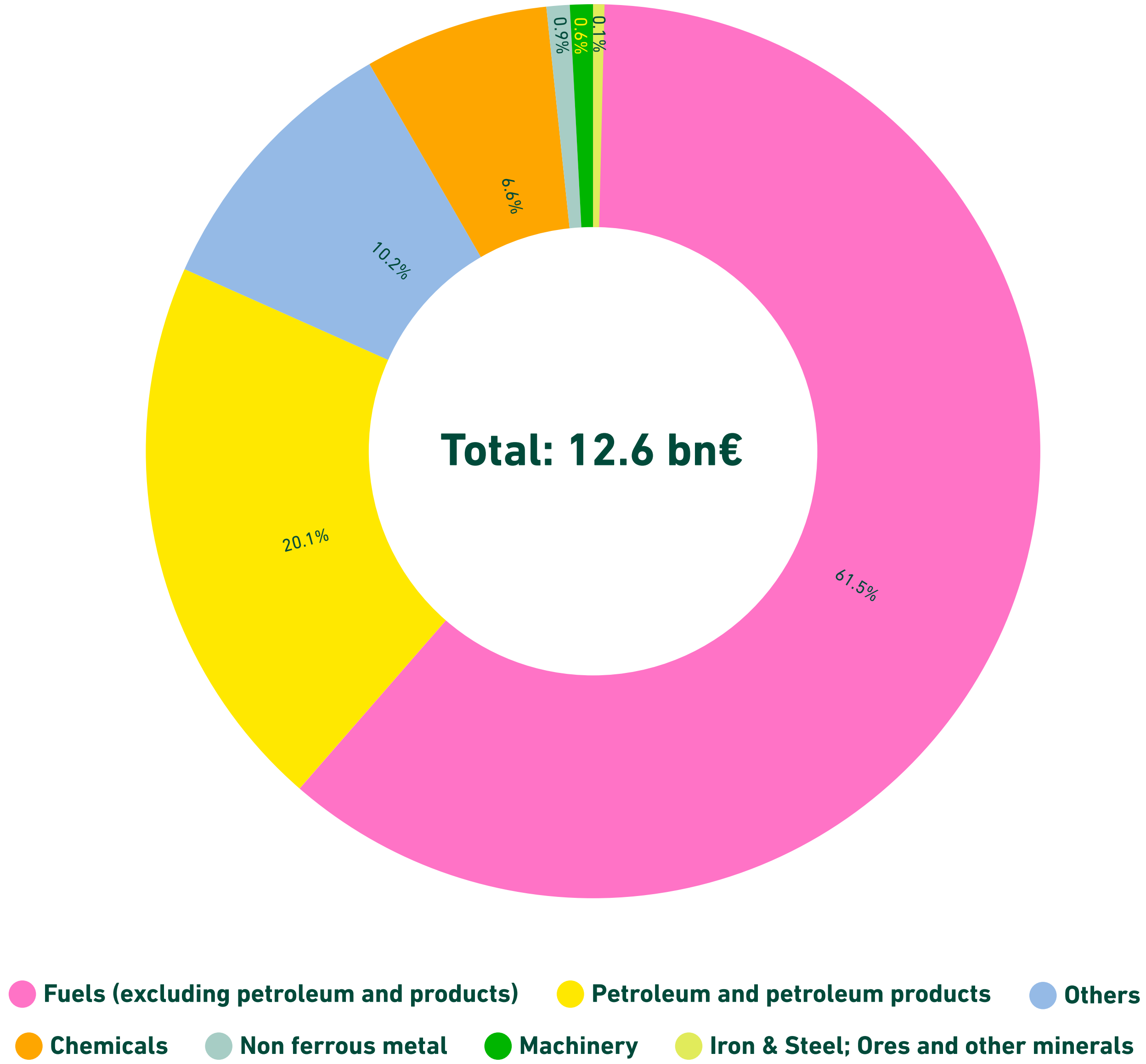

Figure 1. Relative share of main commodities exported by Qatar to different markets by value (Q3-2022) (Qatar Chamber, 2022b).

To align with the embodied carbon regulations for products imported into the EU, and possibly other markets that may follow its lead, Qatar would have to plan and implement measures to reduce carbon emissions associated with the manufacturing of its export commodities.[4] Failure to comply with CBAM results in a default tariff based on the worst-performing EU ETS facilities of the same product, which would affect the competitiveness of Qatari exports.

[4] During the transition period of the CBAM (2023-2025), immediate steps by Qatari producers would include (1) examining the current methodology of greenhouse gas calculation; (2) assessing if CO_2 emissions per product are detailed enough, and (3) determining whether the calculation methodology will allow CBAM requirements to be met. At the same time, technology options for reducing embodied carbon would have to be assessed and, once selected, implemented by 2026.

03

Future projected international hydrogen trade and possible role of Qatar

3.1 Future projected international hydrogen trade

With a growing number of countries and companies showing interest, and several agreements being signed, the international hydrogen market is starting to take shape. However, some agreements may not result in actual trade and therefore the market may change substantially in future. To estimate future hydrogen trade routes and volumes, one can take two different approaches: a) look at current projects, agreement and pledges, or b) at the targets that countries would have to reach in order to deliver on their long-term climate change mitigation goals.

The International Energy Agency's (IEA) 2024 World Energy Outlook (WEO) considers three scenarios: Stated Policies, Announced Pledges, and Net Zero. Hydrogen is included in all these scenarios. However, in the first two, hydrogen market projections are based on current projects, agreements and targets, while in the third they are based on the volumes that would be required to meet long-term climate change mitigation goals, irrespective of current targets. Figure 2 reports the hydrogen demand figures based on the Stated Policies and Announced Pledges scenarios, by region, in 2030 and 2050.

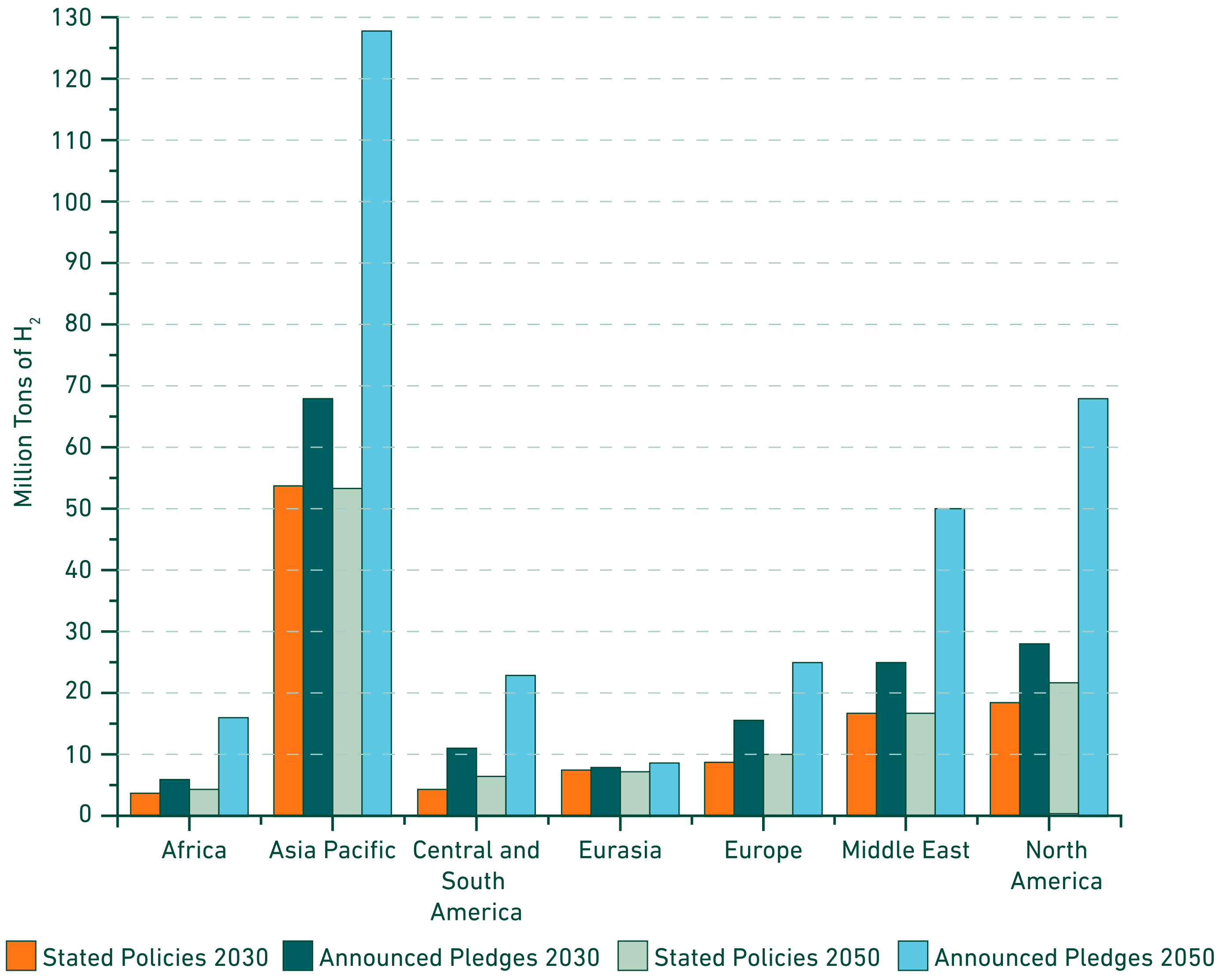

Figure 2. IEA hydrogen demand in main scenarios (International Energy Agency, 2024)

Future projected international hydrogen trade

The IEA scenarios do not specify the end uses of hydrogen and its required purity, which are among the factors influencing the form in which is transported over long distances. Whether the hydrogen is transported pure in liquid form, using a Liquid Organic Hydrogen Carrier (LOHC) or a derivative (ammonia, methanol) has a significant impact on the cost of the infrastructure; hence, to inform this important aspect of the analysis, other sources have been considered where hydrogen demand is broken down by end use: the scenarios from the Hydrogen Council and national targets of those countries that provide such detail.

By doing so, scenarios have been arrived at that, although affected by substantial uncertainty, provide a reasonable range of possible future hydrogen demand levels by end-use sector. These scenarios form the basis of the calculations illustrated in Section 5 where, due to its high purity requirement, it is assumed that hydrogen destined for use in fuel cell road vehicles is transported by liquid hydrogen vessels, while the H_2 for other uses requiring lower purity is transported via H_2 carriers and derivatives.

3.2 Comparison of prospective hydrogen import markets and Qatar's LNG exports

Roughly 35% of Qatar's gas exports go to countries that have disclosed import-oriented hydrogen strategies. The remaining is allocated to countries that either have not developed hydrogen strategies or are focused on producing and exporting it. This is illustrated in Table 2. Additionally, Germany, which is set to start importing Qatari LNG in 2026 for at least fifteen years, has indicated that its hydrogen strategy is import-oriented (QatarEnergy, 2022a).

Table 2. Qatar's Exported Gas Distribution and the customers approach towards H(Belgian Federal Hydrogen Strategy, 2022; EN-H_2 Estratégia Nacional Para o Hidrogénio, 2020; What Role for Hydrogen in Turkey's Energy Future?, 2021; Consejo Económico y Social, 2021; Energy Institute, 2024; Government, 2021; Kowtham Raj & Aayog Pranav Lakhina, 2022; Ministério de Minas e Energia, 2021; Ministerio para la Transición Ecológica y el Reto Demográfico (MTERD), 2020; Ministero dello sviluppo economico, 2020; Ministry of Climate and Environment, 2021; Ministry of Economy and Sustainable Development, 2022; Ministry of Trade and Industry Singapore, 2022; Netherlands Enterprise Agency, 2022; Paris Government, 2020; Sukhankin, 2022; The Government of the Netherlands, 2020)$_2$

Current Gas Customer	% of Total Natural Gas Export (2023)	Qatar's NG local Market Share	H_2 Strategy Approach
South Korea	9.22%	21% - 27%	Import
India	11.72%	36% - 42%	Export
China	17.89%	8% - 7%	
Japan	3.13%	11% - 12%	Import
Pakistan	6.88%	70%	-
Taiwan	5.94%	24% - 25%	-
Thailand	3.05%	22.5%	-
Singapore	1.41%	2%	Import
Other Asia Pacific	4.14%		
Italy	5.23%	8%	Import and local production
UK	2.19%	12% - 14%	Export (by 2030)
Belgium	3.59%	13% - 14%	Import and Transit
Spain	1.02%	6%	Export
France	1.80%	1%	Export
Poland	1.48%	12% - 13%	Self-Reliance and potential exporter
Greece		7%	-
Portugal		4.40%	Export
Turkey		0.47%	Export (by 2040-2050)
Netherlands		< 1.32%	Hydrogen Hub
Croatia		< 30%	Potential Export after 2040
Other EU			
Kuwait	4.06%	59.35%	-
UAE	14.92%	96.72%	Export
Other Middle East	1.17%		
Argentina	0.16%	18.9%	Export (by 2050)

Qatar controls different shares of the importing countries' natural gas market, from as low as 0.47% for Turkey to 96.72% for the UAE. The analysis in this report assumes that Qatar will seek to gain shares in the hydrogen market proportional to those it already holds in the NG market in its export destinations. This assumption does not consider the fact that some countries, including Belgium, the Netherlands and Singapore, aim to become regional hydrogen import hubs to satisfy international demand for hydrogen-fueled transport. This may result in even higher export opportunities for Qatar.

