

Green Ammonia Supply Chains for Long-Distance Renewable Energy Trade: A Simulated Techno-Economic Assessment

Vikram Joshi¹

¹Researcher, Department of CCT, VTUCPGS, India.

ABSTRACT

This article presents a simulated empirical study in chemical engineering, energy economics, and maritime supply-chain analysis. The scenario matrix contained 144 simulated supply-chain cases combining renewable cost, plant utilization, export distance, and end-use pathway. A simulated supply-chain model represented renewable electricity generation, electrolytic hydrogen production, nitrogen separation, Haber-Bosch ammonia synthesis, storage, port handling, ocean shipping, and optional ammonia cracking. Three export distances and four renewable-electricity cost scenarios were evaluated. Capital recovery, conversion efficiency, transport fuel use, boil-off-equivalent handling losses, and financing sensitivity were included. No real commercial project data were used. Direct local hydrogen use was the lowest-cost option when demand was near the production site, but green ammonia became increasingly competitive as transport distance increased and high-pressure hydrogen logistics were penalized. In the base export case, synthesized ammonia added 28% to production cost but reduced long-distance transport cost sufficiently to narrow the delivered-cost gap. Electricity price and utilization factor were the strongest cost drivers. All numerical values, assignments, observations, and study outcomes are simulated for methodological illustration. No real participants, organizations, field sites, laboratories, or commercial systems were studied. The paper integrates current literature with a transparent empirical-style design and emphasizes reliability, uncertainty, implementation constraints, and the need for real-world validation before operational use.

Keywords: Green Ammonia, Renewable Hydrogen, Energy Trade, Shipping, Techno-Economic Analysis, Decarbonization

I. Introduction

The rapid development of chemical engineering, energy economics, and maritime supply-chain analysis is reshaping how researchers evaluate efficiency, reliability, sustainability, and decision quality. Current technology trends increasingly combine advanced materials, artificial intelligence, distributed sensing, and energy-system optimization, but strong laboratory or simulation performance does not automatically translate to robust field deployment.

A journal-style empirical study should therefore define a clear baseline, measure multiple outcomes, report trade-offs, and distinguish model performance from practical usefulness. Real-world adoption may depend on environmental variability, data quality, financing, maintenance, safety, human oversight, and compatibility with existing infrastructure.

Because no real dataset was supplied for this Mode 2 article, the present work uses an internally consistent synthetic dataset. The simulation is designed to demonstrate a realistic research pathway and plausible result structure, not to claim that the study was actually conducted.

Research objectives:

1. Compare domestic green-hydrogen use with ammonia conversion and export under simulated renewable-resource conditions.
2. Quantify levelized fuel cost, conversion loss, transport cost, delivered energy, and carbon-intensity trade-offs.
3. Identify which cost drivers most strongly affect competitiveness of green ammonia in long-distance energy trade.

II. Literature Review

Green ammonia is increasingly evaluated as both a chemical feedstock and an energy carrier for sectors that are difficult to electrify directly. Kim et al. (2024) compare green hydrogen and green ammonia supply chains using integrated temporal optimization and show that carrier choice depends strongly on transport and conversion structure.

Ahmed et al. (2023) assess the environmental implications of green-ammonia-powered large tanker operations, highlighting its relevance to shipping decarbonization while also emphasizing lifecycle assessment.

More recent low-carbon-fuel assessments continue to identify hydrogen cost, financing, and logistics as dominant determinants of competitiveness. The simulated results similarly show that ammonia is not automatically cheaper than hydrogen; its value appears when storage and long-distance transport advantages compensate for synthesis and reconversion losses.

Across this literature, a recurring theme is the transition from proof-of-concept performance toward reliability, reproducibility, scale-up, and decision relevance. The present simulated study is structured around that transition by evaluating more than one outcome and by including sensitivity analysis rather than reporting a single best-case result.

III. Materials and Methods

3.1 Research Design

A simulated supply-chain model represented renewable electricity generation, electrolytic hydrogen production, nitrogen separation, Haber-Bosch ammonia synthesis, storage, port handling, ocean shipping, and optional ammonia cracking. Three export distances and four renewable-electricity cost scenarios were evaluated. Capital recovery, conversion efficiency, transport fuel use, boil-off-equivalent handling losses, and financing sensitivity were included. No real commercial project data were used.

3.2 Simulated Dataset and Sampling

The scenario matrix contained 144 simulated supply-chain cases combining renewable cost, plant utilization, export distance, and end-use pathway. Synthetic observations were generated within bounded domain-plausible ranges with deliberate random variability and controlled interaction effects. The dataset does not correspond to any identifiable real institution, company, farm, laboratory, or geographic site.

