International Journal Of Management And Economics Fundamental

VOLUME Vol.05 Issue 12 2025
PAGE NO. 70-74

Blockchain-Enabled Sustainable and Secure Hydrogen Supply Chains: Integrating Cybersecurity, Evolutionary Game Theory, and Fuzzy Decision-Making for Decarbonized Energy Systems

Dr. Marco Alvarez

Department of Industrial Engineering University of Barcelona, Spain

Received: 01 December 2025; **Accepted:** 15 December 2025; **Published:** 31 December 2025

Abstract: The global transition toward low-carbon and climate-resilient energy systems has intensified scholarly and policy interest in hydrogen as a cornerstone of future decarbonization strategies. Green hydrogen, produced using renewable energy sources, offers particular promise for hard-to-abate sectors such as heavy industry, long-haul transport, and energy-intensive manufacturing. However, the realization of hydrogen's sustainability potential is fundamentally contingent upon the design, governance, and security of its supply chains. These supply chains are characterized by high capital intensity, technological uncertainty, multi-actor coordination challenges, and increasing digital interdependence. In this context, blockchain technology has emerged as a transformative digital infrastructure capable of enhancing transparency, trust, traceability, and incentive alignment across complex energy value networks. At the same time, blockchain integration introduces new cybersecurity risks, governance dilemmas, and adoption barriers that require rigorous theoretical and methodological examination.

This research develops a comprehensive, theory-driven analysis of blockchain-enabled hydrogen supply chains by synthesizing insights from sustainable supply chain management, cybersecurity studies, evolutionary game theory, and fuzzy multi-criteria decision-making. Drawing strictly on the provided scholarly references, the article constructs an integrated conceptual framework that explains how blockchain can simultaneously mitigate supply chain risks, enable fair value distribution, support decarbonization objectives, and reshape institutional trust mechanisms. The study elaborates on how evolutionary game dynamics among supply chain actors influence blockchain adoption decisions, how fuzzy analytic hierarchy process methods can be used to evaluate sustainability and risk trade-offs, and how cybersecurity considerations fundamentally condition system resilience in blockchain-based Internet of Things and energy environments.

Methodologically, the research adopts a qualitative, theory-building approach grounded in interpretive synthesis and analytical generalization. Rather than empirical measurement or mathematical modeling, the study relies on deep conceptual elaboration, comparative reasoning, and cross-disciplinary integration. The results demonstrate that blockchain-enabled hydrogen supply chains can enhance environmental, social, and economic sustainability, but only under specific governance configurations that balance decentralization with regulatory oversight and technological security. The discussion highlights critical limitations related to scalability, interoperability, energy consumption, and behavioral uncertainty, while also identifying future research directions involving hybrid governance models, incentive-compatible smart contracts, and cross-border policy harmonization. The article concludes by positioning blockchain not as a technological panacea, but as an institutional innovation whose sustainability impacts depend on strategic design, stakeholder alignment, and long-term socio-technical co-evolution.

Keywords: Blockchain technology; Green hydrogen; Sustainable supply chains; Cybersecurity; Evolutionary game theory; Fuzzy decision-making

Introduction: The accelerating urgency of climate change mitigation has reshaped global energy policy, industrial strategy, and academic research agendas. As governments and corporations commit to net-zero emissions targets, attention has increasingly shifted toward energy carriers capable of decarbonizing sectors where direct electrification remains technologically or economically infeasible. Hydrogen, particularly when produced using renewable energy sources, has emerged as a central pillar of this transition. Green hydrogen offers the theoretical possibility of deep emissions reductions across steelmaking, chemicals, aviation, shipping, and long-duration energy storage, thereby positioning itself as a strategic asset in the global low-carbon economy (Almutairi et al., 2021; Benalcazar and Komorowska, 2022).

Despite its promise, the hydrogen economy faces profound structural and organizational challenges. Hydrogen supply chains are inherently complex, spanning renewable electricity generation, electrolysis, storage, transportation, distribution, and end-use applications. Each stage involves heterogeneous actors, substantial capital investments, regulatory uncertainty, and technological risk. Moreover, hydrogen supply chains are geographically dispersed and increasingly digitalized, relying on data-intensive monitoring, control systems, and cross-organizational information exchange. These characteristics amplify coordination costs, exacerbate information asymmetries, and heighten exposure to operational and cyber risks (Azadnia et al., 2023; Carlson and Trencher, 2024).

In parallel with the rise of hydrogen as a clean energy vector, blockchain technology has gained prominence as a decentralized digital infrastructure capable of transforming how value chains are governed. Originally conceptualized as a peer-to-peer electronic cash system, blockchain has evolved into a generalized ledger technology supporting secure transactions, smart contracts, and distributed consensus across untrusted networks (Wright, 2008; Wood, 2014). Scholars in operations management and sustainability have argued that blockchain can enhance supply chain transparency, traceability, and accountability, thereby supporting environmental and social sustainability objectives (Bai and Sarkis, 2020; Kouhizadeh et al., 2020).

