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Kong, L. orcid.org/0000-0002-3735-3219, Koh, S.C.L., Sena, V. et al. (2 more authors) (2025) Towards a resilience evaluation framework for hydrogen supply chains: a systematic literature review and future research agenda. International Journal of Hydrogen Energy, 99. pp. 589-606. ISSN 0360-3199

https://doi.org/10.1016/j.ijhydene.2024.12.164

International Journal of Hydrogen Energy 99 (2025) 589–606

Contents lists available at ScienceDirect

International Journal of Hydrogen Energy

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

Towards a resilience evaluation framework for hydrogen supply chains: A systematic literature review and future research agenda

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ARTICLE INFO

Handling Editor: Suleyman I. Allakhverdiev

Keywords:
Systematic literature review
Conceptual framework
Hydrogen supply chains
Complex adaptive systems
Supply chain resilience
Performance evaluations

ABSTRACT

Hydrogen energy is crucial for achieving net zero targets, making the resilience of hydrogen supply chains (HSCs) increasingly important. Understanding current research on HSC resilience is key to enhancing it. Few studies summarise HSC resilience evaluation methods and link them to the general supply chain resilience and complex adaptive system (CAS) evaluation approaches. This study addresses this gap by systematically reviewing the literature on HSC resilience evaluations, defining HSC resilience, and conducting content analysis. It proposes a conceptual framework integrating technical, operational, and organisational perspectives. Each perspective is further subdivided based on the course of events, resulting in a system-based HSC resilience evaluation framework with three layers of analysis. By linking HSC indicators with CAS theory and supply chain performance metrics, the study offers novel insights into HSC resilience evaluations, identifies research gaps, provides practical guidance for practitioners, and outlines future research directions for advancing HSC resilience understanding.

1. Introduction

1.1. Motivation

Because of the rising quantity of carbon dioxide emissions from manufacturing and human activities, climate change has a detrimental influence on ecological and environmental equilibrium. As carbon dioxide emissions increase, the average global temperature will increase, water resources will become less, and supply chain disruptions brought on by extreme weather will become more common [1]. Numerous institutions and governments undertake extended initiatives to manage carbon dioxide emissions and advance sustainable development. For instance, the UK has enshrined its net zero target into law, mandating greenhouse gas (GHG) emissions neutrality by 2050 [2]. With the growing urgency to achieve global GHG emission reduction targets and enhance energy security, governments increasingly recognise the role of renewable energy, such as green hydrogen [3]. In addition to lowering carbon dioxide emissions, switching to green hydrogen will aid in the development of a more responsible and sustainable energy system.

Hydrogen is a highly promising alternative for green transportation, with abundant availability on Earth [4]. It is 39% more efficient than fossil fuels and conserves primary energy resources [5]. Energy-intensive industries such as steel, shipping, and aviation are turning to low-carbon hydrogen to meet ambitious sustainability goals [6]. As an energy carrier, hydrogen must be produced from feedstocks such as water or fossil fuels, adding complexity to its supply chain and raising stakeholder concerns. With the growing emphasis on sustainable development, ensuring the long-term resilience of hydrogen supply chains (HSCs) is increasingly essential [7]. The COVID-19 pandemic underscored this need, pushing the energy sector to adopt resilience-focused supply chain practices [8]. Supply chains, as the most vulnerable component of the energy industry, require greater responsiveness, flexibility, and agility to manage unexpected risks [9]. To build resilient HSCs, it is essential to assess their current resilience and identify areas for improvement. This is particularly vital for large-scale hydrogen production [10]. Factors influencing HSC resilience, such as geopolitical stability and market demand, are interdependent, adding complexity and complicating appropriate decision-making [11].

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https://doi.org/10.1016/j.ijhydene.2024.12.164
Received 25 September 2024; Received in revised form 28 November 2024; Accepted 9 December 2024
Available online 19 December 2024

Therefore, evaluation methods are needed to help stakeholders effectively strengthen HSC resilience.

Resilience, rooted in engineering, psychology, ecology, and disaster relief, has been adapted to supply chain management as supply chain resilience (SCR) [12]. SCR is the capacity to plan for and respond to disruptions, sustain operations, and transition to a more favourable state [13]. Resilience assessments enable benchmarking across supply chains, using metrics tailored to risks that promote desired behaviours and address interdependencies. Metrics include performance-based, time--based, and hazard-related measures [14]. Recovery time, a key post-disruption metric, is often highlighted due to its sensitivity to hazard severity [15]. Hazards in HSCs arise from the properties of hydrogen, resource dependencies, and external conditions. The development of reliable and resilient supply chains necessitates the integration of both system-based and operation-based strategies. Lebrouhi et al. [16] provided a detailed technological and geopolitical analysis of global hydrogen development. Despite extensive research on SCR, there remains a lack of comprehensive, system-based resilience frameworks, particularly for HSCs [17]. This represents a critical gap, given the complexities of HSCs and the uncertainty surrounding efforts to enhance their resilience. Therefore, this study focuses on evaluating HSC resilience from a system perspective, rather than solely examining external factors affecting resilience.

Systematic literature reviews synthesise existing knowledge to accelerate progress, while other methods focus on analyses of specific hypotheses or phenomena [18]. Kiehbadroudinezhad et al. [19] reviewed risks to energy security and green microgrids, highlighting the role of green microgrids in sustainable power and environmental protection. Torres-Rivera et al. [20] explored the resilience of the electromobility supply chain, emphasising its integration with renewables and its ability to recover from disruptions. Sgarbossa et al. [21] proposed a planning matrix for renewable HSCs, detailing planning challenges and tasks critical for managing their evolving dynamics. Pierre et al. [22] reviewed 75 studies that combined economic methodologies with hydrogen engineering. While these reviews address gaps in renewable energy, none specifically focus on HSC resilience or strategies to manage HSC uncertainties, despite hydrogen's key role in replacing fossil fuels.

1.2. Research gaps

This study aims to enhance the understanding of the future energy landscape, particularly the hydrogen economy, and expand existing SCR concepts by identifying HSC resilience indicators. This study answers the following questions:

1) What is the current state of HSC resilience evaluation research?
2) How can we evaluate the resilience of HSCs?
3) What are the future research directions on HSC resilience?

A systematic literature review covering 103 publications has been completed. This review provides a comprehensive examination of the current landscape and evidence-based directions for future actions [23]. The findings are summarised into a conceptual framework that clarifies key concepts in HSC resilience and guides the evaluations of HSC resilience.

The paper is organised as follows: Section 2 examines HSC-specific risks and relevant theoretical foundations. Section 3 details the systematic literature review and framework development methods. Section 4 provides a descriptive analysis of the reviewed literature. Section 5 presents the findings related to the second research question, focusing on the conceptual HSC resilience evaluation framework. Section 6 explores opportunities for future research and practice, answering research question three. Section 7 concludes with implications and study limitations. This study integrates previous HSC resilience research with a complex adaptive system (CAS) perspective to address unique challenges and research gaps in the HSC context. By linking hydrogen energy supply with a broad range of SCR concepts, it extends beyond earlier studies [24]. Viewing the HSC as a 'socio-technical' system, rather than a purely technical system as suggested by two prior studies [25,26], this study identifies key gaps, biases, and best practices in the literature. The novel contribution of this study lies in bridging HSC indicators, CAS theory, and SCR performance metrics, which are typically discussed independently. This study can serve as a springboard for future investigations into the resilience of renewable energy supply chains.

2. State-of-the-art literature

Supply chain risk management and resilience are concepts that are intimately tied to one another [27]. Risk arises from the combination of event probabilities and their potential impacts [28]. Risk assessment has the drawback of being unable to adequately explain low-likelihood and high-consequence events [29]. The concept of SCR can fill this gap and improve current risk management programmes [30]. This study supposes that negative impacts brought by risks are the premise of resilience management.

In practice, both system- and operation-based solutions are indispensable for constructing more resilient supply chains. Research on system-based strategies for energy sources, such as nitrogen, hydrogen, and methane is scarce [17]. Hydrogen possesses low energy density by volume, necessitating specialised infrastructure for efficient transport and storage [31]. The selection of transport and storage infrastructure is contingent upon the specific requirements of end-users and geographic considerations [32]. Both hydrogen and fossil fuels are versatile, with hydrogen being especially suited for energy storage [33]. The specific characteristics of HSCs necessitate a specialised approach to evaluate their resilience comprehensively. Consequently, how to evaluate the levels of HSC resilience via a system-based approach, given the specific objectives of HSCs, is particularly significant.

2.1. Risks in HSCs

HSCs face diverse risks and disruptions. Hydrogen production processes, including electrolysis, steam methane reforming, and biomass gasification, exhibit distinct vulnerabilities [11]. The immaturity of hydrogen technologies raises concerns about maintainability and reliability, with potential issues such as equipment failures and leaks posing environmental and public health risks [34]. High water demand in hydrogen production may worsen water scarcity, requiring careful site selection and resource management to prevent social and environmental conflicts [5].

Beyond technology, HSC risks include supply chain operations, with reliability depending on supplier relationships, transparency, and information flow. Demand fluctuations, competition from alternative energy systems, and regulatory uncertainties add complexity to HSC resilience [35]. A review of HSC risk management identifies key risk categories, including socio-economic, socio-political, technological, operational, governance, natural environmental, and market-related factors, as shown in Table 1 [34,36–38]. Internal risks stem from technical, operational, and organisational vulnerabilities, while external risks arise from supplier dynamics, market conditions, and socio-environmental factors. Addressing these challenges requires viewing HSCs as part of a broader business ecosystem rather than isolated systems. This approach enables optimised infrastructure development and supports a sustainable hydrogen economy [39]. Tailored resilience strategies should align with these risk perspectives to strengthen emerging HSCs.

2.2. Resilience assessments from a CAS perspective

A CAS is a dynamic system of interconnected agents that adapt to environmental and network changes, characterised by self-organisation and adaptability [40]. CAS theory has been proposed as a tool to

Table 1
Risk factors in HSCs (synthesised from Refs. [34,36–38]).

Categories	Risk Factors
Socio-economic	High capital requirements of hydrogen technologies
	Fluctuation in electricity unit prices
	High operation and maintenance costs
	Availability of funding and financial constraints
	Uncertainties in inflation or interest rates
	Currency exchange rates
	Economic recession
	Taxes and tariffs
	Sustained profitability
Socio-political	Government incentives
	Policy and regulation development
	Terrorism and war
	Technical standards
	Political uncertainty
Supply chain operations and governance	Improper location of facilities
	Information distortion
	Power grid disruptions
	Supplier failure
	Collaboration and transparency within supply chain partnerships
	Inventory management and forecasting
	Bargaining power of suppliers
Technological and infrastructure	Failure to provide electricity from renewable energy sources
	Uncertainty regarding capacity for electrolyser
	Limited capacity for storage, transportation, and delivery
	Smart grid failure or shortage
	Lack or malfunction of energy storage system
	Inefficiency of conversion devices
	Quality issues with hydrogen production
	Integration risks for renewable energy
	Rapid technological development in hydrogen production
	Fossil fuel lock-in
	Carbon capture's scalability
	Cleaner technology
	New infrastructure build-out requirements
	Recyclability of end-of-life materials
Natural environment	Saltwater corrosion
	Temperature variations
	Natural disasters and disease outbreaks
	Land, water, and air pollution
	Climate change and availability of renewable energy sources
	Critical minerals availability
	Geological conditions suited to carbon storage
Market environment	Demand variability
	Failure of key customers
	Substitute products
	Bargaining power of customers
	Qualified workforce
	Acceptance of hydrogen from consumers
	Community pressure and sustainability concerns
	Health and safety
	Insufficient public awareness of sustainability
	International equity and justice concerns
	Labour strike

understand the link between supply chain complexity and resilience [41,42]. Recent research has explored techniques for identifying shifts in complex systems, focusing on quantifying ecological resilience [43]. Spatial resilience in social-ecological systems integrates structure and spatial variation into resilience assessments, linking landscape ecology with complex systems [44]. Understanding the relationship between resilience and spatial factors can improve evaluation designs. Shi et al. [45] emphasised analysing city resilience through a CAS lens, proposing a framework for urban systems that examines surroundings, elements, structure, and seven core CAS characteristics. Assessing resilience in CASs highlights the interconnectedness of social-ecological systems, focusing on key players, ecological structures, and their broader interactions. Similarly, HSC resilience can be analysed as part of its business ecosystem.

Resilience assessments and metrics remain incomplete without understanding CAS dynamics. Neglecting endogenous process risks misrepresents intervention impacts, as resilience is inherently dynamic [46]. Metrics should reflect transient results across system tiers under various disruptive scenarios [47]. Recognising CAS's evolving nature, resilience assessments integrate uncertainty planning and learning [46]. Applying a CAS perspective to SCR enhances the development of scenario-specific metrics. While previous research has applied CAS theory to SCR [48,49], Yaroson et al. [50] demonstrated CAS in systematically analysing pharmaceutical SCR. However, CAS has yet to be applied to HSCs. CAS supports multi-level analysis and offers a framework for examining complex adaptive phenomena, particularly in supply chains for sustainable industries such as HSCs [21]. By addressing systemic interactions and long-term adaptation, CAS theory offers a lens to bridge gaps in the HSC resilience literature. Applying CAS theory to HSC resilience research improves the effectiveness and scientific validity of assessment techniques while providing deeper insights into the complexities of hydrogen systems.

2.3. Resilience evaluations in supply chains

From a CAS perspective, complex systems adapt and evolve towards greater resilience, improving their response to similar future disruptions. HSC resilience can thus be evaluated through proactive and reactive capabilities. Proactive capabilities involve pre-disruption skills such as planning, anticipating, alerting, and preparing, while reactive capabilities focus on actions during and after disruptions to ensure recovery [46]. Common themes in definitions of resilience include response, recovery from disruptions, and restoring the system to its desired state. A supply chain disruption reflects a firm's failure to balance supply and demand, negatively impacting its economic performance [51]. Kamalahmadi and Parast [24] proposed a conceptual framework for SCR, incorporating key resilient supply chain components from the literature. Singh et al. [52] developed a SCR framework based on 17 indicators aimed at improving performance and resilience. However, these reviews did not address the feasibility of applying their frameworks in HSC contexts. Previous literature highlights the need to connect general SCR frameworks with specific HSC performance metrics. This study adopts the SCRE Capability-Performance Metrics Framework by Han et al. [51] to categorise relevant indicators into readiness, response, and recovery dimensions, addressing gaps and answering the research questions. This work enhances existing resilience evaluation frameworks [51,52] by incorporating CAS concepts and identifying specific resilience indicators for HSC contexts.

