Int. J. Production Economics 284 (2025) 109613

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

Investigate the effect of green hydrogen supply chain integration on supply chain resilience: Organization information processing theory perspective

Surajit Bag [a,*], Susmi Routray [b], Muhammad Sabbir Rahman [c], Santosh Kumar Shrivastav [b]

[a] Excelia Business School, CERIIM, France
[b] Institute of Management Technology Ghaziabad, Delhi NCR, India
[c] Department of Marketing and International Business, North South University, Dhaka, Bangladesh

ARTICLE INFO

Keywords:
Clean energy
Digitalization
Green hydrogen
Resilience
Supply chain
Sustainable development

ABSTRACT

Integrating green hydrogen supply chains is crucial in enhancing firms' resilience in a world characterized by VUCA (volatility, uncertainty, complexity, and ambiguity). Using organization information processing theory, this study explores the impact of green hydrogen supply chain integration and planning on supply chain resilience under the conditional moderating effect of social uncertainties. The proposed conceptual model is tested using data from 600 professionals in the green hydrogen domain, and hypotheses testing is performed using structural equation modeling. The findings indicate that green hydrogen supply chain integration positively influences resilience. The results support the moderated mediation hypothesis, suggesting that the indirect effect of green hydrogen supply chain integration on green hydrogen supply chain resilience through comprehensiveness of planning in green hydrogen operations is moderated by social uncertainties. This study provides significant theoretical and practical implications for academics and practitioners in the green hydrogen domain.

1. Introduction

'*The stone age didn't end for lack of stones, and the oil age won't end for lack of oil.*' This insightful observation highlights the transformative power of innovation in influencing the trajectory of human progress. Today, green hydrogen (GH_2) offers a viable solution to revolutionize industries and mitigate the impacts of climate change. However, its success depends on establishing a resilient and integrated supply chain capable of navigating uncertainties. This study explores how GH_2 supply chain integration can enhance the resilience of the GH_2 supply chain, ensuring its viability in a VUCA world.

Climate change consequences have led to intense weather patterns, rising sea levels, severe droughts, loss of biodiversity, and adverse impacts on ecosystems and human well-being.[1] High carbon discharges from anthropoid actions primarily drive climate change. GH_2, created using renewable energy sources, offers a sustainable energy, transportation, and industry solution, enabling significant reduction in carbon emissions (Hassan et al., 2024; IRENA, 2021). While the potential of GH_2 is enormous, full-scale manufacturing in renewable-abundant countries is restricted by the challenges of old infrastructure and lack of public acceptance (Gupta et al., 2024).

The GH_2 supply chain begins with production, with water split into hydrogen and oxygen through electrolysis using renewable energy sources like wind, solar, or hydropower (Bique and Zondervan, 2018; Gondal, 2019). However, scaling is hindered by the high costs associated with electrolysis and renewable energy infrastructure (Gondal, 2019). The second step is storage, which is challenging due to hydrogen's low energy density and leakage risks. GH_2 can be stored in either gaseous form under high pressure or liquid form at cryogenic temperatures, both of which require advanced, costly storage systems to minimize energy losses and prevent leaks.[2] A global consortium spearheaded by Shell International, with partners including NASA and the University of Houston, is developing large-scale liquid hydrogen storage technologies to enable international hydrogen trade. The initiative aims to establish a reliable, cost-effective supply chain for hydrogen. "*A cost-effective, long-range hydrogen supply chain can have a transformative impact in*

* Corresponding author.
E-mail addresses: bags@excelia-group.com (S. Bag), sroutray@imt.edu (S. Routray), sabbiriiu@gmail.com (M.S. Rahman), sksrivastava@imt.edu (S.K. Shrivastav).

[1] https://www.co2.earth/.
[2] https://www.energy.gov/eere/fuelcells/hydrogen-storage.

https://doi.org/10.1016/j.ijpe.2025.109613
Received 14 July 2024; Received in revised form 30 January 2025; Accepted 24 March 2025
Available online 25 March 2025

shaping a sustainable future for energy," said Yuri Sebregts, Shell's Chief Technology Officer. However, unlocking this potential requires solving critical technical challenges, chief among which is hydrogen's propensity to leak. Its tiny molecular size makes containment exceptionally difficult. These technical hurdles inflate costs and complicate storage solutions, a problem highlighted by NASA during the Artemis I launch. Persistent leaks of liquid hydrogen fuel delayed the mission, highlighting the need to address storage issues.[3] The third step in the GH_2 supply chain is transportation and utilization. Hydrogen must be moved from production sites to points of use, such as refueling stations or industrial facilities through pipelines, specialized tankers, or vessels. Pipelines require special materials to resist embrittlement caused by hydrogen's small molecular size, while trucks and ships need high-pressure or cryogenic storage systems to safely transport compressed gas or liquid hydrogen.[4] South Korea's Hyosung, a diversified conglomerate, has partnered with Linde to develop and operate liquid hydrogen production, transportation, and refueling infrastructure. Meanwhile, firms like Air Liquide are pursuing diverse strategies to overcome transportation challenges.[5] Shell, for instance, is innovating hydrogen pipeline materials to prevent leaks; however, the sector still grapples with high costs driven by energy-intensive infrastructure requirements.[6] Thus, the GH_2 supply chain differs from conventional supply chains due to its dependency on renewable energy sources, leading to supply uncertainty and requiring cutting-edge technology for transportation and storage (Samsatli and Samsatli, 2019). The sector also faces market and regulatory obstacles, requiring infrastructure and policies tailored to hydrogen's extreme flammability and low density.

GH_2 supply chain resilience is essential to recover from shocks arising from natural and man-made disasters, necessitating global research attention. During the 2021 February storm in Texas, over half of the state's natural gas supply was disrupted due to power outages, frozen equipment, and harsh weather conditions.[7] Geopolitical scenarios, such as the Russia and Ukraine wars, have disrupted natural gas supplies to numerous European nations, sparking an energy crisis and jeopardizing energy security across the region.[8] Additional complexity arises from social uncertainties impacting demand and disasters disrupting the availability of critical materials or components (Asghari et al., 2024; Azadnia et al., 2023). These issues highlight the need for resilient solutions to strengthen the stability and reliability of the supply chain. Recent studies by Azadnia et al. (2023) and Kim et al. (2024) highlight resilience issues in the GH_2 supply chain. However, empirical evidence on how and when firms enhance resilience remains limited.

The GH_2 supply chain involves unpredictable renewable energy sources, evolving technologies, and fluctuating market demand, all of which create high levels of uncertainty. Organizational Information Processing Theory (OIPT) posits that organizations facing high levels of complexity and uncertainty can manage these challenges by enhancing their performance and information-processing capability (Galbraith, 1973, 1977). In the GH_2 context, integrating real-time data from energy sources, production processes, and distribution networks allows companies to make more informed decisions, respond quickly to disruptions, and improve operational efficiency. For instance, vertical integration and real-time decision-making helped Siemens Energy to adapt hydrogen production to evolving conditions. Their Omnivise fleet management solutions include hydrogen generation components like electrolyzers and renewable energy, which enable optimized performance and steady production, despite variability in wind or solar power, by balancing renewable energy with hydrogen output.[9]

Supply chain integration in the GH_2 sector is exemplified by companies like Hype and HysetCo, which are strategically addressing challenges through collaboration by nurturing demand and developing essential infrastructure. For instance, Hype[10] operates the largest hydrogen-powered taxi fleet in Paris, demonstrating the use of hydrogen in urban mobility and encouraging investment in hydrogen production and renewable energy infrastructure. On the supply side, HysetCo,[11] a joint venture between Air Liquide, TotalEnergies, Toyota France, and Kouros, is constructing a network of hydrogen refueling stations across Paris to reduce bottlenecks and spread financial risk through collaboration. Utilizing advanced digital tools and creating coordinated information flows across the supply chain will enable GH_2 companies to reduce uncertainty, optimize resource allocation, and build resilience, thus, aligning with OIPT (Ratnakar et al., 2021). Despite the accepted strategic importance of GH_2 for achieving carbon neutrality and enhancing energy security, substantial gaps remain in understanding how and when companies in GH_2 enhance supply chain resilience. While the literature focuses on the potential of GH_2 and highlights global efforts to promote its deployment, there is limited research on the specific dynamics of GH_2 supply chain integration and the comprehensive planning processes needed for efficient management. According to OIPT, managing such a complex and uncertain environment requires robust integration and planning to enhance information flow and adaptability. However, the application of OIPT principles to dynamic GH_2 supply chains remains unexplored, particularly in relation to how social uncertainties arising from regulatory shifts, public opinion, and labor market fluctuations moderate the effectiveness of integration and planning efforts. This research gap calls for a deeper investigation into OIPT-driven strategies that can enhance scalability and resilience in GH_2 supply chains amid evolving social and environmental demands.

This creates opportunities to explore how supply chain integration enhances GH_2 resilience, through planning, and conditional moderating effect of social uncertainties. Such research is important to address high production costs, infrastructure gaps, and social barriers, the key challenges in the current GH_2 landscape. This raises the subsequent research inquiry:

RQ. How and when does GH_2 supply chain integration affect GH_2 supply chain resilience?

This study provides valuable insights into the relationships between GH_2 supply chain integration, planning, resilience, and social uncertainties. It explores the moderated mediation effect, providing a nuanced understanding of how social uncertainties influence resilience through planning, challenging traditional approaches. The study also advances the debate on system-wide dynamics within GH_2 operations.

The study's research philosophy is grounded in positivism, which

[3] https://www.marketsgroup.org/news/green-hydrogen-challenges-surface?utm_term=&utm_campaign=ALTS+Series+-+July%2724&utm_source=adwords&utm_medium=ppc&hsa_acc=1315941221&hsa_cam=21448482155&hsa_grp=&hsa_ad=&hsa_src=x&hsa_tgt=&hsa_kw=&hsa_mt=&hsa_net=adwords&hsa_ver=3&gad_source=1&gclid=CjwKCAjwjsi4BhB5EiwAFAL0YGB8EHJNW86ENtcsiH7cwMw7iv6M7vIAHZ-2tUgNmcW1OjhNd5d2HhoCESIQAvD_BwE.

[4] https://liftoff.energy.gov/wp-content/uploads/2023/05/20230523-Pathways-to-Commercial-Liftoff-Clean-Hydrogen.pdf.

[5] https://usa.airliquide.com/air-liquide-inaugurates-us-its-largest-liquid-hydrogen-production-facility-world.

[6] https://www.mcdermott-investors.com/news/press-release-details/2021/Shell-Led-Consortium-Selected-by-DOE-to-Demonstrate-Feasibility-of-Large-Scale-Liquid-Hydrogen-Storage/default.aspx.

[7] https://www.texastribune.org/2022/02/15/texas-power-grid-winter-storm-2021/.

[8] https://www.elibrary.imf.org/view/journals/001/2024/039/article-A001-en.xml.

[9] https://www.siemens-energy.com/global/en/home/products-services/product/hydrogen-power-plants.html.

[10] https://hype.taxi/en/homepage-v2-uk/.

[11] https://www.hy24partners.com/press-releases/hydrogen-mobility-pioneer-hysetco-raises-c-200-million-euros-to-advance-transport-decarbonization-solutions/#:~:text=Hy24%20now%20becomes%20the%20majority,in%20supporting%20the%20company's%20development.

emphasizes the importance of objective reality, empirical evidence, and scientific methods to reveal relationships within the data. This philosophy supports an empirical design and primary survey, enabling data collection and quantitative analysis to test hypotheses and address research questions. The study uses quantitative methods to rigorously examine the proposed relationships, thereby, ensuring the reliability and validity of the findings.

