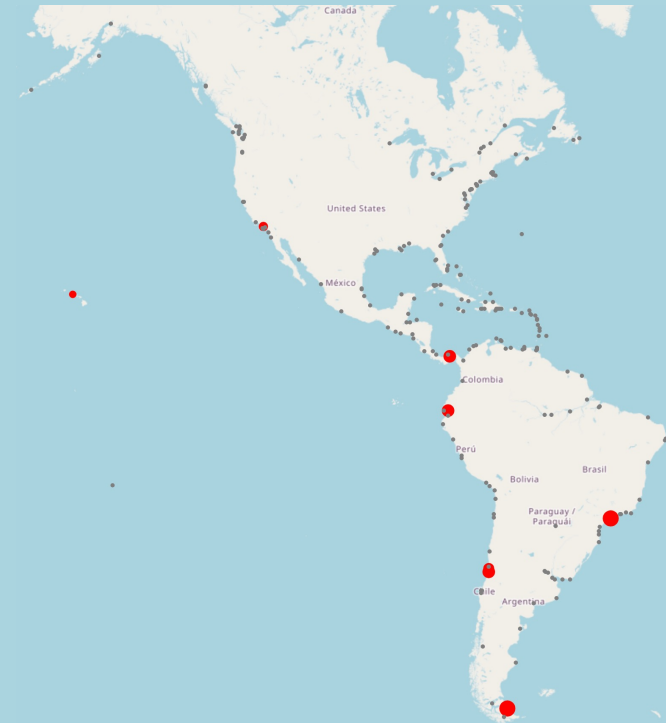


A Cost-Optimization Framework for Assessing Green Ammonia Regional Maritime Demand and Bunkering Location

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Green hydrogen: a cornerstone of the global energy transition

Hydrogen Council

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Hydrogen Insights: Hydrogen project pipeline grows by 35% since January 2023 despite macro-economic headwinds

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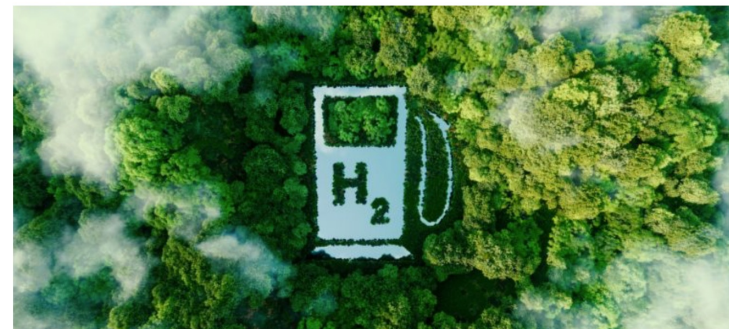
3 Green Hydrogen Stocks Ready to Blast Upward

Sheryl Sheth
Feb 14, 2023 at 03:04 AM

Analyze A+ A-

Story Highlights

Green hydrogen companies are set to benefit from the Inflation Reduction Act (IRA) passed in 2022. While the rules to fit the criteria for availing of tax credits are being written, companies are making huge investments in the green hydrogen sector to benefit from them.



The story is not so rosy...

nature energy



Article

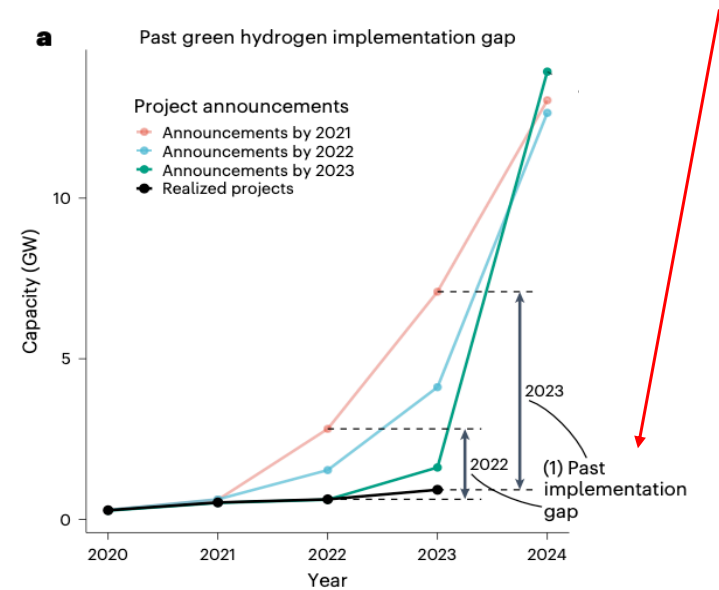
<https://doi.org/10.1038/s41560-024-01684-7>

