

Green Ammonia and Hydrogen: Pathways to a Sustainable Energy Future-The Role of Transportation, Logistics, and Trading

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Abstract

This study explores the development and optimization of a green ammonia supply chain in Egypt, focusing on the post-production stages of storage, handling, and distribution. As global energy systems transition toward sustainability, green ammonia is increasingly viewed as a promising clean fuel and agricultural input. Egypt's strategic location near key ports and trade routes positions it as a viable regional hub for green ammonia logistics. The research employs a mixed-methods approach that integrates a literature review, expert interviews, structured risk assessment, and simulation modeling. Interviews with industry professionals provided practical insights that informed the analysis of real-world constraints and logistics practices. Risk identification and prioritization were conducted using Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), addressing vulnerabilities across six major categories, including safety, infrastructure, and market uncertainty. Simulation tools, specifically AnyLogistix, were used to perform Green Field Analysis, Network Optimization, and Dynamic Simulation, enabling the evaluation of distribution center placement, lead time, and cost-performance trade-offs. The findings highlight the importance of backup planning, fulfillment strategies, and proactive risk management in enhancing supply chain responsiveness and financial viability. Overall, the study offers a data-driven framework to support the design of a resilient and efficient green ammonia distribution network in Egypt.

Keywords

Supply Chain, Green Ammonia, Risk Management, Logistics, Simulation

1. Introduction

The global shift toward sustainable energy systems is central to mitigating the impacts of climate change and achieving long-term environmental and economic resilience. As nations and industries work to decarbonize their operations, attention has increasingly turned to alternative fuels and clean energy carriers. Among these, green ammonia, produced using renewable energy sources, has emerged as a promising solution for reducing emissions in traditionally carbon-intensive sectors such as agriculture, power generation, and maritime transport.

Green ammonia offers a carbon-free alternative to conventional ammonia, whose production accounts for roughly 1.3% of global greenhouse gas emissions. Unlike its fossil-based counterpart, it is synthesized using green hydrogen, generated through the electrolysis of water powered by renewable energy. This makes green ammonia not only a sustainable fertilizer but also an efficient hydrogen carrier and energy storage medium, capable of stabilizing renewable energy systems and supporting decarbonized fuel networks.

This study therefore aims to explore the role of transportation, logistics, and trading in enabling the green ammonia economy, with a particular focus on Egypt's emerging position in the global energy transition. It examines the current

state and future outlook of supply chain infrastructure, storage and maritime transport requirements, the role of ports and regulations, and the potential for developing international trading mechanisms. By integrating risk assessment tools (FMEA and FTA) with AnyLogistix simulation modeling, this research presents a data-driven framework to design a resilient and efficient green ammonia supply chain tailored to Egypt's context.

Despite this significant potential, the large-scale deployment of green ammonia remains constrained by logistical inefficiencies, infrastructure gaps, and unaddressed safety and market risks across the supply chain. Recent institutional and industry studies have emphasized these challenges. The International Energy Agency (IEA) and International Renewable Energy Agency (IRENA) highlight green ammonia's strategic role in achieving net-zero emissions but stress that its commercial success depends on the creation of robust logistics, storage, and trading networks. The DNV Maritime Forecast to 2050 was also conducted by (- Maritime, n.d.) further reinforces this perspective, projecting ammonia to become a leading marine fuel by 2050, while warning that supply chain immaturity, port readiness issues, and regulatory uncertainty pose major barriers to adoption. Although recent technical analyses have advanced understanding of production technologies and energy integration, limited research has explored the post-production stages particularly storage, transportation, and risk management. This lack of integrated, data-driven studies represents a crucial gap, especially in developing economies such as Egypt, where renewable energy potential and geographic positioning could enable regional leadership in green fuel logistics and trade.

