Energy Proceedings
Vol 66, 2026
ISSN 2004-2965

A MUSE-HiQ pathway to evaluate the transition from LNG export to hydrogen: Qatar as a case study

Alaa Al-Qassabi[1*], Adam Hawkes [2], Marcello Contestabile [3]

1 Qatar Environment and Energy Research Institute

1 Imperial College London

2 Imperial College London

3 Qatar Environment and Energy Research Institute

(Corresponding Author: aalqassabi@hbku.edu.qa)

ABSTRACT

Global efforts to transition from fossil fuels towards a hydrogen-based future present Qatar with a strategic opportunity to leverage its fossil fuel endowment for the production of clean hydrogen for export. This paper applies the MUSE simulation platform to evaluate Qatar's potential to consolidate its position as a leading low-carbon energy exporter, building on its established LNG capacity, under three distinct emissions mitigation scenarios. The analysis compares the relative competitiveness of LNG, hydrogen, and ammonia, highlighting the influence of carbon price trajectories and demand levels. Results show that under moderate emissions targets, hydrogen begins to substitute LNG at carbon prices of USD 420-460 per ton CO_2, whereas under more stringent carbon budgets, hydrogen enters the market at lower carbon prices of 90-130 USD per ton CO_2. Ammonia, by contrast, remains structurally uncompetitive against capitalizing in LNG and hydrogen under transition. These findings underscore the pivotal role of policy in shaping export competitiveness and demonstrate the value of model-based analysis in informing strategic policy discourse.

Keywords: hydrogen pathway, Qatar LNG export, energy systems transition, scenario-based analysis, simulation model, energy policy

NONMENCLATURE

Abbreviations	
LNG	Liquefied Natural Gas
SMR	Steam Methane Reforming
CCS	Carbon Capture and Storage
STEPS	Stated Policies Scenario
APS	Announced Pledges Scenario
PC	Paris Compatible
IAM	Integrated Assessment model
NDC	Nationally Determined Contribution

1. INTRODUCTION

The concept of hydrogen-based energy systems can be traced back to the oil crises of the 1970s, when the vulnerability of fossil fuel dependency first drew attention to alternative fuels[1]. However, hydrogen gained renewed momentum in the 1990s following advances in fuel cell technology[1]. In recent decades, global decarbonization pressures have further accelerated its relevance, positioning hydrogen as a potential enabler for deep emission reductions while also offering co-benefits; such as improved air quality[2]. For hydrogen-exporting economies, hydrogen presents an additional strategic advantage: it can be produced from existing non-renewable sources while also offering renewable production routes[3].

Currently, steam methane reforming (SMR) remains the dominant hydrogen production pathway due to its economic competitiveness[4]. When coupled with carbon capture and storage (CCS), it offers a lower-emission alternative relative to other fossil-based options. A variation to this technology is autothermal reforming (ATR) which incorporates partial oxidation of the feedstock and generates a more concentrated CO2 stream[5]. This characteristic makes ATR particularly suitable for large-scale production[5].

On the other hand, renewable hydrogen is produced through electrolysis, which drastically reduces direct CO_2 emissions but raises production costs[1]. This pathway is particularly attractive for regions lacking fossil fuels but rich in renewable potential, especially when supported by incentives or policy mandates[1]. Nonetheless, renewable hydrogen continues to face economic hurdles due to high production costs and the currently limited size of the global hydrogen export market[6].

Hydrogen transmission poses additional economic and technical challenges. It can be transported via pipelines or as liquid hydrogen[4]. Pipelines, while offering low operating costs, require high upfront capital investments due to the specialized materials needed to withstand hydrogen chemical properties[4]. Retrofitting existing natural gas pipelines demands technical adaptation[7], though this constraint is less critical for Qatar, where most natural gas is exported as LNG.