The research paper is structured as follows: Section 2 presents the literature, followed by section 3 detailing the theoretical model and hypotheses. Sections 4 outline the empirical research design and section 5 presents analysis, respectively. Finally, the discussions and concluding remarks are provided in the subsequent sections.

2. Literature review

The GH_2 supply chain emerged in the early 2000s as governments and industries pursued decarbonization strategies to achieve cleaner energy alternatives. More than 100 countries, including the largest current emitters, such as China, the United States, and the European Union, have set targets to achieve net-zero emissions by the middle of this century.[12] Hydrogen's potential as a clean fuel emerged during the 1970s oil crisis but became practical only with the advancements in renewable energy technologies. In the 2000s, early adopters like the European Union, Japan, and the U.S. initiated hydrogen strategies, with Germany launching its National Hydrogen Strategy in 2020.[13] Falling renewable energy costs in the 2010s, particularly in regions rich in solar and wind resources, made green hydrogen more viable. The 2015 Paris Agreement further drove global decarbonization efforts, prioritizing hydrogen. By 2021, the European Green Deal recognized the role of GH_2 in decarbonizing industries and transportation[14] (IRENA, 2018; IEA, 2019).

The global momentum for GH_2 is undeniable, as evidenced by significant initiatives across various countries, each committed to improving production and integration of this clean energy source.[15] On December 8, 2020, seven leading global companies initiated the "Green Hydrogen Catapult," targeting a fiftyfold increase in production over six years. They aim to deploy 25 GW of renewable hydrogen by 2026, significantly reducing costs to below $2 per kilogram, thus impacting power generation, chemicals, steelmaking, and shipping sectors.[16] On December 15, 2021, the European Commission unveiled a legislative proposal to decarbonize the EU gas market by accelerating renewable energy adoption, including hydrogen, as part of efforts to improve energy security.[17] Similarly, the UAE articulated its ambition through its National Hydrogen Strategy, announced in July 2023, targeting leadership in low-carbon hydrogen production by 2031 to support net-zero emissions by 2050, with a focus on sectors like heavy industry and transport.[18] Further east, in May 2021, Japan committed 370 billion yen to propel hydrogen research and development for the next decade.[19] On January 4, 2023, India also stepped up, with the Union Cabinet approving the National GH_2 Mission to stimulate production,[20] utilization, and export, highlighting the significant role of GH_2 in global efforts toward a sustainable energy future. These concerted efforts reflect a robust global consensus on the strategic importance of GH_2 in achieving carbon neutrality and enhancing energy security.

Producing GH_2 is more expensive than grey or blue hydrogen due to the high costs of renewable energy and electrolyzer technology. Siemens Energy has built large-scale electrolyzers for ecological hydrogen generation, although electrolysis costs more than existing techniques. While Siemens is scaling manufacturing and reducing prices, this still limits widespread adoption.[21] Additionally, GH_2 production is dependent on renewable energy sources like solar and wind, which can be inconsistent due to weather conditions and geographical factors.[22] Lhyfe uses offshore wind energy to manufacture GH_2, but installing and maintaining infrastructure in harsh maritime conditions is expensive.[23] Hydrogen's low energy density requires large storage volumes or high compression, while its small molecular size makes it prone to leakage. Additionally, storing liquid hydrogen at cryogenic temperatures (-253 °C) demands costly and advanced cooling systems to prevent evaporation and energy loss.

Transportation of hydrogen faces significant challenges due to infrastructure limitations. Existing pipelines require upgrades to resist hydrogen embrittlement, and transporting hydrogen, particularly in liquid form, is expensive as it needs specialized containers and cryogenic storage. Despite decades of hydrogen pipe experience in Europe and North America, large-scale long-distance pipelines are unfunded. Hydrogen is more explosive than natural gas, making safety and third-party accountability crucial. Beyond accidental leaks, hydrogen service also faces material degradation issues that require scientific investigation, especially as longer, higher-pressure hydrogen pipes increase associated risks.[24] Additionally, the lack of hydrogen refueling stations and distribution networks hinders the scalability of hydrogen mobility and industrial use. Regulatory and policy uncertainties, including changing energy policies and divergent international standards, add further complexity to scaling the green hydrogen supply chain (IRENA, 2018).

Other uncertainties include technological and market challenges, including nascent GH_2 technologies like electrolyzers and fuel cells, where competing systems vie for dominance in efficiency (IRENA, 2018). The timing and scale of GH_2 demand growth remain unpredictable, with fluctuating prices of renewable energy and critical materials like platinum and iridium creating further risks (IRENA, 2022). Social factors, including public opposition to infrastructure projects and labor market volatility, also pose challenges, emphasizing the need for comprehensive planning and supply chain integration to ensure the scalability and resilience of the GH_2 industry (IRENA, 2020).

All these factors contribute to making GH_2 supply chain highly complex and subject to considerable variability. To ensure resilience against disruptions, the GH_2 supply chain requires robust solutions that can manage this complexity and effectively adapt to social uncertainties.

The next section discusses the role of OIPT in addressing these challenges, while also offering insights into how enhanced information processing, integration, and adaptive planning can strengthen GH_2 supply chain resilience.

3. Theoretical underpinning and model development

3.1. OIPT

OIPT explains how organizations can effectively manage and utilize

[12] European Commission. (2020). **A Hydrogen Strategy for a Climate-Neutral Europe**. https://ec.europa.eu/energy/hydrogen-strategy.

[13] International Energy Agency (IEA). (2019). **The Future of Hydrogen**. https://www.iea.org/reports/the-future-of-hydrogen.

[14] International Energy Agency (IEA). (2019). **The Future of Hydrogen**. https://www.iea.org/reports/the-future-of-hydrogen.

[15] https://www.h2greensteel.com/stories/how-digitalization-of-hydrogen-production-will-enable-better-cleaner-industries.

[16] https://climatechampions.unfccc.int/green-hydrogen-catapult/.

[17] https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6682.

[18] https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/2023_UAE_National_Hydrogen_Strategy_Fraunhofer_GHD.pdf.

[19] https://www.reuters.com/business/sustainable-business/japan-allocates-up-34-bln-green-fund-accelerate-rd-hydrogen-2021-05-18/.

[20] https://www.nsws.gov.in/portal/scheme/greenhydrogenpolicy.

[21] https://energydigital.com/articles/top-10-hydrogen-companies.

[22] https://www.deloitte.com/content/dam/assets-shared/docs/industries/energy-resources-industrials/2023/gx-deloitte-green-hydrogen-report-2023.pdf.

[23] https://www.lhyfe.com/.

[24] https://epcmholdings.com/challenges-in-hydrogen-pipeline-design/.

information to address internal and external uncertainties, and complexities. Galbraith (1973, 1977) posits that the effectiveness of an organization depends on its information-processing needs and capabilities. In relatively stable environments with well-understood and standardized tasks, a mechanistic model, as suggested by Galbraith (1973), can resolve exceptional scenarios. Organizational rules, procedures, and clearly defined roles are prevalent, ensuring that operations are predictable and consistent. However, in highly volatile industries like GH_2, with increased uncertainties, market volatility, regulatory changes, and technological advancements, decision-making complexity renders mechanistic models ineffective. According to OIPT, organizations, in such cases, can manage increased uncertainties by enhancing their information-processing capability by investing in both lateral communication channels and vertical information systems (Srinivasan and Swink, 2015). Lateral relations, such as collaboration between stakeholders (e.g., production, storage, transportation) in the GH_2 supply chain, enable real-time information-sharing, which improves energy supply management and technology integration. GH_2 production facilities can share renewable energy projections with storage and transportation units to optimize hydrogen flow and address disruptions. As an example, Air Liquide leverages real-time data across its hydrogen production and distribution networks to streamline operations and respond to shifts in market demand. Vertical information systems improve monitoring, data collecting, and decision-making from operational to strategic management. Predictive analytics can forecast energy availability or optimize logistics routes to streamline GH_2 supply chain operations despite renewable energy source volatility. Linde optimizes its supply chain by using digital technologies and real-time data processing, allowing the company to adjust output based on energy availability and market demand, while maintaining operational efficiency despite fluctuations in wind and solar energy.

Coordinating production, storage, and transportation enables firms to mitigate social and labor risks, such as strikes or regulatory shifts, through operational streamlining and enhanced flexibility. For example, TotalEnergies uses integrated planning tools to manage risks associated with hydrogen production and distribution, ensuring its operations can quickly adapt to external changes like regulatory shifts or supply chain bottlenecks. Horizontal integration, combined with real-time monitoring of policies and international regulations, allows companies to swiftly adapt to changes in standards and regulatory environments across borders.

The GH_2 supply chain is already unpredictable, and social uncertainties add to its complexity (Flage and Aven, 2015; Dubey et al., 2023a,b). Addressing uncertainties requires integrating informational, relational, and operational aspects to ensure comprehensive supply chain planning (Ratnakar et al., 2021). Integration of production, storage, and transportation helps GH_2 firms handle social and labor concerns, such as strikes and regulatory changes by simplifying operations and boosting flexibility. TotalEnergies manages hydrogen production and distribution risks with integrated planning tools to adjust fast to regulatory changes and supply chain constraints. Horizontal integration and real-time policy and international regulation monitoring allow enterprises to quickly react to global norms and laws. This aligns with the OIPT principle (Galbraith, 1973, 1977), which stresses the importance of organizations enhancing their information processing capabilities. Technology enhances an organization's information-processing capabilities (Prajogo and Olhager, 2012). Digital capabilities are crucial for forecasting disruptions and responding proactively in uncertain environments. GH_2 production relies on critical materials like platinum and iridium, requiring companies to develop digital capabilities to anticipate shortages and manage risks. Information systems and technologies facilitate real-time data collection and analysis, support communication across diverse and geographically dispersed entities, and enable complex data integration and predictive analytics. For example, Shell uses advanced analytics to plan for fluctuations in renewable energy availability and accordingly adjust GH_2 production.

In response to market and demand uncertainty, GH_2 organizations must invest in digital capabilities to manage unpredictable growth and price volatility. Additionally, the challenges of inadequate infrastructure and high transportation costs necessitate advanced logistics systems that can optimize transport routes, monitor pipeline conditions, and adjust schedules in real-time to ensure operational efficiency.

3.2. Hypotheses

3.2.1. GH_2 supply chain integration and comprehensiveness of planning in GH_2 operations

Hydrogen, obtained from renewable sources, is a clean energy carrier with huge usage potential in industries with high carbon footprints, such as steel and chemicals; however, high production costs, infrastructural constraints, social uncertainties and the need for hydrogen production technological breakthroughs have slowed GH_2 development and implementation (IEA, 2019; Jin et al., 2022). Exploring its potential requires effective handling of its complex supply chain, necessitating technical and infrastructure advancements (Hassan et al., 2023). The GH_2 supply chain is complex and requires coordination across production, storage, transportation, and distribution. At the production stage, the lack of data on renewable energy availability hinders the cost-intensive electrolysis process and delays decision-making in storage and transportation. Information integration facilitates data sharing and reduces delays in decision-making (Chiarini, 2021; Ratnakar et al., 2021).