The green ammonia supply chain faces a complex network of interrelated risks that impact its safety, scalability, and long-term sustainability. These risks can be categorized into six main domains: safety and environmental hazards, infrastructure and technological limitations, geopolitical and regulatory instability, logistics and cybersecurity vulnerabilities, market and environmental sustainability pressures, and financial and collaborative uncertainties.

Safety and environmental risks are primarily associated with ammonia's toxic, corrosive, and volatile nature, necessitating rigorous containment, detection, and emergency response measures was also conducted by (Chorowski et al., 2023; Valera-Medina et al., 2018) Infrastructure and technological risks emerge from incompatibility with existing facilities, material degradation under cryogenic conditions, and rapid technological obsolescence was also conducted by (Hydrogen Insights A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness, 2021; Rouwenhorst & Castellanos, 2022) Geopolitical and regulatory risks stem from policy fragmentation and dependence on sensitive trade routes, as exemplified by the energy disruptions following the Russia-Ukraine conflict and the Suez Canal blockage was also conducted by (Negro et al., 2023; Notteboom et al., 2024) Logistics and cybersecurity risks involve both physical failures during ammonia transport and digital vulnerabilities within increasingly automated systems was also conducted by (Adeli et al., 2023; Ahmed et al., 2025; Levikhin & Boryaev, 2025; Overland, 2019) Market and environmental sustainability risks arise from high production costs, renewable energy intermittency, and the substantial water requirements of electrolysis processes was also conducted by (Collis & Schomäcker, 2022; Kumar et al., 2024; Reda et al., 2024) Finally, financial and collaborative risks highlight the need for innovative investment mechanisms, such as green bonds, blended finance, and public-private partnerships to reduce capital exposure was also conducted by (Energy Agency, 2024; *Global Hydrogen Trade to Meet the 1.5°C Climate Goal*, 2022; Renewable Energy Agency & Development Bank, 2024)

These interconnected risk dimensions underscore the necessity of a comprehensive, systems-based risk management framework. Integrating Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) provides complementary approaches to identify, evaluate, and mitigate vulnerabilities across the supply chain. Strengthened regulatory governance, technological innovation, and cross-sector collaboration are therefore essential to ensure the resilience and sustainability of the green ammonia industry within the global energy transition was also conducted by (SCALING HYDROGEN FINANCING FOR DEVELOPMENT REPORT In Support Of, 2024).

Understanding these logistical and trading dynamics is essential, as they directly influence the economic competitiveness, safety, scalability, and sustainability of green ammonia. By identifying key bottlenecks and strategic opportunities across the supply chain, this research contributes both practical insights for policymakers and industry stakeholders and academic advancement in sustainable logistics and energy transition studies, supporting Egypt's ambition to become a regional hub for green hydrogen and ammonia.

1.1 Objectives

1. To identify and categorize key risks across the green ammonia supply chain covering technological, operational, strategic, geopolitical, economic, environmental, and policy dimensions.
2. To assess and prioritize critical failure modes using Failure Mode and Effects Analysis (FMEA) to quantify their impact on supply chain performance.
3. To analyze interdependencies and root causes of failures through Fault Tree Analysis (FTA), providing a structured understanding of system vulnerabilities.
4. To simulate and optimize supply chain operations using AnyLogistix tools Green Field Analysis (GFA), Network Optimization (NO), and Dynamic Simulation (DS) to enhance logistics efficiency and responsiveness.
5. To evaluate the financial and operational performance of various network scenarios under normal and disruption conditions.
6. To propose a decision-support framework for policymakers and industry stakeholders to improve port readiness, infrastructure investment, and digital risk management in the green ammonia sector.
7. To position Egypt as a regional hub for green hydrogen and ammonia trading through resilient, sustainable logistics design.

2. Methods

This study adopts a quantitative and simulation-based research design aimed at developing a resilient and risk-informed supply chain framework for green ammonia in Egypt. The methodological framework integrates Failure Mode and Effects Analysis (FMEA), Fault Tree Analysis (FTA), and AnyLogistix simulation modeling to assess, quantify, and optimize post-production supply chain performance.