04

Qatar's hydrogen-relevant policy within a GCC context

At present, Qatar is the only GCC member that has not released a hydrogen strategy or roadmap, or stated an official position on hydrogen (see Table 3). However, this is not preventing Qatar from playing a role in the nascent hydrogen industry. Qatar announced the development of the largest blue ammonia plant to date with a capacity of 1.2 million tons per annum (MTPA), expected to become operational in the first quarter of 2026 (QatarEnergy, 2022b; Reuters, 2022).

This represents a significant first step in the development of a national clean hydrogen industry. However, building a strategy or roadmap is a key step for any country that intends to become a major player in the hydrogen market. A dedicated strategy or roadmap would put Qatar in a better position to develop a successful hydrogen export industry that builds on its well-established commercial relations with the EU and Asia.

Table 3. GCC H_2 targets, strategies, and roadmaps (Heinemann et al., 2022; Hydrogen Central, 2022; Ibrahim & Hussein, 2021; Ministry of Energy, 2021; Ministry of Energy and Infrastructure, 2023; Ministry of Energy and Minerals, 2022a, 2022b; Nakano, 2022; NEOM, 2023; QatarEnergy, 2022a, 2022b; Sukhankin, 2022)

GCC Member	H_2 Strategy Status	Main Elements of Strategy
Bahrain	Does not have a H_2 Strategy. MOU with Air Products to assess the potential development of a hydrogen economy in the country	• The country is more likely to be producing for local consumption. • H_2 export does not seem to be the main objective.
Kingdom of Saudi Arabia	Does not have a H_2 Strategy. NEOM green hydrogen company Final Investment Decision MOU with Germany on hydrogen production and utilization	• Aims to be the world's largest H_2 exporter. • Clean and Green H_2 are being pursued. • USD 8.4 billion in the world's largest carbon-free green hydrogen plant
Kuwait	Does not have a H_2 Strategy. White Paper published by KFAS	• Clean and Green H_2 are being pursued.
Oman	Green Hydrogen in Oman	• Focuses on Green H_2. • Decarbonizing the local industry is the priority. • 8.5 MT of production by 2050.
Qatar	No announcement	-
United Arab Emirates	National Hydrogen Strategy	• Targets to decarbonize the nation's hard to abate sectors, requiring up to 2.1 MTPA and 10.1 MTPA of clean H_2 by 2031 and 2050, respectively. • Aims to export up to 9.6 MT by 2050. • By 2050 clean and green H_2 will account for 95% of the hydrogen production, while the remaining 5% will be pink H_2.

Qatar's hydrogen-relevant policy within a GCC context

QatarEnergy is focusing on its LNG business and is pursuing a two-pronged strategy. On the one hand, QatarEnergy plans to expand LNG production from 77.8 MTPA today to 142 MTPA in 2030, and on the other, reduce its Scope 1 and 2 emissions through a combination of renewables, carbon capture and storage (CCS), and, potentially, hydrogen.

Neither the State of Qatar nor QatarEnergy have committed to long-term net-zero goals. However, both are taking substantial steps to reduce GHG emissions in the 2030 to 2035 timeframe (Government Communications Office, 2022; QatarEnergy, 2023a). Moreover, the State of Qatar is one of the signatories of the Net-Zero Producers Forum – an alliance of oil and gas producing countries that want to demonstrate their commitment to achieving net-zero GHG emissions by mid-century through collective action – which certainly suggests the intention to reduce the GHG footprint of its exports. This can potentially include the development of clean hydrogen production capacity for use as a chemical feedstock in the domestic industry and possibly for export as an energy vector.

Although neither the State of Qatar nor QatarEnergy have committed to a hydrogen strategy or roadmap, and a strong policy driver for clean hydrogen, such as net-zero targets, is still missing, their approach is potentially conducive to the development of a national clean hydrogen industry. Scaling up CCS in Qatar to reduce Scope 1 and 2 emissions from the production of LNG can pave the way to building the additional carbon capture, utilization and storage (CCUS) capacity that blue hydrogen production would require. At the same time, emphasis on reducing the GHG footprint of Qatar's fossil fuel, petrochemical and other energy intensive industries can provide substantial short-term demand for clean hydrogen. Such demand can be met, to an extent, by retrofitting existing SMR capacity with CCS. However, several possible approaches to developing a clean hydrogen industry in Qatar are possible. In the next section, a small set of alternative strategies are defined based on plausible narratives; the strategies will be quantified based on available evidence and, where necessary, logical assumptions; their implications in terms of uncertainties, risks and critical decisions will be analysed.

05

Analysis of possible clean hydrogen industry development strategies for Qatar

5.1 Definition of possible strategies

Given existing infrastructure and know-how, and a global shift towards reducing embodied emissions of energy-intensive commodities, one option for Qatar is to initially focus on decarbonising existing hydrogen production through retrofitting SMR plants with CCS.

Therefore, the first strategy is called "Cleaning Domestic Industry". This strategy focuses on retrofitting existing hydrogen production with CCS and not pursuing additional clean hydrogen production for export. In this strategy, under the assumption that current regional carbon border regulations will eventually be adopted by other jurisdictions, Qatar takes a conservative approach, seeking to maintain its current market for its export commodities by adapting to the EU regulation.

In the context of this strategy, clean hydrogen could also be used to reduce GHG emissions from natural gas liquefaction, which alone constitutes around half of QatarEnergy's GHG emissions from their LNG operations. While not currently done, the clean hydrogen volume required could exceed that currently used as industrial feedstock in Qatar.[5] Building blue hydrogen capacity for natural gas liquefaction while cleaning existing hydrogen production for industrial uses could generate scale economies in both hydrogen production and CCS, de-risking further investments. This effect is not formally included in the analysis of hydrogen strategies.

A more aggressive approach would be for Qatar to take advantage of domestic low natural gas production costs and availability of CCS capacity to expand its production of energy-intensive export commodities. This strategy is called "Clean Industry Expansion". This is in line with the UAE's strategy, which prioritises domestic use of clean hydrogen over export (Ministry of Energy and Infrastructure, 2023).

In this strategy, hydrogen in industry could be used as a chemical feedstock and as a fuel for high-grade heat generation, While both use cases are potentially feasible, the latter is more technically challenging and therefore, the quantitative analysis of investment costs presented in the following sub-sections does not include the use of hydrogen for high-grade heat generation.

Another approach is to accompany clean hydrogen production for use in the domestic industry with additional capacity for hydrogen export. Given the high level of uncertainty associated with global hydrogen trade, Qatar could adopt a cautious approach and only build hydrogen capacity once the demand for hydrogen and its derivatives materializes. This strategy is called "Cautious Hydrogen Exporter". While the strategy is relatively safe, by being a follower in the global hydrogen market, Qatar will not be able to shape the market and gain the market shares it is potentially capable of.

Finally, the most aggressive approach would be to combine the expansion of domestic clean commodity manufacturing with being an early mover in the development of hydrogen production for global markets. This strategy is called "Major Hydrogen Exporter". In this strategy, Qatar can seek to shape future hydrogen markets and influence the development of standards that do not deprioritise "blue" hydrogen over "green". It could also take the lead in developing and scaling up new technologies for producing hydrogen from natural gas, particularly natural gas pyrolysis. Deploying new production infrastructure based on autothermal reforming with CCS, while also leading on natural gas pyrolysis, would afford Qatar the opportunity to lead on two complementary technologies and further strengthen its position in the industry. Figure 3 provides an overview of the four strategies.

[5] A more detail discussion of this option can be found in Appendix II.

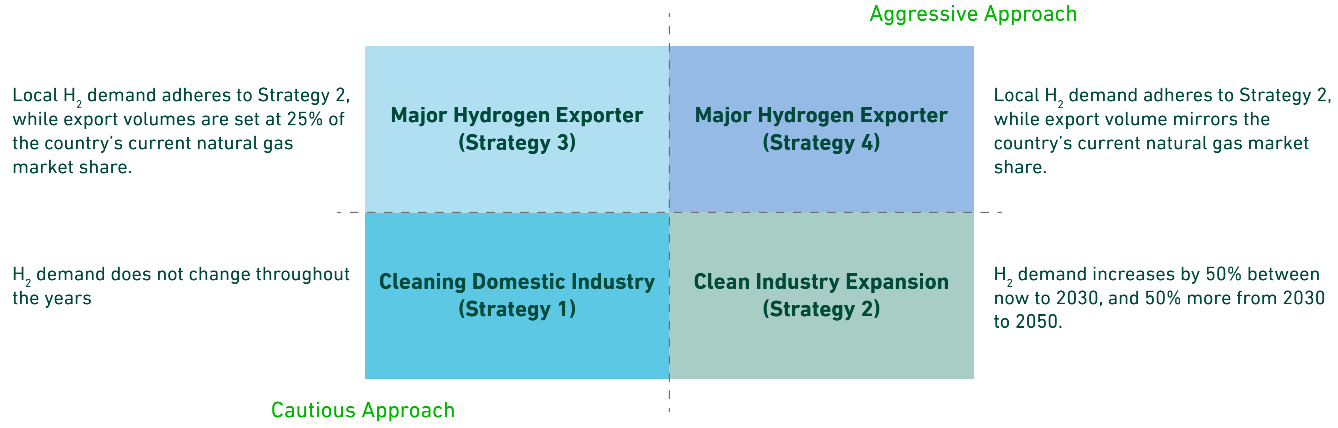

Figure 3. Four main strategies considered in the study.

The main assumption underpinning the four strategies is that Qatar's current NG production infrastructure has – and will continue to have – the necessary capacity to satisfy the requirements of both hydrogen and natural gas markets. Another major assumption is that the development of the global hydrogen export market does not happen at the expense of the LNG market. All technology cost data and assumptions used in the analysis of the four strategies can be found in Appendix III.

5.2 Strategy 1: Cleaning Domestic Industry

In this strategy, Qatar invests in decarbonizing existing hydrogen production capacity by retrofitting it with CCS: moving from grey to blue hydrogen. Demand for hydrogen from oil refining, ammonia, methanol and steel manufacturing is assumed to remain constant at today's level of 1.20 MTPA until 2050. The breakdown of this is roughly 0.23 MTPA for oil refining, 0.68 for ammonia, 0.21 for methanol and 0.09 for steel (see Table 1). This translates into a total natural gas requirement of 5.40 bcm/year, which amounts to less than 2% of Qatar's planned LNG production. Total CCS capacity required is 12.5 MTPA. This would require more than doubling QatarEnergy's current CCS target capacity of 11 MTPA in 2035 to reduce CO_2 emissions from LNG operations. This suggests that, even for the most cautious scenario, building extensive CCS infrastructure is a decision that must be made early on.