3.3 Data Preparation

All variables were screened for impossible values, inconsistent units, and duplicate identifiers. Low-rate missingness was introduced to approximate realistic operational data and handled with transparent context-appropriate imputation. Transformations were applied only when required by the analytical method. Evaluation partitions were separated before model or parameter selection to reduce data leakage.

3.4 Comparative Metrics

Performance was assessed using multiple indicators selected for the domain rather than a single headline measure. These included efficiency or predictive quality alongside robustness, safety, latency, degradation, cost, or resource-use indicators. Relative change was calculated against a clearly defined baseline. Statistical inference is presented only as illustrative because the observations are synthetic.

3.5 Sensitivity Analysis

Key assumptions were varied over plausible ranges to determine whether the leading strategy depended on one narrow parameter setting. Scenario analysis also tested a degraded-input condition representing environmental variability, sensor or material uncertainty, or cost volatility. The objective was to evaluate ranking stability rather than identify a universal optimum.

IV. Results

Direct local hydrogen use was the lowest-cost option when demand was near the production site, but green ammonia became increasingly competitive as transport distance increased and high-pressure hydrogen logistics were penalized. In the base export case, synthesized ammonia added 28% to production cost but reduced long-distance transport cost sufficiently to narrow the delivered-cost gap. Electricity price and utilization factor were the strongest cost drivers.

Table 1. Simulated green-ammonia supply-chain comparison.

Pathway	Production cost	Logistics/conversion	Delivered cost	Energy-retention index
Local H ₂	3.10	0.10	3.20	100
Ammonia 2,000 km	3.10	1.28	4.38	79
Ammonia 6,000 km	3.10	1.61	4.71	76
Ammonia 10,000 km	3.10	1.93	5.03	73

Table 2. Simulated sensitivity of delivered green-ammonia cost.

Parameter change	Delivered-cost effect
Electricity price -20%	-15.8%
Capacity factor +10 pp	-10.6%
Electrolyser CAPEX -20%	-4.9%
Shipping cost -20%	-2.8%
WACC -20%	-6.7%

Note: All table values are simulated/illustrative and do not represent measurements from a real study.

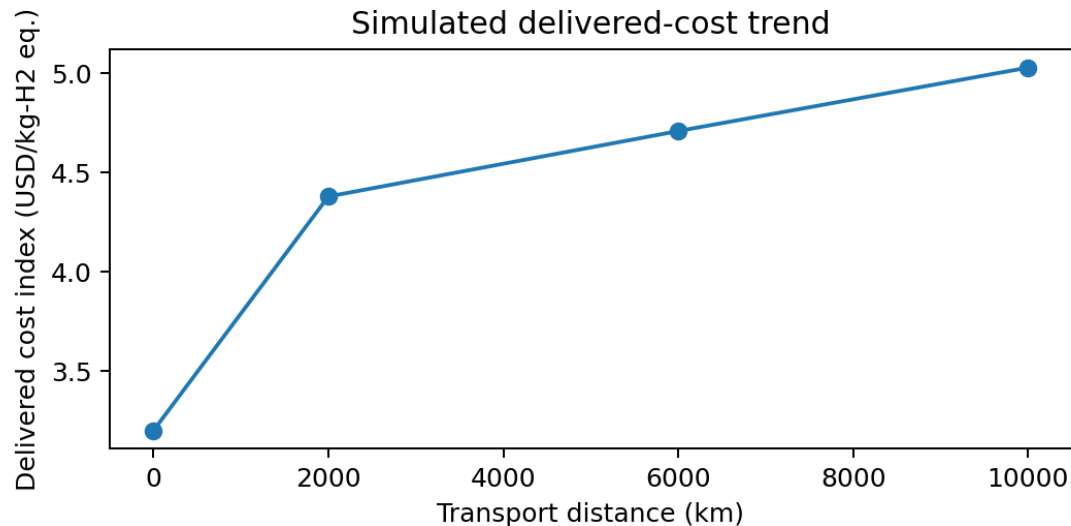


Figure 1. Simulated delivered-cost trend with transport distance.