Secondary data were collected from international and institutional sources including the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and DNV Maritime Forecast to 2050 (2025 Edition), supplemented by reports from Egyptian energy authorities and port operators. These datasets provided baseline values for production capacity, transport distances, infrastructure cost, and demand forecasts.

The FMEA technique was employed to identify potential failure modes within storage, transportation, and distribution operations. Each failure mode was evaluated in terms of Severity (S), Occurrence (O), and Detection (D), and the resulting Risk Priority Number (RPN) was used to rank and prioritize key risks (Masowski, 2021). Subsequently, Fault Tree Analysis (FTA) was conducted to trace the logical interrelationships and root causes of critical failures, enabling a structured understanding of system vulnerabilities (Ruijters & Stoelinga, n.d.).

The AnyLogistix platform was used to model Egypt's green ammonia distribution network under varying demand and capacity scenarios. The model included modules for Green Field Analysis (GFA) to identify optimal facility locations, Network Optimization (NO) to minimize total logistics costs, and Dynamic Simulation (DS) to assess network performance over time under stochastic demand conditions.

Model outcomes were compared with global benchmarks and validated through parameter sensitivity analysis. The integration of risk assessment and simulation ensured methodological consistency between qualitative evaluation and quantitative modeling.

3. Results and Discussion

The Failure Mode and Effects Analysis (FMEA) was employed to systematically identify and evaluate potential failure modes across the green ammonia supply chain. A total of 22 risk factors were examined within seven categories: operational, technological, strategic, geopolitical, economic, environmental, and policy related. Each failure mode was assessed using three prioritization levels high, medium, and low to determine its relative significance. The analysis revealed that cybersecurity threats represented the most critical failure mode, achieving the highest Risk Priority Number (RPN) score of 36, indicating a substantial potential for supply chain disruption arising from system hacking or data breaches. These findings underscore the growing importance of digital infrastructure protection in modern, technology dependent logistics systems. (As Shown in Table 1)

Table 1. Failure Modes & Effects Analysis (FMEA)

FMEA of Green Ammonia Supply Chain									
Risk No.	Risk Factor	Category	Failure Mode	Effect	S	O	D	RPN	Mitigation
1	Cybersecurity threat	Technological	Hackers disrupt systems	Safety, data loss	4	3	3	36	Implement robust firewalls, encryption, and regular security audits. Train staff on cybersecurity protocols. Use intrusion detection systems.
2	Political instability	Geopolitical	Government collapse, policy reversal	Project disruption, import/ export bans	4	2	4	32	Diversify supply chains across regions. Monitor geopolitical trends and establish contingency contracts with alternative partners.
3	Land, water, and air pollution	Environmental	Leak/spill contamination	Legal fines, damage	5	2	3	30	Install leak detection systems and secondary containment. Train staff on spill response and comply with environmental regulations.
4	Rapid tech development	Strategic	Current tech becomes obsolete	Investment loss	3	3	3	27	Invest in modular, upgradable technologies. Monitor tech trends and participate in industry R&D collaborations.
5	Tariffs & trade barriers	Policy	Sudden increase in imports	Procurement cost rises	3	3	3	27	Negotiate trade agreements and diversify import sources. Use local suppliers where feasible to reduce tariff exposure.
6	Substitute products	Strategic	New fuel gains favor	Loss of market share	3	3	3	27	Differentiate green ammonia through cost, reliability, and sustainability. Invest in R&D to stay competitive with substitutes.
7	Supplier failure	Operational	Key supplier shuts down	Supply disruption	4	2	3	24	Qualify multiple suppliers and maintain strategic stockpiles. Develop long-term supplier partnerships with performance monitoring.