3. Methodology

A systematic literature review was conducted using Seuring and Gold's [53] content analysis approach. It consists of four processes: (1) content collection; (2) descriptive analyses; (3) category selection; and (4) content analyses. Following cutting-edge principles for conducting such reviews ensures the validity and reliability of these process steps, which are widely accepted and used in management studies and literature reviews [54,55].

Step 1 Content collection

The databases selected were Web of Science, IEEE Xplore, EBSCOhost, and Scopus, thereby covering the majority of hydrogen research. In line with other systematic literature reviews on SCR [46,51,52], several defined keywords were used as search criteria. The following keyword string was used to identify relevant papers: "hydrogen" AND ("supply chain" OR "operations management" OR "production process" OR "production" OR "process" OR "engineering" OR "industry" OR "manufacturing" OR "network" OR "distribution" OR "infrastructure" OR "storage" OR "transport" OR "utilisation" OR "community" OR "socio-ecological system") AND ("resilience" OR "resiliency" OR "resilient" OR "risk management" OR "flexibility" OR "responsiveness" OR "agility" OR "robustness" OR "redundancy" OR "visibility" OR "IT capability" OR "information sharing" OR "collaboration" OR "awareness" OR "sensitiveness" OR "velocity" OR "market position" OR "revenue sharing" OR "public–private partnership" OR "business continuity") AND ("measurement" OR "indicators" OR "assessment" OR "evaluation" OR "quantification" OR "metric" OR "performance" OR "assess" OR "indices"). The logical operator 'OR' was applied to construct search strings for articles containing at least one of the keywords in their title, abstract, or keyword list. We deliberately excluded specific types of hydrogen, such as green hydrogen, from our literature search, focusing solely on general methods for evaluating resilience in HSCs. Literature from January 01, 2010 to February 29, 2024 was reviewed, prioritising peer-reviewed journal articles, book chapters, and conference papers. This time frame reflects the rapid development of hydrogen technology, ensuring the proposed framework is relevant to current contexts. Conference papers were included due to the early stage of HSC resilience research. Articles not addressing HSC resilience were excluded. Relevant papers were identified using a specified keyword string, and the review followed the PRISMA protocol. (see Fig. 1). Six additional articles were identified through hand-searching and cross-referencing citations. Hand-searching targeted key journals on HSC studies to identify studies missed during the database search. Ultimately, 103 articles that satisfied the requirements were chosen to serve as the foundation for content analyses.

Step 2 Descriptive analyses

An overview was included of the year of publication, applied research methodology, and resilience capabilities covered in the publications. The results are presented in section 4. The identified resilience capabilities in this step form the basis of the conceptual framework, addressing research question one.

Step 3 Category selection

This step defined and categorised the evaluation objectives of SCR. A comprehensive review of SCR frameworks and related theories identified key definitions and categories. Existing resilience evaluation frameworks and management theories were assessed for their applicability to HSC resilience. Based on the review phases, a conceptual framework for HSC resilience evaluation was developed. The research methodology flow is presented (Fig. 2).

Jabareen [56] proposed that constructing a conceptual framework requires a thorough and inclusive process to ensure validity through comprehensive mapping and information collection. Following this approach and as discussed in Section 2, we identified three key areas for investigation: CAS, HSCs, and SCR evaluations. CAS and SCR evaluations are secondary topics within the broader HSC field. HSC element resilience, derived from content analyses of the literature, addresses the challenge of HSC resilience evaluation (research question two). Other layers of the framework are informed by the CAS evaluation framework, covering non-HSC elements not fully addressed in the review. Resilience capabilities beyond HSCs will be discussed in Section 6 as future research directions (research question three).

Step 4 Content analyses

We began by identifying HSC risks and resilience capabilities from the literature. Concepts from HSCs and CAS [45,57] were synthesised based on logical correlations and compatibility, with findings documented through a structured review process. Using Seuring and Gold's [53] method, we compared categories and data through inductive and deductive iterations, recognising alignment between resilience capabilities [52] and identified indicators. CAS theory provided practical tools to understand HSC resilience.

A three-level conceptual framework was developed to generate new insights and ensure qualitative integrity [58]. Key organisational goals during disruption stages guided the identification of time sequences for evaluations [51]. First-order concepts and second-order themes

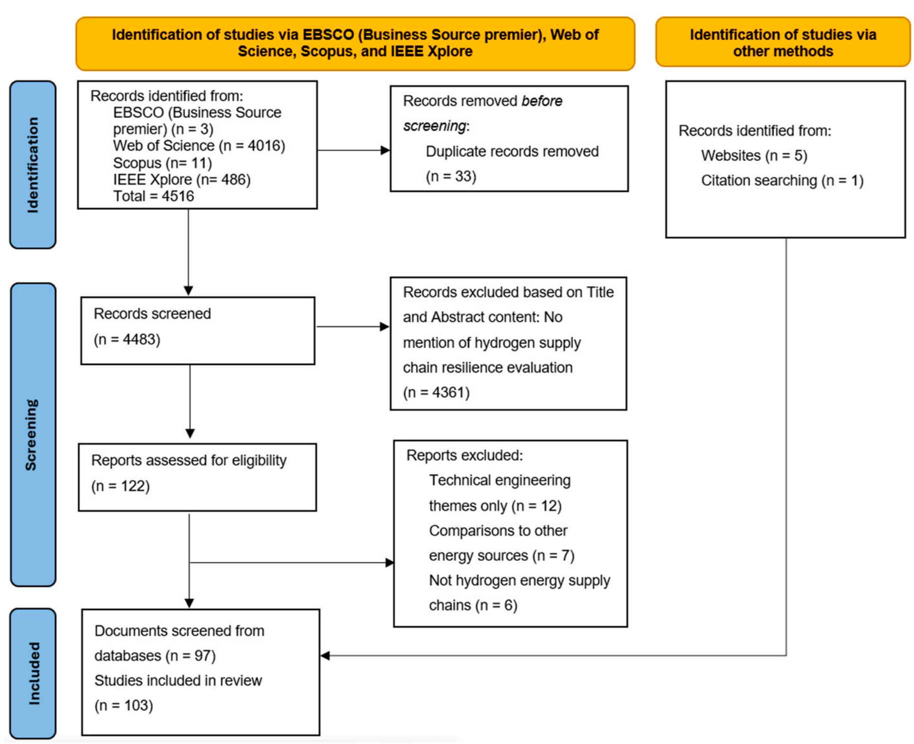

Fig. 1. PRISMA protocol.

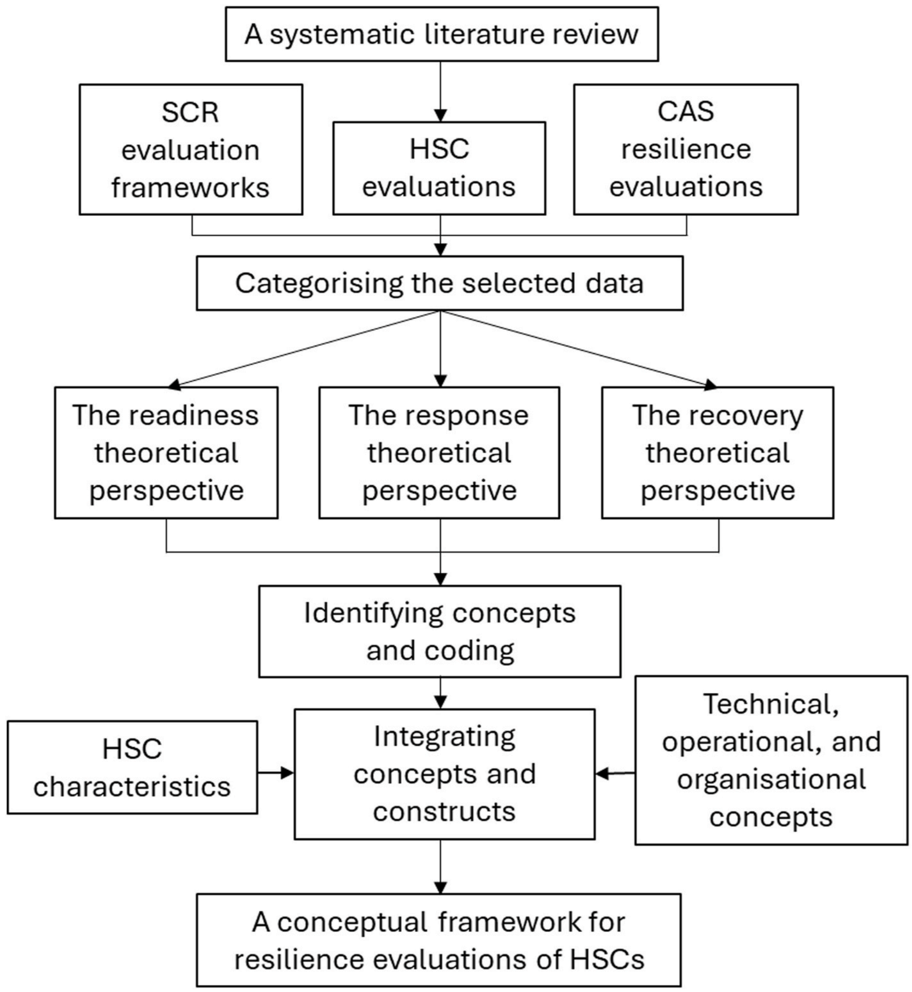

Fig. 2. The process of conceptual framework development.

informed the development of third-order elements—technical, organisational, and operational resilience—to address specific risks outlined in Section 2.1. Each concept was linked to its construct to ensure thorough coverage. The first iteration involved coding components, while the second incorporated updated HSC studies, CAS evaluations, and peer reviews to refine the framework. This resulted in a comprehensive methodology for evaluating HSC resilience, advancing knowledge, fostering new theories, and addressing research question three [59].

4. Results

As shown in Fig. 3, interest in studying HSC resilience has grown over time, particularly after 2019. This may be due to the increased need for studies on SCR to understand how companies threatened by COVID-

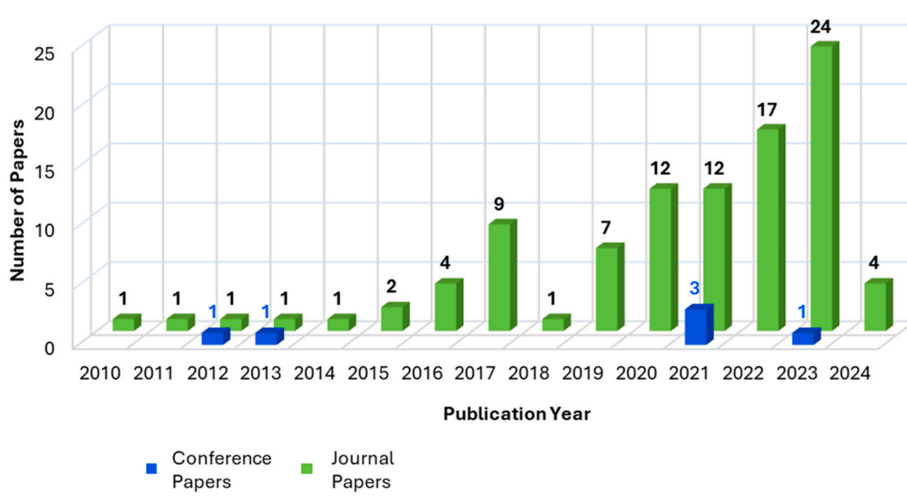

Fig. 3. Profile of the selected literature review on HSC resilience evaluations, 2010–2024.

19 can develop defences against future disruptions [60]. Although 2024 is not fully covered, the figure illustrates variations in the number of papers published across the years. Our findings align with Sgarbossa et al. [21], indicating that despite the increasing interest in resilience evaluations of HSCs, relatively few articles have been published in journals focused on supply chain management and operations management.

Two papers out of the 103 were published in journals related to supply chain management [61,62]. The subjects of the included studies further supported the absence of a supply chain management viewpoint in hydrogen research. The entire HSC process—sourcing, production, storage, distribution, and use—was only examined in 6 articles [5,10, 62–65]. Furthermore, it is intriguing to observe that most publications discuss only one or two supply chain processes, indicating that we are still in the early stages of research and that hydrogen value chains have not yet been fully formed [21].

A variety of research approaches were employed (Fig. 4). Simulation is the most common method, used in 68% of articles (70/103), followed by mathematical modelling (66%), statistical analyses (54.4%), case studies (41.7%), and risk analyses (34%). Survey methods, data mining, and questionnaires were rarely used, reflecting the emerging nature of SCR research in HSCs. Meredith [66] and Hmouda et al. [18] noted that models and simulations typically predominate in the early phases of field construction, with case studies and surveys following later. This review highlights a transition from literature reviews, experiments, and surveys to simulation, mathematical modelling, and statistical analysis, suggesting directions for future research.

We have systematically identified and categorised metrics for assessing the resilience of HSCs, drawing from the definitions outlined by Singh et al. [52] and Han et al. [51]. As depicted in Fig. 5, our analysis reveals that most studies highlight the importance of security capabilities, supply chain network and infrastructure design, as well as sustainability and optimisation strategies. Conversely, agility and risk control/revenue-sharing received comparatively less attention, indicating notable research gaps within the social science domains of HSC resilience studies.

Moreover, beyond the parameters outlined in existing frameworks, we realised the significance of additional capabilities such as maintainability and vulnerability assessment in ensuring the resilience of hydrogen systems by reviewing and synthesising literature [67]. Our synthesis of the included studies suggested that the resilience requirements across technical, operational, and organisational systems might involve a range of concepts, a nuance insufficiently explored in the existing literature. These identified gaps have led us to develop a novel conceptual framework that integrates insights from existing models while addressing the specific resilience needs of hydrogen systems.