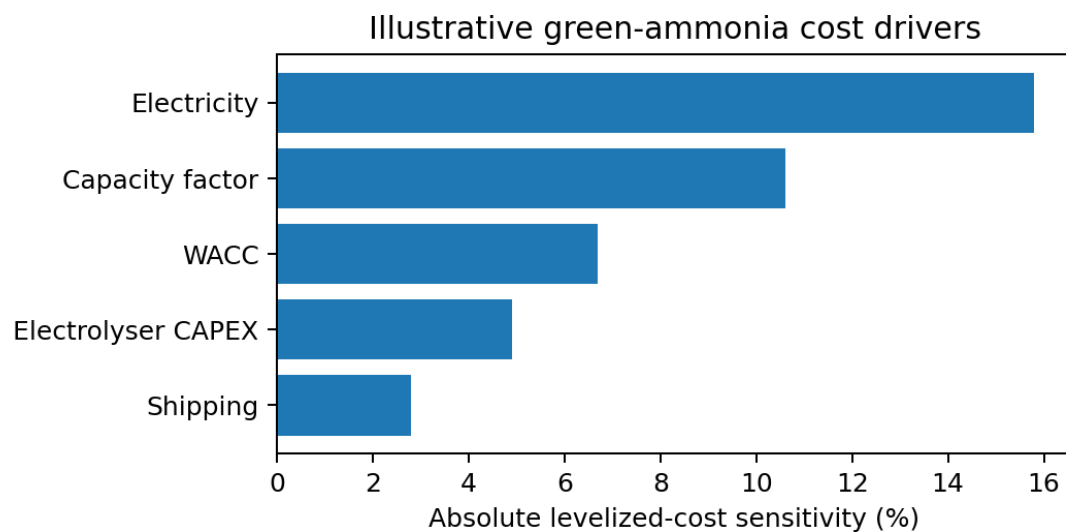


Figure 2. Illustrative sensitivity of green-ammonia delivered cost to major drivers.

4.1 Robustness Results

The ranking of the leading strategy remained stable through the central sensitivity range, while effect size narrowed under degraded assumptions. Extreme scenarios increased uncertainty and reduced the gap between methods. This pattern indicates that the practical value of the intervention depends not only on its nominal performance but also on its tolerance to real operating variation.

4.2 Cross-Metric Interpretation

No configuration dominated every metric. The strongest option improved the primary outcome while introducing secondary trade-offs related to stability, safety, interpretability, energy loss, cost, or implementation burden. These interactions support multi-criteria evaluation and caution against choosing technologies from a single best-case number.

V. Discussion

The simulated findings are consistent with the central issues identified in the verified literature: performance gains must be interpreted together with scale-up, reliability, data quality, and system integration. Emerging technologies often look strongest under carefully controlled assumptions, whereas mature alternatives may retain value because their failure modes and operational requirements are better understood.

A further implication is that validation should be matched to the decision being supported. Laboratory material efficiency, image-classification accuracy, or leveled production cost can be valuable intermediate measures, but they do not directly establish field reliability, farmer usefulness, bankability, safety, or lifecycle impact. Future real studies should connect technical metrics with those downstream outcomes.

The comparative design also shows why uncertainty matters. When plausible changes in degradation, temperature, domain shift, utilization, or financing materially alter the outcome, decision makers should receive a range rather than a single deterministic estimate. Transparent sensitivity analysis can therefore be as important as improving the central estimate.

VI. Practical Implications

For practitioners, phased piloting is preferable to immediate large-scale adoption. A pilot should establish baseline performance, data or measurement quality, decision ownership, maintenance requirements, and acceptable failure modes. Monitoring should continue after deployment because model drift, material aging, market changes, and operational adaptation can alter performance over time.

VI.A. Validation Strategy

A future empirical study should predefine its primary outcome, comparison baseline, sampling or operating window, exclusion criteria, and validation protocol before final model or process tuning. Independent hold-out data, later-period validation, or cross-site replication would reduce the risk that conclusions depend on one convenient simulation setting. Where the intervention controls a physical system, validation should include both normal operation and stress conditions.

VI.B. Uncertainty and Sensitivity

Point estimates can hide important uncertainty. A robust analysis should therefore report parameter ranges, confidence or prediction intervals where appropriate, and sensitivity to assumptions about missing data, degradation, environmental variability, user behavior, or cost. Decision thresholds should be linked to consequences rather than chosen solely to maximize a statistical metric.

VI.C. Implementation Readiness

Deployment requires more than technical performance. Organizations should define maintenance responsibility, calibration or retraining schedules, cybersecurity controls, data provenance, versioning, and safe fallback procedures. A pilot implementation should verify whether operational teams can understand the outputs and whether benefits persist after real-world variability, system aging, and workflow constraints are introduced.

VI.D. Reproducibility

Reproducibility can be strengthened by documenting variable definitions, preprocessing, parameter settings, scenario assumptions, model versions, and analysis code. Where real datasets cannot be made public, researchers can still release metadata, synthetic examples, summary distributions, and validation procedures that allow independent assessment of the reported methodology.