The green hydrogen ambition and implementation gap

Received: 1 June 2024

Adrian Odenweller^{1,2} & Falko Ueckerdt¹

Accepted: 12 November 2024



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The Green Hydrogen Reckoning: An Analysis of Project Cancellations and the Path to a Viable Market



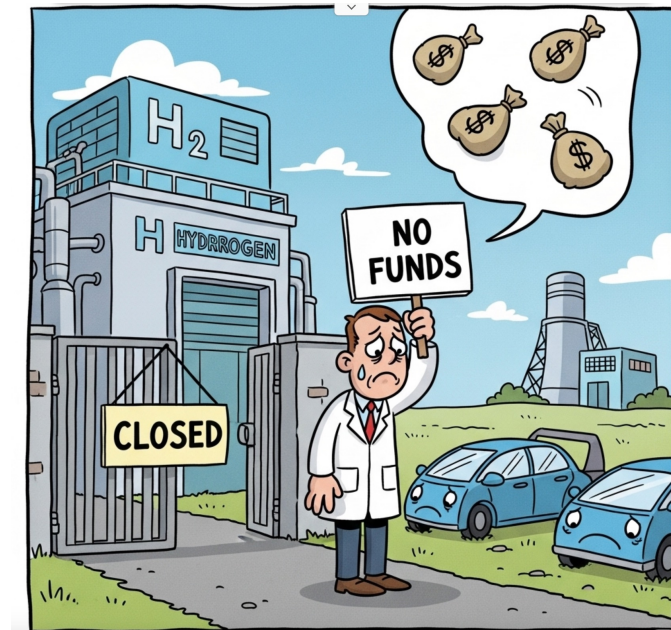
Editor

26 Jul 2025 · 28 min read

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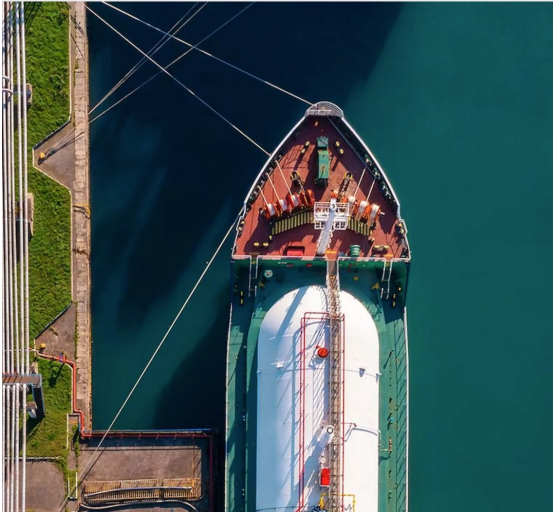
What happened?

- Production costs not as low as expected
- Policy uncertainty
- Lack of infrastructure
- The “chicken-and-egg” offtake impasse



Green ammonia for maritime transport

Green ammonia can be produced from green hydrogen.
⇒ potential large source of demand as marine fuel!



DNV

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INDUSTRY INSIGHTS • DECARBONIZATION

Ammonia as a marine fuel: Prospects and challenges

Ammonia is gaining traction as a marine fuel, backed by regulatory progress, engine innovation and early fleet adoption. Due to high costs and infrastructure gaps, shipowners are advised to plan strategically when choosing the right future fuel. How far and fast ammonia as an alternative fuel can propel shipping decarbonization is examined in the DNV paper Ammonia in Shipping.

7 Minutes 30 September, 2025 Share Print

BUT: How to estimate that demand?

- Green-fuel uptake depends on policy, fuel costs, ship conversion, and bunkering infrastructure.
- For export-oriented green ammonia, the strategic question is not only production cost; it is whether the shipping network can create spatially concentrated demand.

Problem statement: the fuel market is endogenous, not given

Conventional assumption

Many alternative-fuel studies start with a fixed demand or assumed fuel availability, then optimize bunkering or fleet decisions.

Our work's proposal

Demand appears only if a vessel conversion, a refueling network, and a supply origin are jointly cost-minimizing under policy constraints.

Why it matters

A carbon price can fail to activate the market if infrastructure or fuel costs dominate the avoided fossil-fuel and emission costs.