The convergence of blockchain and hydrogen supply chains represents a critical yet underexplored research frontier. On one hand, blockchain offers tools for certifying green hydrogen provenance, automating transactions through smart contracts, enabling peer-to-peer energy markets, and aligning incentives among producers, transporters, regulators, and consumers (Bhavana et al., 2024). On the other hand, blockchain integration introduces new challenges, including cybersecurity vulnerabilities, governance disputes, energy consumption concerns, and adoption barriers rooted in behavioral and institutional factors (Alajlan et al., 2023; Zheng et al., 2018).

Existing literature has largely examined blockchain, hydrogen, cybersecurity, and supply chain sustainability in isolation. While valuable, this fragmented approach limits theoretical depth and practical relevance. There is a pressing need for integrative frameworks that explain not only how blockchain can be applied to hydrogen supply chains, but also under what conditions such applications enhance sustainability, resilience, and trust. Furthermore, most studies emphasize technical feasibility or economic optimization, while underemphasizing strategic interaction among actors, risk perception, and decision-making under uncertainty.

This article addresses these gaps by developing a comprehensive, interdisciplinary analysis of blockchain-enabled hydrogen supply chains. Drawing on evolutionary game theory, the study examines how strategic interactions among supply chain participants shape adoption trajectories and governance outcomes (Smith and Price, 1973; Newton, 2018; Zhu et al., 2023). Fuzzy decision-making methods are incorporated to conceptualize how stakeholders evaluate sustainability, risk, and performance trade-offs in uncertain and imprecise environments (Chang, 1996; Arman et al., 2021; Arman, 2022). Cybersecurity is treated not as a peripheral technical issue, but as a foundational determinant of system viability in blockchain-based energy and Internet of Things ecosystems (Alajlan et al., 2023).

By synthesizing these perspectives, the article contributes to theory and practice in several ways. First, it advances sustainable supply chain scholarship by embedding blockchain adoption within broader socio-technical and strategic contexts. Second, it enriches hydrogen energy research by foregrounding governance, digital trust, and risk management considerations. Third, it demonstrates the value of evolutionary and fuzzy approaches for analyzing complex, multi-actor sustainability transitions. The following sections elaborate the methodological approach, present a detailed descriptive analysis of theoretical findings, and discuss implications, limitations, and future research directions.

Methodology

The methodological foundation of this research is qualitative, interpretive, and theory-driven. Rather than pursuing empirical testing or quantitative modeling, the study adopts an analytical synthesis approach aimed at generating deep conceptual insights from existing scholarly work. This choice is justified by the emergent and interdisciplinary nature of blockchain-enabled hydrogen supply chains, where theoretical integration and explanatory clarity are prerequisites for meaningful empirical investigation.

The primary methodological strategy involves systematic conceptual integration of the provided references. Each source is treated as a theoretical building block contributing distinct yet complementary perspectives. For instance, studies on blockchain and sustainable supply chains provide insights into transparency, trust, and adoption barriers (Bai and Sarkis, 2020; Kouhizadeh et al., 2020), while hydrogen energy research elucidates techno-economic risks and decarbonization imperatives (Almutairi et al., 2021; Azadnia et al., 2023). Cybersecurity literature highlights vulnerabilities and resilience requirements in blockchain-based systems (Alajlan et al., 2023), and game theory sources explain strategic behavior and incentive alignment among interacting agents (Smith and Price, 1973; Leyton-Brown and Shoham, 2008; Zhu et al., 2023).

The analysis proceeds through iterative interpretation, comparison, and abstraction. Concepts such as trust, risk, incentive compatibility, and sustainability are examined across domains to identify convergences and tensions. Evolutionary game theory is employed as an interpretive lens to explain how repeated interactions and adaptive strategies influence blockchain adoption and governance outcomes over time. Unlike classical game theory, which assumes fully rational agents and static equilibria, evolutionary approaches emphasize bounded rationality, learning, and population-level dynamics, making them particularly suitable for analyzing emerging technologies and institutional change (Newton, 2018).

Fuzzy decision-making methods, including fuzzy analytic hierarchy process and interval type-2 fuzzy sets, are incorporated conceptually to explain how decision-makers navigate ambiguity and incomplete information (Chang, 1996; Arman et al., 2021; Arman, 2022). Rather than implementing these methods computationally, the study uses them as theoretical metaphors for understanding how sustainability criteria are weighted and negotiated in practice.

Throughout the methodology, strict adherence is maintained to the constraint of no mathematical exposition or visual representation. All analytical reasoning is conveyed through descriptive and interpretive text. The outcome is a cohesive theoretical narrative that integrates multiple strands of literature into a unified framework for understanding blockchain-enabled hydrogen supply chains.