Although the precise future role of hydrogen in the global energy mix by 2050 remains uncertain[1], it is clear that the sector is moving toward gradual deployment. In the modelling framework applied here, investment in hydrogen is restricted to post-2030 to reflect realistic technology diffusion timelines reported in the literature[1,8]. This ensures consistency with technology readiness considerations.

This paper aims to evaluate the future competitiveness of fossil fuel exports in a global energy market increasingly shifting toward hydrogen under emissions reduction targets. Using MUSE simulation model, the analysis explores the implications of this transition for energy-exporting countries, with a specific focus on Qatar as a case study due to its prominent position in the global fossil fuel market, While Qatar is used as the primary example, the approach is generalizable and can be applied to assess similar challenges faced by other major fossil fuel exporters.

2. MATERIALS AND METHODS

2.1 MUSE Simulation Model

This work applies the ModUlar Energy systems Simulation Environment (MUSE) to assess the competitiveness of energy export commodities within Qatar energy system. MUSE is a novel Integrated Assessment Model (IAM) developed at Imperial College London. It is a bottom-up simulation framework that seeks cost-efficient system configurations. The model spans the entire energy value chain, beginning with supply, followed by conversion and demand sectors, and converged to a partial equilibrium through a market-clearing algorithm[9], Fig 1.

For this study, MUSE is implemented as MUSE-HiQ, calibrated to the Qatari energy system with a base year of 2015 and projected to mid-century. The model incorporates existing hydrocarbon production and processing assets, electricity generation capacity, and domestic energy demand outlets. The export sector reflects Qatar current petroleum product exports, with LNG dominating the portfolio. Given LNG’s central role, this export channel forms the primary focus of the analysis.

2.2 Modelling Specifications

The technology profile encompasses a portfolio of hydrogen producing technologies, including steam methane reforming (SMR), autothermal reforming (ATR), and their variations with CCS. Production pathways based on non-fossil fuel resources are excluded to ensure that the analysis remains focused on the role of fossil fuels in enabling clean hydrogen transition. On the demand side, the export sector module is configured to comprise export technologies, specifying alternative routes for the delivery of energy commodities.

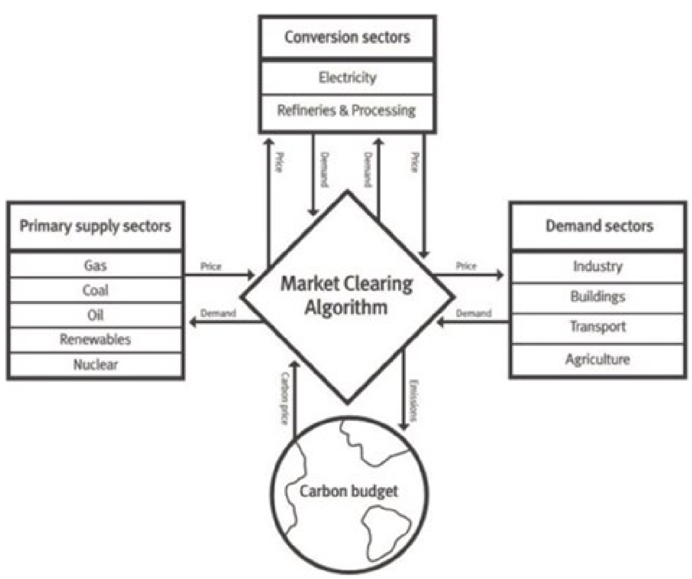

Fig. 1 MUSE architecture

A critical assumption underpinning this study is the internalisation of the export sector by accounting for transport and combustion emissions, specifically under Scope 3 Category 4 emissions[10,11,12]. Without such consideration, the economic results would consistently favour LNG even under stringent carbon budget constraints. This is primarily due to LNG established infrastructure and the availability of carbon removal technologies to mitigate its emissions profile. However, by incorporating transport-related emissions, additional costs are attributed to each commodity. These costs must be acknowledged by importers to comply with emerging energy standards, and by exporters to preserve long-term market competitiveness[10].