Research question

Under what carbon-price and production-cost conditions does green ammonia become economically viable for container vessels in the Americas, and where should the bunkering network be deployed?

Literature review

Alternative fuels

LNG, methanol, hydrogen, biofuels and ammonia are compared on emissions, storage, safety, and technological readiness.

Market-based measures

Carbon pricing and emission regulation are needed because green fuel pathways are usually more capital-intensive and costlier.

Supply-chain optimization

Bunkering location, fleet renewal, route choice, and fuel supply models provide the methodological basis for network planning.

The three aspects are typically studied separately!

- Infrastructure models often treat vessel adoption and demand as exogenous.
- Shipowner models often assume alternative fuels are available when needed.
- Green-corridor models are spatially narrow and may miss wider network demand patterns.

Gap and contribution: integrating actors and revealing demand

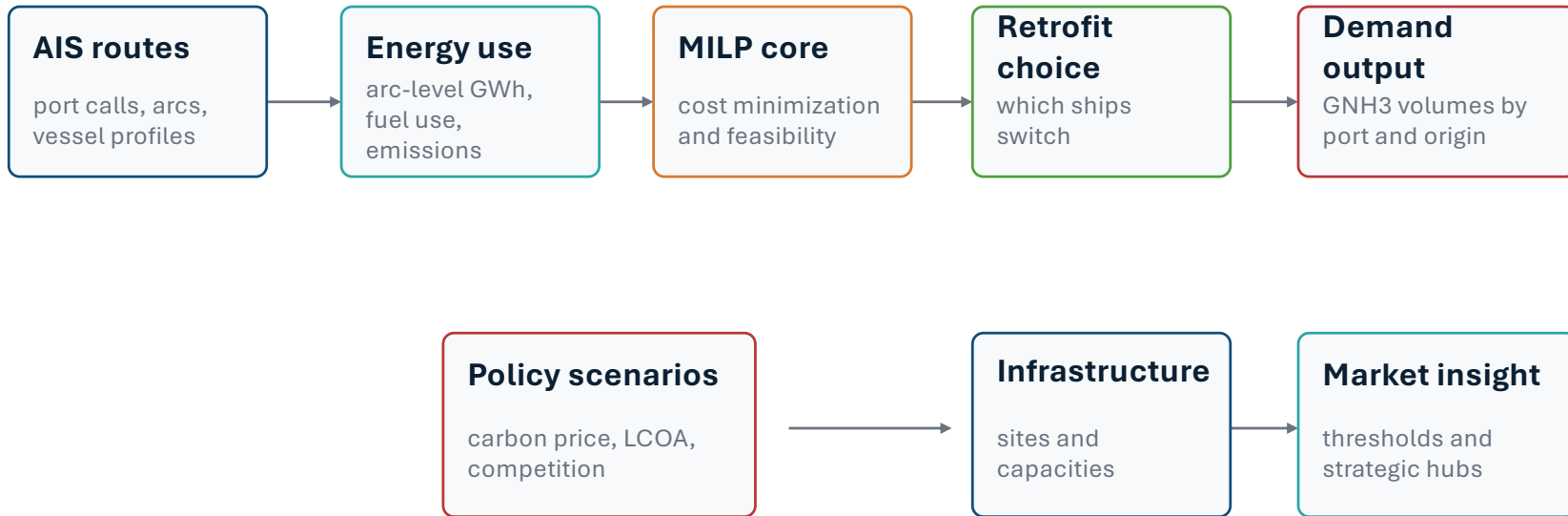
Gap

- No explicit estimation of green-ammonia maritime demand as an endogenous optimization output.
- Limited joint representation of supplier location, bunkering infrastructure, and shipowner retrofit decisions.
- Limited full-network assessment for container shipping across the Americas.

Contribution

- A spatial MILP that jointly chooses retrofitted vessels, bunkering locations, capacity, and GNH3 origin, based on production and transportation costs.
- AIS-based route and energy-demand construction for 2024 container ships with port calls in the Americas.
- Policy and investment insights on carbon-price thresholds, hub formation, and Chile's competitiveness.

Framework logic



Demand appears only when route energy, fuel cost, infrastructure, and carbon policy jointly make green ammonia cost-minimizing.

Methodology: data pipeline and network construction

2057

container vessels

4400

routes

377

ports

126551 GWh

annual energy in the sample

AIS route construction

Identify container-ship routes with at least one port call in the Americas; represent each route as an ordered sequence of arcs.