OIPT posits that improved information-processing capabilities help organizations handle complexity and uncertainty (Galbraith, 1973, 1977), which can be achieved through supply chain integration. Vertical integration speeds up crucial information processing and assists organizations in managing environmental complexity, improving communication, and making decisions, thereby improving information-processing capability. Real-time data integration is needed to manage supply and demand for variable renewable energy sources like solar and wind (IRENA, 2019). Logistics are complicated by the absence of pipelines and refueling stations, which slow down transportation and distribution (IEA, 2019). The integrated GH_2 supply chain, that is, production, storage, and transportation, enhances information flow across operational stages, improving information-processing capability. This vertical integration through information and operational integration ensures that information about production, storage, and distribution is effectively communicated from operational levels to higher management, thus, facilitating strategic planning (IRENA, 2021). For example, Siemens Energy provides end-to-end services for electrolyzer plants and energy assets across the entire hydrogen value chain, highlighting vertical integration in their offerings. By combining maintenance, support, and digital services, they ensure reliable and cost-effective operations.[25] Linde optimizes storage and transportation using integrated logistics solutions, decreasing uncertainty and improving operational planning.[26]

Further, the GH_2 supply chain has various stakeholders from production to the utilization stage, including renewable energy producers, electrolyzer manufacturers, water suppliers, hydrogen production facility operators, logistics and transportation companies, infrastructure developers, hydrogen refueling stations, energy distributors, and government and regulatory bodies, highlighting the need for horizontal integration (Azadnia et al., 2023). Coordinating and promoting stronger collaboration with stakeholders is significant yet complex for proper supply chain planning (Chen and Paulraj, 2004). For example, HysetCo

[25] https://www.siemens-energy.com/global/en/home/products-services/product-offerings/hydrogen-solutions.html#accordion-dc80c03b73-item-c77f362bb4.

[26] https://assets.linde.com/-/media/global/corporate/corporate/documents/sustainable-development/2022-sustainable-development-report.pdf.

combines hydrogen production and fleet operations into a seamless system, enhancing flexibility and operational resilience. This leads to our first hypothesis:

H1. GH_2 supply chain integration positively impacts the comprehensiveness of planning in GH_2 operations.

3.2.2. Comprehensiveness of planning in GH_2 operations and GH_2 supply chain resilience

OIPT emphasizes that organizations need decentralized decision-making and flexibility in dynamic environments. The GH_2 supply chain faces uncertainties and variabilities from production to the utilization stage. Decisions concerning the types and location of facilities, storage, and transportation methods require comprehensive planning to address the variability and intermittent nature of renewable resources and market demands (Bhattacharyya et al., 2022). Regulatory policies and geo-political scenarios may also impact production, necessitating measures to build a resilient supply chain. Comprehensive planning helps organizations manage variability in energy inputs, regulatory changes, and market variations (Dubey et al., 2017), ensuring swift adaptability to uncertainties like energy shortages, labor demands or technology advances. For example, HysetCo integrates extensive planning throughout its refueling stations and hydrogen infrastructure to ensure flexibility in fleet operations and refueling schedules.

With comprehensive planning and strategic partnerships, the Torrent Group can address its supply chain challenges and is the frontrunner in India's green hydrogen journey.[27] Canada's hydrogen strategy promotes a decentralized structure and allows each jurisdiction to handle its projects. The Netherlands is forging relational integration by forging public-private partnerships to promote GH_2.[28] Air Liquide uses integrated planning systems for production, storage, and distribution to respond quickly to disruptions and increase resilience. Linde uses big data and predictive analytics to modify operations to changes in renewable energy supply, closely aligning with OIPT. This theory posits that organizations must balance information-processing capabilities with the demands arising from environmental complexities and uncertainties (Galbraith, 1973, 1977). In a volatile environment, comprehensive planning helps GH_2 enterprises respond proactively and maintain steady operations. Supply chain planning for GH_2 operations requires coordinated demand forecasting, supply management, production scheduling, inventory control, logistics, and risk reduction to optimize resource allocation, stabilize hydrogen supply to meet demand fluctuations, and reduce production, storage, and distribution costs (IRENA, 2020). This approach addresses uncertainties and enables effective mitigation strategies (Srinivasan and Swink, 2015; Gondal, 2019; Zhang et al., 2024), creating a resilient supply chain (Ratnakar et al., 2021; Azadnia et al., 2023). Thus, we propose the following hypothesis:

H2. Comprehensive operations planning enhances the resilience of the GH_2 supply chain.

3.2.3. Integration and resilience in the GH_2 supply chain

Information integration, enabling timely sharing and processing of relevant data, enhances supply chain visibility, which is critical for managing disruptions (Brandon-Jones et al., 2014). In the complex GH_2 supply chain, strong collaboration and relational integration optimize operations, promote innovation, and support strategic partnerships that share risks and rewards, resulting in a culture of risk management (Bode et al., 2011; Kim, 2014; Liu et al., 2016; Chowdhury and Quaddus, 2016). Additionally, operational integration is vital in the supply chain, enabling close coordination with partners on procurement, demand forecasting, and operations. This alignment optimizes resource allocation, improves demand accuracy, and streamlines processes across production, storage, and distribution (Lambert and Cooper, 2000). For instance, working together to develop a Paris hydrogen ecosystem for urban transportation, Hype and Hysetco demonstrate operational integration in the green hydrogen supply chain. Hype, a hydrogen-powered taxi service, and Hysetco, a collaborative effort between Air Liquide, Idex, STEP and Toyota, focus on demand forecasting, infrastructure development, and refueling station administration. This alliance helps them efficiently allocate resources, improve demand planning, and coordinate hydrogen production, storage, and delivery, boosting citywide hydrogen-powered mobility.[29]

Innovation capabilities support resilience during disruptions (Golgeci and Y. Ponomarov, 2013). Given the complex nature of the GH_2 supply chain, which includes renewable energy variability, various stakeholders, and other complexities, integration is key to enhancing its effectiveness (Leuschner et al., 2013). For example, HysetCo integrates hydrogen refueling infrastructure with fleet operations to ensure supply continuity and reduce interruptions. Connecting supply chain stages helps GH_2 organizations predict disturbances, manage resources, and make appropriate adjustments, establishing a robust architecture in keeping with OIPT's emphasis on information processing for uncertainty.

In Sussex and Greater Brighton, the "Hydrogen Sussex Strategy" brought together stakeholders, including local authorities, public sector bodies, transport operators, and engineering firms, to establish integrated local GH_2 production and storage infrastructure. This collaboration enabled proactive identification of risks such as future water scarcity, with planning prioritizing water recycling solutions to enhance supply chain resilience.[30] This alignment of information processing capabilities to address environmental uncertainties is crucial for effectively managing the supply chain, in line with OIPT (Lee et al., 1997; Kulp et al., 2004). Growing uncertainties in the external environment highlight the need for GH_2 supply chain resilience to ensure rapid recovery from disruptions. We posit that integrating the GH_2 supply chain across three dimensions, information (data-sharing systems), operations (production-to-distribution coordination), and relationships (stakeholder collaboration), synergistically enhances resilience. This holistic integration mitigates uncertainties through advanced technologies like predictive analytics and creates operational agility, thereby, improving overall supply chain performance. Thus, we propose the following hypothesis:

H3. GH_2 supply chain integration positively impacts its resilience.

3.2.4. Moderated mediation effect

GH_2 is emerging as a key element in the transition to sustainable energy, yet its supply chain faces challenges in managing uncertainty and complexity. GH_2 supply chain integration enables organizations to share critical data and improve decision-making. The comprehensiveness of planning in GH_2 operations helps translate supply chain integration into resilience, enhancing overall effectiveness (Sheffi and Rice Jr, 2005; Kembro et al., 2017). For example, Air Liquide uses detailed planning to ensure smooth coordination throughout operational issues in its hydrogen production, storage, and transportation divisions, thus, enabling it to manage risks and increase resilience. TotalEnergies manages hydrogen production and distribution risks with integrated planning tools to quickly adjust to regulatory changes and supply chain constraints. Linde optimizes hydrogen production and logistics resource allocation to improve operational resilience amid supply chain

[27] https://static.pib.gov.in/WriteReadData/specificdocs/documents/2024/may/doc2024510336301.pdf.

[28] https://assets.publishing.service.gov.uk/media/657a2a92095987000d95e086/hydrogen-projects-planning-barriers-and-solutions-report.pdf.

[29] https://www.hysetco.com/.

[30] https://assets.publishing.service.gov.uk/media/657a2a92095987000d95e086/hydrogen-projects-planning-barriers-and-solutions-report.pdf.

disruptions. These examples reflect how thorough, data-driven, and systematic planning enables organizations to anticipate, prepare for, and respond to potential disruptions. When GH_2 supply chains adopt a more integrated approach, it is hypothesized that they are better equipped to engage in comprehensive planning, which, in turn, contributes to improved GH_2 supply chain resilience.

Resilience is the supply chain's ability to adapt to disruptions, recover quickly, and continue operations effectively. While integration and planning are essential, social uncertainties introduce unpredictability into the GH_2 environment. Depending on their intensity, these uncertainties can either amplify or reduce the need for planning. As a result, it is expected that social uncertainties conditionally moderate the relationship between GH_2 supply chain integration and comprehensiveness of planning in GH_2 operations, thereby, influencing the indirect effect of integration on GH_2 supply chain resilience through comprehensiveness operations planning.

OIPT suggests that organizations need to match their information-processing capabilities with the challenges they face in their external environment. GH_2 supply chain integration plays a crucial role in helping organizations manage the flow of information in the GH_2 supply chain. It promotes better collaboration and coordination among different parts of the supply chain. We propose that the comprehensiveness of planning in GH_2 operations acts as a mediator between supply chain integration (SCI) and supply chain resilience. The comprehensiveness of operations planning allows the advantages of GH_2 supply chain integration to be effectively translated into actionable plans, thereby, enhancing GH_2 supply chain resilience.

However, the relationship between GH_2 supply chain integration, comprehensiveness of planning in operations, and supply chain resilience is influenced by the level of social uncertainties in the environment. These uncertainties, including external factors like political instability, changes in regulations, and societal resistance, can create unpredictability in the supply chain (Coskun and Erturgut, 2023; Odulaja et al., 2023). TotalEnergies proactively communicates with labor unions and government agencies, decreasing the impact of labor strikes and regulatory changes on its hydrogen supply chain.[31] HysetCo uses extensive scenario modelling to address regulatory and labor issues that potentially affect its operations,[32] adapting fleet operations and refueling schedules depending on regulatory or labor changes, using supply chain data and predictive algorithms. Air Liquide also uses planning tools to anticipate public and regulatory responses to its initiatives, addressing societal concerns and ensuring supply chain continuity.[33]

We argue that social uncertainties moderate how GH_2 supply chain integration impacts its resilience through comprehensiveness of operations planning. High social uncertainties increase the need for information processing, making GH_2 supply chain integration and comprehensive planning crucial for resilience. On the other hand, when social uncertainties are low, the mediation effect of planning may be less significant due to fewer external challenges. We argue that the mediation effect of the comprehensiveness of operations planning on the relationship between supply chain integration and its resilience is moderated by social uncertainties. Hence, the following hypothesis is proposed:

H4. The mediation effect of comprehensiveness of planning in GH_2 operations (COP) on the relationship between GH_2 supply chain integration (SCI) and GH_2 supply chain resilience (GSCR) is moderated by social uncertainties (SOU), such that the indirect effect of GH_2 supply chain integration (SCI) on GH_2 supply chain resilience (GSCR) through comprehensiveness of planning in GH_2 operations (COP) depends on the level of social uncertainties (SOU).