Results

The integrative analysis yields several substantive findings that collectively illuminate the role of blockchain in shaping sustainable and secure hydrogen supply chains. These findings are presented descriptively, focusing on conceptual patterns and theoretical implications rather than numerical outcomes.

One central finding is that blockchain's value in hydrogen supply chains lies less in technological novelty and more in institutional restructuring. Blockchain enables shared ledgers that reduce information asymmetry among actors, thereby lowering transaction costs and mitigating opportunistic behavior. In hydrogen contexts, this transparency is particularly valuable for certifying green hydrogen attributes, such as renewable energy inputs, carbon intensity, and compliance with regulatory standards (Bai and Sarkis, 2020; Bhavana et al., 2024). By making such information tamper-resistant and auditable, blockchain supports trust among stakeholders who may otherwise lack direct relational ties.

A second finding concerns the conditional nature of sustainability benefits. Blockchain does not automatically enhance environmental or social outcomes. Its impact depends on governance design, incentive structures, and stakeholder engagement. Evolutionary game theory suggests that actors adopt blockchain when perceived benefits outweigh costs, but these perceptions evolve over time based on observed outcomes and peer behavior (Smith and Price, 1973; Newton, 2018). Early adopters may incur higher costs and risks, while later adopters benefit from learning effects. Without mechanisms to share risks and rewards equitably, adoption may stagnate, undermining system-wide sustainability gains (Zhu et al., 2023).

Cybersecurity emerges as a third critical finding. While blockchain is often portrayed as inherently secure, its integration with Internet of Things devices, smart meters, and energy management systems introduces vulnerabilities at the interface between digital and physical infrastructures. Attacks on data integrity, consensus mechanisms, or smart contracts can propagate through hydrogen supply chains, causing operational disruptions and eroding trust (Alajlan et al., 2023; Zheng et al., 2018). Therefore, cybersecurity is not merely a technical add-on but a core sustainability concern.

A fourth finding relates to decision-making under uncertainty. Hydrogen supply chains operate under volatile market conditions, evolving regulations, and technological uncertainty. Fuzzy decision-making frameworks capture how stakeholders prioritize criteria such as cost, risk, environmental impact, and social acceptance when precise quantification is impossible (Chang, 1996; Arman et al., 2021). Blockchain can support such decision-making by providing reliable data, but it cannot eliminate underlying ambiguity.

Finally, the analysis reveals that blockchain-enabled hydrogen supply chains have the potential to reconfigure value distribution. Smart contracts and decentralized platforms can facilitate fairer profit-sharing arrangements and peer-to-peer transactions, aligning economic incentives with sustainability objectives (Huang et al., 2020; Bhavana et al., 2024). However, these benefits depend on inclusive governance and regulatory alignment to prevent concentration of power or exclusion of smaller actors.

Discussion

The findings underscore the importance of viewing blockchain-enabled hydrogen supply chains as socio-technical systems rather than purely technological solutions. From a theoretical perspective, the integration of evolutionary game theory reveals that adoption dynamics are shaped by learning, imitation, and feedback loops. Actors do not simply calculate optimal strategies once; they adapt based on experience and observation. This insight challenges deterministic narratives that portray blockchain adoption as inevitable or universally beneficial.

Cybersecurity considerations further complicate the picture. While decentralization can reduce single points of failure, it also expands the attack surface and diffuses responsibility for security governance. This paradox highlights the need for hybrid governance models that combine decentralized architectures with coordinated oversight (Alajlan et al., 2023; Carlson and Trencher, 2024).

The application of fuzzy decision-making concepts emphasizes that sustainability is inherently subjective and context-dependent. Different stakeholders assign different weights to environmental, economic, and social criteria, and these weights may shift over time. Blockchain can enhance transparency but cannot resolve value conflicts. Addressing such conflicts requires deliberative processes and institutional arrangements beyond technology alone (Chaudhuri et al., 2023).

Several limitations warrant discussion. The study is conceptual and does not provide empirical validation. Additionally, the reliance on existing literature constrains the scope of analysis to established themes, potentially overlooking emerging innovations. Future research could build on this framework through case studies, simulations, or mixed-methods approaches to examine real-world blockchain-enabled hydrogen projects.

Conclusion

This article has developed a comprehensive theoretical analysis of blockchain-enabled sustainable and secure hydrogen supply chains by integrating insights from supply chain management, cybersecurity, evolutionary game theory, and fuzzy decision-making. The analysis demonstrates that blockchain has significant potential to enhance transparency, trust, and sustainability in hydrogen value networks, but only under carefully designed governance and security conditions. Rather than a technological panacea, blockchain should be understood as an institutional innovation whose impacts depend on strategic interaction, stakeholder alignment, and socio-technical co-evolution. By advancing an interdisciplinary framework, this research contributes to a deeper understanding of how digital technologies can support the global transition toward decarbonized energy systems.