Accordingly, this sectoral module integrates the full transport costs of LNG, liquid hydrogen (LH2), and ammonia (NH3), ensuring that competitiveness is assessed not only at the point of production but also across the supply chain. Transport cost assumptions are derived from published literature[13,14], with values indicating that LNG transport is generally more cost-efficient relative to LH2 and NH3. Nonetheless, when combustion emissions at the final point of use are included, the competitiveness of zero-carbon carriers such as hydrogen and ammonia improves significantly compared to LNG.

Additional considerations include constraining hydrogen exports to commence only after 2030, under the assumption that a hydrogen-ready market will emerge by that time[8]. An initial export capacity of approximately 1.20 Mt is permitted, equivalent to current hydrogen production levels in Qatar and roughly matching the volume of LNG delivered to Japan in 2024[15,16]. This constraint is designed to avoid unrealistic modelling artefacts, such as an immediate large-scale phase-out of LNG exports, thereby ensuring a more credible transition trajectory.

2.3 Scenario Assumptions

International energy demand trajectories are derived from the IEA hydrogen outlook in the World Energy Outlook 2024 (WEO)[17], with the upper bound reflecting the Announced Pledges Scenario (APS) and lower bound based on the Stated Policies Scenario (STEPS). Three policy cases are considered for the context of Qatar: A Business-as-Usual (BAU) benchmark scenario with no emissions constraints; a STEPS case that incorporates Qatar's Nationally Determined Contribution (NDC), including a 25% emissions reduction target by 2030; and a Paris Compatible (PC) case, which extends the STEPS framework but delays carbon neutrality by 2060.

3. RESULTS AND DISCUSSION

3.1 Fuel Substitution Dynamics under Carbon Pricing

The relative competitiveness of LNG, hydrogen, and ammonia as export commodities varies across demand trajectories and emissions reduction targets. In the STEPS (Lower-demand) scenario, Fig 2, which combines low energy demand growth with moderate emissions constraints, hydrogen emerges only briefly as an export commodity between 2035-2040. Its entry is triggered at a carbon price of 420 USD/tCO_2, reflecting its potential role in mitigating system-wide emissions as the carbon budget tightens. However, with hydrogen exports exogenously capped at limited capacity, LNG continues to dominate the portfolio through mid-century. By 2050, LNG contributes approximately 27.7 MtCO_2 from liquefaction plants alone. This contribution is, nevertheless, already reduced by 46% relative to the baseline due to carbon capture integration, underscoring both the persistence of LNG and the marginal role of hydrogen in this scenario.

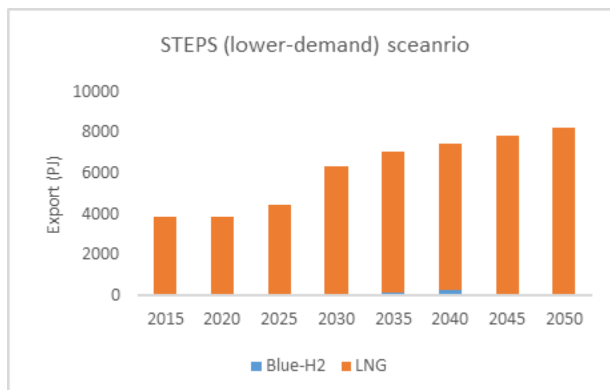

Fig. 2 Export mix in STEPS scenario showing continued export of LNG under moderate emissions reduction target and low energy demand

Under the same policy case (STEPS) but under higher demand, Fig 3, a more pronounced transition occurs as existing LNG assets gradually retire, and hydrogen progressively displaces LNG. This shift is triggered at carbon prices of approximately 460 USD/tCO_2 which steadily erode the competitiveness of LNG export portfolio. In this pathway, hydrogen is supplied exclusively through ATR with carbon removal utilities at a competitive LCOE value of 12.3 USD/GJ. By mid-century, this transition delivers a ~30% reduction in export-related emissions relative to the baseline, highlighting the potential of hydrogen to substitute LNG under more stringent demand pressures and higher carbon pricing.