5. Thematic findings

5.1. HSCs as complex systems

HSC is a complex system comprising upstream (sourcing, hydrogen generation, storage) and downstream (distribution networks, users) components [65]. Complex system behaviours are unpredictable, as disturbances in one node can spread throughout the system [46]. As the hydrogen economy develops, emergent behaviours may include shifts in geopolitical conditions, production techniques, distribution strategies, and pricing mechanisms [68]. HSCs are expected to demonstrate self-organisation, emergent behaviours, and the ability to adapt to market demand over time [69]. Decentralised hydrogen production, such as on-site refuelling stations, offers greater flexibility in adapting to demand changes and reducing transportation costs [70]. HSC elements should self-organise to optimise processes, respond to changes, and improve efficiency without central coordination. Heterogeneity refers to the variety of entities, activities, and people involved in the HSC [46]. This diversity enables the HSC to adapt its components. As agents within the HSC continuously perceive and respond to the external environment, the ecosystem's boundaries are constantly shifting [71]. Consequently, the complexity of the HSC evolves due to ongoing interactions between the external environment and the system [72].

The dynamic and emergent realities of the HSC arise from its interaction with the surrounding environment, leading to co-evolution and feedback between systems, resulting in either competition or

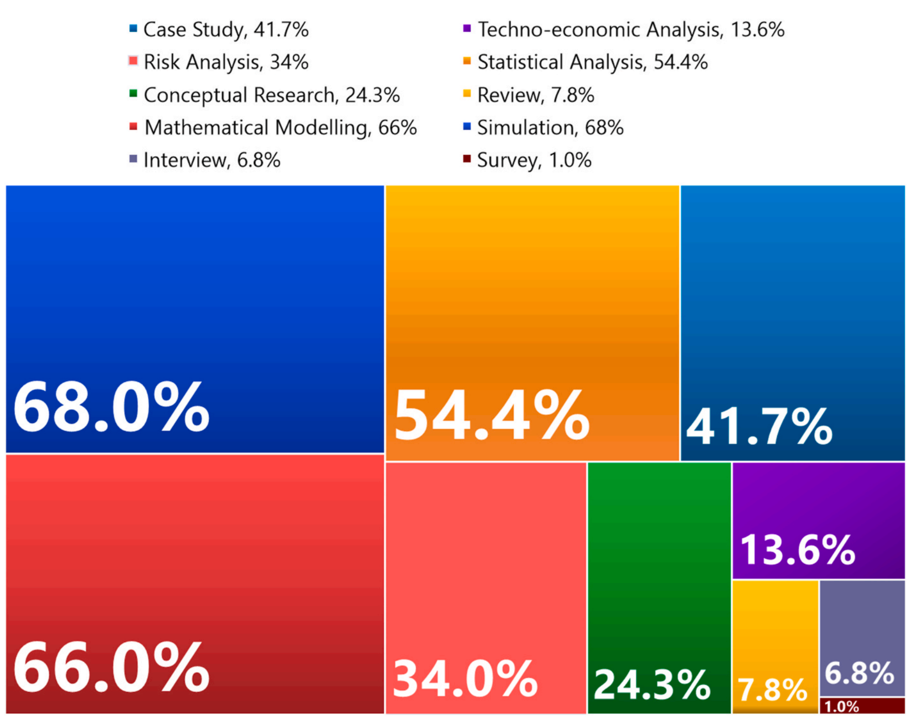

Fig. 4. Research methodologies employed in the reviewed studies.

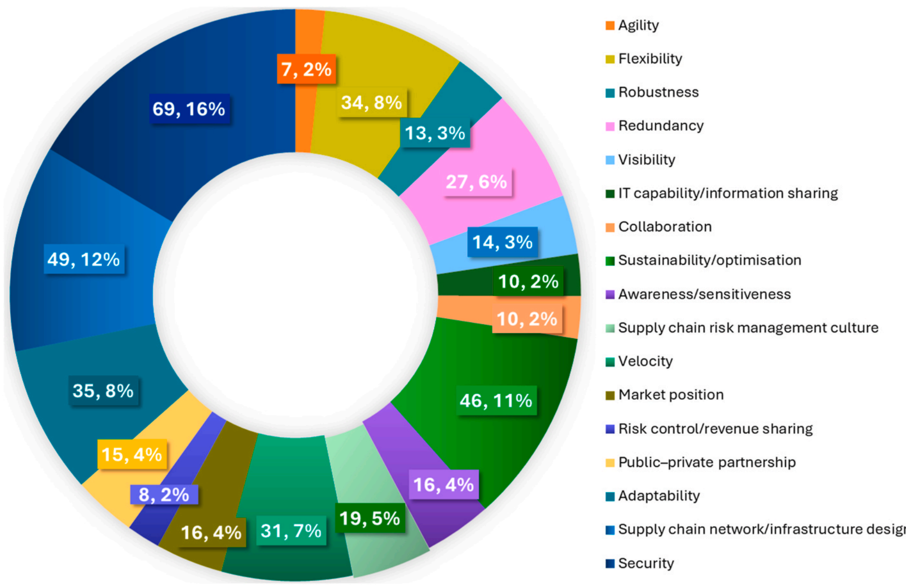

Fig. 5. Frequency of supply chain capabilities mentioned by the articles.

cooperation [46]. In the short term, HSCs are market-responsive supply chains focused on fulfilling market functions. The HSC ecosystem includes characteristics such as uncertain market demands, evolving technology, and short product life cycles [73]. Hydrogen companies should prioritise high adaptability, ensure flexible production, and prevent product obsolescence [74]. In the long term, resilient HSCs achieve a quasi-equilibrium with their surroundings. As hydrogen energy becomes demand-inelastic, HSCs will function as efficient supply chains, similar to fossil fuels, with a focus on fulfilling physical supply chain functions [75]. Market demands and technologies stabilise, while hydrogen companies aim to achieve economies of scale and reduce costs. Resilience will become an inherent characteristic of hydrogen business ecosystems as CASs.

5.2. Definition of HSC resilience

Hydrogen production is inherently dependent on the availability of feedstock and the integration of associated power networks [76,77]. As an emerging value chain, HSC resilience is significantly influenced by stakeholders, including suppliers, customers, shareholders, governments, and the media [64]. Understanding HSC resilience depends on stakeholders' perceptions of the hydrogen production system [65]. Viewing resilience from a production and operational perspective broadens planning to include customers [78,79]. HSC operations are often shaped by government actions [80]. The goal of HSC development is to establish a net-zero socio-ecological system, requiring sustainable development. HSC resilience should be viewed as a long-term blueprint, rather than just a return to pre-disruption performance, especially considering hydrogen storage challenges. Due to their unique characteristics, HSCs require a specialised approach to fully understand their resilience. This paper redefines HSC resilience from the perspective of a business ecosystem.

We define the resilience of the HSCs as follows: throughout operations, HSCs can adjust to both predictable (e.g., preventive maintenance) and unexpected disruptions (e.g., natural disasters, emerging events) by aligning functions with current demand and available resources, supported by cost-effective information and technologies, while keeping a competitive advantage over other alternative systems. The hydrogen production system leverages renewable energy and ensures technical reliability, maintainability, and independence, enabling rapid recovery after disruptions. With robust, agile, and adaptive features, the production system fosters a resilient hydrogen ecosystem, characterised by optimised, transparent, and adaptable operations, while maintaining social acceptance and the resilience of associated systems. Resilience and sustainability contribute to the vitality of the business ecosystems of HSCs. This definition emphasises that resilient HSCs evolve to meet demands in a timely manner rather than simply return to their original performance after experiencing disruptions, overcoming challenges such as hydrogen embrittlement and storage issues. Built upon the existing resilience concepts, the resilience defined in this paper is further explained in the following four aspects.

a) Resilience is an HSC organisation's capability to design reliable technologies, control technical vulnerabilities, optimise operations, and remain robustly organised to evaluate, predict, and withstand both expected risks and unexpected events when preventing system disruptions [81].
b) Resilience is the ability of agile decision-making, transparent sharing, and transaction control within HSC subsystems to sustain functions and performance during disruptions [46].
c) After disruptions, HSC resilience is demonstrated by the system's ability to adapt operations dynamically and optimise the supply network, maintaining carbon-neutral and sustainable development goals despite inevitable changes [82].
d) When recovering from disruptions, resilience in the HSC system is defined by its regenerative and learning capacities, enabling swift service restoration and the maintenance of a competitive edge. Continuity is ensured by leveraging learning and innovation capabilities to transform vulnerabilities into controllable factors [50].

5.3. HSC elements in the resilience evaluation framework

Based on the concepts and challenges of HSC resilience, we present a conceptual framework for its theoretical analysis (Fig. 6), outlining the functional characteristics of HSCs according to the sequence of the events. HSC resilience is a comprehensive concept encompassing technical, operational, and organisational aspects within the hydrogen production system. The circular design of the framework reflects the interchangeability of pre- and post-event indicators.

Our framework outlines resilience analysis and evaluation methods across three layers: the HSC element layer, the HSC network layer, and the hydrogen business ecosystem layer. The following subsections and Tables 2–4 will introduce and clarify constructs related to HSC element resilience from technical, organisational, and operational perspectives,

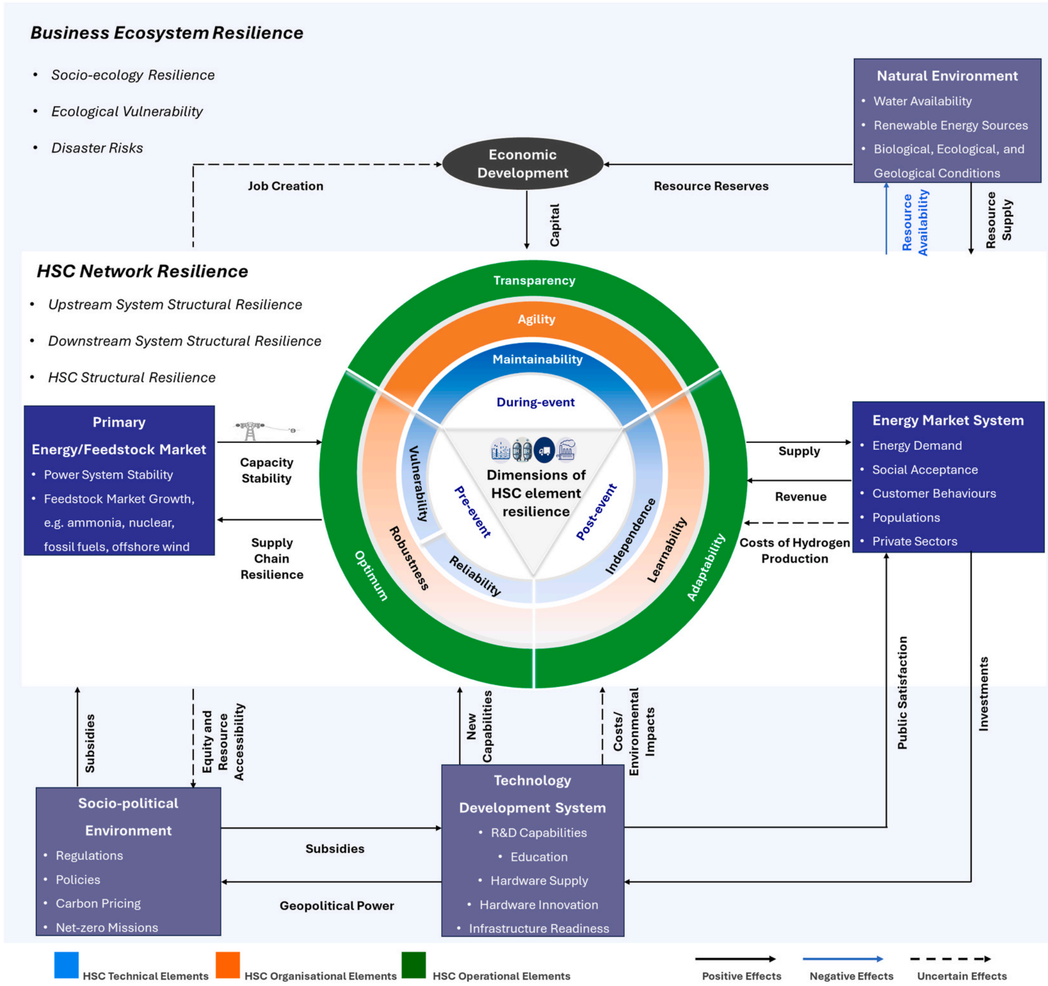

Fig. 6. Resilience evaluation framework of the hydrogen business ecosystem.

referencing the reviewed research.

5.3.1. Technical resilience analyses

Proactive capabilities enable organisations to plan or respond promptly to an event, reducing or avoiding its impact [46]. At the technical level, this work proposes evaluating the reliability and vulnerability of HSCs. Reliability assessments focus on system efficiency to defend against hazards (security) [111], while vulnerability evaluations consider external factors, such as geopolitical stability, to assess the system's dynamic complexity [94].

Reliability analyses help identify areas for improvement and strategies to prevent supply chain disruptions. Key indicators of reliability in hydrogen generation systems include leakage rates and frequencies. Chang et al. [112] proposed a dynamic Bayesian network methodology to detect hydrogen leakage in generation units. Hydrogen–oxygen management during production was emphasised by Gardner et al. [110] and Pankhedkar et al. [118]. Hadef et al. [85] and Almeida et al. [117] highlighted the importance of periodic equipment maintenance, such as for reactors, pumps, valves, and pipes, to ensure proper hydrogen production. Li et al. [92] proposed a reliability index based on the burst pressure of composite pressure vessels (CPVs) exceeding their critical pressure. Reliability assessment tools such as Failure Modes, Effects, and Criticality Analysis (FMECA), Failure Tree Analysis (FTA), and Event Tree Analysis (ETA) were commonly used to evaluate failure risks in substation components [109,113,115]. FTA calculates system failure probability using Boolean algebra, standardised under German DIN 25424 and global EN 61025 standards [114]. For downstream operations, graph topology, which shows node connections and patterns, can assess the stability of distribution networks [94,125,130]. Evaluations should consider the balance of capacity and demand, economic and environmental feasibility, and recoverable construction options [61,123,126,166]. International standards, such as the IGF code for hydrogen fuel cell vessels and ISO 20519:2017 for LNG bunkering, can guide hydrogen utilisation reliability [104]. However, these standards may need adaptation to address the unique risks and properties of hydrogen.