The necessary SMR capacity is already in place, so the only initial investment required is for the CCS retrofit. However, the cost of retrofitting can vary significantly depending on the desired rate of capture of CO_2. SMR is a two-step process: 60% of CO_2 emitted comes from the first step, is more concentrated and, therefore, easier to capture; the remaining CO_2 comes from the second step and is more diluted, therefore, more costly to remove. To meet the latest international standards, calculations are based on 90% CO_2 capture rate.Once the existing SMR plants reach the end of their life, they are replaced by autothermal reforming (ATR) plants because of certain advantages when combined with CCS. ATR has a higher capital cost than SMR. However, when considering the capital cost of the associated carbon capture, the overall capital cost of ATR (including CCS) is lower than that of SMR. ATR also requires less natural gas per unit of hydrogen produced and generates slightly less CO_2 than SMR.

The annual capital investment profile associated with this strategy from 2025 to 2050 is illustrated in Figure 4, where the upper and lower range values are based on the technology cost ranges provided in Table 5, Appendix III. Initially, substantial investment of up to USD 2.5 billion per year is needed to retrofit existing SMR capacity with CCS. No major investment will be required until after 2030, when some of the retrofitted SMR facilities reach end of life and are replaced with ATR plants. These estimates assume that retrofitted SMR facilities are retired in a linear fashion, hence capital expenditure plateaus between 2035 and 2050.

(European Parliament Council of the European Union, 2024; METI Agency for Natural Resources and Energy, 2024; S&P Global, 2024; US Department of Energy, 2023)

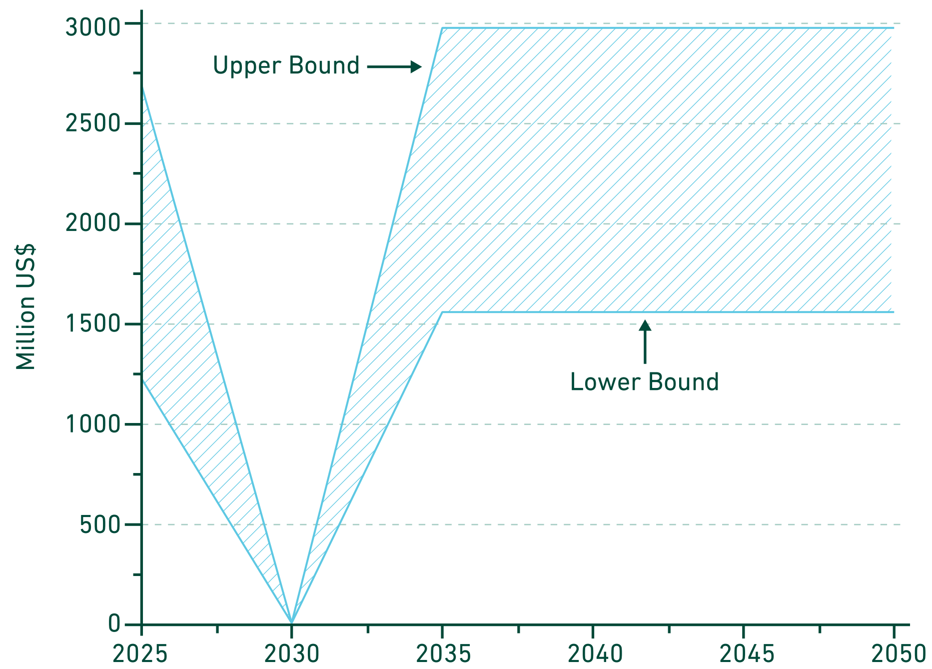

Figure 4. CAPEX required to build hydrogen production and delivery infrastructure in Strategy 1; Upper and Lower bounds reflect the range of technology investment costs considered.

5.3 Strategy 2: Clean Industry Expansion

The second strategy entails decarbonizing existing hydrogen production for use in oil refining and in the manufacturing of ammonia, methanol and steel, and expanding the production of the latter commodities. This strategy relies on Qatar's competitive advantage in producing low-cost natural gas and potential CCS capacity, creating conducive conditions for the production of "clean" ammonia, methanol and low-carbon steel for international export. The analysis in this strategy assumes that ammonia and methanol are sold into the market for fertilisers and chemicals, rather than sold as fuels, for which a market is yet to develop. The use of ammonia as a fuel is considered in Strategies 3 and 4. The markets for clean commodities and fuels are likely to develop at different rates and are, affected by different levels of uncertainty, and may therefore require different strategic approaches.

This strategy assumes current SMR plants are operating at full capacity and, therefore, as production capacity of ammonia, methanol and steel is gradually expanded, new ATR hydrogen capacity with CCS will be added.

The analysis also assumes 50% expansion of production capacity from today to 2030, and 50% more from 2030 to 2050. Demand for hydrogen from oil refining is assumed to remain constant.

Compared to Strategy 1, demand for hydrogen grows significantly, starting at 1.79 MTPA and increasing to 2.67 MTPA in 2050. Demand for natural gas reaches 10.23 bcm/year in 2050, which corresponds to roughly 5% of Qatar's planned LNG production. In this strategy, CCS capacity required goes up to 26 MTPA in 2050.

The capex required for this strategy has a different profile, compared to Strategy 1. In Strategy 2, capex starts at the same level in 2025 and then grows steadily until 2030 due to the cost of building the new ATR and CCS capacity needed to expand production capacity of ammonia, methanol and steel. From 2035 onwards, annual capex plateaus, driven by linear market growth and replacement of SMR plants that reach end of life. This is illustrated in Figure 5.

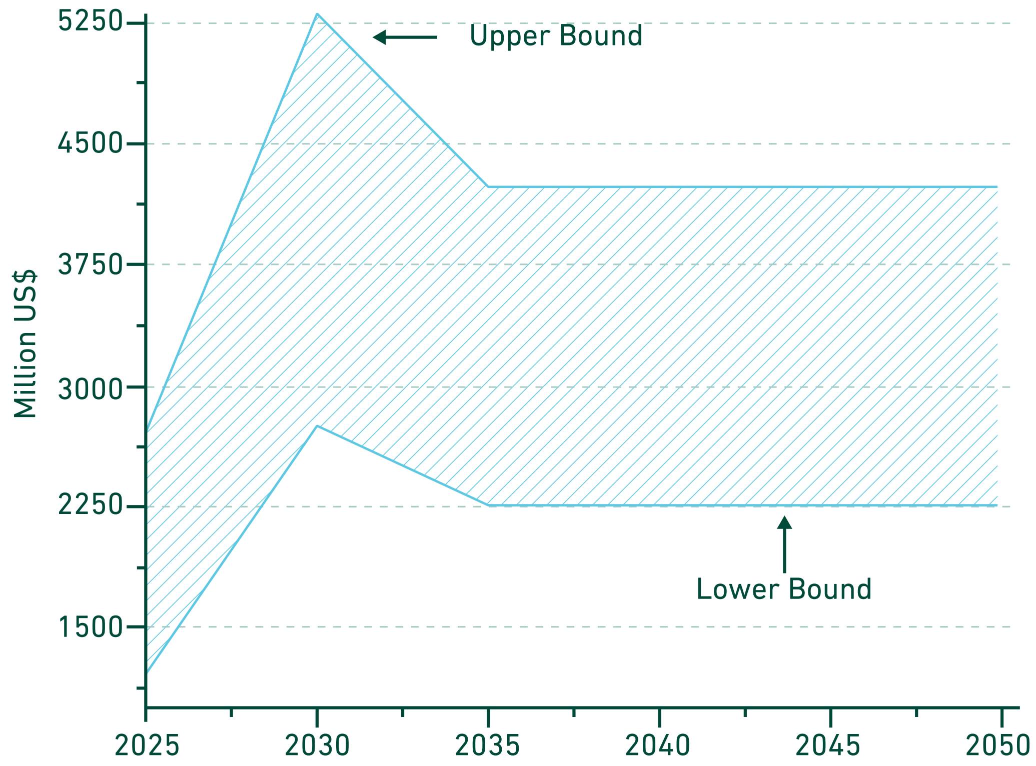

Figure 5. CAPEX required to build hydrogen production and delivery infrastructure in Strategy 2; Upper and Lower bounds reflect the range of technology investment costs considered.

5.4 Strategy 3: Cautious Hydrogen Exporter

This strategy involves expanding clean hydrogen production to meet additional demand generated by the expansion of ammonia, methanol and steel production, and building new production capacity for clean hydrogen exports as a fuel, in form of either pure hydrogen or one of its derivatives. In this strategy, Qatar adopts a cautious approach and only invests in the necessary export capacity once the market is established. This will result in gaining a relatively small market share because other players, particularly first movers in green or blue hydrogen production, will have already secured a strong position. This strategy assumes that Qatar will gain a share of the international clean hydrogen market that corresponds to 25% of its current LNG market share. The rate of growth of the hydrogen market depends on the scenarios under consideration, so different hydrogen production build-up rates are based on each of the IEA scenarios discussed in Section 2. These are shown in Figure 6. The figure also shows the breakdown between hydrogen produced for domestic industry and that supplied to Europe and Asia respectively. In all cases except the NZE scenario, the majority of the clean hydrogen produced in Qatar will be destined for domestic industry.

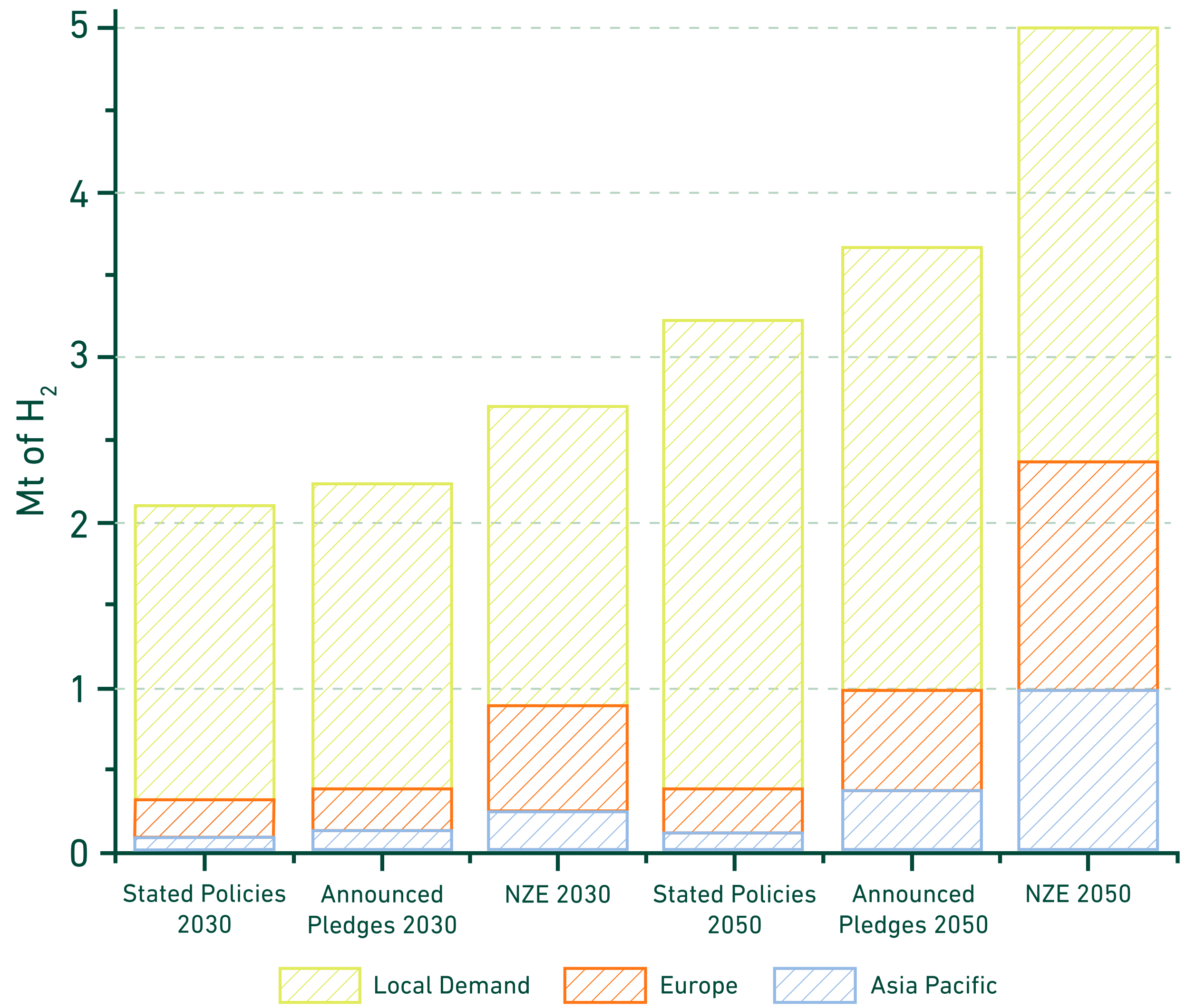

Figure 6. H_2 production build-up under Strategy 3 based on different international hydrogen market scenarios.