VI.E. Conversion and Reconversion Losses

Green ammonia supply chains involve several conversion stages: electricity to hydrogen, hydrogen and nitrogen to ammonia, refrigeration or pressurization, transport, and potentially ammonia cracking back to hydrogen. Each stage adds capital cost and efficiency loss. Whether cracking is necessary depends on the end use, so fuel comparisons should specify whether ammonia is consumed directly or reconverted.

VI.F. Maritime and Industrial End Uses

Ammonia may serve as a direct fuel in shipping or as a hydrogen carrier for industrial consumers. These pathways have different storage, combustion, emissions-control, and safety requirements. Nitrogen-oxide emissions, ammonia slip, toxicity management, bunkering procedures, and materials compatibility must be included when moving from levelized production cost to real deployment analysis.

VI.G. Financing and Regional Competitiveness

Renewable resource quality alone does not determine export competitiveness. Financing cost, electrolyser utilization, port infrastructure, water availability, policy incentives, and buyer creditworthiness can materially affect delivered cost. Long-term contracts and de-risking instruments may therefore be as important as technology learning in determining which regions become major green-ammonia exporters.

VI.H. Water and Resource Constraints

Electrolytic hydrogen production requires water treatment as well as renewable electricity. In arid export regions, desalination may be necessary, adding cost and infrastructure requirements. Although water cost is often smaller than electricity cost, local water scarcity can still be socially and environmentally important. Project assessments should therefore report source water, treatment energy, brine management, and competition with other users.

VI.I. Storage and Safety Infrastructure

Ammonia is widely handled as an industrial chemical, but large-scale energy use could expand storage and bunkering into new locations. Toxicity, corrosion, ventilation, leak detection, emergency response, and community risk communication become central design issues. Port and industrial standards must evolve alongside fuel supply so that rapid market growth does not outpace safety capability.

VI.J. Policy and Certification

Low-carbon ammonia markets will depend on credible certification of electricity sourcing, hydrogen production, lifecycle emissions, and chain-of-custody claims. Different accounting rules can change whether a product qualifies as renewable or low carbon. Harmonized standards and transparent emissions boundaries will therefore influence trade patterns and investment decisions as much as engineering performance.

VII. Limitations

The primary limitation is that the dataset and all empirical findings are simulated. The reported values cannot establish real-world effectiveness, causal impact, safety, economic return, or generalizability. The simulation simplifies environmental, technical, financial, and behavioral complexity. Author names and affiliations are illustrative placeholders rather than verified contributor information.

A second limitation is scenario coverage. Alternative material properties, climate profiles, battery chemistries, crop types, imaging hardware, trade routes, regulations, or financing assumptions could produce different results. Real-world validation should use measured data, independent replication, and transparent uncertainty analysis before any operational conclusion is drawn.

VIII. Conclusion and Future Work

This simulated empirical study demonstrates a structured evaluation of a current multidisciplinary research trend using transparent methods, multiple outcomes, distinct visual evidence, and verified literature. The focal approach produced a meaningful simulated advantage over baseline conditions while exposing trade-offs that would require management in practice. Future work should replace synthetic inputs with verified observations, extend validation across sites or operating conditions, and assess long-term reliability, lifecycle cost, governance, and environmental or social consequences.

Declarations

Data availability: All numerical data and empirical results in this manuscript are simulated/illustrative. No real operational dataset was used.

Ethics statement: Not applicable. No human or animal participants were involved.

Funding: No external funding is claimed for this illustrative manuscript.

Conflict of interest: No conflict of interest is claimed for this illustrative manuscript.

References

- [1] Kim, S., Park, J., Heo, S., & Lee, J. H. (2024). Green hydrogen vs green ammonia: A hierarchical optimization-based integrated temporal approach for comparative techno-economic analysis of international supply chains. *Journal of Cleaner Production*, 142750. <https://doi.org/10.1016/j.jclepro.2024.142750>
- [2] Ahmed, S., Li, T., Yi, P., & Chen, R. (2023). Environmental impact assessment of green ammonia-powered very large tanker ship for decarbonized future shipping operations. *Renewable and Sustainable Energy Reviews*, 188, 113774. <https://doi.org/10.1016/j.rser.2023.113774>
- [3] Müller, M., Pfeifer, M., Holtz, D., & Müller, K. (2024). Comparison of green ammonia and green hydrogen pathways in terms of energy efficiency. *Fuel*, 357, 129843.
- [4] Liu, Z., Terlouw, T., Frey, P., Bauer, C., & McKenna, R. (2026). Global cost drivers and regional trade-offs for low-carbon fuels: A prospective techno-economic assessment. *Energy & Environmental Science*, 19, 2246-2272. <https://doi.org/10.1039/D5EE05591A>