Reliability evaluations often overlook high-consequence, low-probability events [172], with probability being a key difference between vulnerability and reliability [173]. Systematic vulnerability analyses can address this limitation. Vulnerability assessments evaluate the likelihood and extent of disruptions in the presence of external threats [94], focusing on a system's ability to resist interference. A higher vulnerability level indicates a greater chance of accidents and more severe outcomes. Even with high reliability, uncontrollable external factors should be considered [89]. Both vulnerability and reliability evaluations aim to assess supply chain safety and dependability [174]. However, the concept of vulnerability in HSC systems requires further clarification. Quantitative risk assessments and system dynamics modelling can explore vulnerability patterns related to geopolitical issues, failure rates, and hazards across HSC nodes [72,93]. Zhang et al. [94] developed a methodology for assessing hydrogen station vulnerability, combining the COWA operator, ordinal relationship method, and cloud gravity centre theory. Vulnerability assessments of downstream hydrogen systems cover personnel, facilities, materials, environment,

Table 2
Constructs of technical resilience evaluations.

Third-order category	Dimensions	Second-order themes	The components of hydrogen systems	First-order concepts	References
Technical resilience: The scope of technical resilience encompasses the resilience of manufacturing techniques, processes, and equipment.	Pre-event	Vulnerability: Network and infrastructure design, as well as awareness	Upstream (production and storage)	Hazard identification, vulnerability transmission mechanism, risk assessment, weakness identification, penetration testing, fuzzy theory, decision preference, distance to shore, seabed condition and water depth, low pressure storage in fuel cells (96% of energy efficiency)	[72,83–95]
			Downstream (distribution and utilisation)	Locations, infrastructure readiness, meteorological conditions, IEC 60079-10–1:2015 standard, annual average daily traffic per lane, the tunnel length, the percentage both of heavy good vehicles and dangerous goods vehicles, Bayesian network models, CFD simulations	[61,76,86,88,94, 96–108]
		Reliability: Security and efficient operations	Upstream (production and storage)	Failure modes, effects, and criticality analysis (FMECA), failure Tree analysis (FTA), event Tree analysis (ETA), periodic maintenance of equipment, process control (hydrogen-oxygen management), compressibility factor, universal gas constant [J/(kg•K)], and gas temperature [K], Bayesian models, repair rate, mean time to failure (MTTF), mean time between failures (MTBF), leak frequencies, public acceptance, loss of load probability, expected demand not supplied	[25,83,85,92,97, 109–122]
			Downstream (distribution and utilisation)	The vehicle usage and intact rate, network node density, network complexity, average service/ point availability, network connectivity, capacity reliability, energy consumption under different temperature environments, unit contribution, resource utilisation, refuelling time, driving range, customer average interruption duration, graph topology, network flow model, user needs, user nature, consumption habits, IGF-code, ISO 20519:2017 for LNG-bunkering	[61,63,94,96,97, 107,114, 123–130]
	During-event	Maintainability: Velocity and accessibility	Upstream (production and storage)	Average repair time, fault detection rate, fault isolation rate, accessibility, standardisation, interchangeability, mean time to restoration (MTTR), maintenance safety, compatibility, automatic detection, technical feasibility, failure risks, repair coverage, quality impact, priority satisfaction, S-LCA, LCC	[5,11,78,80,83, 90,96,126,131, 132,132–136]
			Downstream (distribution and utilisation)	MTTR, point availability, network priorities, customer average interruption duration	[80,114,129, 137]
	Post-event	Independence: Redundancy	Upstream (production and storage)	Expert experience, patents, availability of tools and resources, resource reserves (the average purchase number of feedstocks; automatic frequency restoration reserves), standard development, R&D	[11,64,65,114, 136,138–141]
			Downstream (distribution and utilisation)	Independent load supply without the electricity grid, marginal utility evaluations, high technology exports, technical cooperation grants	[65,70,142]

and emergency response capabilities [102]. Methods such as Bayesian network modelling and CFD simulations can predict hydrogen-related hazards such as fires or explosions [101,103]. In the vulnerability evaluations, the properties of hydrogen must be considered, in particular, the strong buoyancy of gaseous hydrogen [86,104]. For hydrogen transport, factors such as traffic volume, tunnel length, and the presence of hazardous goods should be examined [76]. Hazardous area zoning can follow the IEC 60079-10-1:2015 standard [104]. Vulnerability is central to HSC resilience, as it reflects the emergence of complex systems. To assess vulnerability levels, the thresholds proposed by Aarskog et al.[104], adjusted for hydrogen's properties and the OGP 434 Risk Assessment Directory, can be used.

During disruptions, system resilience involves reactive capabilities to efficiently withstand small perturbations [46]. The maintainability of HSC technology is a key attribute for the system to withstand disruptions. Maintainability implies the velocity, accessibility, bottleneck solutions, and cost-effectiveness of maintenance activities [90,96]. A maintainable system ensures that technology resources are accessible during disruptions, allowing for restoration and adaptation under specified conditions and timeframes [123,132]. For example, performing maintenance in areas with high wind speeds (up to 20 m/s) and large wave heights (over 2.0 m) is dangerous. Hybrid renewable energy systems combine multiple sources to ensure consistent power, offsetting the unreliability of single sources while reducing emissions. Their proximity to demand points minimises transmission risks and allows faster repairs and maintenance [5]. Unfavourable weather, such as storms during winter, complicates offshore maintenance [90]. The mean time to repair/restoration (MTTR) indicates the duration to restore a component post-failure, influenced by staff availability, replacement parts, and repair ease [78,126]. Uhrig et al. [114] introduced point availability, which measures the likelihood of a system point functioning with constant failure and recovery rates. Maintenance prioritisation, such as anti-corrosive treatments for high-risk HSC sections, can be guided by risk ratings using methods such as utility theory and ELECTRE TRI [80]. Decisions for timely recovery can incorporate social and economic sustainability aspects through social life cycle assessment (S-LCA) and life

Table 3
Constructs of organisational resilience evaluations.

Third-order category	Dimensions	Second-order themes	The components of hydrogen systems	First-order concepts	References
Organisational resilience: The scope of organisational resilience encompasses the resilience of process, structure, and culture.	Pre-event	Robustness: Risk control and risk management culture	HSCs	Process risk index, internal environment stability, contingency planning, maintenance scheduling, risk assessment, regulation compliance, cross-functions and skill redundancy, trust, leadership, proactive scheduling decisions	[26,77,79,87,93,113,128,134,135,137,143–145]
	During-event	Agility	HSCs	Shift focus, changed management and responsibilities, loss absorption capacity, feedback loops, the total time for a system to meet minimum performance requirements within given time constraints, incident response procedures, resources required, timeframes, prioritisation	[11,64,128,132,133,145,146]
	Post-event	Learnability: Public-private partnership, collaboration, and market position	HSCs	Stakeholder alignment, continuity, consistency, cohesiveness, collaboration and interconnection, situational understanding, creation and originality, political intention, employee involvement	[26,77,79,128,143,146–149]

Table 4
Constructs of operational resilience evaluations.

Third-order category	Dimensions	Second-order themes	The components of hydrogen systems	First-order concepts	References
Operational resilience: The scope of operational resilience encompasses the resilience of logistics, information flow, and cash flow.	Pre-event	Optimum: Sustainability	HSCs	Budgeting, quality control, demand management, delivery time, defect rates, cycle time, real-time data availability, techno-economic analyses, cash flow performance metrics, running costs, OPEX, low loss of power supply probability (LPSP, 0–5%)	[5,11,62,65,90,111,124,130,131,138,142,148,150–159]
	During-event	Transparency: Visibility, IT capability, and information sharing	HSCs	Frequency of information sharing, system visibility, traceability, data disclosure, data system, demand responsiveness (travel time), information accessibility, stakeholder engagement	[64,65,80,115,126,138,139,144,147,160–163]
	Post-event	Adaptability: Flexibility, optimisation, and redundancy	HSCs	Inventory of the key nodes, system capacity to reconfigure (peak shaving ability), feedback loops, system redundancy, resource allocation, resource optimisation, expected load not served, flexible engineering system design, renewable energy consumption	[31,79,114,124,130,136,137,140,141,153,154,159,161,164–171]

cycle costing (LCC) [11]. Evaluation methods focus on the trade-offs in maintaining the system [78,131,133].

Facing an uncertain environment, organisations should proactively adapt to changes by rebuilding and regaining their market positions through the accumulation and reconfiguration of their capabilities and resources [46]. The technological independence of HSCs functions as a 'redundant' resource, enabling the system to recover from disruptions, adapt to new circumstances, and mitigate future disruptions. Redundancy for hydrogen companies means having independent hydrogen production, manufacturing capabilities, necessary equipment, patent knowledge, and expertise to mitigate system vulnerability [140]. In addition to maintaining the necessary technology and backup equipment, it is crucial to stockpile key components that enable the rapid repair or replacement of damaged equipment [11]. The technology system can be independent to avoid the time of coordinating with external systems [138,139]. Bartolucci et al. [142] proposed a resilience index describing the ability of the system to provide the load independently of the electrical grid. A highly resilient system guarantees the reliability of the services and lessens the impact of fluctuations in local renewable energy sources on the grid [142]. Moreover, the independence of technology means that companies and countries can assess damage, mobilise resources, and restore operations efficiently, minimising downtime and relying less on external systems for support [65].

5.3.2. Organisational resilience analyses

At the organisational level, robust hydrogen organisations prevent disruptions by minimising risks to their processes, culture, and structure [175]. A strong risk management culture enhances organisational resilience. Robustness refers to an organisation's ability to withstand adverse conditions, maintaining stability in its processes, structure, and culture [113]. Clear administrative procedures and a well-defined organisational structure are essential, as complexity increases the risk of instability. For instance, a wind-photovoltaic-hydrogen storage plant station contains three separate parts, leading to structural complexity and management challenges [79]. Related evaluations such as process risk index (PRI) can map risk and explore the effect of process deviations on process robustness [143]. In addition, risk prevention and contingency plans are frequently highlighted [77,116,144]. Yazdi et al. [26] proposed that cultivating a safety culture, robust training, and maintenance scheduling were effective safety interventions to prevent the failure of the system. Trust, leadership, staff empowerment, goal clarification, and staff inspiration to enhance communication skills are all essential to build organisational robustness [26]. Stringent rules and policies are aligned to improve personnel safety management, equipment maintenance, and preventing potential secondary incidents [134]. While establishing a structure with autonomic and self-correcting capabilities is a key objective, achieving structural resilience requires a balanced approach that integrates both structural stability and adaptive decision-making [176].

During disruptions, agile hydrogen organisations demonstrate the ability to respond efficiently, with agility reflecting their capacity to react promptly. The quality of decision-making in such situations is closely linked to the organisation's processes, strategic objectives, and risk culture [11,123]. At the organisational level, it is critical for enterprises to cultivate agile processes while embedding risk management awareness and culture into the core of their operations, supported by effective incentive mechanisms. Once risks are identified, organisations could critically assess their current processes to evaluate their preparedness for mitigating and responding to these hazards [146]. This assessment should go beyond surface-level reviews of policies and procedures, examining more deeply the organisation's loss absorption capacity, the recovery potential of its resource reserves, and the overall effectiveness of existing response plans [64]. Agile response indicators include incident response procedures, action evaluation, prioritisation, and implementation timeframes to enable strategic decisions during disruptions [128]. Given agility as an indicator of temporal resilience, the time required for the energy system to meet minimum performance standards within specified constraints becomes a relevant metric [145]. Evaluations of organisational resilience during disruptions tend to prioritise short-term, temporal factors, rather than long-term adaptability and the capacity for innovation in addressing complex and unforeseen challenges [124].

Knowledge and relationship management are necessary capabilities in the recovery dimension [51], which are summarised as learnability in this work. The learnability of organisations enhances their decision-making and enables timely adaptation to new contexts via developing public-private partnerships, collaboration, and improved market positioning. After disruptions, organisations may assess the learnability of their structures to determine if they support a resilient mindset. The consistent perceptions held by employees can serve as an indicator of structural learnability [177]. Consequently, the evaluation process may assess employees' attitudes toward risks, openness to change, and their willingness to collaborate and learn from past experiences [143,147,148]. By fostering a culture that values resilience, organisations can better equip themselves to respond to unexpected challenges. However, it is crucial to assess whether fostering resilience at the cultural level is sufficient, or if more profound structural and systemic transformations are required to navigate highly volatile environments effectively. Maintaining positive relationships with the general public can foster trust and collaboration across HSCs, contributing to increasing information exchange and provision in risk management activities [149]. It is important to scrutinise the depth and authenticity of these relationships. The learnability of an organisation reflects the cohesion among its employees and stakeholders when faced with adverse circumstances [146,178]. Sub-indicators of organisational learnability include political intention, employee involvement, situational understanding, creativity and originality, and awareness/commitment [26]. To evaluate these abstract qualities effectively, the assessment should capture the complex and dynamic nature of organisational resilience, and account for factors such as power dynamics, resource disparities, and broader socio-political contexts.

5.3.3. Operational resilience analyses

At the operational level, the logistics, information flow, and capital flow of HSCs can be considered [65,148]. Hydrogen organisations within HSCs can proactively prevent potential disruptions by implementing optimum operations or optimisation. Optimisation, as a management approach, focuses on streamlining processes to minimise waste and maximise quality and efficiency, ensuring all activities benefit customers [179]. Applying optimisation methods is key to achieving sustainable development [180]. The concept of optimisation emphasises material flows are adjusted based on customer demand [181]. This practice can mitigate the risks associated with hydrogen storage [182]. By reducing flaws and unpredictability through standardisation, optimal information flow enhances the quality and reliability of HSCs. Additionally, optimal cash flow strengthens the robustness of hydrogen organisations by lowering costs. Analytical techniques based on optimum principles and the theory of constraints (TOC) can analyse resilience and identify bottlenecks in HSCs [154,183]. This approach assumes that HSC resilience is determined by its weakest subsystem [124,130]. Techno-economic analyses help identify compact capacities with minimal investment risks, ensuring optimal cash flow for hydrogen organisations [117,138,151,153]. Achieving the optimal setup for off-grid hybrid renewable systems involves balancing the loss of power supply probability (LPSP) and minimising total life-cycle cost (TLCC) from a design perspective. For low LPSP values (0–5%), a hydrogen and photovoltaic (PV) system, integrated with weather forecasting, is the most economical option. At an LPSP of 10%, the cost-effective solution shifts to a hybrid system combining wind, PV, and hydrogen [5].