The theoretical model is presented in Fig. 1.

4. Method

4.1. Context

The research study is performed in France, which is committed to a sustainable energy transition to reduce its carbon footprint and achieve energy independence.[34] GH_2, produced using renewable energy sources, plays a crucial role in this transition. By addressing key challenges in GH_2 supply chain resilience, the study provides actionable insights to advance France's environmental and energy transition goals.[35] The findings will inform policy development, enhance operational practices, and leverage technological advancements to support the sustainable growth of its GH_2 industry.

4.2. Operationalization of constructs

This research employs a survey method to test the proposed hypotheses, as surveys are commonly used in the hypothetico-deductive approach in supply chain research (Adamides et al., 2012; Zhao et al., 2023). The constructs are identified from the literature, and the respective items are adapted from prior studies.

We rigorously reviewed the literature to identify valid survey items for the proposed constructs. To ensure conceptual soundness, we applied translation/back-translation, following Huang et al. (2023). The target industry was sourced from literature and policy papers. A systematic search on supply chain resilience, hydrogen energy, and renewable energy in France was conducted using ABS3 journals and recent publications to identify relevant industries and supply chain practices. All constructs and respective items are listed in Annexure A1. For instance, GH_2 Supply Chain Integration (SCI) is a construct with first-order reflective and second–order formative comprising Information Integration (II) (4 items), Operational Integration (OI) (4 items), and Relational Integration (RI) (3 items). The items are adapted from Gondal (2019), Liu et al. (2016), Schubert and Williams (2022), and Zhang et al. (2024). Comprehensiveness of Planning in GH_2 Operations (COP) consists of three items adapted from Jin et al. (2022). Social Uncertainties in the GH_2 Supply Chain (SOU) consist of three items adapted from Fazli-Khalaf et al. (2020) and Blohm and Dettner (2023). GH_2 Supply Chain Resilience (GSCR) consists of four items adapted from Brandon-Jones et al. (2014), Azadnia et al. (2023), and Jiang et al. (2024).

After identifying the construct items, we pretested them with ten senior GH_2 supply chain executives, each with over five years of experience in GH_2 supply chain management in France. Face-to-face semi-structured interviews, lasting 25–30 min each, were conducted by appointment. Executives were asked open-ended questions, including: How does GH_2 supply chain integration affect its resilience at the firm and industry level? How and when does the comprehensiveness of planning in GH_2 operations help develop supply chain resilience? What is the role of social uncertainties on GH_2 supply chain resilience? They also reviewed the proposed items and construct definitions within the context of this study. For instance, GH_2 supply chain integration was defined by them as: Integrating the green hydrogen supply chain calls for aligning data and information sharing (Information Integration), streamlining operational processes and standards (Operational Integration), and building cooperative, trust-based relationships (Relational

[31] https://totalenergies.com/system/files/documents/2023-03/Sustainability_Climate_2023_Progress_Report_EN.pdf.

[32] https://mission-innovation.net/wp-content/uploads/2022/09/H2RDD-France-FINAL.pdf.

[33] https://hydrogennews.airliquide.com/air-liquide-makes-strategic-investment-support-large-scale-renewable-hydrogen-production-france.

[34] https://surfeo.eu/green-hydrogen-a-new-step-in-the-energy-transition/.

[35] https://world.businessfrance.fr/nordic/how-france-and-normandy-bet-on-hydrogen-to-accelerate-the-green-transition/.

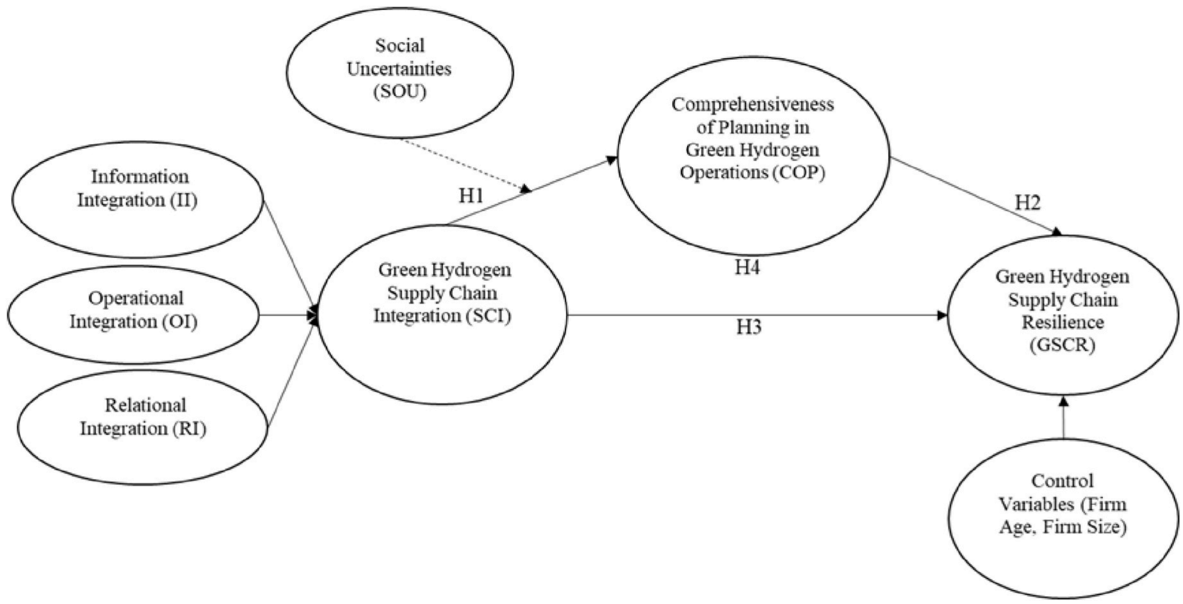

Fig. 1. Theoretical model (Note: GH_2 supply chain integration is a 2nd-order construct).

Integration). Together, these elements develop a cohesive and resilient supply chain that advances GH_2 as a sustainable energy solution. Based on the results from the semi-structured interviews, we revised the items that practitioners identified as more important and refined the wording to enhance clarity. For instance, four senior supply chain executives suggested revising certain items, while others recommended removing two items, one from information integration and the second from the operational integration dimension.

This study applied a 5-point Likert scale with "1" for "strongly disagree" and "5" for "strongly agree for all the items under each construct. Finally, a pilot survey was performed with 30 respondents to understand their perception and ability to respond the proposed survey questions. We controlled for firm size and firm age to isolate their effects and ensure clearer insights into factors influencing GH_2 supply chain resilience.

4.3. Sampling strategy and data collection

Data was collected between 2022 and 2023 from employees of companies based in France. An online survey link was sent to 1500 potential respondents involved in transportation, mining and mineral processing, auto industry, engineering, and infrastructure. It also targeted entrepreneurs, production and distribution of electricity, gas, steam, air conditioning, technology, and other sectors in the GH_2 supply chain.

This study collected data through surveys from companies in France for two vital reasons. First, these firms play a significant role globally in addressing climate emergency, as France has committed to achieving carbon neutrality by the year 2050. It is also widely recognized for its strong focus on energy law and policy, which influence regulations governing firms in the country (Zalzar et al., 2020; Vieira et al., 2021). For instance, the Air France-KLM group has signed an agreement with TotalEnergies to facilitate up to 1.5 million tons of more sustainable aviation fuel (SAF) to the airlines over a 10-year period, till 2035.[36] Second, the national strategic plan inspires and compels numerous manufacturing and service firms to invest heavily in innovation and implementation of GH_2 to build a sustainable ecosystem to support global decarbonization (Cany et al., 2018; Millot et al., 2020; Pereira and Marques, 2020).

Management science researchers have increasingly adopted data collection via firm's employees, particularly for studies on supply chain resilience in the digital age (Al-Banna et al., 2022; Dubey et al., 2023a, b). This study applied multiple strategies as a priori criteria to select participants' responses to enhance data quality. For instance, a specific question at the beginning of the online survey instrument was useful to assess the eligibility of the survey respondents. Survey forms with missing values were excluded, followed by responses that reflected straight-line answering patterns (Khan and Hinterhuber, 2024).

Finally, we only received 600 completed questionnaires, indicating a 40% response rate, which is adequate to test our proposed hypotheses. Data with 600 responses is also sufficient to test our proposed hypotheses and fulfil the minimum sample requirement as confirmed via the G*power test (Bartlett, 2019). The overall features of the survey participants are highlighted in Table 1.

4.4. Common method bias (CMB)

The presence of common method bias (CMB) is a major concern in survey-based research studies. CMB penetrates the dataset due to poor questionnaire design, resulting in confusion among respondents. Misunderstanding questions or using overly technical language can be problematic, as respondents may avoid putting too much cognitive effort into answering. Therefore, based on the guidelines of Podsakoff et al. (2003), we adopted procedural remedies to reduce CMB involvement in our data, incorporating multiple remedies in the research design and operationalization of the survey phase. All items under each construct were clear, concise, and adapted from reliable measures from multiple studies. We validated the survey questions through multiple academics and managers. After adding their feedback, a pilot survey was conducted with 63 respondents to understand the respondents' motivation and their ability to answer the survey question to minimize further the potential concern of CMB (MacKenzie and Podsakoff, 2012).

Respondents were ensured their anonymity during data collection period. Measurement items of independent and dependent variables were separated into different sections of the survey question (Podsakoff et al., 2003; Hulland et al., 2018). After data collection, the collinearity test was performed to check whether the variance inflation factor (VIF) values of the constructs were greater than 3.30 (Kock and Lynn, 2012).

[36] https://totalenergies.com/news/press-releases/air-france-klm-ramps-its-saf-offtake-agreement-totalenergies-which-will-supply.

Table 1
Details of respondents.

Demographic Variable	Description	Frequency (N = 600)
Industry Sector	Transport	25
	Mining and mineral processing	14
	Auto industry	196
	Engineering, infrastructure and entrepreneurs	67
	Production and distribution of electricity, gas, steam and air conditioning	210
	Technology	76
	Others	12
Company Size	Small (less than 50 employees)	6
	Medium (50–250 employees)	107
	Large (more than 250 employees)	487
Company Age	Less than 5 years	5
	5–10 years	42
	11–20 years	358
	More than 20 years	195
Respondent Designation	Executive	67
	Senior Manager	318
	Manager	156
	Supervisor	29
	Other (Specify)	30
Work Experience (Years)	10–20 years	534
	Less than 10 years	66

Note: Our sample includes firms from various industries that play critical roles in the GH_2 ecosystem. Specifically, we studied companies involved in transportation, mining and mineral processing, automotive, engineering, infrastructure development, and technology, as well as those in the production and distribution of electricity, gas, steam, and air conditioning. Each of these sectors is significant to the broader GH_2 landscape in France, providing insights into cross-industry approaches to resilience. We sought to obtain a thorough understanding of GH_2 use, social uncertainties, and tactics used by businesses to strengthen their resilience in this changing energy industry by examining a wide range of industries.