FMEA of Green Ammonia Supply Chain									
Risk No.	Risk Factor	Category	Failure Mode	Effect	S	O	D	RPN	Mitigation
8	Lack of storage/transport	Operational	Insufficient infrastructure	Supply delays	4	3	2	24	Invest in scalable storage and transport infrastructure. Partner with logistics firms to ensure capacity during peak demand.
9	Inflation	Economic	Rising input and logistics costs	Budget overruns	3	4	2	24	Hedge against inflation with fixed-price contracts. Optimize logistics to reduce fuel and labor costs.
10	Government incentives change	Policy	Incentives removed unexpectedly	Budget failure, project pause	4	2	3	24	Secure long-term contracts for incentives. Diversify funding sources, including private investment, to reduce reliance on subsidies.
11	Skilled labor shortage	Operational	Cannot operate the plant safely	Low productivity, safety risk	4	3	2	24	Invest in training programs and automation to reduce labor dependency. Partner with educational institutions to build a talent pipeline.
12	Labour strike	Operational	Workforce halts operations	Supply chain stops	4	2	3	24	Foster good labor relations and fair contracts. Develop contingency plans, including temporary staffing or automation.
13	Disease outbreak	Environmental	Worker shortage, lockdown	Delayed operations	4	2	3	24	Implement health protocols, remote work options, and cross-training to maintain operations. Maintain insurance for disruptions.
14	Economic recession	Economic	Funding dries up	Project delays, investment loss	4	2	3	24	Secure diverse funding sources, including private capital. Optimize costs to maintain project viability during downturns.
15	War/conflict	Geopolitical	Supply routes blocked or destroyed	Severe supply delays or loss	5	1	4	20	Develop alternative supply routes and maintain emergency stockpiles. Use insurance to cover conflict-related losses.
16	Health and safety	Safety	Ammonia exposure	Injury or fatality	5	2	2	20	Install gas detection systems and PPE. Train workers on ammonia handling and emergency response. Conduct regular safety audits.

FMEA of Green Ammonia Supply Chain									
Risk No.	Risk Factor	Category	Failure Mode	Effect	S	O	D	RPN	Mitigation
17	Poor inventory forecasting	Operational	Over/ under stocking	Financial and operational loss	3	3	2	18	Deploy advanced demand forecasting tools using AI. Maintain flexible contracts with suppliers to adjust inventory levels dynamically.
18	Consumer acceptance	Strategic	Low demand due to perception	Market failure	3	3	2	18	Conduct public awareness campaigns on green ammonia benefits. Engage stakeholders to build trust and demonstrate reliability.
19	Poor information flow	Operational	Late data or errors	Slow or wrong decisions	3	3	2	18	Implement integrated ERP systems for real-time data sharing. Train staff on data accuracy and establish clear communication protocols.
20	Currency exchange rate	Economic	Fluctuations affect import costs	Cost unpredictability	3	3	2	18	Use currency hedging strategies. Negotiate contracts in stable currencies or diversify supplier regions to mitigate exposure.
21	Natural disaster	Environmental	Earthquake, flood	Facility damage	5	1	3	15	Build facilities to withstand local hazards (e.g., seismic design). Maintain insurance and develop disaster recovery plans.
22	Improper facility location	Operational	Far from the port or the grid	High transport/storage cost	3	2	2	12	Conduct thorough site selection studies, prioritizing proximity to ports and grids. Use modeling tools to optimize location decisions.

The Fault Tree Analysis (FTA) further illustrated the interdependencies among failure events, demonstrating how isolated operational disruptions could cascade into large-scale supply chain failures. The FTA framework emphasized that systemic resilience requires integrated risk management, where mitigation strategies address both individual risks and complex causal linkages across technological, operational, and geopolitical dimensions. This analytical approach revealed that failures related to communication systems, equipment malfunction, and inadequate monitoring mechanisms often acted as initiating events in broader disruption pathways. (As Shown in Figure 1)