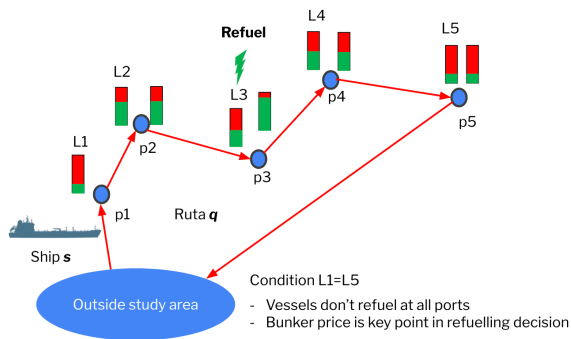
Energy and emissions

Estimate arc-level consumption using the Fourth IMO GHG Study methodology; assign legacy fuel types from vessel data.

Tank capacity

Use reported data when available; impute missing HFO and LNG tank capacities with fitted log-linear regressions.

Optimization model: decisions and cost structure



Decisions

- Build a bunkering facility at port p .
- Install storage capacity at port p .
- Retrofit vessel s for GNH3 operation.
- Select refueling quantities by vessel, port call, and origin of fuel.
- Track the vessel tank level along the route. (Traditional OR Inventory Management Problem)

Cost logic

- GNH3 procurement cost, depending on origin of fuel
- Vessel retrofit CAPEX
- Bunkering CAPEX and OPEX
- Legacy fuel cost plus carbon cost for non-retrofitted vessels

A ship is retrofitted only if the model can also provide feasible bunkering and if the avoided fossil fuel + carbon cost justifies the green system cost.

Optimization model: decision variables

Decision Variables:

$y_p \in \{0, 1\}$: Equals 1 if a bunkering facility is built at port $p \in P$, 0 otherwise.

$l_{qsip} \geq 0$: Fuel tank level of ship $s \in S^q$ at port call $i \in J^q$ (port $p \in P^q$) of route $q \in Q$ (GWh).

$x_{qsipo} \geq 0$: Quantity of GNH_3 loaded by ship $s \in S^q$ at port call $i \in J^q$ (port $p \in P^q$) of route $q \in Q$, sourced from origin $o \in O$ (GWh).

$z_p \geq 0$: Bunkering storage capacity installed at port $p \in P$ (GWh).

$r_s \in \{0, 1\}$: Equals 1 if ship $s \in S$ is retrofitted for GNH_3 operation, 0 otherwise.

Optimization problem : objective function

Total annualized system cost

$$\begin{aligned}
 \min \quad & \underbrace{\sum_{q \in Q} \sum_{s \in S^q} \sum_{i \in J^q} \sum_{p \in \{P^q[i]\}} \sum_{o \in O} p_{po} x_{qsipo}}_{\text{(i) } \text{GNH}_3 \text{ fuel cost}} + \underbrace{\sum_{s \in S} \text{CAPEX}^{ret} r_s \text{TEU}_s}_{\text{(ii) vessel retrofit}} \\
 & + \underbrace{\sum_{p \in I^p} \left(\text{CAPEX}^{lnk} \lambda z_p + \text{CAPEX}^{ves} \lambda y_p + \text{FC}_p y_p + \text{VC}_p z_p \right)}_{\text{(iii) bunkering infrastructure}} + \underbrace{\sum_{q \in Q} \sum_{s \in S} (\text{CE}_{qs} + \text{CFUEL}_{qs}) (1 - r_s)}_{\text{(iv) legacy fuel and carbon cost}}
 \end{aligned}$$

- The carbon-price policy enters through the cost of emissions for vessels that remain on legacy fuels.
- The optimization compares the incumbent fossil-fuel path against the complete green-ammonia pathway, not fuel price alone.
- The result is a threshold behavior: below a certain carbon price, the optimal green investment is zero.

Optimization problem : vessel fuel feasibility

$$l_{qsjp} = l_{qsip} - c_{qsij} r_s + \sum_{o \in O} x_{qsipo},$$

Inventory balance: consumption between ports and refueling at port call i .

$$l_{qsip} + \sum_{o \in O} x_{qsipo} \geq l_{s,\min},$$

Safety reserve: the tank level after refueling must stay above the minimum threshold.

$$l_{qsip} + \sum_{o \in O} x_{qsipo} \leq l_{s,\max},$$

Tank capacity: refueling cannot exceed physical capacity.

$$l_{qs,1,p} = l_{qs,\max\{J^q\},p},$$

Route cyclicity: end-of-route tank level must match the start for repeated liner operations.