All VIF values were below 3.3, with and without the inclusion of random variable, suggesting that data was free from CMB (Kock, 2015). In addition, we also performed Harman's single factor test and found that the first factor accounted for 39.732 % variance, which is below the threshold level, i.e., 50 %. This research also assesses CMB by examining the correlation among the constructs, which should be less than 0.90, as per Bagozzi et al. (1991). All principal constructs in the correlation matrix were not more than 0.70, signifying the absence of CMB in the dataset. This suggested we could proceed with data analysis without any concerns of biased findings.

4.5. Nonresponse bias

According to Armstrong and Overton (1977), nonresponse bias is a major concern in mail surveys, as it could result in biased results. Since we adopted online email-based surveys for this research, it was important to reduce and check for the presence of nonresponse bias in the data. We attempted to reduce nonresponse bias through online and offline meetings with potential respondents. In the survey, we received 226 completed responses in the first phase (early wave), and after follow-ups, we received 374 responses (late wave). Therefore, it is necessary to compare the early versus late wave and see if the data is homogenous or different. We analyzed the datasets in SPSS, and found that Leven statistics and significance values were not significant, indicating that they are homogenous. This indicates that nonresponse bias is not an issue in our survey data.

5. Data analysis

This study applied partial least squares based structural equation modeling (PLS-SEM) for analyzing data to align with the research objective, which is predicting an unexplored phenomenon and empirically testing the handling of the higher-order construct and complexity of the suggested relationships (See Fig. 1) (Hair et al., 2011; Sarstedt et al., 2014). The method is chosen because the aim of the research is prediction; that is, it aims to confirm the predictive power shown by the proposed theoretical framework with regard to GH_2 supply chain resilience (Chin et al., 2003). Equally, PLS-SEM is also applicable when the hypotheses are developed from a strong theoretical paradigm where the unresolved variables are known, the theory is not solidly developed and contributed, and the observed variable or factor is measured at different levels of measurement (Alonso-Garcia et al., 2023). In addition, if the measures of the variables are not fully developed, extracted from literature and interviews with experts, and do not have a larger sample, it is better to employ PLS-SEM for hypotheses testing than CB-SEM (Richter et al., 2016). The measurement of the outer and inner models was tested through SmartPLS. The structural model was analyzed by applying the bootstraps process. The collected dataset was analyzed using PLS-SEM with Smart-PLS 4 software. This study is not concerned with detecting a "pure" mediation analysis; rather, it examines the specific condition (social uncertainties) under which the proposed relationship between GH_2 supply chain integration and resilience operates (Blanchard et al., 2016). Examining such a complex relationship guides stakeholders and policymakers in understanding whether indirect effects are conditional on different contexts (such as social uncertainties) (Preacher et al., 2007; Demming et al., 2017). Above all, we not only strive to determine the presence of the mediation role in the proposed model (comprehensiveness planning in GH_2 operations); rather, we aim to investigate if a moderator changes the strength of the indirect effect of comprehensiveness planning in GH_2 operations between GH_2 supply chain integration and GH_2 supply chain resilience. Thus, the present study applied model-7, (Hayes, 2017; Hayes et al., 2017), and performed the analysis using Process in SmartPLS software.

5.1. Measurement model

First, the measurement model with reflective items was assessed for convergent validity via factor loadings and average variance extracted (AVE) (Hair Jr et al., 2016). The analysis finds that all values of all constructs for composite reliability (CR) are within the threshold level, ensuring reliability. Factor loadings of each construct are above 0.60, and AVE values are above 0.45, thus, meeting the threshold criterion, which is an adequate justification of convergent validity (See Table 2).

Table 2
Measurement model quality criterion assessment for reflective constructs.

Constructs	Item	Loadings	CR (rho_c)	AVE
Information Integration (II)	II1	0.723	0.790	0.486
	II2	0.621		
	II3	0.737		
	II4	0.702		
Operational Integration (OI)	OI1	0.748	0.817	0.528
	OI2	0.768		
	OI3	0.708		
	OI4	0.679		
Relational Integration (RI)	RI1	0.751	0.785	0.550
	RI2	0.738		
	RI3	0.736		
Comprehensiveness of Planning in Green Hydrogen Operations (COP)	COP1	0.775	0.796	0.566
	COP2	0.746		
	COP3	0.735		
Social Uncertainties in the Green Hydrogen Supply Chain (SOU)	SOU1	0.773	0.820	0.602
	SOU2	0.804		
	SOU3	0.751		
Green Hydrogen Supply Chain Resilience (GSCR)	GSCR1	0.756	0.824	0.539
	GSCR2	0.713		
	GSCR3	0.724		
	GSCR4	0.742		

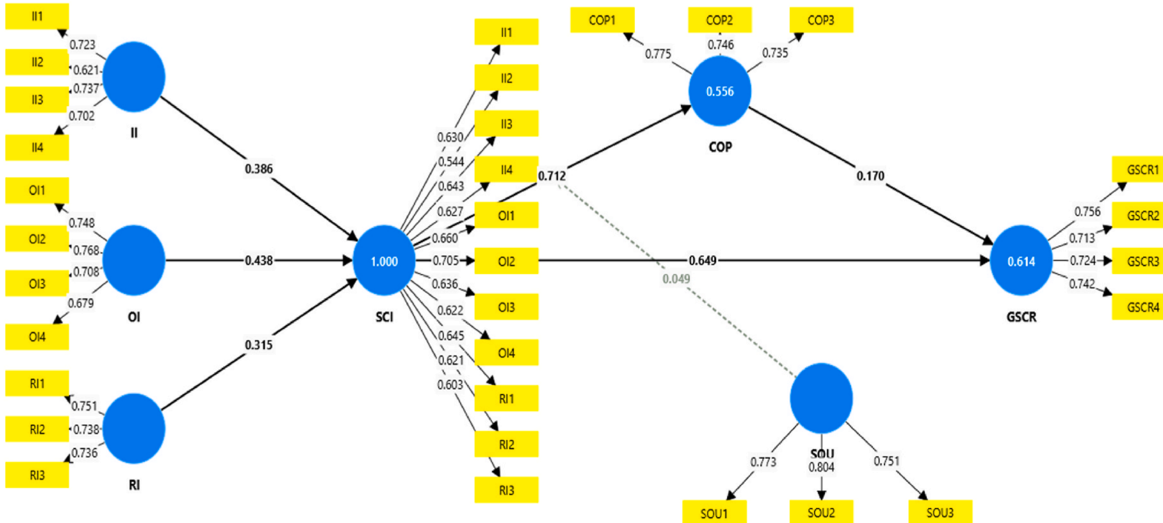

Fig. 2. Evaluation of measurement model (PLS-4 algorithm).

Fig. 2 also shows the loadings of the factors and respective path coefficients generated from the PLS algorithm function. In addition, to examine discriminant validity, the study also considered cross-loadings and the Forner-Lacker criterion by Hair Jr et al. (2016). The results show that outer loadings of all items are greater than the respective latent variables. Also, the square roots of AVE of the latent variables are greater than their correlation with other latent variables, as shown in Table 3.

This study applied three key measures, convergent validity, collinearity evaluation, and the significance and relevance of indicator weights to assess the higher order construct, i.e., formative measure of GH_2 supply chain integration- SCI (Hair et al., 2011; Hair Jr et al., 2014). Thus, the standard construct that forms SCI (information integration-II, operational integration-OI, relational integration-RI) was adapted from literature and pre-tested by experts before its inclusion in the survey instrument for final data collection to examine convergent validity of SCI. The analysis reflects the acceptable magnitude level for their respective endogenous construct (GH_2 supply chain integration- SCI and comprehensiveness of planning in GH_2 operations - CO) and GH_2 supply chain integration (SCI and GH_2 supply chain resilience -GSCR) (see Fig. 3). We also examined the collinearity between the constructs by assessing the VIF values and found them to be below 5.00 for all the predictors. Thus, there is no issue of collinearity among the indicators (Hair et al., 2011; Hair Jr et al., 2014). We applied the bootstrapping procedure by using 10,000 subsamples to examine the significance of the weights and loadings of the formative indicators; all construct weights were above 0.10 with significant p-values, providing empirical justification to retain them and their respective items to measure SCI (Lohmöller, 1989; Chin, 2010) (See Fig. 3 and Tables 4 and 5).

The empirical findings confirm the significance of all three dimensions, information integration-II, operational integration-OI, and relational integration-RI, as the formative indicators of the GH_2 supply chain integration (higher order construct) in this study.

Table 3
Fornell-Larcker criterion.

Constructs	COP	GSCR	II	OI	RI	SOU
COP	0.752					
GSCR	0.652	**0.734**				
II	0.630	0.682	**0.697**			
OI	0.686	0.708	0.674	**0.727**		
RI	0.631	0.639	0.623	0.651	**0.741**	
SOU	0.646	0.673	0.634	0.656	0.625	**0.776**

5.2. Structural model

The relationship between the variables was examined using bootstrapping process (10,000 subsamples) to determine the p-values for the proposed structural model analysis (Hair et al., 2019). This study found that 61.20 % variance occurred in GH_2 supply chain resilience (GSCR), explained by GH_2 supply chain integration (SCI) and comprehensiveness of planning in GH_2 operations (COP). Also, 55.50 % variance occurred in COP, explained by SCI (see Fig. 3).

The value of Q^2 is also higher than zero (COP = 0.546, GSCR = 0.597), justifying the model's predictive relevance (Falk and Miller, 1992). The f^2 value (0.033) also falls within the recommended range suggested by Cohen (2013), which explains the medium effects. The results of hypotheses testing of the structural model revealed that SCI has a positive impact on COP, with a standardized beta value ($\beta = 0.687$, $p < 0.000$), which signifies H1 is supported. The second important predictor for GSCR is COP, which is positive and significant with standardized beta ($\beta = 0.173$, $p < 0.001$). Thus, H2 is also supported. The effects of SCI on GSCR are also positive and significant ($\beta = 0.645$, $p < 0.000$), so H3 is supported by the analysis (See Fig. 3).

5.3. Test of moderated mediation

GH_2 is rapidly gaining attention as a critical component in the transition toward sustainable energy systems. However, the development and operation of GH_2 supply chains face considerable challenges, particularly in managing uncertainty and complexity. This study focuses on understanding these relationships, particularly examining how SCI influences resilience through COP in GH_2 operations, and how SOU affect this dynamic.