Based on the analysis of current policies of import-oriented countries, possible future demand for hydrogen is estimated for different sectors, each with different purity requirements. In particular, the road transport sector requires high-purity H_2, for which exports of hydrogen will be in the form of cryogenic liquid (LH_2).

Figure 7 shows the shares of LH_2 and other hydrogen carriers – such as LOHC and ammonia – for export markets under each of the IEA scenarios. The need for costly LH_2 infrastructure is relatively modest, with most of the hydrogen exported as LOHC or ammonia.

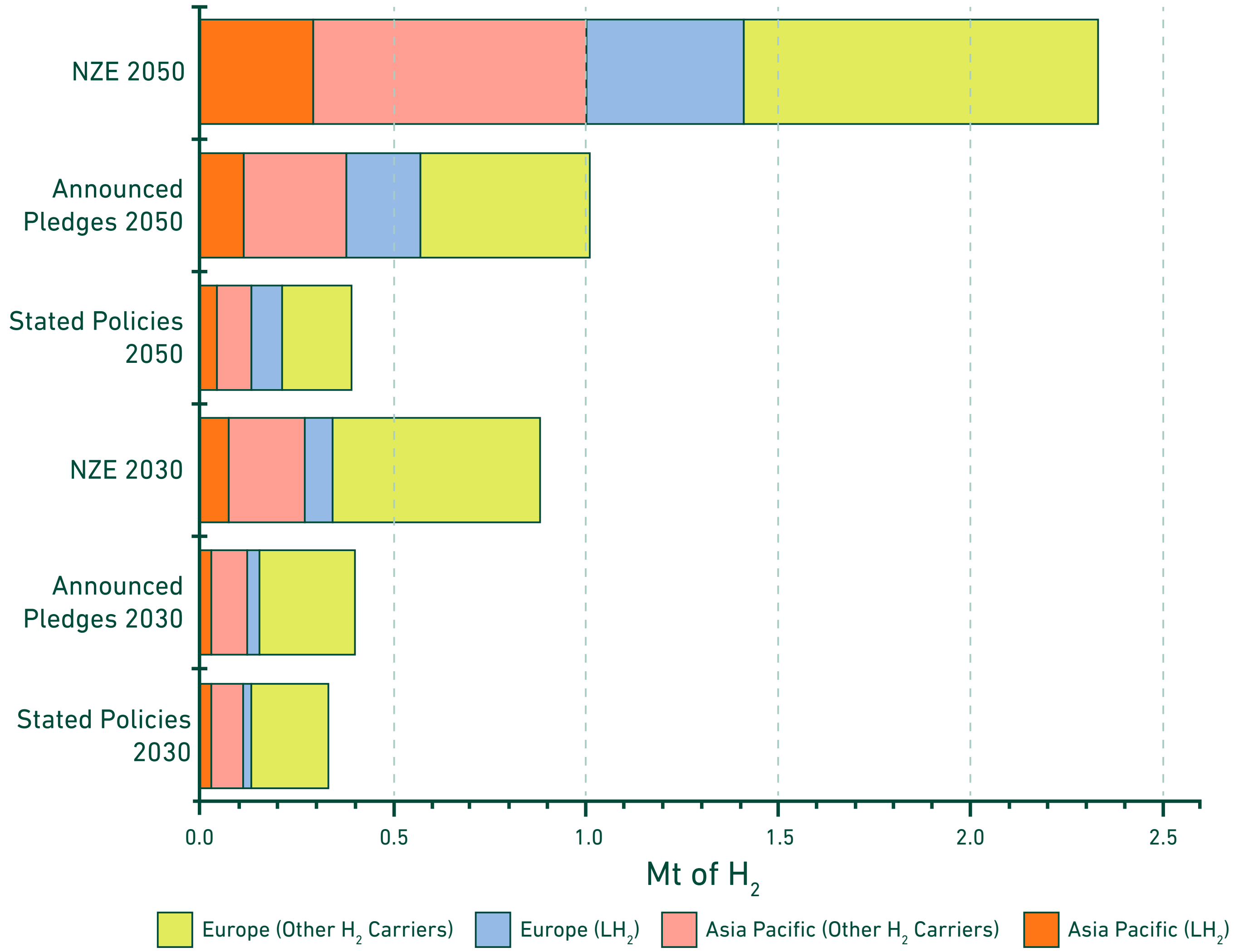

Figure 7. Breakdown of hydrogen production for export, by destination and carrier type, in Strategy 3.

Strategy 3: Cautious Hydrogen Exporter

Figure 8 shows the volumes of natural gas that would be required to produce hydrogen for both domestic use and export under different international market growth scenarios. For the Net Zero scenario, nearly 19 bcm of natural gas would be required by 2050, which corresponds to around 9% of Qatar's planned LNG production. Moreover, up to 2 MTPA of additional natural gas would be consumed for hydrogen liquefaction in 2050 under the Net Zero scenario (see Figure 9).

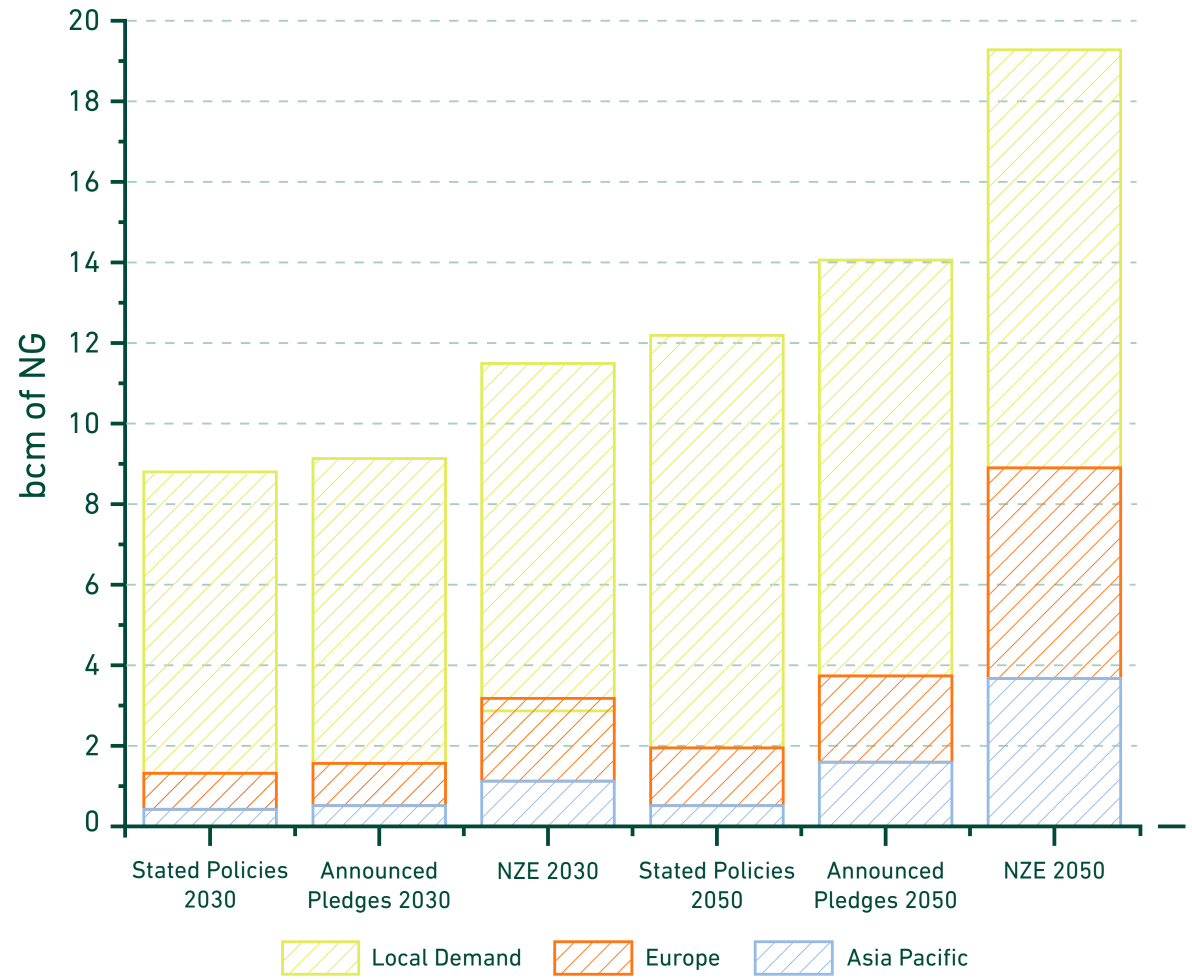

Figure 8. Natural gas volumes required to produce H_2 for both domestic use and export under different international hydrogen market scenarios (Strategy 3)

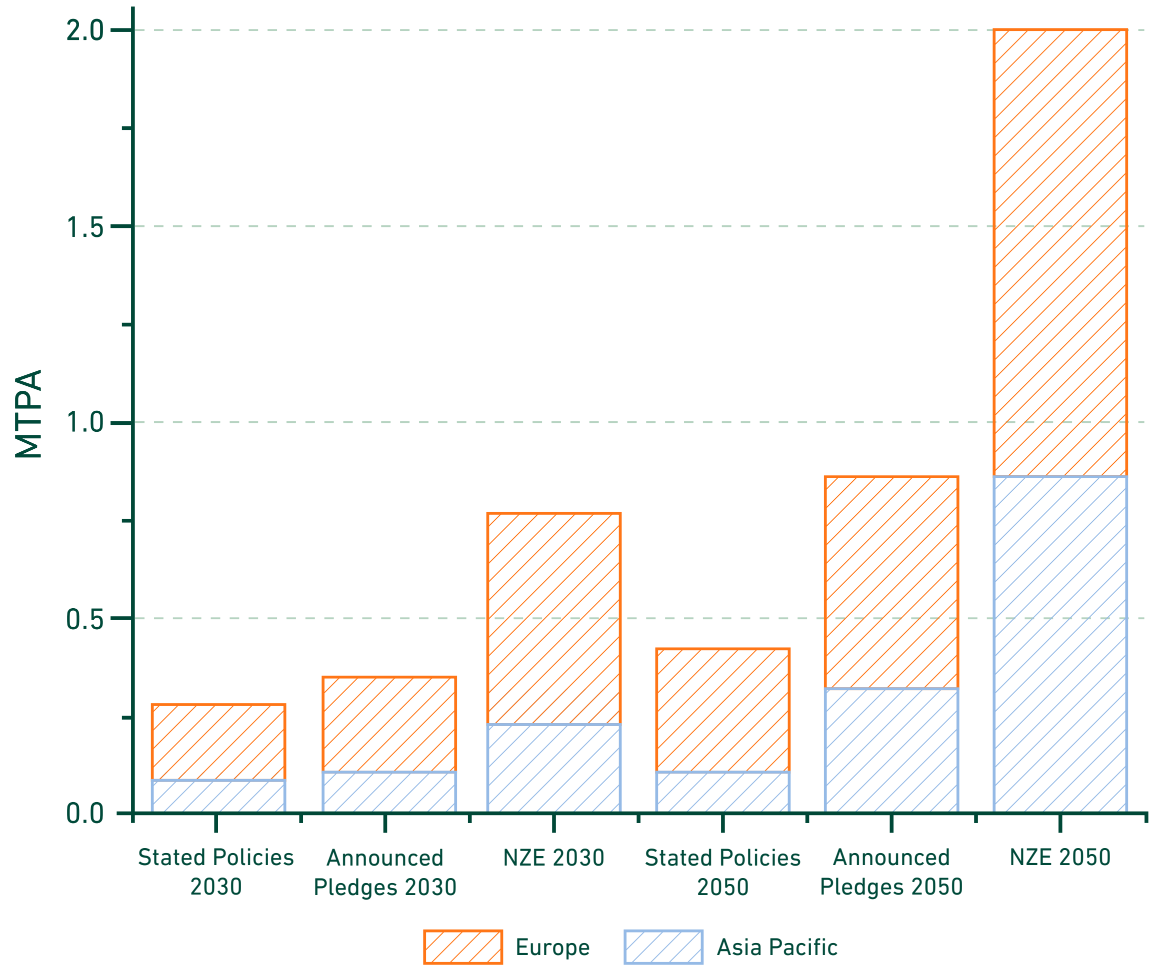

Figure 9. Natural gas volumes required for H_2 liquefaction alone, by destination and under different international hydrogen market scenarios (Strategy 3)

Strategy 3: Cautious Hydrogen Exporter

The CCS capacity associated with the hydrogen production volumes in Figure 6 starts at a minimum of 21 MTPA by 2030 and, in the highest demand scenario, reaches 48 MTPA, all of which involves a rapid ramp-up of CCS infrastructure (see Figure 10).