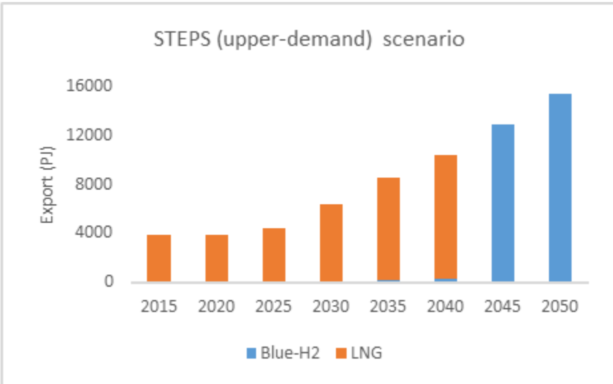

Fig. 3 Export mix in STEPS scenario showing continued export of LNG under moderate emissions reduction target and low energy demand

By contrast, under the PC scenario, Fig 4, progressively tightening carbon policy shifts the balance decisively in favour of hydrogen. However, Qatar's current hydrogen production capacity of 144 PJ is insufficient to establish competitiveness; exports only materialize once this capacity is doubled, underscoring the requirement for upstream scaling. Once these capacity constraints are lifted, hydrogen becomes fully competitive and begins to displace LNG in the export portfolio.

A pivotal milestone occurs by 2040**,** when hydrogen achieves cost parity with LNG at a carbon price ~90 USD/tCO_2 under the lower-demand case and ~130 USD/tCO2 under the higher-demand case, reducing export-related emissions by 31-33% relative to baseline. Prior to this threshold, at ~70 USD/tCO2, LNG continues to dominate exports.

Across all scenarios, ammonia remains uncompetitive even under extreme carbon price trajectories aimed at net-zero by 2060, as least-cost investment and capital allocation consistently favour LNG and hydrogen. These underscores underlying economic difficulties of repositioning ammonia from fertilizer commodity to energy carrier within the transition projections from the perspective of competing with LNG and blue hydrogen.

3.2 Carbon-Conscious Markets

This progression in energy export competitiveness, depicted in Fig 1, is shaped by three factors: the rising

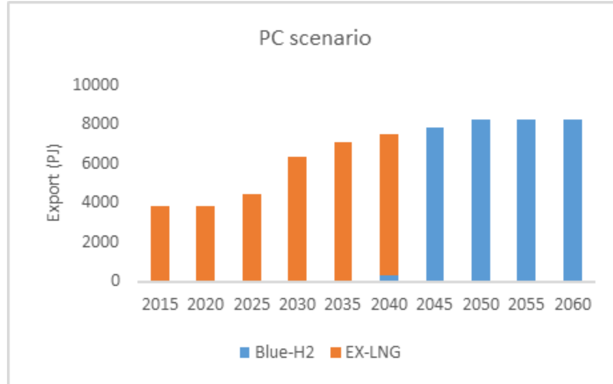

Fig. 4 Export mix in PC scenario, similar at both upper and lower demand cases, demonstrating a shift in the export portfolio towards hydrogen as the environmental cost of LNG can no longer compete with hydrogen

environmental cost reflected in carbon price trajectories that progressively erode LNG advantage; the timing of market entry with demand growth which signals early-movers advantage but also risks stranded or underutilized infrastructure; and the strength of policy mandates that ultimately steer export choices.

4. CONCLUSION

The global transition away from fossil fuels toward alternative energy carriers presents both challenges and opportunities for hydrocarbon-dependent economies such as Qatar, a leading exporter of LNG. By leveraging low-emissions, fossil-based production routes, Qatar can position itself as a supplier of clean hydrogen and its derivatives. This study applies a simulation model to evaluate the competitiveness of LNG, hydrogen, and ammonia in the export market under varying demand trajectories and emissions targets. The findings aim to inform policy discourse and identify the transition levers necessary to sustain Qatar's role as a major energy exporter while aligning with its climate mitigation goals.