We explain the moderated mediation hypothesis based on OIPT, which suggests that the relationship between SCI, COP, and GSCR is influenced by the level of SOU in the environment. SOU includes external factors like political instability, changes in regulations, and societal resistance, which can create unpredictability in the supply chain. We hypothesize that SOU moderates the impact of SCI on GSCR through COP. When SOU is high, organizations face increased demands for information processing, which makes the role of SCI and COP more critical for achieving resilience. We argue that the mediation effect of COP in GH_2 operations on the relationship between SCI and GSCR is moderated by SOU. Specifically, the indirect effect of SCI on GSCR through COP varies depending on the level of SOU, with the mediation effect being stronger when SOU are higher. Thus, this study applied model 7 of Hayes and performed the analysis using Process in SmartPLS-

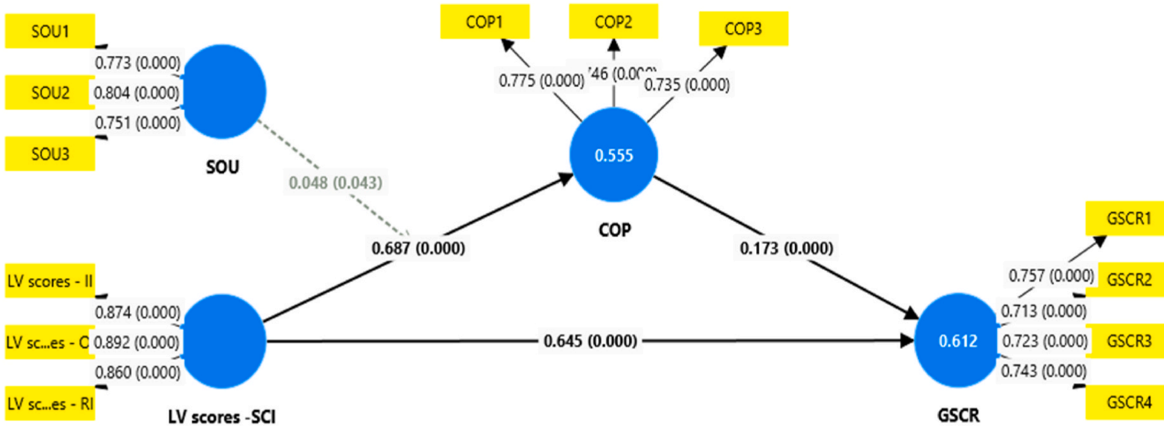

Fig. 3. Structural model of GH_2 supply chain integration on GH_2 supply chain resilience (PLS bootstrapping).

Table 4
Outer loadings of formative higher-order construct.

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
LV scores - II < - LV scores -SCI	0.874	0.874	0.012	70.472	0.000
LV scores - OI < - LV scores -SCI	0.892	0.892	0.009	99.479	0.000
LV scores - RI < - LV scores -SCI	0.860	0.860	0.013	68.320	0.000

Table 5
Outer weights of formative higher-order construct.

	Original sample (O)	Sample mean (M)	Standard deviation (STDEV)	T statistics (|O/STDEV|)	P values
LV scores - II < - LV scores -SCI	0.377	0.377	0.009	44.206	0.000
LV scores - OI < - LV scores -SCI	0.400	0.400	0.009	45.823	0.000
LV scores - RI < - LV scores -SCI	0.365	0.365	0.008	42.948	0.000

4 software. The detailed results of the conditional moderation mediation test are highlighted in Fig. 4 and Table 6.

The analysis shows that the mediation path (SCI → COP → GSCR) is significant. For instance, the relationship between COP and GSCR is statistically significant ($T = 4.168$, $p = 0.000$), indicating that COP significantly influences GSCR. The path from SCI to COP is significant ($T = 3.869$, $p = 0.000$), suggesting SCI has a direct positive effect on COP. The direct effect of SCI on GSCR is also significant ($T = 16.186$, $p = 0.000$), implying SCI directly influences GSCR, apart from the mediation. Hence, the specific indirect effect (SCI → COP → GSCR) is proved statistically significant ($T = 2.975$, $p = 0.003$), supporting the presence of mediation. The confidence interval result (0.037–0.113) does not include zero, reinforcing the mediation effect. For moderation effect of SOU between SCI → COP, results show that the direct effect of SOU on COP is not significant ($T = 1.305$, $p = 0.192$), indicating SOU does not independently influence COP. On the other hand, the interaction effect of SOU × SCI → COP (Interaction Effect) is marginally significant ($T = 1.926$, $p = 0.054$), indicating that SOU moderates the relationship between SCI and COP at a 10 % significance level. With respect to conditional direct effect (SCI → COP at different levels of SOU), at +1 SD (high SOU), the effect is significant ($p = 0.000$), and at −1 SD (low SOU), it is also significant ($p = 0.000$). Thus, the results indicate that the strength of the SCI → COP path changes at different levels of SOU, supporting the moderation hypothesis. Finally, we also examine the moderated mediation path (SCI → COP → GSCR Moderated by SOU). The results support the conditional indirect effects (SCI → COP → GSCR at different levels of SOU). For instance, at +1 SD (high SOU), the conditional indirect effect is significant ($p = 0.000$). On the other hand, at −1 SD (low SOU), the conditional indirect effect is also significant ($p = 0.000$). The confidence intervals for all levels of SOU do not include zero, supporting moderated mediation. Above all, the results suggest that the indirect effect of GH_2 supply chain integration on GH_2 supply chain resilience through comprehensiveness of planning in GH_2 operations are moderated by social uncertainties in the GH_2 supply chain. Thus, H4 was supported.

6. Discussion

The results of this study are significant as they provide empirical evidence of the positive impact of GH_2 supply chain integration on the comprehensiveness of planning and resilience. This highlights the need for coordinated efforts and robust planning frameworks to address the challenges associated with GH_2 production and integration. The findings emphasize the importance of digital advancements and effective information processing in enhancing resilience, offering practical implications for improving operational outcomes in the GH_2 sector. Findings on the conditional moderating effect of SOU provide a better understanding of the external factors influencing supply chain resilience through planning, informing future research and policy development to nurture a conducive environment for GH_2 initiatives.

Results also highlight that GH_2 supply chain integration positively impacts the comprehensiveness of planning in operations, extending the works by Samsatli and Samsatli (2019) and Ratnakar et al. (2021), who posit that integrating the GH_2 supply chain significantly enhances the comprehensiveness of planning in GH_2 operations. The variable nature of the GH_2 supply chain and the involvement of stakeholders make it necessary to integrate the supply chain for better planning.

It is also found that the comprehensiveness of planning in GH_2 operations positively impacts GH_2 supply chain resilience. This was highlighted in the “Hydrogen Sussex Strategy,” where the Group aims to

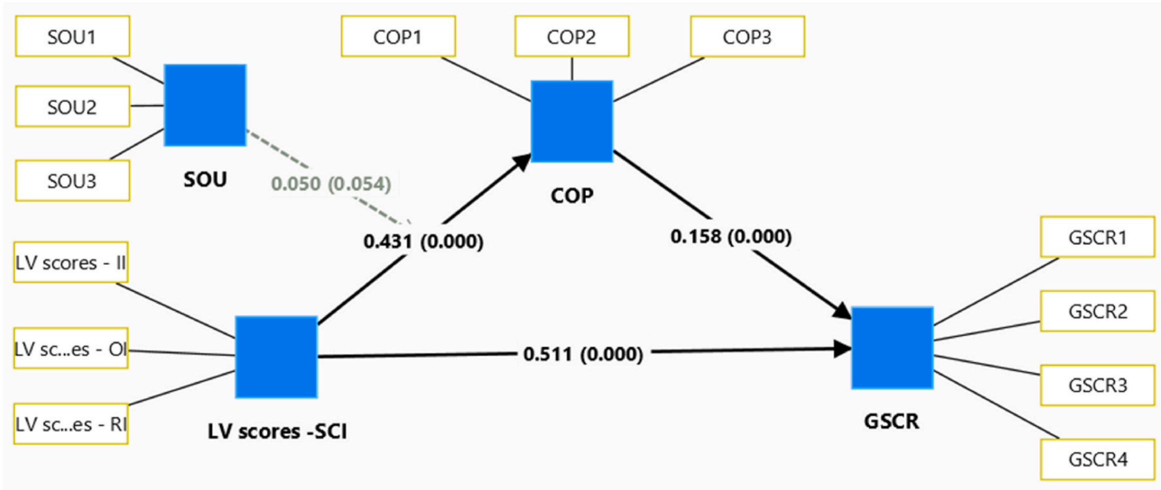

Fig. 4. Moderated mediation analysis using process (Bootstrapping using 10,000 subsamples and significance level: 0.10).

Table 6
Results of conditional moderated mediation analysis.

Direct Relationships		Unstandardized Coefficient		T values
SCI→COP		0.431		3.869
COP→GSCR		0.158		4.168
SCI→GSCR		0.511		16.186
SOU x SCI → COP		0.050		0.054
Conditional direct Relationship	**Effect**	**Standard deviation**	**Confidence interval low/ high**	**T values**
SCI → COP conditional on SOU at Mean	0.608	0.052	0.521/0.691	11.745
SCI →COP conditional on SOU at +1 SD	0.649	0.053	0.563/0.737	12.234
SCI → COP conditional on SOU at −1 SD	0.566	0.059	0.468/0.661	9.638
Conditional indirect Relationship	**Effect**	**Standard deviation**	**Confidence interval low/ high**	**T values**
SCI → COP → GSCR conditional on SOU at +1 SD	0.103	0.026	0.062/0.148	3.900
SCI → COP→GSCR conditional on SOU at −1 SD	0.090	0.023	0.055/0.130	3.912
SCI → COP → GSCR conditional on SOU at Mean	0.096	0.024	0.058/0.139	3.949
R square adjusted values	**Original sample**	**Standard deviation**	**T statistics**	**P values**
COP	0.551	0.029	19.141	0.000
GSCR	0.598	0.029	20.306	0.000

Notes: Green hydrogen Supply Chain Integration (SCI), Comprehensiveness of Planning in Green Hydrogen Operations (COP), Social Uncertainties in the Green Hydrogen Supply Chain (SOU), Green Hydrogen Supply Chain Resilience (GSCR).

prevent future water scarcity and implement comprehensive planning to address uncertainty. Comprehensive planning helps to pre-empt uncertainty and manage it effectively. These findings concur with existing studies (Ratnakar et al., 2021; Azadnia et al., 2023).

The study also found that GH_2 supply chain integration positively impacts its resilience. The results extend the findings of Ruel et al. (2024) and Brandon-Jones et al. (2014), which support that integrating the GH_2 supply chain leads to comprehensive planning, reducing potential disruptions, and enhancing overall resilience.

Also, the comprehensiveness of planning in GH_2 operations mediates the relationship between GH_2 supply chain integration and its resilience under the moderating effect of social uncertainties, extending the findings by Srinivasan and Swink (2015) and Jiang et al. (2024). The result, thus, demonstrates that comprehensive planning serves as a crucial intermediary, enhancing the positive effects of supply chain integration on resilience.

6.1. Theoretical implications

The first finding shows that planning becomes more thorough with the integration of different components of the GH_2 supply chain. Integration facilitates more effective information flow, lowers uncertainty, and improves the organization's capacity for in-depth planning. This supports the focus of OIPT on the value of information processing in managing complexity and enhancing decision-making. Second, planning strengthens resilience by facilitating more effective contingency planning and anticipating possible disruptions. This strengthens OIPT by demonstrating how more information processing (with careful planning) can reduce uncertainty and improve resilience and adaptability. Thirdly, the association between supply chain integration and resilience highlights the significance of integrated information systems and processes in mitigating uncertainties and augmenting adaptive capability. This supports the OIPT tenet that integration increases the capacity for information processing, enhancing organizational resilience. Fourth, the mediation role of comprehensive planning in the relationship between supply chain integration and resilience, under the conditional moderation effect of social uncertainties, highlights the processes for enhancing increased information-processing capability. It implies that integration develops more thorough planning, directly and indirectly developing resilience. Describing how internal processes mediate the impact of integration on performance outcomes depending on social uncertainties, helps in expanding OIPT.

6.2. Practical implications

Our results offer several practical implications. First, GH_2 companies should invest in digital technologies and systems that enhance supply chain integration. Technology investment is vital for the sustainability of GH_2 businesses as it enhances visibility and agility, enabling better decision-making.

Second, the comprehensiveness of planning positively impacts GH_2

supply chain resilience. Managers should prioritize comprehensive planning, including detailed contingency plans for potential disruptions. Regularly reviewing planned versus actual performance is essential. During crises, deviations from the plan may occur, but an alternate plan should be in place to address any shortfalls, ensuring that customer deliveries are met within the committed timelines.