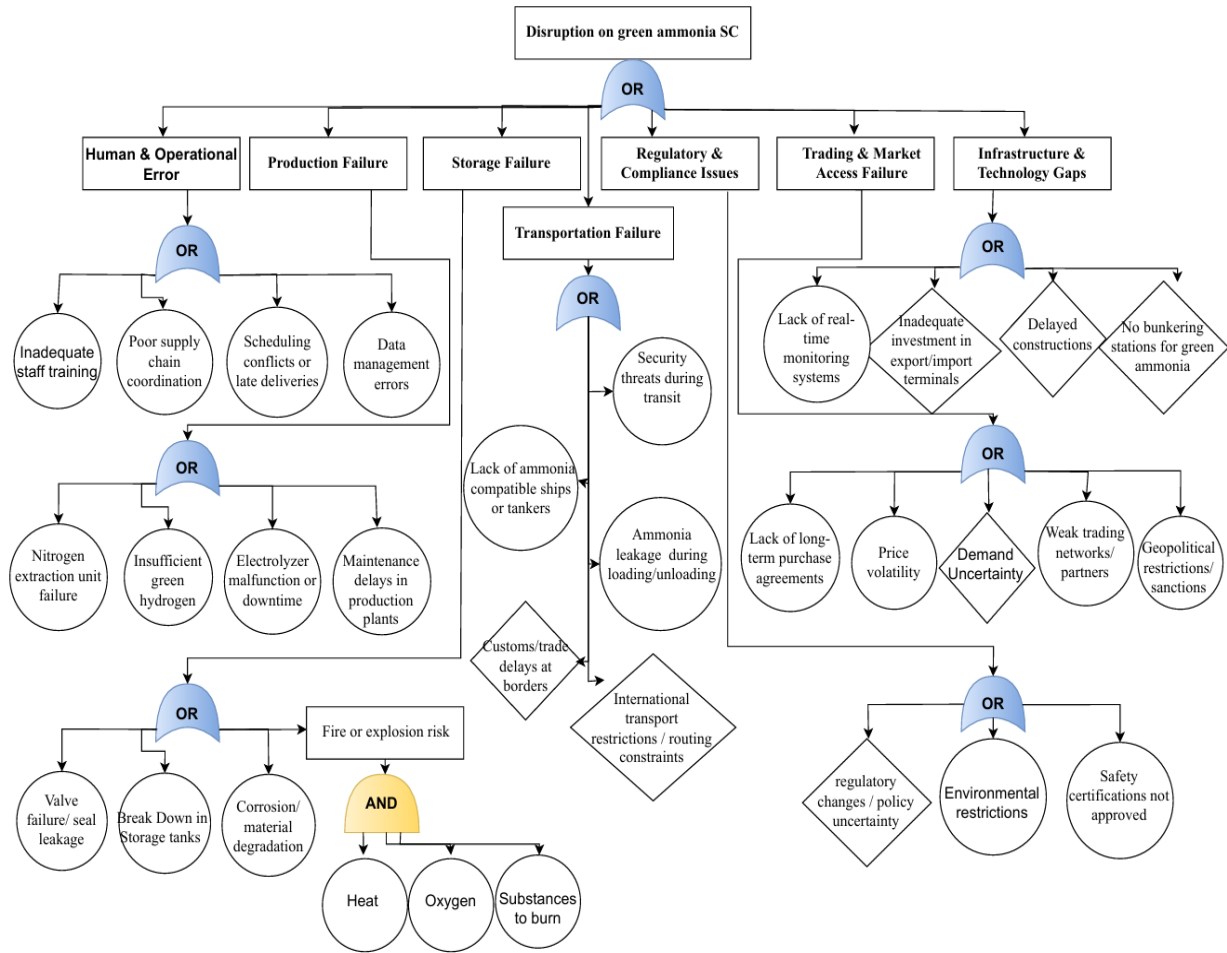


Figure 1. Fault Tree Analysis (FTA)