During the event, focal firms in HSCs can swiftly respond to unexpected conditions through transparent operations. Operational transparency involves visibility, IT capabilities, and information sharing across supply chains, driving synergy, demand satisfaction, and efficiency. Transparent operations allow HSC agents to monitor the behaviour of others, fostering emergent responses and preventing worsening conditions. Reliable information on materials and capital is essential for resilient operations, enabling organisations to predict, identify, and address disruptions swiftly and effectively [51]. Evaluation factors encompass system visibility, traceability, and data disclosure [65,80]. Visualisation technologies and digital infrastructure facilitate the coordination of HSC subsystems, such as production, logistics, and markets, enhancing risk monitoring and response capabilities [162]. Sharifpour et al. [163] introduced the R-OEMA approach that tactically integrates preventive scheduling methods for hydrogen systems, renewable units, controllable distributed generators, and demand response initiatives. The R-OEMA framework's effectiveness is assessed through numerical simulations on a test system that includes microgrids. The assessment emphasises the responsiveness of the operational team to positive and negative impacts. Responsiveness is primarily evaluated based on two dimensions: time (e.g., order response and delivery time) and synergy (e.g., information sharing and technical support) [144].

As the HSC recovers from disruptions, operational evaluations focus on its adaptability, defined as the system's ability to meet current demands while adjusting to changing environments, thereby ensuring resilience against future disturbances. Adaptability is assessed from flexibility (time), optimisation, and redundancy (resource) perspectives, considering key node inventory levels and system capacity [161,171]. In other words, optimal flexibility and redundancy enable adaptable operations. System redundancy is an indicator of adaptable operations. More control variables in hydrogen networks with hydrogen headers, purifiers, and compressor capacity redundancy may enhance indirect scheme-equipped hydrogen network performance [154]. The peak-shaving capacity and renewable energy consumption of hydrogen companies improve the adaptability of hydrogen pipeline networks [141]. Evaluations can compare capital flow and feedback loops of focal firms to assess whether their operational abilities surpass pre-event conditions [143]. Beyond environmental and economic perspectives, social cost-benefit analyses aid in designing adaptable systems and optimising resources, factoring in costs such as hydrogen use, fuel, platinum, carbon, and noise [31]. Zheng et al. [171] proposed an optimisation technique for car charging stations, where hydrogen/electric energy is allocated to vehicles, reducing refuelling station operational costs and user queuing time. By incorporating optimised system designs, emergency response strategies, and flexible procurement strategies, a comprehensive resilience model for HSCs can minimise recovery costs and boost competitive advantages after disruptions [153]. The comprehensive consideration of environmental, social, and economic perspectives of the resilient HSC design indicates that sustainability evaluations inherently are rooted in HSC resilience evaluations [184].

6. Discussion

As outlined in Section 5.1, HSC resilience is shaped by internal and external factors, requiring a holistic evaluation of the entire business ecosystem. The external layers of the resilience evaluation framework (Fig. 6) highlight gaps and set an agenda for further empirical research.

We discuss the framework through four dimensions: business ecosystem resilience (BER), HSC network resilience (HNR), HSC element resilience (HER), and HSC structural resilience (HSR). The evaluations of system resilience can use the weighted average of BER, HNR, HER, and HSR, though the exact weights require further research. Future research should explore the relationships among BER, HNR, and HER, addressing: (i) the nature of their interconnections, (ii) their mutual influences, and (iii) associated feedback mechanisms. The framework assumes an existing, fully operational HSC with nonlinear component functions, rather than a newly designed system with incomplete value chains.

6.1. Evaluations of business ecosystem resilience (BER)

The hydrogen business ecosystem refers to the external environment interacting with the HSC. As suggested by Shi et al. [45], assessing the environmental resilience of the HSC could involve three key elements: socio-ecological environment, ecological vulnerability, and disaster risks. Disaster risks include both natural and man-made events that can disrupt hydrogen supply operations, causing varying levels of economic loss. Typically, the likelihood of environmental calamities negatively correlates with BER [45]. However, the precise effects of disaster risks on hydrogen system resilience remain unclear and could be explored using disaster risk assessment methods such as fuzzy theory and Bayesian network models [119].

Ecological vulnerability refers to the susceptibility of an ecosystem to negative impacts from environmental changes. The disruptions within the hydrogen business ecosystem highlight the impacts of external interventions and the probability and severity of ecological issues. Future studies could draw on the methods proposed by Zhang et al. [94] for assessing such vulnerabilities. The HSC operates within a dynamic socio-economic environment influenced by government policies, market dynamics, and technological advances. Governments are introducing incentives to promote the hydrogen industry, particularly green hydrogen, as part of decarbonisation strategies. These policies foster public-private partnerships, attract investment, and create economic opportunities [154]. Additionally, HSC resilience depends on market forces and consumer adoption, as hydrogen production costs impact its pricing and competitiveness with alternative energy sources [64].

The transition to a hydrogen-based economy offers significant potential to drive global decarbonisation efforts. However, the development of resilient HSCs is fraught with substantial uncertainties, presenting complex challenges that require careful and strategic management [37]. These uncertainties span the BER dimension, emphasising the need for this comprehensive framework to effectively evaluate HSC resilience. Societal disruptions, such as shifts in employment, infrastructure, energy stability, and lifestyles, could impact public perception [185]. Resistance may arise if societal costs, such as job losses or infrastructure changes, outweigh perceived benefits, threatening hydrogen adoption and HSC resilience [39].

Equity and justice concerns add complexity to the development of the hydrogen economy. Ensuring an equitable distribution of hydrogen's benefits and costs is crucial for widespread adoption, particularly in economically disadvantaged or underserved regions [186]. Affordability will be key to making hydrogen technologies accessible, while local environmental impacts—such as land use changes, high water consumption for green hydrogen production, or emissions from blue hydrogen processes—could weaken HSC resilience [5]. These issues should be addressed to avoid environmental injustices. As the hydrogen ecosystem grows, social acceptance, safety, environmental impacts, and long-term sustainability become critical to HSC resilience [31]. Technological advancements may enhance resilience by improving supply chain capabilities and cost efficiency [65]. However, the interplay between ecological vulnerability, socio-ecological settings, and hydrogen system resilience requires empirical validation to determine whether these relationships are positive or negative. HSC business environmental resilience can be measured through an index system with assigned weight values [45], providing a structured approach to evaluating resilience.

6.2. Evaluations of HSC network resilience (HNR)

The resilience of hydrogen energy production is closely related to the state of upstream networks and market feedback. HNR evaluations focus on the structural resilience of both upstream and downstream networks. Structural resilience refers to the inherent strength of a supply network in the absence of external risks [187]. For power networks, structural resilience metrics can be calculated using the Kirchhoff index of the Laplacian matrix, as demonstrated by Ma et al. [70]. Connectivity within power networks is particularly critical during unforeseen events.

Shi et al. [45] proposed five factors for assessing hydrogen downstream user network resilience: hierarchy, matching, transmissibility, vulnerability, and robustness. HSC resilience may correlate positively with hierarchy, matching, and robustness, while vulnerability and transmissibility might show negative correlations with HNR. User network resilience is particularly important for the growth of the hydrogen economy, as it influences the feasibility of energy transition and switching costs to other energy sources [64]. Higher switching costs discourage users from adopting alternative energy, thereby enhancing HSC resilience. Yu et al. [187] provided methodologies for evaluating structural resilience and vulnerability in hydrogen-related contexts.

6.3. Evaluations of HSC element resilience (HER)

HSCs comprise technical, organisational, and operational subsystems. Evaluating the resilience of these subsystems is crucial for assessing the HER. Unlike the resilience functions proposed by Afgan and Veziroglu [63], which assume a simple aggregation of subsystem evaluations, we consider resilience as a non-linear superposition of these components. This non-linearity arises from interactions, reciprocal influences, and feedback loops both within and between subsystems and the broader business ecosystem [31].

Section 5.3 outlined unique resilience indicators for each subsystem, but the specific weights assigned to them require empirical investigation. Effective evaluations should incorporate reactive and proactive capacities, time-dependent attributes, and non-linear performance behaviours. Future research could explore the interrelationships of performance-based resilience metrics within HSCs and test their temporal sensitivity using a mixed quantitative and qualitative approach [188].

6.3.1. Evaluations of HSC structural resilience (HSR)

The internal structural resilience of HSCs can be evaluated using methods proposed by Shi et al. [45] and Yu et al. [187], though future empirical studies are needed to refine these approaches. Current research categorises supply chain complexity into structural and dynamic dimensions [48]. Dynamic complexity arises from network interactions, such as delivery, supplier, and demand fluctuations, while structural complexity involves factors such as scale, horizontal versus spatial complexity, and product diversity [189,190].

The primary goal of HSC structural resilience is to optimise functionality at minimal cost [132]. Resilience depends on the specific risks faced and the nature and magnitude of their impacts [139]. Assessments should consider different operational modes, such as large-scale hydrogen production with long- or short-distance transportation and small-scale production for refuelling stations [90,107,135]. In each mode, focal firms represent resilience bottlenecks. Key differences between modes include electricity transmission methods for hydrogen production and transportation distances.

Given the diverse risks in HSCs, resilience assessments may assign varying weights to hazards based on their significance. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) can prioritise hazards and determine risk values, while fuzzy Decision-Making Trial and Evaluation of Laboratory (DEMATEL) is useful for analysing relationships among risk indices and calculating their weights [30]. This approach assumes interconnected hazards within the system. The ratio of the system's actual effective performance to its optimal performance during operation, rather than temporal resilience evaluations, reflects overall system resilience [145].

7. Conclusion

This research broadens the perspective on SCR evaluations in HSCs by considering both the internal characteristics of HSCs and external dynamic environments. The primary objective is twofold: first, to understand and assess HSC resilience, and second, to identify methods for evaluating it. A systematic literature review of the current literature on HSCs and SCR evaluations gives a holistic understanding of the field. Drawing upon our understanding, it is the first comprehensive review to capture the current state of research on HSC resilience and evaluations. This study offers a clear definition of resilience in the context of HSCs, aiding in the understanding of HSC objectives and overall resilience. The findings are concluded as an evaluation framework, bridging the general SCR concepts and performance metrics of HSCs and presenting a system-oriented approach to assess resilience. The proposed conceptual framework offers a comprehensive horizon to identify future research potentials. The framework evolves the general SCR evaluation frameworks by categorising resilience indicators into technical, organisational, and operational subsystems across events. This conceptual approach enhances the predictive function of CAS theory, guiding future research on the resilience of HSCs [191].

7.1. Implications

The storage challenges and inherent properties of hydrogen make HSCs vulnerable and costly, hindering sustainable development. Sustainability-driven rather than economic-driven presents a barrier, directly affecting the HSC performance, reliability, and resilience. Preparation, response, and recovery strategies can address these vulnerability factors to overcome resilience barriers [52,192]. Key competencies such as contingency planning, agility, and adaptability are widely studied as preventative measures against supply chain disruptions [193]. However, resilience capacities may not always align with supply chain features. The selection of resilience indicators for HSCs has not been adequately addressed in the literature, particularly from a CAS perspective. CAS theory explores how systemic changes emerge from interactions between agents over time [41]. This study adopts a holistic approach, demonstrating how CAS theory can fill gaps in HSC resilience research.

The proposed framework outlines evaluation methodologies of resilience from the layers of the hydrogen production system, the HSC network, and the hydrogen business ecosystem. The framework lacks classifying upstream and downstream components of HSCs for the operational and organisational dimensions since the literature review reveals their indifferent evaluation approaches. Nevertheless, this conceptual framework provides specific resilience indicators of the HSC element, founded on the chronological sequence of disruption events. The framework considers different system perspectives and their interactions, which indicates future research directions.

Capacities play a critical role in SCR evaluation metrics. Key studies have explored various capacities, classifying them into reactive and proactive categories [51]. Examples from recent literature are summarised (Table 5). Dubey et al. [15] analysed data from 250 enterprises to conceptualise the effects of supply chain visibility, cooperation, trust, and behavioural risk on SCR. Juan et al. [194] examined how the five elements of SCR—visibility, velocity, flexibility, robustness, and collaboration—interacted with and influenced supply chain performance during disruptions. While these conceptual frameworks and empirical studies provide valuable insights, none propose resilience evaluation methods as comprehensive as those presented in this study. The framework presented here categorises resilience capabilities into the technical, organisational, and operational components of supply chains, aligned with specific disruption stages [15,192,195]. This approach resolves conflicts between common resilience indicators such as robustness and agility [177] and enables timely evaluations by decision-makers. Highlighting information-driven operations, this framework may apply to supply chains with storage vulnerabilities and extend beyond HSC contexts. Since the review involves upstream renewable energy supply and power systems, this resilience evaluation framework may offer guidance for other renewable energy supply chains [196].

Table 5
Comparisons with other frameworks (Y=Yes, N=No).