Third, GH_2 supply chain integration positively impacts GH_2 supply chain resilience. Managers should strengthen relationships with all stakeholders to ensure faster recovery after any crisis, leveraging their support and collaboration.

Fourth, the comprehensiveness of operations planning mediates the relationship between GH_2 supply chain integration and GH_2 supply chain resilience under the moderating effect of social uncertainties. This point articulates "how" and 'when' managers can build high resilience in the GH_2 supply chain. The findings show that the comprehensiveness of planning is critical for helping companies that have strategically integrated their supply chain to achieve superior resilience. When social uncertainties are high, the comprehensiveness of planning will lead to a higher degree of resilience. Managers need to develop plans to improve integration and planning capabilities since social uncertainties are beyond their control.

7. Concluding remarks

The study reveals that integrating information, operational, and relational aspects within the GH_2 supply chain enhances the ability to process complex and unpredictable information, ensuring coordinated and effective management of production, storage, and distribution. This integration aligns with OIPT, which emphasizes the need for effective information-processing capabilities to match environmental demands. IT integration improves planning satisfaction and operational efficiency, making supply chains resilient and capable of withstanding disruptions. Also, comprehensive planning in GH_2 operations mediates the relationship between supply chain integration and resilience, highlighting the importance of strategic planning and infrastructure development in maximizing the benefits of GH_2 under the moderation effect of social uncertainties.

This study advances the theoretical debate on supply chain management within the GH_2 industry by extending the application of OIPT. It demonstrates that integrating information, operational, and relational dimensions within a supply chain enhances the ability to manage complex and unpredictable information flows, critical for the efficient management of GH_2 production, storage, and distribution. This study emphasizes how IT integration improves planning satisfaction and operational efficiency, strengthening the argument that supply chain resilience is built not only through technical advancements but also through comprehensive strategic planning. This offers a refined understanding of how supply chain integration aligns with OIPT, suggesting that the capability to process information effectively is a cornerstone of resilient supply chains, especially in emerging sectors like GH_2, where uncertainties are prevalent.

The study also provides insights into the mediating role of comprehensive planning in maximizing the impact of supply chain integration on resilience. This highlights strategic planning and infrastructure development as key levers in harnessing the potential of GH_2. The conditional moderation effect of social uncertainties adds a nuanced perspective to the debate, indicating that while integration is essential, its effectiveness may vary depending on external social factors, underlining the need for adaptive planning in supply chains facing unpredictable external conditions.

Limitations of this study involve the use of cross-sectional data for analysis. Future studies should consider longitudinal studies to examine the dynamic nature of social uncertainties. Additionally, studying the impact of blockchain and AI technology on the integration processes can provide further insights into enhancing the resilience of the GH_2 supply chain. Future studies could take a multi-disciplinary approach by examining the role of regulatory frameworks, environmental policies, and economic incentives in shaping the effectiveness of planning and integration efforts within the GH_2 sector. Comparative studies between GH_2 and other renewable energy supply chains could provide valuable insights into the unique integration challenges and resilience strategies specific to GH_2, enhancing generalizability across renewable energy sectors. The findings can be expanded upon in these directions, providing a more thorough grasp of how theoretical models such as OIPT can be used to address actual supply chain issues in the GH_2 sector.

CRediT authorship contribution statement

Surajit Bag: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Data curation, Conceptualization, Formal analysis, Writing – review & editing. **Susmi Routray:** Writing – original draft, Writing – review & editing. **Muhammad Sabbir Rahman:** Writing – original draft, Visualization, Formal analysis. **Santosh Kumar Shrivastav:** Writing – review & editing, Resources.

Appendix

Annexure A1
Operationalization of constructs.

Construct	Sub-dimensions	Item No	Items	Adapted from
Green Hydrogen Supply Chain Integration (SCI) (2nd Order Formative and 1st-Order Reflective Construct)	Information Integration (II)	II1	"We provide partners with any information that might help them."	Gondal (2019); Liu et al. (2016); Schubert and Williams (2022); Zhang et al. (2024)
		II2	"We keep each other informed about events or changes that may affect the other party."	
		II3	"We exchange information timely with partners."	
		II4	"We ensure the information shared is accurate and relevant to the partners' needs."	
	Operational Integration (OI)	OI1	"We coordinate with partners on procurement."	
		OI2	"We jointly plan the development of demand forecasts with partners."	
		OI3	"We coordinate with partners with respect to different operational activities."	

(*continued on next page*)

Annexure A1 (*continued*)

Construct	Sub-dimensions	Item No	Items	Adapted from
		OI4	"We align our production and service schedules with partners to ensure seamless operations."	
	Relational Integration (RI)	RI1	"We and our partners often agree on the best interest of the supply chain."	
		RI2	"We and our partners work with one another to improve the supply chain as a whole."	
		RI3	"We and our partners consider our relationships as a long-term alliance or partnership."	
Comprehensiveness of Planning in Green Hydrogen Operations (COP) (Reflective Construct)		COP1	"We employ formalized and disciplined planning processes across various areas of our green hydrogen operations."	Jin et al. (2022)
		COP2	"Our planning processes include identifying contingencies through risk analysis to ensure preparedness for potential disruptions."	
		COP3	"Our planning efforts address both long-term strategic objectives and short-term operational goals in green hydrogen operations."	
Social Uncertainties in the Green Hydrogen Supply Chain (SOU) (Reflective Construct)		SOU1	"Social barriers toward acceptance and awareness of green hydrogen technology."	Fazli-Khalaf et al. (2020); Blohm and Dettner (2023)
		SOU2	"Low community engagement and support in the green hydrogen supply chain."	
		SOU3	"Poor perceptions among stakeholders regarding the social benefits of green hydrogen."	
Green Hydrogen Supply Chain Resilience (GSCR) (Reflective Construct)		GSCR1	"Material flow within the green hydrogen supply chain would be swiftly restored following disruptions."	Brandon-Jones et al. (2014); Azadnia et al. (2023); Jiang et al. (2024)
		GSCR2	"It would not take an extended period to restore normal operating performance within the green hydrogen supply chain after disruptions."	
		GSCR3	"The green hydrogen supply chain has the capability to easily recover to its original state after encountering disruptions."	
		GSCR4	"Disruptions within the green hydrogen supply chain are promptly addressed, allowing for quick resolution and recovery."	

Data availability

Data will be made available on request.

References

Adamides, E.D., Papachristos, G., Pomonis, N., 2012. Critical realism in supply chain research: understanding the dynamics of a seasonal goods supply chain. Int. J. Phys. Distrib. Logist. Manag. 42 (10), 906–930.

Al-Banna, A., Franzoi, R.E., Menezes, B.C., Al-Enazi, A., Rogers, S., Kelly, J.D., 2022. Roadmap to digital supply chain resilience. Comput. Aided Chem. Eng. 49, 571–576. Elsevier.

Alonso-Garcia, J., Pablo-Marti, F., Núñez-Barriopedro, E., Cuesta-Valiño, P., 2023. Digitalization in B2B marketing: omnichannel management from a PLS-SEM approach. J. Bus. Ind. Market. 38 (2), 317–336.

Armstrong, J.S., Overton, T.S., 1977. Estimating nonresponse bias in mail surveys. J. Mark. Res. 14 (3), 396–402.

Asghari, M., Afshari, H., Jaber, M.Y., Searcy, C., 2024. Designing a resilient hydrogen hub under disruption risks and non-stationary demand distribution. Int. J. Prod. Res. 1–26.

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. Renew. Sustain. Energy Rev. 182, 113371.

Bagozzi, R.P., Yi, Y., Phillips, L.W., 1991. Assessing construct validity in organizational research. Adm. Sci. Q. 421–458.

Bartlett, J., 2019. Introduction to sample size calculation using G* Power. Eur. J. Soc. Psychol. 1–35.

Bhattacharyya, R., Singh, K.K., Bhanja, K., Grover, R.B., 2022. Leveraging nuclear power-to-green hydrogen production potential in India: a country perspective. Int. J. Energy Res. 46 (13), 18901–18918.

Bique, A.O., Zondervan, E., 2018. An outlook towards hydrogen supply chain networks in 2050—design of novel fuel infrastructures in Germany. Chem. Eng. Res. Des. 134, 90–103.

Blanchard, S.J., Carlson, K.A., Hyodo, J.D., 2016. The favor request effect: requesting a favor from consumers to seal the deal. J. Consum. Res. 42 (6), 985–1001.

Blohm, M., Dettner, F., 2023. Green hydrogen production: integrating environmental and social criteria to ensure sustainability. Smart Energy 11, 100112.

Bode, C., Wagner, S.M., Petersen, K.J., Ellram, L.M., 2011. Understanding responses to supply chain disruptions: insights from information processing and resource dependence perspectives. Acad. Manag. J. 54 (4), 833–856.

Brandon-Jones, E., Squire, B., Autry, C.W., Petersen, K.J., 2014. A contingent resource-based perspective of supply chain resilience and robustness. J. Supply Chain Manag. 50 (3), 55–73.

Cany, C., Mansilla, C., Mathonnière, G., Da Costa, P., 2018. Nuclear contribution to the penetration of variable renewable energy sources in a French decarbonised power mix. Energy 150, 544–555.

Chen, I.J., Paulraj, A., 2004. Towards a theory of supply chain management: the constructs and measurements. J. Operat. Manag. 22 (2), 119–150.

Chiarini, A., 2021. Industry 4.0 technologies in the manufacturing sector: are we sure they are all relevant for environmental performance? Bus. Strat. Environ. 30 (7), 3194–3207.

Chin, W.W., Marcolin, B.L., Newsted, P.R., 2003. A partial least squares latent variable modeling approach for measuring interaction effects: results from a Monte Carlo simulation study and an electronic-mail emotion/adoption study. Inf. Syst. Res. 14 (2), 189–217.

Chin, W.W., 2010. How to write up and report PLS analyses. In: Vinzi, V.E., Chin, W.W., Henseler, J., Wang, H. (Eds.), Handbook of Partial Least Squares: Concepts, Methods and Applications in Marketing and Related Fields. Springer, Berlin, pp. 655–690.

Chowdhury, M.M.H., Quaddus, M., 2016. Supply chain readiness, response and recovery for resilience. Supply Chain Manag.: Int. J. 21 (6), 709–731.

Cohen, J., 2013. Statistical Power Analysis for the Behavioral Sciences. Academic Press, New York, NY, USA.

Coskun, A.E., Erturgut, R., 2023. How do uncertainties affect supply-chain resilience. The moderating role of information sharing for sustainable supply-chain management. Sustainability 16, 131.

Demming, C.L., Jahn, S., Boztuğ, Y., 2017. Conducting mediation analysis in marketing research. Marketing: ZFP–J. Res. Manag. 39 (3), 76–93.

Dubey, R., Bryde, D.J., Dwivedi, Y.K., Graham, G., Foropon, C., Papadopoulos, T., 2023a. Dynamic digital capabilities and supply chain resilience: the role of government effectiveness. Int. J. Prod. Econ. 258, 108790.

Dubey, R., Bryde, D.J., Dwivedi, Y.K., Graham, G., Foropon, C., Papadopoulos, T., 2023b. Dynamic digital capabilities and supply chain resilience: the role of government effectiveness. Int. J. Prod. Econ. 258, 108790.