A comparative evaluation of financial performance across simulated scenarios revealed substantial differences in profitability under varying market and disruption conditions. The scenario featuring an increase in the selling price of green ammonia from 650 USD/ton to 1,000 USD/ton generated the highest financial return, corresponding to a 1.54× increase in revenue. This outcome highlights the sensitivity of the green ammonia supply chain to market pricing dynamics, where strategic price adjustments significantly enhance profitability. Furthermore, the analysis demonstrated that the inclusion of backup planning mechanisms improves financial resilience under disruption scenarios. For example, in the event of a fire incident, financial losses at the Sadat Distribution Center (DC) were notably higher than those at the Green Field Analysis (GFA)-based DC, indicating that facility location and risk exposure play decisive roles in maintaining financial stability. (As Shown in Figure 2)

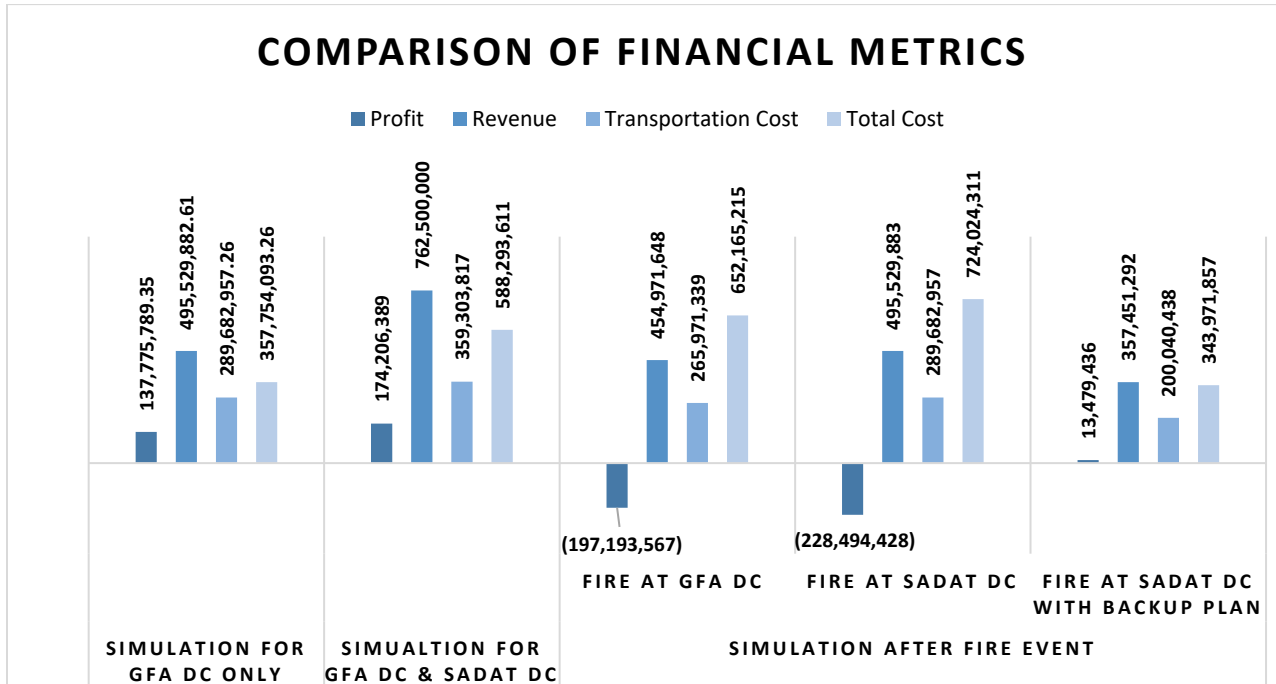


Figure 2. Financial Metrics Comparison

An assessment of operational performance metrics across all scenarios provided further insight into the efficiency gains achieved through network optimization. The optimized scenario achieved 100% on-time demand fulfillment with zero leftover inventory, reflecting exceptional responsiveness and resource utilization. Moreover, the average lead time decreased from 31.57 days to 2.65 days, representing a 92% improvement compared with the baseline scenario. These results confirm that strategic decisions, such as positioning distribution centers near demand clusters and maintaining backup facilities, substantially enhance supply chain agility and service quality under both normal and disrupted conditions (As Shown in Figure 3)