References

1. Alajlan, R., Alhumam, N., Frikha, M., 2023. Cybersecurity for blockchain-based IoT systems: a review. Applied Sciences, 13(13), 7432.

2. Almutairi, K., Dehshiri, S.S.H., Dehshiri, S.J.H., Mostafaeipour, A., Issakhov, A., Techato, K., 2021. A thorough investigation for development of hydrogen projects from wind energy: a case study. International Journal of Hydrogen Energy, 46(36), 18795–18815.

3. Arman, H., 2022. A simple noniterative method to accurately calculate the centroid of an interval type-2 fuzzy set. International Journal of Intelligent Systems, 37(12), 12057–12084.

4. Arman, H., Hadi-Vencheh, A., Arman, A., Moslehi, A., 2021. Revisiting the approximated weight extraction methods in fuzzy analytic hierarchy process. International Journal of Intelligent Systems, 36(4), 1644–1667.

5. Azadnia, A.H., McDaid, C., Andwari, A.M., Hosseini, S.E., 2023. Green hydrogen supply chain risk analysis: a European hard-to-abate sectors perspective. Renewable and Sustainable Energy Reviews, 182, 113371.

6. Bai, C., Sarkis, J., 2020. A supply chain transparency and sustainability technology appraisal model for blockchain technology. International Journal of Production Research, 58(7), 2142–2162.

7. Benalcazar, P., Komorowska, A., 2022. Prospects of green hydrogen in Poland: a techno-economic analysis using a Monte Carlo approach. International Journal of Hydrogen Energy, 47(9), 5779–5796.

8. Bhavana, G.B., Anand, R., Ramprabhakar, J., Meena, V.P., Jadoun, V.K., Benedetto, F., 2024. Applications of blockchain technology in peer-to-peer energy markets and green hydrogen supply chains: a topical review. Scientific Reports, 14(1), 21954.

9. Carlson, J.T., Trencher, G., 2024. A framework for considering decarbonisation risks emerging from low-carbon hydrogen supply chains. Energy Research and Social Science, 116, 103685.

10. Chang, D.-Y., 1996. Applications of the extent analysis method on fuzzy AHP. European Journal of Operational Research, 95(3), 649–655.

11. Chaudhuri, A., Bhatia, M.S., Kayikci, Y., Fernandes, K.J., Fosso-Wamba, S., 2023. Improving social sustainability and reducing supply chain risks through blockchain implementation: role of outcome and behavioural mechanisms. Annals of Operations Research, 1–33.

12. Huang, Y., Zeng, Y., Ye, F., Yang, Y., 2020. Fair and protected profit sharing for data trading in pervasive edge computing environments. Proceedings of the IEEE INFOCOM 2020 Conference on Computer Communications, 1718–1727.

13. Kouhizadeh, M., Saberi, S., Sarkis, J., 2020. Blockchain technology and the sustainable supply chain: theoretically exploring adoption barriers. International Journal of Production Economics, 231, 107831.

14. Leyton-Brown, K., Shoham, Y., 2008. Essentials of Game Theory: A Concise Multidisciplinary Introduction. Springer Nature, Berlin.

15. Newton, J., 2018. Evolutionary game theory: a renaissance. Games, 9, 31.

16. Sharma, V., 2025. Insurance transformation: From risk prevention to risk assumption, powered by blockchain. World Research of Business Administration Journal, 5(3), 150–161.

17. Smith, J.M., Price, G.R., 1973. The logic of animal conflict. Nature, 246, 15–18.

18. Tapscott, D., Williams, A., 2010. Macrowikinomics: Rebooting Business and the World. Atlantic Books, London.

19. Wood, D.D., 2014. Ethereum: A secure decentralised generalised transaction ledger. Ethereum Project Yellow Paper.

20. Wright, C., 2008. Bitcoin: A peer-to-peer electronic cash system.

21. Yuan, S., Li, J., Wu, C., 2022. JORA: Blockchain-based efficient joint computing offloading and resource allocation for edge video streaming systems. Journal of Systems Architecture, 133, 102740.

22. Yuan, S., Li, J., Chen, H., Han, Z., Wu, C., Zhang, Y., 2023. JIRA: Joint incentive design and resource allocation for edge-based real-time video streaming systems. IEEE Transactions on Wireless Communications, 22, 2901–2916.

23. Zheng, Z., Xie, S., Dai, H.N., Chen, X., Wang, H., 2018. Blockchain challenges and opportunities: A survey. International Journal of Web and Grid Services, 14, 352–375.

24. Zhu, Q., Zong, R., Xu, M., 2023. Three-party stochastic evolutionary game analysis of supply chain finance based on blockchain technology. Sustainability, 15, 3084.