Name	This framework	[15]	[52]	[192]	[194]	[195]	[197]	[198]	[199]	[200]
Field of supply chains:	Hydrogen	General	General	General	General	General	General	Food and pharmaceutical	General	General
Dimensions:										
Stages of disruptions	Y	N	Y	Y	N	N	Y	N	Y	Y
Different hazards and their risk values	Y	N	N	Y	N	N	N	N	N	N
Subsystems of supply chains	Y	Y	N	Y	N	Y	N	N	N	N
Categories of performance metrics:										
Performance of discerning possible disruptions	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Performance of fulfilling customer requirements	Y	Y	Y	Y	Y	Y	Y	Y	N	Y
Efficiency of completing supply chain processes	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Efficiency of recovery to normality	Y	N	Y	Y	N	N	Y	N	Y	Y
Performance of production and inventory	Y	N	Y	Y	Y	N	Y	Y	Y	Y
Performance of relationship management	Y	Y	Y	Y	Y	N	Y	Y	Y	Y
Financial performance/cost-effectiveness	Y	N	Y	Y	N	N	Y	N	N	Y
Performance of overseeing the supply chain situation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Damage of disruptions (vulnerability)	Y	N	N	N	N	N	Y	N	N	Y
Efficiency of responding to disruptions	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Reconstruction of the supply chain	Y	N	Y	Y	N	N	N	N	N	Y

7.2. Limitations and future directions

The main limitation of the proposed framework is its theoretical and conceptual nature. The reactive and proactive resilience capabilities may vary depending on the objectives and operations of hydrogen organisations. While the framework may be applied to other supply chains, it requires further evidence. Additionally, quantifying resilience as a fuzzy concept needs the design of flexible and context-dependent metrics [188]. Such an approach can result in significant differences in objectives, reflecting the wide range of definitions for resilience. Simulations can test the framework under various hypothetical scenarios. By adding appropriate application backgrounds to the framework, the methodology provided in this research may apply to SCR evaluations in broader contexts.

It is important to note that this work discusses HSC resilience in a positive context. The hydrogen economy holds great potential as a transformative energy solution, while environmental and technical constraints should be addressed to ensure its sustainability and resilience. Environmentally, hydrogen production is constrained by issues such as high energy and water demands, along with hydrogen leakage. Leakage can increase atmospheric water vapour, disrupt stratospheric chemistry, delay ozone recovery, and contribute to climate shifts, impacting ecosystems and human life [5]. Technically, large-scale hydrogen deployment faces barriers, including high costs, scalability limitations, and inefficiencies in storage and distribution. Although biomass gasification has lower emissions compared to wind-driven electrolysis, it is hindered by operational and infrastructure challenges [201]. Market volatility and pricing fluctuations further undermine economic feasibility, disproportionately affecting vulnerable populations. Addressing these issues requires integrated socio-technical solutions, including improved regulatory frameworks, support for renewable energy communities, and greater public participation in the energy transition [202]. These measures are vital to fostering a resilient hydrogen economy that promotes environmental sustainability and social equity.

This systematic literature review reveals limited research on the organisational governance of hydrogen companies. Beyond the gaps outlined in section 6, this review suggests using supply chain mapping to explore the link between SCR and the maturity of the hydrogen business ecosystem. Studies can investigate the trade-offs between sustainability and resilience in HSCs [26], conflicts between centralised and decentralised system design [169], and balancing renewable energy integration with supply chain complexity [132]. Finally, future research should empirically determine the weights of HSC elements to construct appropriate HSC resilience measurements.

CRediT authorship contribution statement

Liang Kong: Writing – original draft, Visualization, Formal analysis. **S.C. Lenny Koh:** Supervision, Conceptualization. **Vania Sena:** Supervision, Methodology. **Darren Robinson:** Writing – review & editing, Supervision. **Matthew Wood:** Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the funding from Research England and support from the South Yorkshire Sustainability Centre, the Energy Institute, and the Faculty of Social Sciences at the University of Sheffield, UK.

References

[1] Xu S, Govindan K, Wang W, Yang W. Supply chain management under cap-and-trade regulation: a literature review and research opportunities. Int J Prod Econ 2024;271:109199. https://doi.org/10.1016/j.ijpe.2024.109199.
[2] Dixon J, Bell K, Brush S. Which way to net zero? A comparative analysis of seven UK 2050 decarbonisation pathways. Renew Sustain Energy Transit 2022;2:100016. https://doi.org/10.1016/j.rset.2021.100016.
[3] Choi W, Kang S. Greenhouse gas reduction and economic cost of technologies using green hydrogen in the steel industry. J Environ Manag 2023;335:117569. https://doi.org/10.1016/j.jenvman.2023.117569.
[4] Aydin MI, Karaca AE, Qureshy AMMI, Dincer I. A comparative review on clean hydrogen production from wastewaters. J Environ Manag 2021;279:111793. https://doi.org/10.1016/j.jenvman.2020.111793.
[5] Kyriakopoulos GL, Aravossis KG. Literature review of hydrogen energy systems and renewable energy sources. Energies 2023;16:7493. https://doi.org/10.3390/en16227493.
[6] Deng Y, Li S, Appels L, Dewil R, Zhang H, Baeyens J, Mikulcic H. Producing hydrogen by catalytic steam reforming of methanol using non-noble metal catalysts. J Environ Manag 2022;321:116019. https://doi.org/10.1016/j.jenvman.2022.116019.
[7] Soderholm P. The green economy transition: the challenges of technological change for sustainability. Sustain Earth 2020;1:1–11. https://doi.org/10.1186/s42055-020-00029-y.
[8] Kazancoglu I, Ozbiltekin-Pala M, Kumar Mangla S, Kazancoglu Y, Jabeen F. Role of flexibility, agility and responsiveness for sustainable supply chain resilience during COVID-19. J Clean Prod 2022;362:132431. https://doi.org/10.1016/j.jclepro.2022.132431.
[9] Raj A, Mukherjee AA, de Sousa Jabbour ABL, Srivastava SK. Supply chain management during and post-COVID-19 pandemic: mitigation strategies and practical lessons learned. J Bus Res 2022;142:1125–39. https://doi.org/10.1016/j.jbusres.2022.01.037.
[10] Fredershausen S, Lechte H, Willnat M, Witt T, Harnischmacher C, Lembcke TB, Kolbe L. Towards an understanding of hydrogen supply chains: a structured literature review regarding sustainability evaluation. Sustain 2021;21:11652. https://doi.org/10.3390/su132111652.
[11] Markert F, Marangon A, Carcassi M, Duijm NJ. Risk and sustainability analysis of complex hydrogen infrastructures. Int J Hydrog Energy 2017;11:7698–706. https://doi.org/10.1016/j.ijhydene.2016.06.058.
[12] Ali A, Mahfouz A, Arisha A. Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. Supply Chain Manag 2017;1:16–39. https://doi.org/10.1108/SCM-06-2016-0197.
[13] Ponomarov SY, Holcomb MC. Understanding the concept of supply chain resilience. Int J Logist Manag 2009;20:124–43. https://doi.org/10.1108/09574090910954873.
[14] Jasiūnas J, Lund PD, Mikkola J. Energy system resilience – a review. Renew Sustain Energy Rev 2021;150:111476. https://doi.org/10.1016/j.rser.2021.111476.
[15] Dubey R, Gunasekaran A, Childe SJ, Papadopoulos T, Blome C, Luo Z. Antecedents of resilient supply chains: an empirical study. IEEE Trans Eng Manag 2019;1:8–19. https://doi.org/10.1109/TEM.2017.2723042.
[16] Lebrouhi BE, Djoupo JJ, Lamrani B, Benabdelaziz K, Kousksou T. Global hydrogen development—a technological and geopolitical overview. Int J Hydrog Energy 2022;47:7016–48. https://doi.org/10.1016/j.ijhydene.2021.12.076.
[17] Emenike SN, Falcone G. A review on energy supply chain resilience through optimization. Renew Sust Energ Rev 2020;134:110088. https://doi.org/10.1016/j.rser.2020.110088.
[18] Hmouda AM, Orzes G, Sauer PC. Sustainable supply chain management in energy production: a literature review. Renew Sustain Energy Rev 2024;191:114085. https://doi.org/10.1016/j.rser.2023.114085.
[19] Kiehbadroudinezhad M, Hosseinzadeh-Bandbafha H, Rosen MA. The role of energy security and resilience in the sustainability of green microgrids: paving the way to sustainable and clean production. Sustain Energy Technol Assess 2023;60:103485. https://doi.org/10.1016/j.seta.2023.103485.
[20] Torres-Rivera AD, Mc Namara Valdes AJ de J, Florencio Da Silva R. The resilience of the renewable energy electromobility supply chain: review and trends. Sustain 2023;15:10838. https://doi.org/10.3390/su151410838.
[21] Sgarbossa F, Arena S, Tang O, Peron M. Renewable hydrogen supply chains: a planning matrix and an agenda for future research. Int J Prod Econ 2023;255:108674. https://doi.org/10.1016/j.ijpe.2022.108674.
[22] Pierre C, Catherine AP, Sylvain B, Catherine MV. Beyond the "bottom-up" and "top-down" controversy: a methodological inquiry into hybrid modeling methods for hydrogen supply chains. Int J Prod Econ 2024;268:109091. https://doi.org/10.1016/j.ijpe.2023.109091.
[23] Sauer PC, Seuring S. How to conduct systematic literature reviews in management research: a guide in 6 steps and 14 decisions. Rev Manag Sci 2023;17:1899–933. https://doi.org/10.1007/s11846-023-00668-3.
[24] Kamalahmadi M, Parast MM. A review of the literature on the principles of enterprise and supply chain resilience: major findings and directions for future research. Int J Prod Econ 2016;171:116–33. https://doi.org/10.1016/j.ijpe.2015.10.023.
[25] Li H, Yazdi M. Integration of the bayesian network approach and interval type-2 fuzzy sets for developing sustainable hydrogen storage technology in large metropolitan areas. In: advanced decision-making methods and applications in