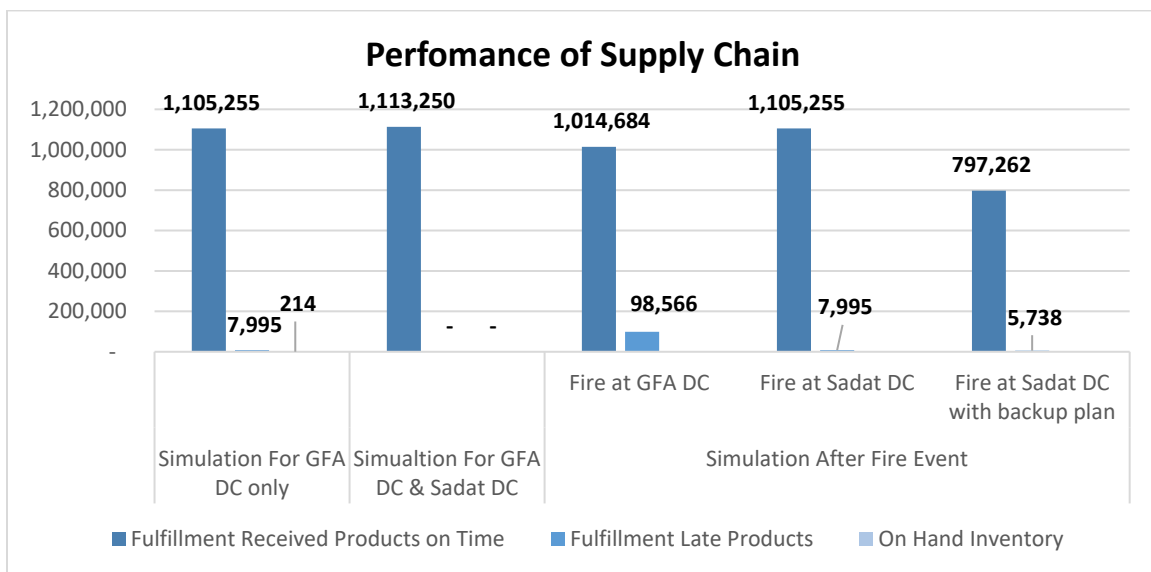


Figure 3. Performance of Supply Chain

Collectively, the FMEA, FTA, and AnyLogistix simulation results demonstrate that the integration of risk-based analysis with data-driven network optimization can effectively strengthen the resilience and performance of Egypt's emerging green ammonia logistics system.

4. Conclusion

This study developed an integrated framework combining FMEA, FTA, and AnyLogistix simulation to enhance the resilience and efficiency of the green ammonia supply chain in Egypt. The findings demonstrate that data-driven network design and proactive risk management are essential for achieving reliable, cost-effective, and sustainable logistics performance. The results also confirm Egypt's strong potential to serve as a regional hub for green ammonia distribution and storage, supported by its strategic location and emerging renewable energy capacity. Beyond its technical contribution, the framework provides a practical tool for businesses and policymakers to evaluate risks, optimize infrastructure decisions, and strengthen contingency planning. It offers a pathway from conceptual planning to implementation, reducing uncertainty for future green fuel investments. Overall, this research contributes to the growing field of sustainable energy logistics by presenting a replicable, quantitative approach to post-production supply chain design. Future studies should extend this work through life-cycle assessment, stochastic risk modeling, and regional comparative analyses to enhance the framework's global applicability and support the broader clean energy transition.

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