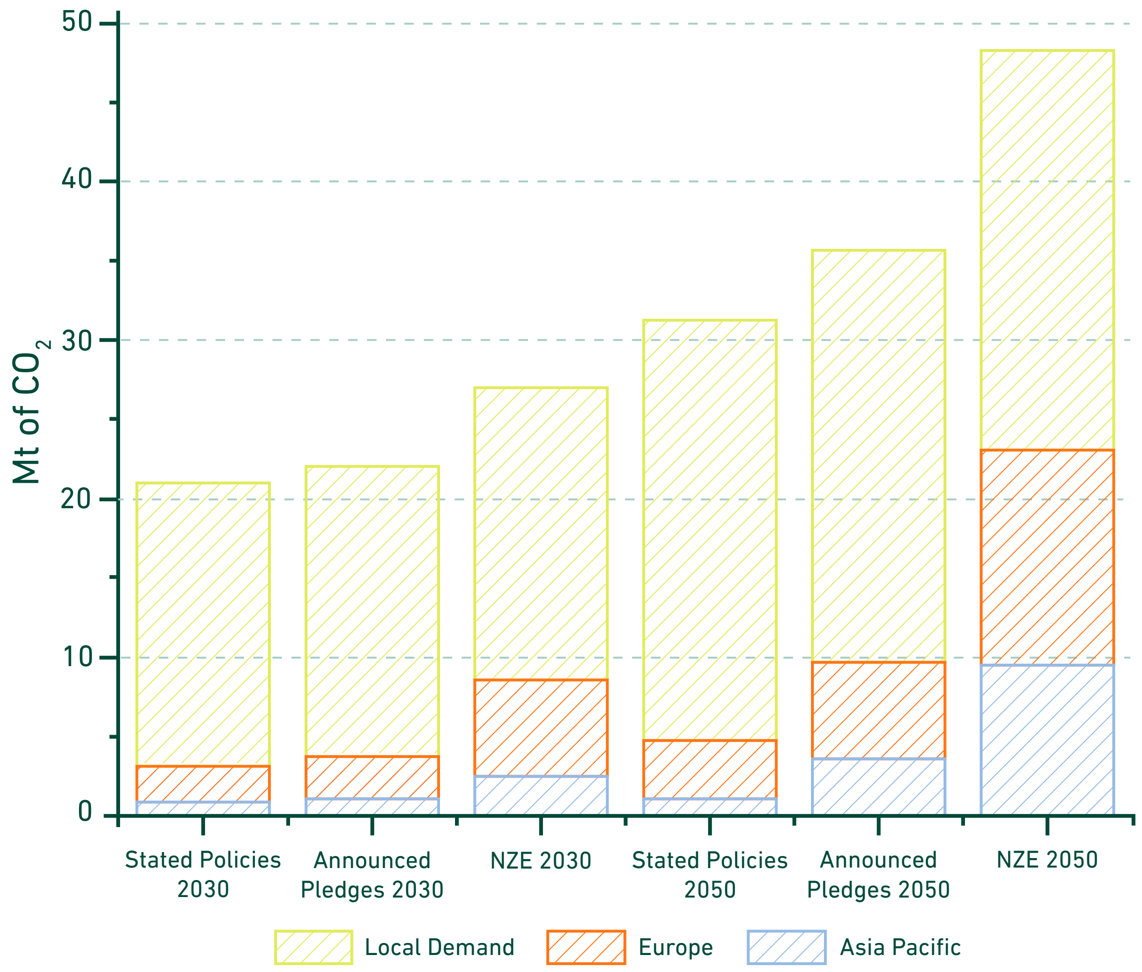

Figure 10. CCUS capacity associated with H_2 production volumes of Strategy 3.

Strategy 3: Cautious Hydrogen Exporter

The capex profile for Strategy 3 is qualitatively similar to that of Strategy 2 (see Figure 11). However, it is significantly higher due to the high capital cost of the hydrogen liquefaction plants, LH_2 cryogenic vessels and, to a lesser extent, LOHC and ammonia infrastructure.

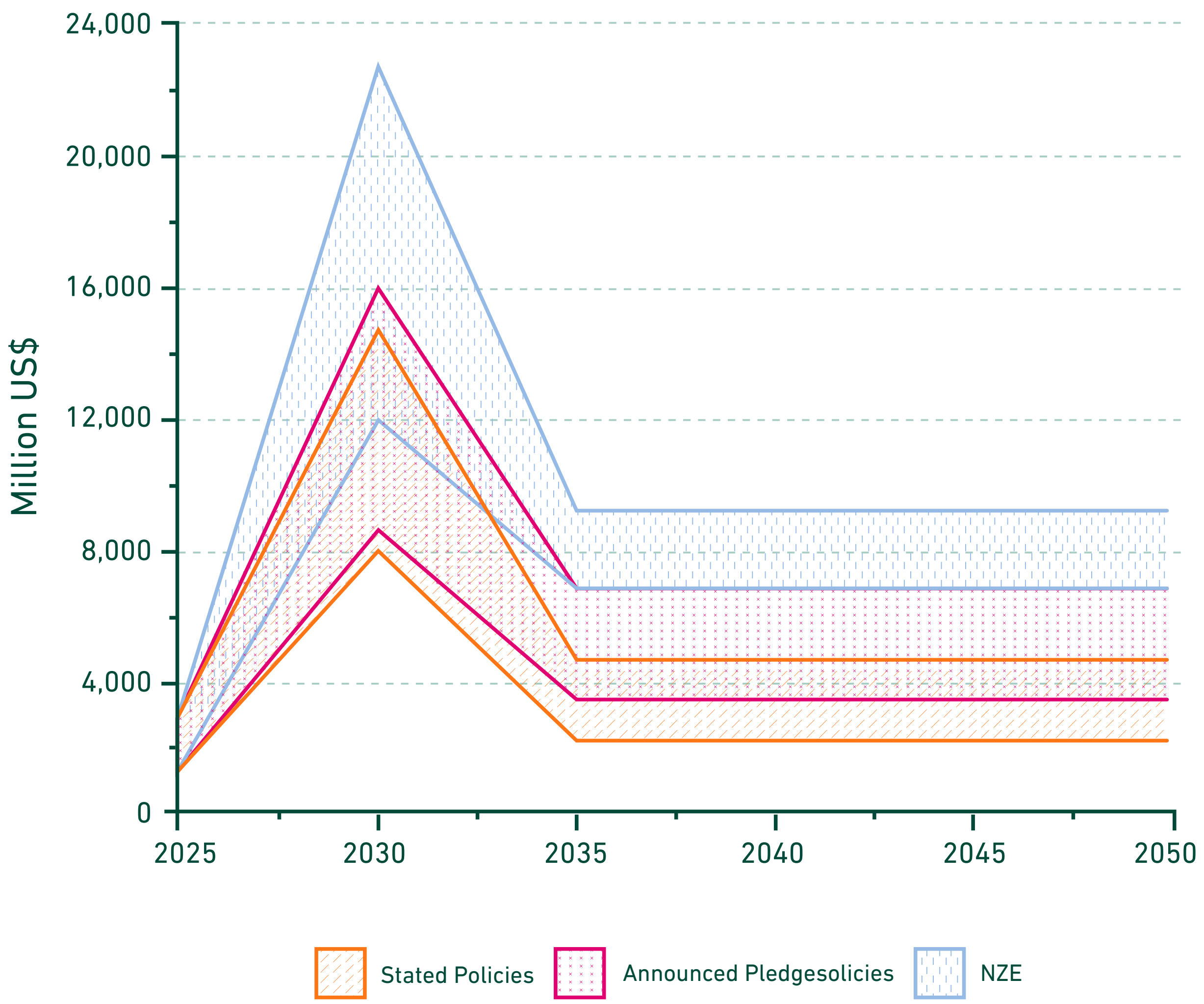

Figure 11. CAPEX required to build the H_2 production and delivery infrastructure of Strategy 3; upper and lower ranges reflect the range of technology investment costs considered.

5.5 Strategy 4: Major Hydrogen Exporter

In this strategy, Qatar expands its production of clean commodities (ammonia, methanol and steel) and adopts a more aggressive strategy in the international hydrogen market. In this strategy, Qatar will seek to achieve the same share of the global hydrogen market as its current share in the global natural gas market (10.47%). It is assumed that Qatar's share of the hydrogen market will be equally distributed between Asia (Japan and South Korea) and Europe. The volumes of clean hydrogen production associated with this strategy are reported in Figure 12. In most scenarios the volume of clean hydrogen produced for export outstrips that produced for the domestic industry. Figure 13 provides the breakdown of liquid hydrogen delivery versus other modes (LOHC, ammonia) under the three IEA scenarios. Based on these scenarios, LH_2 is the required form for roughly 15% of the exported hydrogen by 2030, and 30% of the exported hydrogen by 2050.

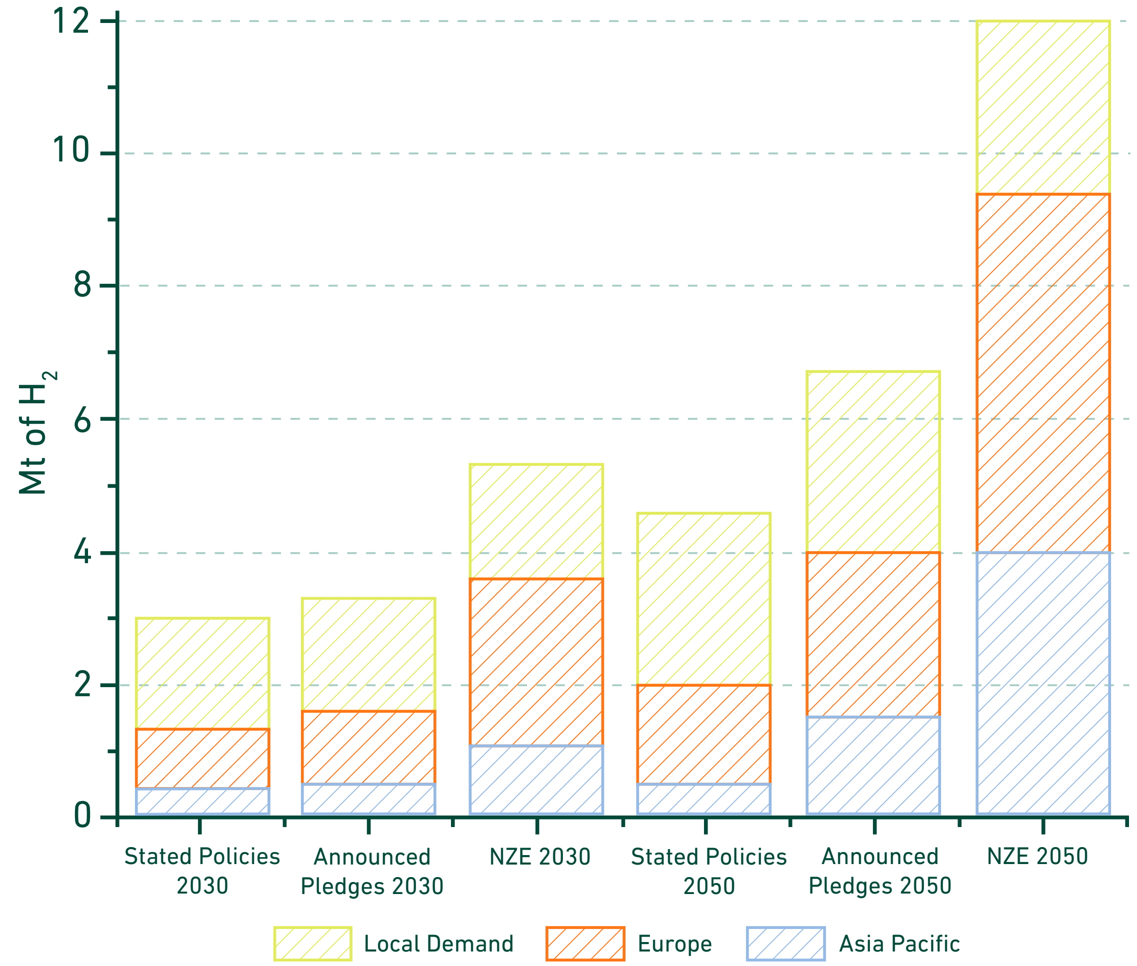

Figure 12. H_2 production build-up under Strategy 4 based on different international hydrogen market scenarios.