Optimization problem : infrastructure and supply feasibility

$$z_p \leq y_p T^{max},$$

Facility activation: a port can have positive capacity only if the binary build decision is active.

$$z_p \geq \sum_{q \in Q} \sum_{s \in S^q} \sum_{i \in J^q} \sum_{o \in O} x_{qsipo},$$

Capacity adequacy: installed storage must cover annual throughput assigned to that port.

$$\sum_{q \in Q} \sum_{s \in S^q} \sum_{i \in J^q} \sum_{p \in \{P^q[i]\}} x_{qsipo} \leq C_o,$$

Production limit: each origin can supply only up to its annual GNH3 capacity.

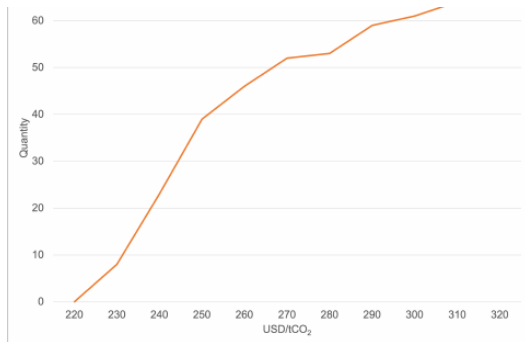
The experimental design: Chilean supply hubs

Experiments

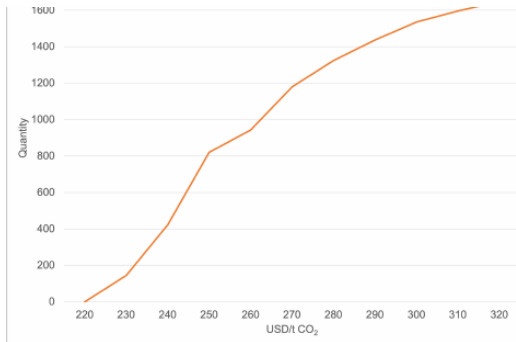
1. Chile-only carbon-price scenarios from 220 to 320 USD/tCO₂.
 - Two Chilean export hubs are modeled:
 - Magallanes (462 USD/t)
 - Antofagasta (483 USD/t)
 - Transport cost depends on maritime distance, freight rate, berthing time, Panama Canal tolls, and port fees.
2. Competitiveness analysis with additional candidate suppliers.