Dubey, R., Gunasekaran, A., Childe, S.J., Papadopoulos, T., Blome, C., Luo, Z., 2017. Antecedents of resilient supply chains: an empirical study. IEEE Trans. Eng. Manag. 66 (1), 8–19.

Falk, R.F., Miller, N.B., 1992. A Primer for Soft Modeling. University of Akron Press, Akron, OH, USA.
Fazli-Khalaf, M., Naderi, B., Mohammadi, M., Pishvaee, M.S., 2020. Design of a sustainable and reliable hydrogen supply chain network under mixed uncertainties: a case study. Int. J. Hydrogen Energy 45 (59), 34503–34531.
Flage, R., Aven, T., 2015. Emerging risk—Conceptual definition and a relation to black swan type of events. Reliab. Eng. Syst. Saf. 144, 61–67.
Galbraith, J.R., 1973. Designing complex organizations. Addison-Wesley Pub. Co, Reading, MA.
Galbraith, J.R., 1977. Organization Design. Addison-Wesley Publishing Company.
Golgeci, I., Y Ponomarov, S., 2013. Does firm innovativeness enable effective responses to supply chain disruptions? An empirical study. Supply Chain Manag.: Int. J. 18 (6), 604–617.
Gondal, I.A., 2019. Offshore renewable energy resources and their potential in a green hydrogen supply chain through power-to-gas. Sustain. Energy Fuels 3 (6), 1468–1489.
Gupta, S., Kumar, R., Kumar, A., 2024. Green hydrogen in India: prioritization of its potential and viable renewable source. Int. J. Hydrogen Energy 50, 226–238.
Hair Jr, J.F., Hult, G.T.M., Ringle, C., Sarstedt, M., 2014. A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM). Sage Publications.
Hair Jr, J.F., Hult, G.T.M., Ringle, C., Sarstedt, M., 2016. A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM). Sage Publications.
Hair, J.F., Ringle, C.M., Sarstedt, M., 2011. PLS-SEM: indeed, a silver bullet. J. Market. Theor. Pract. 19 (2), 139–152.
Hair, J.F., Sarstedt, M., Ringle, C.M., 2019. Rethinking some of the rethinking of partial least squares. Eur. J. Market. 53 (4), 566–584.
Hassan, Q., Abdulateef, A.M., Hafedh, S.A., Al-samari, A., Abdulateef, J., Sameen, A.Z., et al., 2023. Renewable energy-to-green hydrogen: a review of main resources routes, processes and evaluation. Int. J. Hydrogen Energy 48 (46), 17383–17408.
Hassan, Q., Algburi, S., Sameen, A.Z., Salman, H.M., Jaszczur, M., 2024. Green hydrogen: a pathway to a sustainable energy future. Int. J. Hydrogen Energy 50, 310–333.
Hayes, A.F., 2017. Introduction to Mediation, Moderation, and Conditional Process Analysis: A Regression-Based Approach. Guilford publications.
Hayes, A.F., Montoya, A.K., Rockwood, N.J., 2017. The analysis of mechanisms and their contingencies: PROCESS versus structural equation modeling. Australas. Market J. 25 (1), 76–81.
Huang, K., Wang, K., Lee, P.K., Yeung, A.C., 2023. The impact of industry 4.0 on supply chain capability and supply chain resilience: a dynamic resource-based view. Int. J. Prod. Econ. 262, 108913.
Hulland, J., Baumgartner, H., Smith, K.M., 2018. Marketing survey research best practices: evidence and recommendations from a review of JAMS articles. J. Acad. Market. Sci. 46, 92–108.
IEA, 2019. The Future of Hydrogen: Seizing Today's Opportunities. IEA, pp. 1–204. https://www.iea.org/reports/the-future-of-hydrogen.
IRENA, 2018. Hydrogen from renewable power: technology outlook for the energy transition. International Renewable Energy Agency, Abu Dhabi, pp. 1–52. ISBN: 978-92-9260-077-8. https://www.irena.org/publications/2018/Sep/Hydrogen-from-renewable-power.
IRENA, 2019. Hydrogen: A Renewable Energy Perspective. IRENA, pp. 1–52. https://www.irena.org/publications/2019/Sep/Hydrogen-A-renewable-energy-perspective.
IRENA, 2020. Green Hydrogen: A Guide to Policy Making. IRENA, pp. 1–52. Available at: https://www.irena.org/publications/2020/Nov/Green-hydrogen.
IRENA, 2021. Green Hydrogen Supply: A Guide to Policy Making. International Renewable Energy Agency, Abu Dhabi. ISBN: 978-92-9260-344-1.
IRENA, 2022. Geopolitics of the Energy Transformation: the Hydrogen Factor. IRENA, pp. 1–118. https://www.irena.org/publications/2022/Jan/Geopolitics-of-the-Energy-Transformation-Hydrogen.
Jiang, Y., Feng, T., Huang, Y., 2024. Antecedent configurations toward supply chain resilience: the joint impact of supply chain integration and big data analytics capability. J. Oper. Manag. 70 (2), 257–284.
Jin, L., Ferrario, A.M., Cigolotti, V., Comodi, G., 2022. Evaluation of the impact of green hydrogen blending scenarios in the Italian gas network: optimal design and dynamic simulation of operation strategies. Renew. Sustain. Energy Trans. 2, 100022.
Kembro, J., Näslund, D., Olhager, J., 2017. Information sharing across multiple supply chain tiers: a Delphi study on antecedents. Int. J. Prod. Econ. 193, 77–86.
Khan, O., Hinterhuber, A., 2024. Antecedents and consequences of procurement managers' willingness to pay for sustainability: a multi-level perspective. Int. J. Oper. Prod. Manag. 44 (13), 1–33.
Kim, D.Y., 2014. Understanding supplier structural embeddedness: a social network perspective. J. Oper. Manag. 32 (5), 219–231.
Kim, S., Park, J., Chung, W., Adams, D., Lee, J.H., 2024. Techno-economic analysis for design and management of international green hydrogen supply chain under uncertainty: an integrated temporal planning approach. Energy *Conversion and Management*, 301, 118010.
Kock, N., 2015. Common method bias in PLS-SEM: a full collinearity assessment approach. Int. J. e-Collaboration 11 (4), 1–10.
Kock, N., Lynn, G., 2012. Lateral collinearity and misleading results in variance-based SEM: an illustration and recommendations. J. Assoc. Inf. Syst. Online 13 (7).
Kulp, S.C., Lee, H.L., Ofek, E., 2004. Manufacturer benefits from information integration with retail customers. Manag. Sci. 50 (4), 431–444.
Lambert, D.M., Cooper, M.C., 2000. Issues in supply chain management. Ind. Mark. Manag. 29 (1), 65–83.
Lee, H.L., Padmanabhan, V., Whang, S., 1997. Information distortion in a supply chain: the bullwhip effect. Manag. Sci. 43 (4), 546–558.
Leuschner, R., Rogers, D.S., Charvet, F.F., 2013. A meta-analysis of supply chain integration and firm performance. J. Supply Chain Manag. 49 (2), 34–57.
Liu, H., Wei, S., Ke, W., Wei, K.K., Hua, Z., 2016. The configuration between supply chain integration and information technology competency: a resource orchestration perspective. J. Oper. Manag. 44 (1), 13–29.
Lohmöller, J.-B., 1989. Latent Variable Path Modeling with Partial Least Squares. Physica-Verlag, Heidelberg, Germany.
MacKenzie, S.B., Podsakoff, P.M., 2012. Common method bias in marketing: causes, mechanisms, and procedural remedies. J. Retailing 88 (4), 542–555.
Millot, A., Krook-Riekkola, A., Maïzi, N., 2020. Guiding the future energy transition to net-zero emissions: lessons from exploring the differences between France and Sweden. Energy Policy 139, 111358.
Odulaja, B.A., Oke, T.T., Eleogu, T., Abdul, A.A., Daraojimba, H.O., 2023. Resilience in the face of uncertainty: a review on the impact of supply chain volatility amid ongoing geopolitical disruptions. Int. J. Appl. Res. Soc. Sci. 5 (10), 463–486.
Pereira, D.S., Marques, A.C., 2020. Could electricity demand contribute to diversifying the mix and mitigating CO2 emissions? A fresh daily analysis of the French electricity system. Energy Policy 142, 111475.
Podsakoff, P.M., MacKenzie, S.B., Lee, J.Y., Podsakoff, N.P., 2003. Common method biases in behavioral research: a critical review of the literature and recommended remedies. J. Appl. Psychol. 88 (5), 879.
Prajogo, D., Olhager, J., 2012. Supply chain integration and performance: the effects of long-term relationships, information technology and sharing, and logistics integration. Int. J. Prod. Econ. 135 (1), 514–522.
Preacher, K.J., Rucker, D.D., Hayes, A.F., 2007. Addressing moderated mediation hypotheses: theory, methods, and prescriptions. Multivariate Behav. Res. 42 (1), 185–227.
Ratnakar, R.R., Gupta, N., Zhang, K., van Doorne, C., Fesmire, J., Dindoruk, B., Balakotaiah, V., 2021. Hydrogen supply chain and challenges in large-scale LH2 storage and transportation. Int. J. Hydrogen Energy 46 (47), 24149–24168.
Richter, N.F., Cepeda, G., Roldan, J.L., Ringle, C.M., 2016. European management research using partial least squares structural equation modeling (PLS-SEM). Eur. Manag. J. 34 (6), 589–597.
Ruel, S., El Baz, J., Ivanov, D., Das, A., 2024. Supply chain viability: conceptualization, measurement, and nomological validation. Ann. Oper. Res. 1–30.
Samsatli, S., Samsatli, N.J., 2019. The role of renewable hydrogen and inter-seasonal storage in decarbonising heat–Comprehensive optimisation of future renewable energy value chains. Appl. Energy 233, 854–893.
Sarstedt, M., Ringle, C.M., Smith, D., Reams, R., Hair, J.F., 2014. Partial least squares structural equation modeling (PLS-SEM): a useful tool for family business researchers. J. Fam. Bus. Strategy 5 (1), 105–115.
Schubert, P., Williams, S.P., 2022. Enterprise collaboration platforms: an empirical study of technology support for collaborative work. Procedia Comput. Sci. 196, 305–313.
Sheffi, Y., Rice Jr, J.B., 2005. A Supply Chain View of the Resilient Enterprise. MIT Sloan Management Review.
Srinivasan, R., Swink, M., 2015. Leveraging supply chain integration through planning comprehensiveness: an organizational information processing theory perspective. Decis. Sci. J. 46 (5), 823–861.
Vieira, L.C., Longo, M., Mura, M., 2021. Are the European manufacturing and energy sectors on track for achieving net-zero emissions in 2050? An empirical analysis. Energy Policy 156, 112464.
Zalzar, S., Bompard, E., Purvins, A., Masera, M., 2020. The impacts of an integrated European adjustment market for electricity under high share of renewables. Energy Policy 136, 111055.
Zhang, M., Tao, L., Nuernberg, M., Rai, A., Yuan, Z.M., 2024. Conceptual design of an offshore hydrogen platform. Int. J. Hydrogen Energy 59, 1004–1013.
Zhao, N., Hong, J., Lau, K.H., 2023. Impact of supply chain digitalization on supply chain resilience and performance: a multi-mediation model. Int. J. Prod. Econ. 259, 108817.