ACKNOWLEDGEMENT

This work is jointly supported by Qatar Environment and Energy Research Institute (QEERI), Qatar National Research Fund (QNRF), Imperial College London, and is in collaboration with Hi-ACT initiative.

REFERENCE

[1] Ball M, Weitschel M. The future of hydrogen – opportunities and challenges. Int J Hydrogen Energy 2009;34:615–627.

[2] SNAM. (2025, September 28) IEA Report. *The future of hydrogen*. Retrieved from https://www.snam.it/en/hydrogen_challenge/iea_report
[3] IEA a. (2025, August 9) Hydrogen. *Latest findings*. Retrieved from https://www.iea.org/energy-system/low-emission-fuels/hydrogen
[4] IEA b. (2025, September 28) Towards hydrogen definitions based on their emissions intensity. Retrieved from https://iea.blob.core.windows.net/assets/acc7a642-e42b-4972-8893-2f03bf0bfa03/Towardshydrogendefinitionsbasedontheiremissionsintensity.pdf
[5] Air Liquide. (2025, September 5) Autothermal Reforming (ATR). *Reforming the future with low-carbon hydrogen*. Retrieved from https://www.airliquide.com/stories/hydrogen/autothermal-reforming-atr-reforming-future-low-carbon-hydrogen
[6] IEA c. (2025, August 30) The future of hydrogen. *Seizing today's opportunities*. Retrieved from https://www.iea.org/reports/the-future-of-hydrogen
[7] Telessy K, Barner L, Holz F. Repurposing natural gas pipelines for hydrogen: Limits and options from a case study in Germany. Int J Hydrogen Energy 2024;80:821–831.
[8] IEA d. (2025, September 7) Hydrogen demand. Retrieved from https://www.iea.org/reports/global-hydrogen-review-2024/hydrogen-demand
[9] Giarola S, Sachs J, D'Avezac M, Kell A, Hawkes A. MUSE: An open-source agent-based integrated assessment modelling framework. Energy Strateg Rev 2022;44:1–22.
[10] Greenhouse Gas Protocol. (2025, September 15) IPCC emissions factor database. Retrieved from https://ghgprotocol.org/Third-Party-Databases/IPCC-Emissions-Factor-Database
[11] De Kleijne K, Huijbregts M, Knobloch F, Van Zelm R, Hilbers J, De Coninck H, Hanssen S. Worldwide greenhouse gas emissions of green hydrogen production and transport. Nature Energy 2024;9:1139–1152.
[12] Global Hydrogen Review. (2025, September 27) Tackling the Scope 3 challenge. Retrieved from https://www.globalhydrogenreview.com/hydrogen/09092024/tackling-the-scope-3-challenge/\
[13] Lee J, Cherif A, Yoon H, Seo S, Bae J, Shin H, Lee C, Kwon H, Lee C J. Large-scale overseas transportation of hydrogen: Comparative techno-economic and environmental investigation. Renew Sustain Energy Rev 2022;165:1–15.
[14] Howardth R. The greenhouse gas footprint of liquefied natural gas (LNG) exported from the United States. Energy Sci Eng 2024;12:4843–4859.
[15] Earthna. (2025, August 30) Developing a clean hydrogen industry in Qatar. *Investment costs, uncertainties, and critical decisions*. Retrieved from https://www.earthna.qa/sites/default/files/publications/attachments/2025-04/Developing%20a%20Clean%20Hydrogen%20Industry%20in%20Qatar-Print-Eng-Digital.pdf
[16] GIIGNL. (2025, August 4) Annual Report. Retrieved from https://www.giignl.org/annual-report
[17] WEO. (2025, August 25) World Energy Outlook. Retrieved from https://iea.blob.core.windows.net/assets/140a0470-5b90-4922-a0e9-838b3ac6918c/WorldEnergyOutlook2024.pdf