Results I: carbon pricing activates adoption with threshold



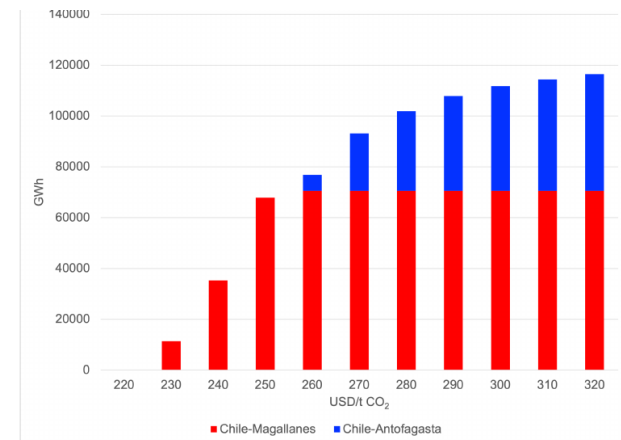
(a) Bunkering facilities



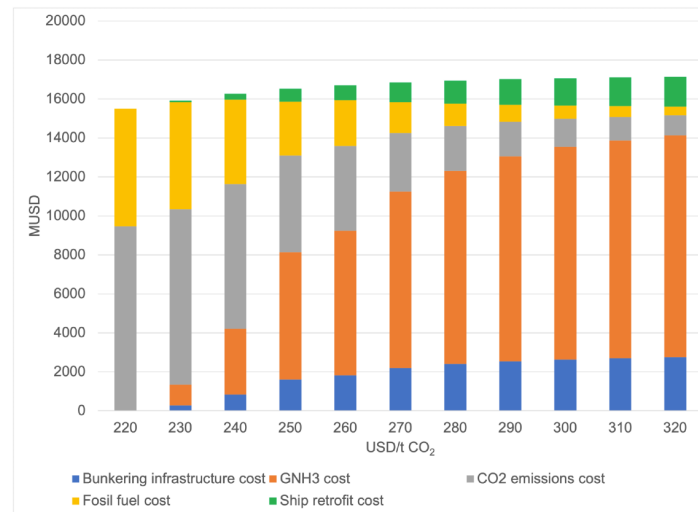
(b) Retrofitted vessels

Main baseline finding

- Carbon prices at or below 220 USD/tCO₂ do not trigger green investment.
- Then, we see an “S” curve, with approx. 60% of demand converted to green ammonia at 250 USD/tCO₂

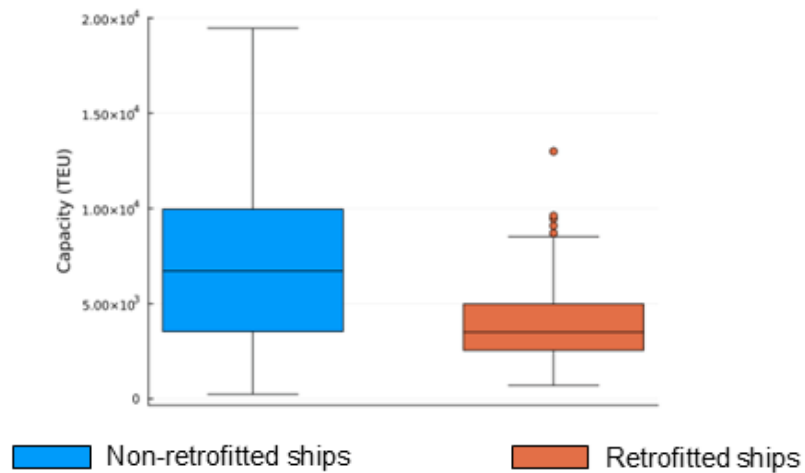


Results II: cost structure and fleet conversion pattern



- At the highest carbon price, infrastructure and retrofits cost accounts for roughly 25% of annualized green cost across analyzed cases.
 - **Policy implication I:** focusing only on the direct fuel-price gap understates the system requirements for adoption.
- LNG-fueled vessels begin to retrofit only above 310 USD/tCO₂, consistent with LNG as a transition fuel.
 - **Policy implication II:** Unless there is a clear carbon price signal, the transitional fuel (LNG) becomes permanent. Signal is important.

Results IV: which ships switch first?