system safety and reliability problems. Stud Syst, Decis Control 2022;211:69–85. https://doi.org/10.1007/978-3-031-07430-1_5. Springer, Cham.
[26] Yazdi M, Zarei E, Pirbalouti RG, Li H. A comprehensive resilience assessment framework for hydrogen energy infrastructure development. Int J Hydrog Energy 2023;51:928–47. https://doi.org/10.1016/j.ijhydene.2023.06.271.
[27] Chowdhury MMH, Quaddus M. Supply chain resilience: conceptualization and scale development using dynamic capability theory. Int J Prod Econ 2017;188: 185–204. https://doi.org/10.1016/j.ijpe.2017.03.020.
[28] Pettit TJ, Fiksel J, Croxton KL. Ensuring supply chain resilience: development of a conceptual framework. J Bus Logist 2010;31:1–21. https://doi.org/10.1002/j.2158-1592.2010.tb00125.x.
[29] Vilko JP, Hallikas JM. Risk assessment in multimodal supply chains. Int J Prod Econ 2012;140:586–95. https://doi.org/10.1016/j.ijpe.2011.09.010.
[30] Li Y, Zobel CW. Exploring supply chain network resilience in the presence of the ripple effect. Int J Prod Econ 2020;228:107693. https://doi.org/10.1016/j.ijpe.2020.107693.
[31] Almaraz SDL, Rácz V, Azzaro-Pantel C, Szántó ZO. Multiobjective and social cost-benefit optimisation for a sustainable hydrogen supply chain: application to Hungary. Appl Energy 2022;325:119882. https://doi.org/10.1016/j.apenergy.2022.119882.
[32] Nunes P, Oliveira F, Hamacher S, Almansoori A. Design of a hydrogen supply chain with uncertainty. Int J Hydrog Energy 2015;46:16408–18. https://doi.org/10.1016/j.ijhydene.2015.10.015.
[33] Garcia-Navarro J, Isaacs MA, Favaro M, Ren D, Ong WJ, Grätzel M, Jiménez-Calvo P. Updates on hydrogen value chain: a strategic roadmap. Global Chall 2023;8:2300073. https://doi.org/10.1002/gch2.202300073.
[34] Azadnia AH, McDaid C, Andwari AM, Hosseini SE. Green hydrogen supply chain risk analysis: a European hard-to-abate sectors perspective. Renew Sustain Energy Rev 2023;182:113371. https://doi.org/10.1016/j.rser.2023.113371.
[35] Mothafar NA, Zhang J, Alsoffary A, Aslam MA, AL-Barakani A, Alhady OS, Esangbedo CO, Kone SD. Effecting the adoption of blockchain technology enablers in supply chain sustainability with green hydrogen acceptance role as a mediator: evidence from complex decarbonization industries in the United Arab Emirates. Int J Hydrog Energy 2024;84:1085–100. https://doi.org/10.1016/j.ijhydene.2024.08.243.
[36] Tokimatsu K, Wachtmeister H, McLellan B, Davidsson S, Murakami S, Höök M. Energy modeling approach to the global energy-mineral nexus: a first look at metal requirements and the 2°C target. Appl Energy 2017;207:494–509. https://doi.org/10.1016/j.apenergy.2018.05.047.
[37] Fazeli R, Beck FJ, Stocks M. Recognizing the role of uncertainties in the transition to renewable hydrogen. Int J Hydrog Energy 2022;47:27896–910. https://doi.org/10.1016/j.ijhydene.2022.06.122.
[38] Carlson JT, Trencher G. A framework for considering decarbonisation risks emerging from low-carbon hydrogen supply chains. Energy Res Soc Sci 2024;116: 103685. https://doi.org/10.1016/j.erss.2024.103685.
[39] Martins FP, De-León Almaraz S, Botelho Junior AB, Azzaro-Pantel C, Parikh P. Hydrogen and the sustainable development goals: synergies and trade-offs. Renew Sustain Energy Rev 2024;204:114796. https://doi.org/10.1016/j.rser.2024.114796.
[40] Choi T, Dooley K, Rungtusanatham M. Supply networks and complex adaptive systems: control versus emergence. J Oper Manag 2001;19:351–66. https://doi.org/10.1016/S0272-6963(00)00068-1.
[41] Day JM. Fostering emergent resilience: the complex adaptive supply network of disaster relief. Int J Prod Res 2014;7:1970–8. https://doi.org/10.1080/00207543.2013.787496.
[42] Tukamuhabwa BR, Stevenson M, Busby J, Zorzini M. Supply chain resilience: definition, review and theoretical foundations for further study. Int J Prod Res 2015;53:5592–623. https://doi.org/10.1080/00207543.2015.1037934.
[43] Dakos V, Carpente SR, van Nes EH, Scheffer M. Resilience indicators: prospects and limitations for early warnings of regime shifts. Philos Trans R Soc Lond B Biol Sci 2015;370:1–10. https://doi.org/10.1098/rstb.2013.0263.
[44] Quinlan AE, Berbés-Blázquez M, Haider LJ, Peterson GD. Measuring and assessing resilience: broadening understanding through multiple disciplinary perspectives. J Appl Ecol 2016;3:677–87. https://doi.org/10.1111/1365-2664.12550.
[45] Shi Y, Zhai G, Xu L, Zhou S, Lu Y, Liu H, Huang W. Assessment methods of urban system resilience: from the perspective of complex adaptive system theory. Cities 2021;112:103141. https://doi.org/10.1016/j.cities.2021.103141.
[46] Nair A, Reed-Tsochas F. Revisiting the complex adaptive systems paradigm: leading perspectives for researching operations and supply chain management issues. J Oper Manag 2019;60:80–92. https://doi.org/10.1002/joom.1022.
[47] Bianconi G, Arenas A, Biamonte J, Carr LD, Kahng B, Kertesz J, Kurths J, Lü L, Masoller C, Motter AE, Perc M, Radicchi F, Ramaswamy R, Rodrigues FA, Sales-Pardo M, San Miguel M, Thurner S, Yasseri T. Complex systems in the spotlight: next steps after the 2021 Nobel Prize in Physics. J Phys Complex 2023;1:10201. https://doi.org/10.1088/2632-072X/ac7f75.
[48] Iftikhar A, Purvis L, Giannoccaro I, Wang Y. The impact of supply chain complexities on supply chain resilience: the mediating effect of big data analytics. Prod Plan Control 2022;33:1–21. https://doi.org/10.1080/09537287.2022.2032450.
[49] Yan F, Yin S, Chen L, Jia F. Complexity in a platform-based servitization: a complex adaptability theory perspective. Int J Logist Res Appl 2022;27: 1092–111. https://doi.org/10.1080/13675567.2022.2112159.
[50] Yaroson EV, Breen L, Hou J, Sowter J. Advancing the understanding of pharmaceutical supply chain resilience using complex adaptive system (CAS) theory. Supply Chain Manag 2021;3:323–40. https://doi.org/10.1108/SCM-05-2019-0184.
[51] Han Y, Chong WK, Li D. A systematic literature review of the capabilities and performance metrics of supply chain resilience. Int J Prod Res 2020;58:4541–66. https://doi.org/10.1080/00207543.2020.1785034.
[52] Singh CS, Soni G, Badhotiya GK. Performance indicators for supply chain resilience: review and conceptual framework. J Ind Eng Int Suppl 2019;1:105–17. https://doi.org/10.1007/s40092-019-00322-2.
[53] Seuring S, Gold S. Conducting content-analysis based literature reviews in Supply Chain Manag. Supply Chain Manag 2012;5:544–55. https://doi.org/10.1108/13598541211258609.
[54] Pournader M, Shi Y, Seuring S, Koh SCL. Blockchain applications in supply chains, transport and logistics: a systematic review of the literature. Int J Prod Res 2020; 58:2063–81. https://doi.org/10.1080/00207543.2019.1650976.
[55] Durach CF, Kembro J, Wieland A. A new paradigm for systematic literature reviews in supply chain management. J Supply Chain Manag 2017;53:67–85. https://doi.org/10.1111/jscm.12145.
[56] Jabareen Y. Building a conceptual framework: philosophy, definitions, and procedure. Int J Qual Methods 2009;4:49–62. https://doi.org/10.1177/160940690900800406.
[57] Burger A, Kennedy WG, Crooks A. Organizing theories for disasters into a complex adaptive system framework. Urban Sci 2021;5:61. https://doi.org/10.3390/urbansci5030061.
[58] Gioia DA, Corley KG, Hamilton AL. Seeking qualitative rigor in inductive research. Organ Res Methods 2013;16:15–31. https://doi.org/10.1177/1094428112452151.
[59] Snyder H. Literature review as a research methodology: an overview and guidelines. J Bus Res 2019;104:333–9. https://doi.org/10.1016/j.jbusres.2019.07.039.
[60] El Baz J, Ruel S. Can supply chain risk management practices mitigate the disruption impacts on supply chains' resilience and robustness? Evidence from an empirical survey in a COVID-19 outbreak era. Int J Prod Econ 2021;233:107972. https://doi.org/10.1016/j.ijpe.2020.107972.
[61] Tao Y, Qiu J, Lai S, Sun X. Coordinated planning of electricity and hydrogen networks with hydrogen supply chain for fuel cell electric vehicles. IEEE Trans Sustain Energy 2023;14:1010–23. https://doi.org/10.1109/TSTE.2022.3232596.
[62] Kim S, Park J, Chung W, Adams D, Lee JH. Techno-economic analysis for design and management of international green hydrogen supply chain under uncertainty: an integrated temporal planning approach. Energy Convers Manag 2024;301:118010. https://doi.org/10.1016/j.enconman.2023.118010.
[63] Afgan N, Veziroglu A. Sustainable resilience of hydrogen energy system. Int J Hydrog Energy 2012;7:5461–7. https://doi.org/10.1016/j.ijhydene.2011.04.201.
[64] Schlund D, Schulte S, Sprenger T. The who's who of a hydrogen market ramp-up: a stakeholder analysis for Germany. Renew Sust Energ Rev 2022;154:111810. https://doi.org/10.1016/j.rser.2021.111810.
[65] Mukelabai MD, Wijayantha KGU, Blanchard RE. Hydrogen technology adoption analysis in Africa using a Doughnut-PESTLE hydrogen model (DPHM). Int J Hydrog Energy 2022;74:31521–40. https://doi.org/10.1016/j.ijhydene.2022.07.076.
[66] Meredith J. Theory building through conceptual methods. Int J Oper Prod Manag 1993;13:3–11. https://doi.org/10.1108/01443579310028120.
[67] Kyriakopoulos GL, Arabatzis G. Electrical energy storage systems in electricity generation: energy policies, innovative technologies, and regulatory regimes. Renew Sustain Energy Rev 2016;56:1044–67. https://doi.org/10.1016/j.rser.2015.12.046.
[68] Gils HC, Gardian H, Schmugge J. Interaction of hydrogen infrastructures with other sector coupling options towards a zero-emission energy system in Germany. Renew Energy 2021;180:140–56. https://doi.org/10.1016/j.renene.2021.08.016.
[69] Zhao L, Yang G, Wang W, Chen Y, Huang JP, Ohashi H, Stanley HE. Herd behaviour in a complex adaptive system. Proc Natl Acad Sci USA 2011;37: 15058–63. https://doi.org/10.1073/pnas.1105239108.
[70] Ma X, Zhou H, Li Z. Toward the resilient design of interdependencies between hydrogen refuelling and power systems. IEEE Trans Ind Appl 2022;2:2792–802. https://doi.org/10.1109/TIA.2021.3122401.
[71] Bolat P, Thiel C. Hydrogen supply chain architecture for bottom-up energy systems models. Part 1: developing pathways. Int J Hydrog Energy 2014;17: 8881–97. https://doi.org/10.1016/j.ijhydene.2014.03.176.
[72] Groth KM, Hecht ES. HyRAM: a methodology and toolkit for quantitative risk assessment of hydrogen systems. Int J Hydrog Energy 2017;42:7485–93. https://doi.org/10.1016/j.ijhydene.2016.07.002.
[73] Randall TR, Morgan RM, Morton AR. Efficient versus responsive supply chain choice: an empirical examination of influential factors. J Prod Innovat Manag 2003;6:430–43. https://doi.org/10.1111/1540-5885.00041.
[74] Obayi R, Koh SCL, Oglethorpe D, Ebrahimi SM. Improving retail supply flexibility using buyer-supplier relational capabilities. Int J Oper Prod Manag 2017;37(3): 343–62. https://doi.org/10.1108/IJOPM-12-2015-0775.
[75] Ebrahimi S, Koh SCL, Genovese A, Kumar N. Structure-integration relationships in oil and gas supply chains. Int J Oper Prod Manag 2017;2:424–45. https://doi.org/10.1108/IJOPM-02-2016-0089.
[76] Caliendo C, Genovese G. Quantitative risk assessment on the transport of dangerous goods vehicles through unidirectional road tunnels: an evaluation of the risk of transporting hydrogen. Risk Anal 2021;9:1522–39. https://doi.org/10.1111/risa.13653.
[77] Ilbahar E, Çolak M, Karasan A, Kaya I. A combined methodology based on Z-fuzzy numbers for sustainability assessment of hydrogen energy storage systems. Int J