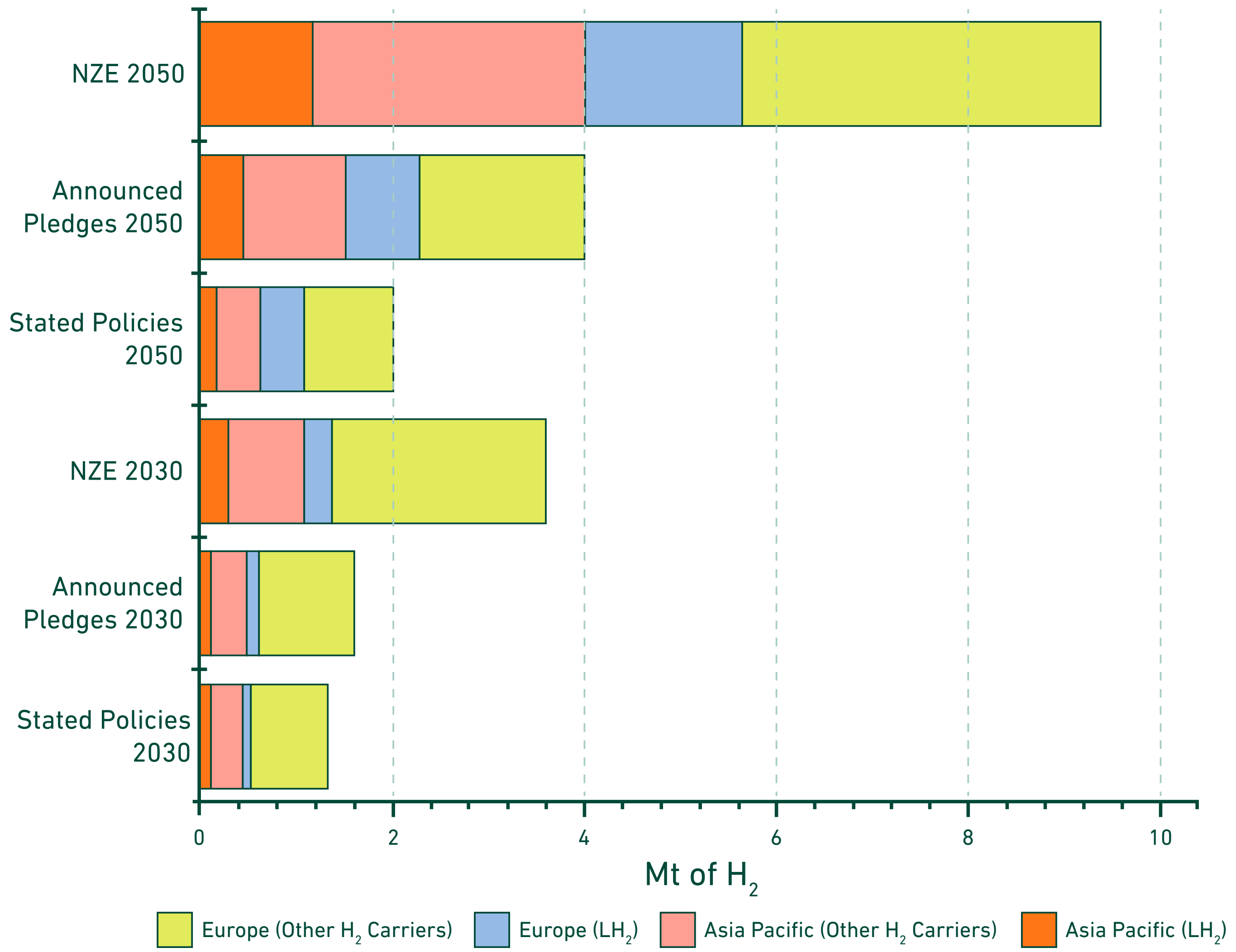

Figure 13. Breakdown of hydrogen production for export, by destination and carrier type, in Strategy 4.

This strategy assumes that Qatar will pursue multiple hydrogen production technologies and will invest in developing and scaling up methane pyrolysis. This is a critical technology that can allow clean hydrogen production from natural gas in regions where CCS capacity is not available, because the by-product of the process is a solid (carbon black, graphene or other carbon-based material) and not a gas (CO_2). Methane pyrolysis, therefore, could be deployed near the end use point of hydrogen and would allow Qatar to continue to export LNG to countries where hydrogen demand is located rather than shipping hydrogen. If methane pyrolysis fully replaced reforming though, the amount of solid carbon generated would likely exceed demand. So, in principle, methane reforming and pyrolysis could coexist. To scale up methane pyrolysis, it is assumed that Qatar will initially deploy it domestically and later invest in plants abroad. Due to uncertainty around timescales for technology development and commercialization and the size of the market for the solid carbon, pursuing reforming and pyrolysis in parallel could be beneficial for Qatar's role in the international clean hydrogen market. For this reason, this strategy assumes that 30% of the capacity deployed in the country will be pyrolysis and the rest ATR and CCS.

To produce these volumes of clean hydrogen, the volume of natural gas required may reach 52 bcm/year, which corresponds to around 25% of planned LNG production (see Figure 14).

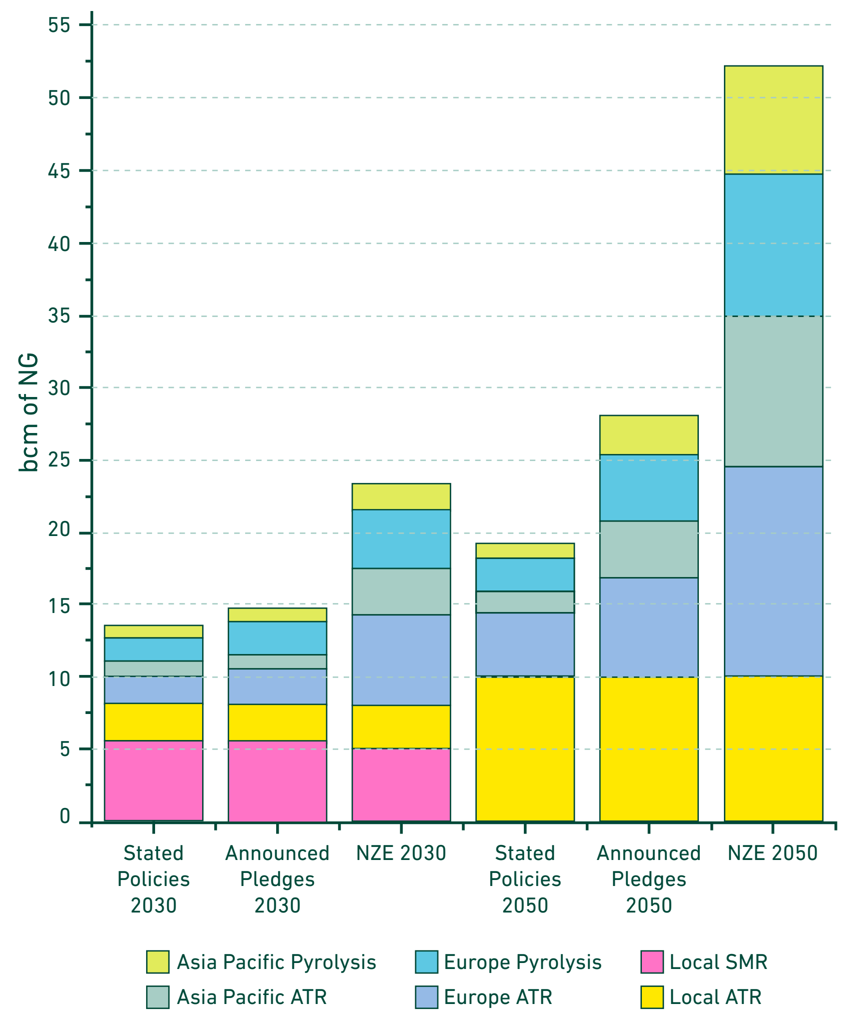

Figure 14. Natural gas volumes required to produce H_2 for both domestic use and export under different international hydrogen market scenarios (Strategy 4)

Figure 15 shows how introducing pyrolysis in the mix reduces the overall need for CCS: compared with Strategy 3, CCS requirements in 2050 for the Net Zero scenario increases 1.24 times, while hydrogen production increases 2.4 times.

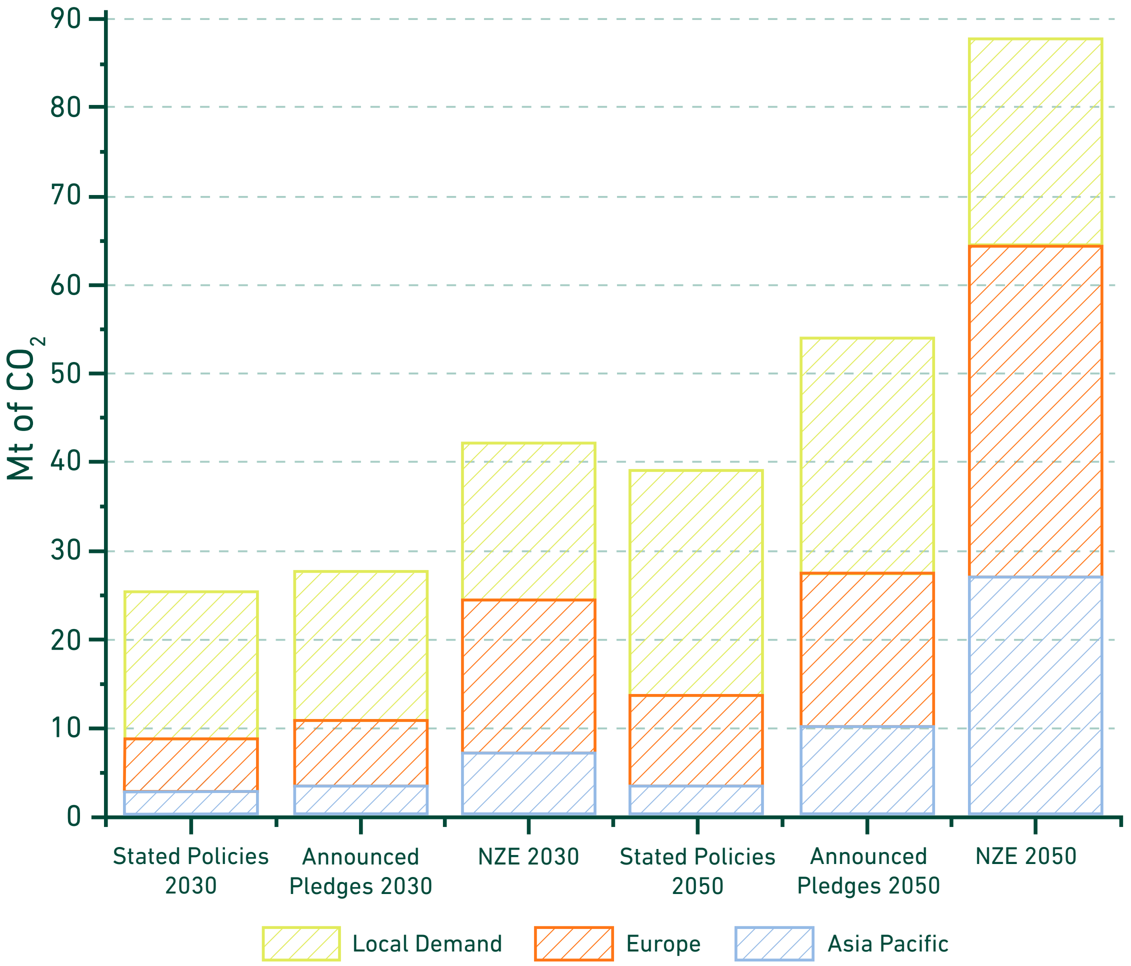

Figure 15. CCUS capacity associated with H_2 production volumes of Strategy 4.