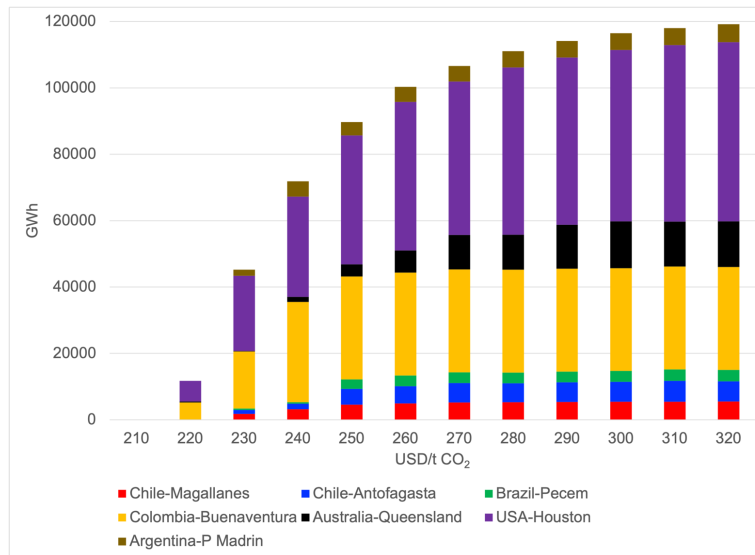


Interpretation

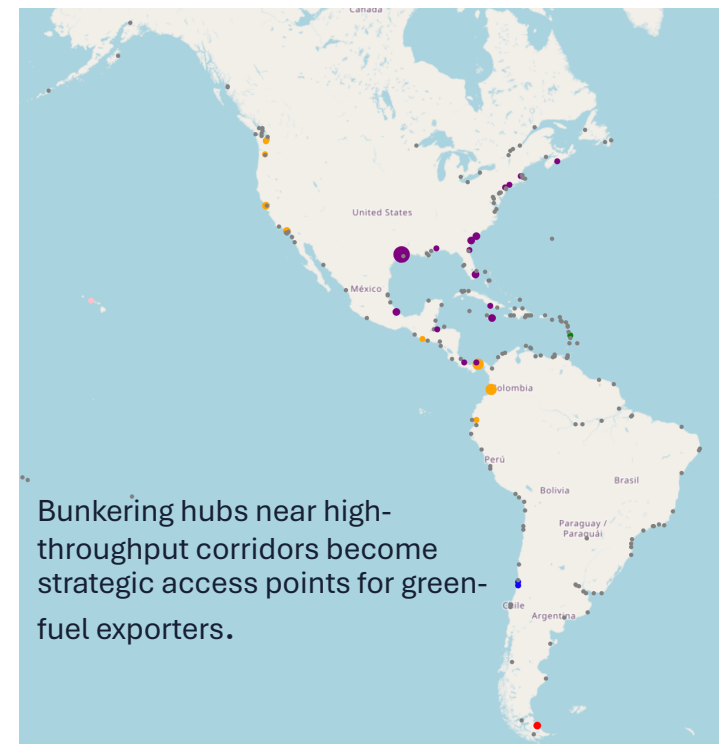
- At the first adoption threshold, retrofitted vessels tend to be smaller-capacity ships with high annual energy use and long traveled distances.
- The cost logic favors vessels for which the carbon-cost savings accumulate quickly relative to retrofit cost.

Sensitivity analysis

For this experiment, we assume that other GH2-producing countries have the same LCOA as Chile.

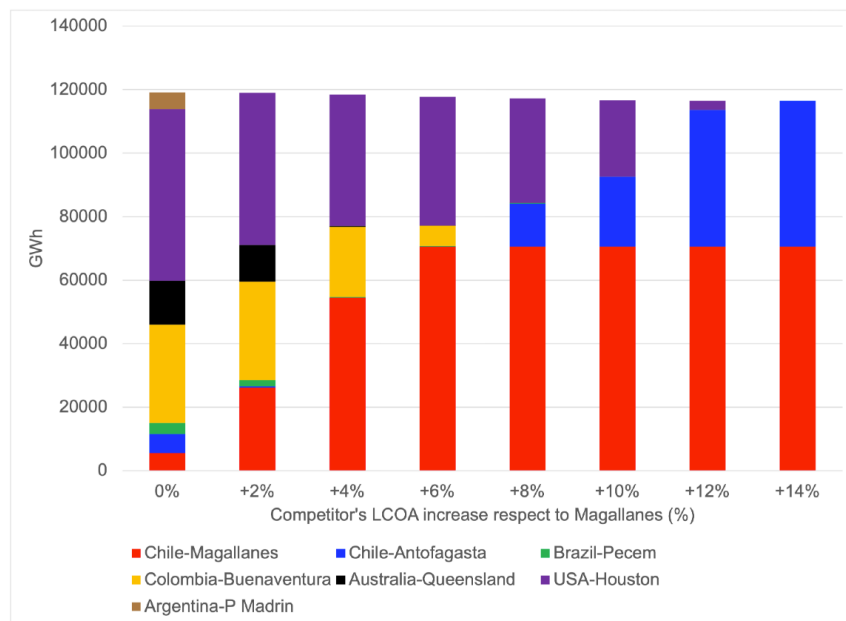


- Houston and Colombia are the major sources, due to their geographic centrality.



Chile must compensate geography with production-cost advantage

For this experiment, we assume that other GH2-producing countries have increasingly higher production costs, compared to Chile.



Strategic implications

- Chile's participation depends on maintaining a cost advantage large enough to offset longer distances to some demand centers.
- However, the transportation contribution is not very high, so a 10% production cost advantage already yields a large market share (80%).

Conclusions and takeaways

- A carbon price of roughly 230 USD/tCO₂ s required to trigger adoption of green ammonia.
- GNH₃ cost dominates green cost, but infrastructure and retrofit costs are relevant.
- LNG retrofits require higher carbon prices.
- LCOA assumptions and competition strongly reshape policy thresholds and market shares.
- Transportation contributes a relatively small portion of the GNH₃ fuel cost; thus, countries with lower production costs (such as Chile) are more competitive.

Future extensions

Stochastic fuel prices, multi-period fleet renewal, explicit port constraints, uncertainty in regulation, and comparison with methanol or hydrogen.