The capex profile is similar to those of Strategy 2 and 3, however, the required capital is much higher (see Figure 16). This is due to two factors: a) the additional hydrogen liquefaction capacity and LH_2 cryogenic vessels needed, compared with Strategy 3; and b) the presence of a significant amount of methane pyrolysis capacity that, in the short term, will have a much higher capital cost than the corresponding methane reforming infrastructure.

Figure 16. CAPEX required to build the H_2 production and delivery infrastructure of Strategy 4; upper and lower ranges reflect the range of technology investment costs considered.

06

Discussion

Discussion

The analysis presented in Section 5 shows the implications of the four strategies for new hydrogen production and shipping infrastructure, volume of natural gas and CCS capacity required, and associated annual capital expenditure. Having discussed each strategy individually, this section compares the different strategies to derive insights into the relative risks, uncertainties and possible critical decisions. The four strategies will be compared with the 2023 UAE hydrogen strategy as a regional reference.

Investment risk is generally defined as the likelihood of incurring losses or not achieving the expected returns. Risk increases with the size of an investment and uncertainty over its returns. Investing in expanding LNG capacity is, in the short to medium term, low risk for Qatar, as both the technology and market are mature. By comparison, investing in manufacturing clean commodities is riskier: a market exists for standard commodities, but for clean commodities the technology and market are continuously evolving. Investing in clean hydrogen production for export as an energy vector even riskier. Clean hydrogen is still a nascent industry and the technologies needed for production, delivery and end-use are still under development.

Taking this into account, the four strategies considered in this analysis involve different risk levels: moving from Strategy 1 to Strategy 4, technology and market uncertainty increases and so does the size of the investment. Figure 17 illustrates the required hydrogen production volumes for each strategy, based on the three IEA scenarios (see Section 3.1). The UAE aims to become a leading clean hydrogen producer, and its strategy identifies 1.4 MTPA of clean hydrogen as the minimum required by 2030 to achieve that. Qatar could achieve similar levels of production by adopting the relatively low-risk Strategy 2. However, beyond 2030, international hydrogen markets are expected to grow, and Qatar will need to make a decision about what share it plans to capture.

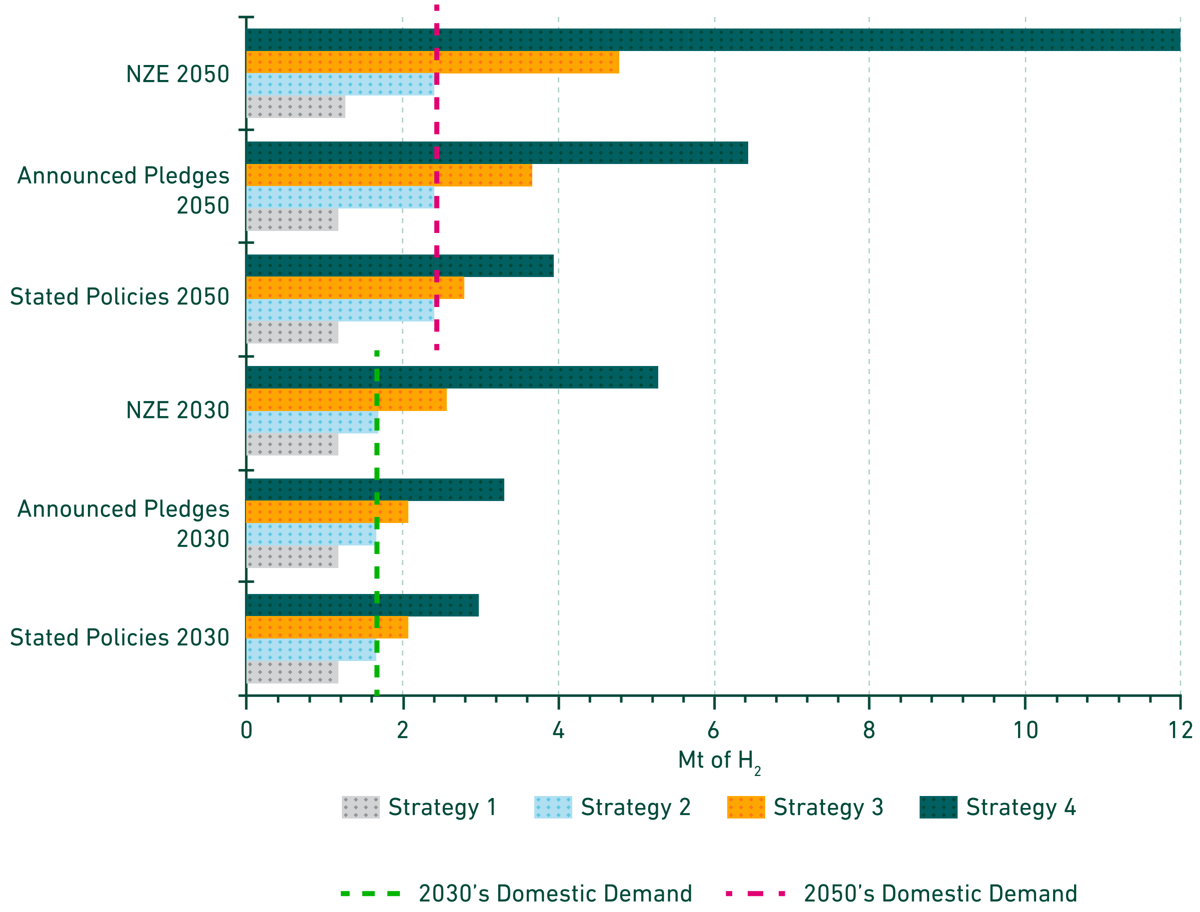

Figure 17. Qatar hydrogen production volumes for each one of the 4 strategies considered; the volumes cover both domestic demand and export volumes, with the latter based on IEA market projections.

Figure 18 illustrates the cumulative investment costs for each strategy over 5-year intervals (the error bars represent uncertainties in technology costs as well as in clean hydrogen demand for export, which in this case we have reduced by excluding the Net Zero scenario). Both the size of the required investment and the uncertainty around it increase rapidly from Strategy 1 to Strategy 4. Except for Strategy 1, committing to any of the four strategies involves an investment that is higher in the initial 5-year period than in subsequent ones. To put things into perspective, the initial investment required by strategy 4 is in the order of USD 30 billion over 5 years, which is comparable to that of Qatar's North Field East LNG expansion from 77 MTPA to 142 MTPA. This illustrates the level of risk associated with Strategy 4.

Figure 18. Estimated cumulative capital expenditure for each strategy considered, compared with that of the North Field East LNG expansion. Each section represents a time interval and its associated CAPEX range (based on the Stated Policies and Announced Pledges scenarios) within the period.

The UAE hydrogen strategy is mostly aligned with Strategy 3. The main difference is that the UAE targets a five-fold growth of domestic use of clean hydrogen to 2050, while in Strategy 3 the growth is only two-fold. The higher growth in the UAE strategy is associated with the use of clean hydrogen as feedstock for sustainable fuels for shipping, aviation and road transport. While this is potentially relevant to Qatar, these sectors have not been considered. The UAE considers the market for clean commodities a key opportunity with acceptable risk levels, which justifies a strategy of rapid expansion of domestic production. On the other hand, the UAE's strategy sees the international market for clean hydrogen as much more uncertain and, therefore, despite taking the necessary steps to enter it, it does not plan to pursue it as aggressively as in Strategy 4.

This initial high investment for 3 out of 4 strategies is associated with high costs of technologies that are yet to be developed. These costs will be incurred by any early mover in the clean hydrogen market. The initial decisions involved in developing a clean hydrogen industry will require Qatar to commit to a certain strategy. Switching to a different one later may prove difficult due to various factors, including:

- **Policy:** the development of a national clean hydrogen industry requires a conducive policy framework for both the supply and demand side; leaving clean hydrogen out of the energy-environmental policies currently being developed may lead to long delays in the future, potentially ruling out hydrogen altogether.
- **Infrastructure lead times:** planning clean hydrogen infrastructure, securing permits and the necessary investments, procuring the equipment and building the infrastructure can take several years.
- **Resource allocation:** it is assumed that clean hydrogen and LNG in Qatar can proceed independently of one another. In reality, these and other possible industrial projects may have to compete for financial resources, CCUS capacity and land, and allocation of resources may need to be planned several years if not decades ahead.

The aforementioned factors, among others, are an area of further research and duly considered when seeking to develop a robust clean hydrogen strategy for Qatar.

07

Conclusions

Conclusions

This report presents an initial assessment of the possible investment risks and critical decisions involved in developing a clean hydrogen industry in Qatar. Four possible strategies have been explored, characterized by an increasing level of ambition: "Cleaning Domestic Industry", "Clean Industry Expansion", "Cautious Hydrogen Exporter" and "Major Hydrogen Exporter". The level of hydrogen demand associated with the strategies was defined based on existing domestic hydrogen consumption in Qatar, its potential expansion, and IEA scenarios on future international clean hydrogen market. Hydrogen infrastructure costs, both current and future, are based on the best available data and projections.

Combining future hydrogen demand profiles of each strategy with the investment required to build the infrastructure, cost profiles and related uncertainties are estimated for each of the four strategies until year 2050. Investment costs and associated risks increase rapidly from low-risk Strategy 1 to high-risk, aggressive Strategy 4. Moreover, for all strategies except Strategy 1 the highest investment costs are incurred early on. Initial investments for all strategies can be high and, in the case of Strategy 4, comparable with that of Qatar's major LNG projects. The long lead times involved with developing the necessary policies and building the necessary infrastructure, together with possible competition with LNG and other industrial projects over financial resources, CCUS capacity and land, suggest that the decision on which strategy to adopt will need to be made early and may prove difficult to reverse later on.

Thinking about what a clean hydrogen industry may look like in Qatar is important and warrants further research, to better understand the extent to which different strategies can coexist. The uncertainties could be better characterized, statistical methods could be deployed to build more detailed scenarios, risks and opportunities could be assessed using financial analysis methods, and critical decisions could be explored with the support of other modelling techniques. This would add to the evidence base available to inform decision-making in Qatar and other fossil-fuel exporting countries.

08

Acknowledgments

Acknowledgments

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09

Acronyms

Acronyms

ATR	Autothermal Reforming
CAPEX	Capital Expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilization and Storage
ETS	Emission Trading System
EU	European Union
GCC	Gulf Cooperation Council
GDP	Gross Domestic Product
GHG	Green House Gas
GTL	Gas to Liquids
LNG	Liquefied Natural Gas
LOHC	Liqued Organic Hydrogen Carriers
LPG	Liquefied Petroleum Gas
MTPA	Million Tons Per Annum
NFE	North Field East
NG	Natural Gas
NZE	Net Zero Emissions
QAFAC	Qatar Fuel Additives Company Limited
QAFCO	Qatar Fertiliser Company
QAPCO	Qatar Petrochemical Company
QNV	Qatar National Vision
QVC	Qatar Vinyl Company
SMR	Steam Methane Reforming
UK	United Kingdom
WEO	World Energy Outlook

Appendix I – Review of relevant clean hydrogen strategy studies

The development of clean hydrogen industries as a means of achieving the multiple objectives of reducing energy-related GHG emissions, improving energy security and increasing industrial competitiveness has attracted much attention from researchers and governments since at least the early 2000s, particularly in Europe, the US and Japan. Initially driven by the research community, a vast number of studies have been conducted exploring all aspects of developing hydrogen industries, ranging from cost-effective long-term technology pathways to the impact that these new industries could have on societies. Building on such vast body of knowledge, governments of industrialised countries, mostly net energy importers, have developed hydrogen strategies and roadmaps, in close collaboration with the domestic industry; particularly worth noting are those of the UK, Germany, the Netherlands, Japan, South Korea, China, the USA and Australia (COAG Energy Council Hydrogen Working Group and Department of Industry Innovation and Science, 2019; Department for Energy Security & Net Zero, 2023; Federal Ministry for Economic Affairs and Energy, 2020; Ministry of Trade Industry and Energy, 2019; The Government of the Netherlands, 2020; The Ministerial Council on Renewable Energy, 2023; U.S. Department of Energy, 2023; Yushan and Corbeau, 2023). Such strategies generally reflect the perspectives of countries with advanced economies that have committed to aggressive GHG mitigation targets and that see clean hydrogen as an imperative to address hard-to-abate sectors, while also enhancing energy security and economic competitiveness. The emphasis is therefore on building national clean hydrogen industries as rapidly and cost-effectively as possible, to deliver hydrogen for domestic use, complementing domestic production with imports if needed. In some cases, becoming an import hub or developing extra capacity for export is also considered, as in the case of the Netherlands, the US and Australia.

The interest of the oil & gas exporting countries of the GCC in building clean hydrogen industries is much more recent; their motivations are somewhat different from those of the net energy importing, industrialised countries and perhaps more nuanced. GCC countries are increasingly announcing large clean hydrogen projects and some, like the UAE and Oman, have published roadmaps and strategies (Ministry of Energy and Infrastructure, 2023; Ministry of Energy and Minerals, 2022b). At the same time, those GCC countries that are in the position to do so are also substantially expanding production of fossil fuels. Overall, the continued reliance of these countries on oil & gas exports coupled with the uncertainty surrounding the development of hydrogen technologies and markets makes developing clean hydrogen strategies for GCC countries an altogether different problem than in the case of import-oriented, more developed economies.

The literature on clean hydrogen in the GCC is also relatively recent. Some studies review the potential for the GCC and MENA regions to become leaders in clean hydrogen but tend to be high-level (Khan and Al-Ghamdi, 2023; Olabi and Jouhara, 2024; Razi and Dincer, 2022). Several country-specific studies also exist, however many of them are technical and focus on individual technologies; these are not discussed here. Those country-specific studies that aim to inform national clean hydrogen strategies by combining techno-economic, policy and market analyses. For Saudi Arabia, particularly worth mentioning is a book that covers all aspects of technology, markets and policy and provides a strong evidence base for Saudi Arabia and other GCC countries seeking to develop a leadership role in the industry (Shabaneh and Braun, 2024). For the UAE, some studies have addressed strategic aspects of developing a national clean hydrogen industry, particularly with regards to green hydrogen, its use in hard-to-abate sectors and the policies required to support it (Gandhi et al., 2022; Zaiter et al., 2023). For Oman, studies have assessed current national plans, their economic and sustainability drivers as well as barriers and how these could be overcome (Amoatey et al., 2024; Ashraf et al., 2024). Lastly, for Qatar, research articles have assessed different clean hydrogen technology pathways for the country, using different methods (Eljack and Kazi, 2020; Okonkwo et al., 2021); a study also assessed the potential impact of global clean hydrogen trade on the LNG market (Al-Kuwari and Schönfisch, 2022).

The studies reviewed provide assessments of the potential for a clean hydrogen industry to develop in specific GCC countries, considering both domestic use of the hydrogen and its export. They characterise environmental and suggest economic benefits of different pathways, make recommendations on preferred options and suggest policy interventions required to deliver them. The studies also tend to advocate the need to develop national clean hydrogen strategies aimed at becoming regional or global leaders. While acknowledging the major uncertainties that affect the market and technology projections included in their analysis, a systematic treatment of such uncertainties is missing. Moreover, studies generally call for the need for rapid action to gain a leadership position in the industry, and in some cases set targets for it, however they do not explore different possible strategies and the risks and rewards that may be associated with them.

Appendix II – Decarbonisation of natural gas liquefaction through hydrogen

QatarEnergy has set aggressive goals for the reduction of GHG emissions of its operations; in particular, by year 2035 it is aiming to achieve a 25% reduction of the carbon intensity of its upstream operations and a 35% reduction of the carbon intensity of its LNG facilities, relative to 2013 levels (QatarEnergy, 2023a). QatarEnergy's LNG operations (Scope 1 and 2) emissions amounted to 32.06 million tons of CO_2e in 2022 (QatarEnergy, 2023a), around half of which can be attributed to the operation of the natural gas liquefaction trains alone (based on our own calculations; please refer to Table 4). Different options exist for abating GHG emissions from the LNG trains. The first is by retrofitting the LNG trains with CCS. In this way, 90% or more of the CO_2 emissions from the trains could be abated, however the CO_2 concentration in the flue gas from the gas turbines is typically in the order of 3-5% by volume, which makes the CO_2 capture process both capital and energy intensive (Akram et al., 2015; GE, 2021; Majeed and Svendsen, 2018; Wang and Song, 2020). Another option consists in replacing the gas turbines that mechanically drive the cooling cycle with electric motors. Electric motors have operational advantages over gas turbines in terms of reduced maintenance cost and faster start-up, however this solution is only advantageous from a CO_2 emissions perspective if low-carbon electricity is used (Vara et al., 2021; Vara and Pouran, 2016). Lastly, clean hydrogen can also be used to abate GHG emissions from natural gas liquefaction. Clean hydrogen can be mixed up to 30% in volume with the natural gas that is fed to the gas turbines without the need for the latter to be modified in a significant way, thereby partly reducing their GHG emissions (see Table 4). However, to achieve near complete abatement of CO_2 emissions, 100% hydrogen would have to be used, which requires dedicated gas turbines that differ substantially from conventional natural gas turbines. Replacing conventional gas turbines with others that can run on pure hydrogen brings additional costs; however, when clean hydrogen is used, it also offers a more effective alternative to the post-combustion capture of CO_2 previously discussed (Ishaq and Dincer, 2020; Pashchenko, 2023). Should QatarEnergy decide to use clean hydrogen as the main solution to reduce GHG emissions from natural gas liquefaction, the volume required to do so would be substantial (see Table 4).

Table 4. Potential clean H_2 demand for LNG liquefaction and associated CO_2 emission reduction, based on the total LNG capacity of 142 MTPA and liquefaction energy requirement of 500 kWh/ton[a]

H_2 Blend	NG Requirement (MTPA)[b]	H_2 Requirement (MTPA)[b]	CO_2 Emissions After Blend[c]
0%	4.554	-	29.31
5%	4.327	0.0284	28.88
10%	4.099	0.0569	28.42
30%	3.188	0.1706	26.14
100%	-	2.1321	2.93

[a] Value taken from (Mehrpooya et al., 2018)

[b] Considering 1bcm of natural gas equals to 35.7 trillion BTU (QatarEnergy, 2023b)

[c] Assuming 90% CO_2 capture rate (IEA Greenhouse Gas R&D Programme, 2003; Power et al., 2018; Voldsund et al., 2016; Zang et al., 2024)

Appendix III – Technology data and assumptions

When assessing the infrastructure build-up needs associated with each of the four strategies outlined in Section 5.1, the analysis makes use of the domestic and export hydrogen volumes discussed in Sections 2.1 and 3.1. Figure 19 illustrates how clean hydrogen demand is quantified in the analysis.

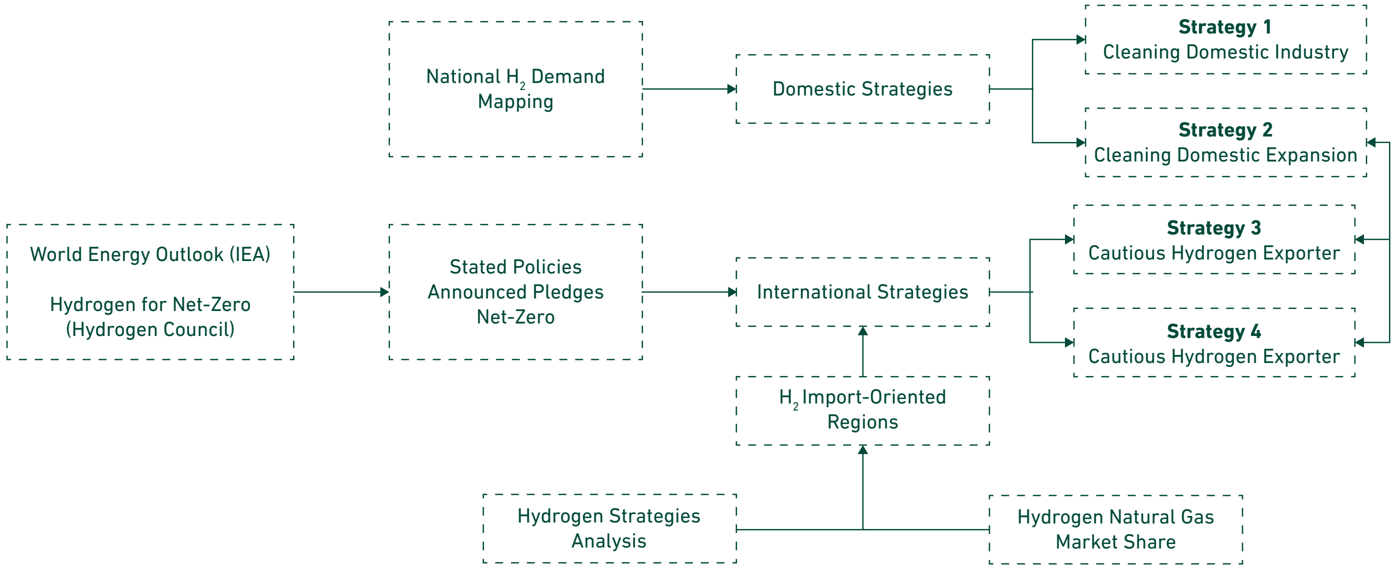

Figure 19. Illustration of the approach followed to quantify hydrogen demand in each of the 4 strategies considered.

Technology capital investment costs are calculated based on figures from the literature; see Table 5 below.

Table 5. Capital investment costs in USD of relevant clean hydrogen production technologies used for the analysis presented in the following sections. requirement of 500 kWh/ton[a]

Technology	Lower Bound	Upper Bound	Reference
SMR Retrofit (500 ton/day)	**137,500,00**	**300,000,000**	(Power et al., 2018)
ATR (500 ton/day)	**692,200,000**	**1,300,000,000**	(IDTechEx, 2023; Khojasteh Salkuyeh et al., 2017)
Pyrolysis (500 ton/day)	**778,600,000**	**3,100,000,000 (by 2030)** **1,600,000,000 (by 2050)**	(Parkinson et al., 2018)
Tankers	**412,000,000 (11 k ton capacity)**	**481,000,000 (19.6 k ton capacity)**	(Alkhaledi et al., 2022; Lee et al., 2022)
H_2 Liquefaction Plant (500 ton/day)	**1,000,000,000**	**2,000,000,000**	(DOE Hydrogen and Fuel Cells Program, 2019; McDermott and Gasconsult, 2023; NCE Maritime Cleantech, 2019)
LOHC[a] (500 ton/day)	**201,300,000**		(Carvalho et al., 2021)

[a] Capital cost of the LOHC plants which, based on the literature, is in the order of 10-20% of that of a similar-size hydrogen liquefaction plant.

The infrastructure costs used in our analysis are based on the capital cost of the relevant clean hydrogen production plants to which, where appropriate, we have added the capital cost of the required hydrogen conditioning and transport infrastructure. In particular, for clean hydrogen exported as LH_2, we have also factored in the cost of building the necessary liquefaction capacity and acquiring the cryogenic vessels to transport it via sea routes. For clean hydrogen exported as LOHC, however, we have not included the cost of the vessels because we assume that the available conventional vessels can be used. A similar reasoning also applies to the hydrogen transported as ammonia. We have also excluded from our analysis the cost of the infrastructure needed to reconvert the H_2 carrier to pure H_2 at the receiving end, because we assume that the investment cost will be borne by the importer.

10

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