Hydrog Energy 2022;47:15528–46. https://doi.org/10.1016/j.ijhydene.2022.01.010.
[78] Kuckshinrichs W, Ketelaer T, Koj JC. Economic analysis of improved alkaline water electrolysis. Front Energy Res 2017;5:1. https://doi.org/10.3389/fenrg.2017.00001.
[79] Wu Y, Chu H, Xu C. Risk assessment of wind-photovoltaic-hydrogen storage projects using an improved fuzzy synthetic evaluation approach based on cloud model: a case study in China. J Energy Storage 2021;38:102580. https://doi.org/10.1016/j.est.2021.102580.
[80] Viana FFCL, Alencar MH, Ferreira RJP, De Almeida AT. Multidimensional risk assessment and categorization of hydrogen pipelines. Int J Hydrogen Energy 2022;42:18424–40. https://doi.org/10.1016/j.ijhydene.2022.04.057.
[81] Brusset X, Teller C. Supply chain capabilities, risks, and resilience. Int J Prod Econ 2017;184:59–68. https://doi.org/10.1016/j.ijpe.2016.09.008.
[82] Katsaliaki K, Galetsi P, Kumar S. Supply chain disruptions and resilience: a major review and future research agenda. Ann Oper Res 2022;1:965–1002. https://doi.org/10.1007/s10479-020-03912-1.
[83] Mohammadfam I, Zarei E. Safety risk modeling and major accidents analysis of hydrogen and natural gas releases: a comprehensive risk analysis framework. Int J Hydrog Energy 2015;39:13653–63. https://doi.org/10.1016/j.ijhydene.2015.07.117.
[84] Sakamoto J, Nakayama J, Nakarai T, Kasai N, Shibutani T, Miyake A. Effect of gasoline pool fire on liquid hydrogen storage tank in hybrid hydrogen–gasoline fuelling station. Int J Hydrog Energy 2016;41:2096–104. https://doi.org/10.1016/j.ijhydene.2015.11.039.
[85] Hadef H, Negrou B, Ayuso TG, Djebabra M, Ramadan M. Preliminary hazard identification for risk assessment on a complex system for hydrogen production. Int J Hydrog Energy 2020;45:11855–65. https://doi.org/10.1016/j.ijhydene.2019.10.162.
[86] Hansen OR. Hydrogen infrastructure—efficient risk assessment and design optimization approach to ensure safe and practical solutions. Process Saf Environ Protect 2020;143:164–76. https://doi.org/10.1016/j.psep.2020.06.028.
[87] Li X, Han Z, Zhang R, Zhang Y, Zhang L. Risk assessment of hydrogen generation unit considering dependencies using integrated DEMATEL and TOPSIS approach. Int J Hydrog Energy 2020;53:29630–42. https://doi.org/10.1016/j.ijhydene.2020.07.243.
[88] Mouli-Castillo J, Haszeldine SR, Kinsella K, Wheeldon M, McIntosh A. A quantitative risk assessment of a domestic property connected to a hydrogen distribution network. Int J Hydrog Energy 2021;29:16217–31. https://doi.org/10.1016/j.ijhydene.2021.02.114.
[89] Yoo B-H, Wilailak S, Bae S-H, Gye H-R, Lee C-J. Comparative risk assessment of liquefied and gaseous hydrogen refueling stations. Int J Hydrog Energy 2021;71:35511–24. https://doi.org/10.1016/j.ijhydene.2021.08.073.
[90] Kumar S, Arzaghi E, Baalisampang T, Garaniya V, Abbassi R. Insights into decision-making for offshore green hydrogen infrastructure developments. Process Saf Environ Protect 2023;174:805–17. https://doi.org/10.1016/j.psep.2023.04.042.
[91] Zarei E, Khan F, Yazdi M. A dynamic risk model to analyze hydrogen infrastructure. Int J Hydrog Energy 2021;46:4626–43. https://doi.org/10.1016/j.ijhydene.2020.10.191.
[92] Li W, Lv H, Zhang L, He P, Zhang C. Reliability analysis and optimization design of hydrogen storage composite pressure vessel with hybrid random-fuzzy uncertainties. J Reinforc Plast Compos 2023;0. https://doi.org/10.1177/07316844231220707.
[93] Sun D, Guo D, Xie D. Using multicriteria decision making to evaluate the risk of hydrogen energy storage and transportation in cities. Sustain 2023;2:1088. https://doi.org/10.3390/su15021088.
[94] Zhang J, Lang X, Jing Y, Kang J, You Q, Shang Z, Shi M, Dai H. Vulnerability assessment of hydrogen stations based on cloud center of gravity theory. Int J Hydrog Energy 2023;90:35407–18. https://doi.org/10.1016/j.ijhydene.2023.05.295.
[95] González EL, Llerena FI, Pérez MS, Iglesias FR, Macho JG. Energy evaluation of a solar hydrogen storage facility: comparison with other electrical energy storage technologies. Int J Hydrog Energy 2015;40:5518–25. https://doi.org/10.1016/j.ijhydene.2015.01.181.
[96] Alencar MH, de Almeida AT. Assigning priorities to actions in a pipeline transporting hydrogen based on a multicriteria decision model. Int J Hydrog Energy 2010;8:3610–9. https://doi.org/10.1016/j.ijhydene.2010.01.122.
[97] LaChance J, Tchouvelev A, Engebo A. Development of uniform harm criteria for use in quantitative risk analysis of the hydrogen infrastructure. Int J Hydrog Energy 2011;36:2381–8. https://doi.org/10.1016/j.ijhydene.2010.03.139.
[98] Kim E, Park J, Cho JH, Moon I. Simulation of hydrogen leak and explosion for the safety design of hydrogen fuelling station in Korea. Int J Hydrog Energy 2013;38:1737–43. https://doi.org/10.1016/j.ijhydene.2012.08.079.
[99] Dadashzadeh M, Ahmad A, Khan F. Dispersion modelling and analysis of hydrogen fuel gas released in an enclosed area: a CFD-based approach. Fuel 2016;184:192–201. https://doi.org/10.1016/j.fuel.2016.07.008.
[100] Nakayama J, Sakamoto J, Kasai N, Shibutani T, Miyake A. Preliminary hazard identification for qualitative risk assessment on a hybrid gasoline-hydrogen fuelling station with an on-site hydrogen production system using organic chemical hydride. Int J Hydrog Energy 2016;41:7518–25. https://doi.org/10.1016/j.ijhydene.2016.03.143.
[101] Huang Y, Ma G. A grid-based risk screening method for fire and explosion events of hydrogen refuelling stations. Int J Hydrog Energy 2018;43:442–54. https://doi.org/10.1016/j.ijhydene.2017.10.153.
[102] Gye H-R, Seo S-K, Bach Q-V, Ha D, Lee C-J. Quantitative risk assessment of an urban hydrogen refueling station. Int J Hydrog Energy 2019;44:1288–98. https://doi.org/10.1016/j.ijhydene.2018.11.035.
[103] Tolias IC, Giannissi SG, Venetsanos AG, Keenan J, Shentsov V, Makarov D, et al. Best practice guidelines in numerical simulations and CFD benchmarking for hydrogen safety applications. Int J Hydrog Energy 2019;44:9050–62. https://doi.org/10.1016/j.ijhydene.2018.06.005.
[104] Aarskog FG, Hansen OR, Strømgren T, Ulleberg Ø. Concept risk assessment of a hydrogen driven high speed passenger ferry. Int J Hydrog Energy 2020;2:1359–72. https://doi.org/10.1016/j.ijhydene.2019.05.128.
[105] Russo P, de Marco A, Parisi F. Assessment of the damage from hydrogen pipeline explosions on people and buildings. Energies 2020;13:5051. https://doi.org/10.3390/en13195051.
[106] Xing Y, Wu J, Bai Y, Cai J, Zhu X. All-process risk modelling of typical accidents in urban hydrogen refueling stations. Process Saf Environ Protect 2022;166:414–29. https://doi.org/10.1016/j.psep.2022.08.047.
[107] Casado RSGR, Alencar MH, de Almeida AT. Portfolio-based decision model for enhancing the mitigation of multidimensional risks in hydrogen pipeline sections. Process Saf Environ Protect 2023;175:700–14. https://doi.org/10.1016/j.psep.2023.05.051.
[108] Yu X, Kong D, He X, Ping P. Risk analysis of fire and explosion of hydrogen-gasoline hybrid refueling station based on accident risk assessment method for industrial system. Fire 2023;5:181. https://doi.org/10.3390/fire6050181.
[109] Duan Y, Zhao J, Chen J, Bai G. A risk matrix analysis method based on potential risk influence: a case study on cryogenic liquid hydrogen filling system. Process Saf Environ Protect 2016;102:277–87. https://doi.org/10.1016/j.psep.2016.03.022.
[110] Gardner LB, Ryland DK, Suppiah S. Development of a hydrogen management concept for the Canadian supercritical water-cooled reactor. CNL Nucl Rev 2017;6:1–8. https://doi.org/10.12943/CNR.2017.00004.
[111] Acar C, Dincer I. Review and evaluation of hydrogen production options for better environment. J Clean Prod 2019:835–49. https://doi.org/10.1016/j.jclepro.2019.02.046.
[112] Chang Y, Zhang C, Shi J, Li J, Zhang S, Chen G. Dynamic Bayesian network-based approach for risk analysis of hydrogen generation unit leakage. Int J Hydrog Energy 2019;48:26665–78. https://doi.org/10.1016/j.ijhydene.2019.08.065.
[113] Shi J, Chang B, Khan F, Chang Y, Zhu Y, Chen G, Zhang C. Stochastic explosion risk analysis of hydrogen production facilities. Int J Hydrog Energy 2020;24:13535–50. https://doi.org/10.1016/j.ijhydene.2020.03.040.
[114] Uhrig F, Kadar J, Müller K. Reliability of liquid organic hydrogen carrier-based energy storage in a mobility application. Energy Sci Eng 2020;6:2044–53. https://doi.org/10.1002/ese3.646.
[115] Correa-Jullian C, Groth KM. Data requirements for improving the quantitative risk assessment of liquid hydrogen storage systems. Int J Hydrog Energy 2022;6:4222–35. https://doi.org/10.1016/j.ijhydene.2021.10.266.
[116] Zhao H, Du H, Zhang T, Wang H. Thermodynamic performance study of hydrogen–oxygen combined cycle with high-pressure proton exchange membrane electrolysis cell for hydrogen energy storage. Energy Convers Manag 2022;268:116019. https://doi.org/10.1016/j.enconman.2022.116019.
[117] Almeida P de S, de Menezes CA, Augusto IMG, Paulinetti AP, Lovato G, Rodrigues JAD, Silva EL. Integrated production of hydrogen and methane in a dairy biorefinery using anaerobic digestion: scale-up, economic and risk analyses. J Environ Manag 2023;348:119215. https://doi.org/10.1016/j.jenvman.2023.119215.
[118] Pankhedkar N, Gudi R, Biswas P. Polygeneration of hydrogen and power using chemical looping water splitting with dual loops of oxygen carrier. Ind Eng Chem Res 2023;62:2768–76. https://doi.org/10.1021/acs.iecr.2c02900.
[119] Pirbalouti RG, Dehkordi MK, Mohammadpour J, Zarei E, Yazdi M. An advanced framework for leakage risk assessment of hydrogen refueling stations using interval-valued spherical fuzzy sets (IV-SFS). Int J Hydrog Energy 2023;54:20827–42. https://doi.org/10.1016/j.ijhydene.2023.03.028.
[120] Wang S, Hui H, Zhai J. Short-term reliability assessment of integrated power-gas systems with hydrogen injections using universal generating function. IEEE Trans Ind Appl 2023;5:5760–73. https://doi.org/10.1109/TIA.2023.3286821.
[121] Wu T, Wang J. Reliability evaluation for integrated electricity-gas systems considering hydrogen. IEEE Trans Sustain Energy 2023;14:920–34. https://doi.org/10.1109/TSTE.2022.3229896.
[122] Wang S, Hui H, Ding Y, Song Y. Long-term reliability evaluation of integrated electricity and gas systems considering distributed hydrogen injections. Appl Energy 2024;356:122374. https://doi.org/10.1016/j.apenergy.2023.122374.
[123] Al-Shanini A, Ahmad A, Khan F. Accident modelling and safety measure design of a hydrogen station. Int J Hydrog Energy 2014;35:20362–70. https://doi.org/10.1016/j.ijhydene.2014.05.044.
[124] Ma L-C, Castro-Dominguez B, Kazantzis NK, Ma Y-H. Economic performance evaluation of process system design flexibility options under uncertainty: the case of hydrogen production plants with integrated membrane technology and CO2 capture. Comput Chem Eng 2017;99:214–29. https://doi.org/10.1016/j.compchemeng.2017.01.020.
[125] Nakayama J, Misono H, Sakamoto J, Kasai N, Shibutani T, Miyake A. Simulation-based safety investigation of a hydrogen fuelling station with an on-site hydrogen production system involving methylcyclohexane. Int J Hydrog Energy 2017;42:10636–44. https://doi.org/10.1016/j.ijhydene.2016.11.072.
[126] Liu F, Sun Z, Ding M, Bian H. Research progress of hydrogen behaviors in nuclear power plant containment under severe accident conditions. Int J Hydrog Energy 2021;73:36477–502. https://doi.org/10.1016/j.ijhydene.2021.08.151.

[127] Yan Z, Sun Z, Liu P, Wang C, Li N. A comprehensive performance evaluation method for fuel cell commercial vehicles. In: 7th annual international conference on network and information systems for computers (ICNISC); 2021. p. 894–9. https://doi.org/10.1109/ICNISC54316.2021.00168. Guiyang, China.
[128] Yazdi M, Moradi R, Pirbalouti RG, Zarei E, Li H. Enabling safe and sustainable hydrogen mobility: circular economy-driven management of hydrogen vehicle safety. Process 2023;9:2730. https://doi.org/10.3390/pr11092730.
[129] Yuvaraj T, Suresh TD, Ananthi Christy A, Babu TS, Nastasi B. Modelling and allocation of hydrogen-fuel-cell-based distributed generation to mitigate electric vehicle charging station impact and reliability analysis on electrical distribution systems. Energies 2023;19:6869. https://doi.org/10.3390/en16196869.
[130] Zhang J, Sun K, Li C, Yang H, Zhou B, Hou X, Ge R. MPC-based co-optimization of an integrated PV-EV-Hydrogen station to reduce network loss and meet EV charging demand. eTransport 2023;15:100209. https://doi.org/10.1016/j.etran.2022.100209.
[131] Cheekatamarla P. Performance analysis of hybrid power configurations: impact on primary energy intensity, carbon dioxide emissions, and life cycle costs. Int J Hydrog Energy 2020;58:34089–98. https://doi.org/10.1016/j.ijhydene.2020.09.269.
[132] Hashemifar SMA, Joorabian M, Javadi MS. Two-layer robust optimization framework for resilience enhancement of microgrids considering hydrogen and electrical energy storage systems. Int J Hydrog Energy 2022;79:33597–618. https://doi.org/10.1016/j.ijhydene.2022.07.255.
[133] Naughton J, Riaz S, Cantoni M, Zhang X-P, Mancarella P. Comprehensive optimization-based techno-economic assessment of hybrid renewable electricity-hydrogen virtual power plants. J Mod Power Syst Clean Energy 2023;2:553–66. https://doi.org/10.35833/MPCE.2022.000324.
[134] Zhang G, Guo J, Tan Y, Chen G, Zhou C, Li W, Xia L. Safety analysis and evaluation of hydrogen cylinder periodic inspection station. Energies 2022;18:6617. https://doi.org/10.3390/en15186617.
[135] Cao X, Cao T, Xu Z, Zeng B, Gao F, Guan X. Resilience constrained scheduling of mobile emergency resources in electricity-hydrogen distribution network. IEEE Trans Sustain Energy 2023;2:1269–84. https://doi.org/10.1109/TSTE.2022.3217514.
[136] Zheng Y, Huang C, You S, Zong Y. Economic evaluation of a power-to-hydrogen system providing frequency regulation reserves: a case study of Denmark. Int J Hydrog Energy 2023;67:26046–57. https://doi.org/10.1016/j.ijhydene.2023.03.253.
[137] Yazdi M, Zarei E, Pirbalouti RG, Li H. A comprehensive resilience assessment framework for hydrogen energy infrastructure development. Int J Hydrog Energy 2024;51:928–47. https://doi.org/10.1016/j.ijhydene.2023.06.271.
[138] Schnuelle C, Wassermann T, Fuhrlaender D, Zondervan E. Dynamic hydrogen production from PV and wind direct electricity supply – modelling and techno-economic assessment. Int J Hydrog Energy 2020;55:29938–52. https://doi.org/10.1016/j.ijhydene.2020.08.044.
[139] Gabbar HA. Resiliency analysis of hybrid energy systems within interconnected infrastructures. Energies 2021;14:7499. https://doi.org/10.3390/en14227499.
[140] Da Silva PR, Aragão ME, Trierweiler JO, Trierweiler LF. A systematic approach for flexible cost-efficient hydrogen network design for hydrogen management in refineries. Chem Eng Res Des 2021;172:53–70. https://doi.org/10.1016/j.cherd.2021.05.030.
[141] Qiu Y, Zhou S, Gu W, Ding S, Han G, Zhang K, Lv H. Multi-stage flexible planning of regional electricity-HCNG-integrated energy system considering gas pipeline retrofit and expansion. IET Renew Power Gener 2022;15:3339–67. https://doi.org/10.1049/rpg2.12586.
[142] Bartolucci L, Cordiner S, Mulone V, Pasquale S. Hydrogen based multi-energy systems: assessment of the marginal utility of increasing hydrogen penetration on system performances. Int J Hydrog Energy 2021;78:38588–602. https://doi.org/10.1016/j.ijhydene.2021.09.108.
[143] Chau K, Djire A, Vaddiraju S, Khan F. Process Risk Index (PRI) – a methodology to analyze the design and operational hazards in the processing facility. Process Saf Environ Protect 2022;165:623–32. https://doi.org/10.1016/j.psep.2022.07.049.
[144] Dadkhah A, Bozalakov D, De Kooning JDM, Vandevelde L. Techno-economic analysis and optimal operation of a hydrogen refuelling station providing frequency ancillary services. IEEE Trans Ind Appl 2022;4:5171–83. https://doi.org/10.1109/TIA.2022.3167377.
[145] Zhao H, Xiang Y, Shen Y, Guo Y, Xue P, Sun W, Cai H, Gu C, Liu J. Resilience assessment of hydrogen-integrated energy system for airport electrification. IEEE Trans Ind Appl 2022;2:2812–24. https://doi.org/10.1109/TIA.2021.3127481.
[146] Vasbinder P, de Vries A, Westerman W. Hydrogen infrastructure project risks in The Netherlands. Energies 2021;14:6009. https://doi.org/10.3390/en14196009.
[147] Skjold T, Siccama D, Hisken H, Brambilla A, Middha P, Groth KM, LaFleur AC. 3D risk management for hydrogen installations. Int J Hydrog Energy 2017;11:7721–30. https://doi.org/10.1016/j.ijhydene.2016.07.006.
[148] Farag HEZ, Al-Obaidi A, Khani H, El-Taweel N, El-Saadany EF, Zeineldin HH. Optimal operation management of distributed and centralized electrolysis-based hydrogen generation and storage systems. Elec Power Syst Res 2020;187:106476. https://doi.org/10.1016/j.epsr.2020.106476.
[149] Lee Y, Cho MH, Lee MC, Kim YJ. Evaluating hydrogen risk management policy PR: lessons learned from three hydrogen accidents in South Korea. Int J Hydrog Energy 2023;63:24536–47. https://doi.org/10.1016/j.ijhydene.2023.03.142.
[150] O'Donnell L, Maine E. Techno-economic analysis of hydrogen production using FBMR technology. In: 2012 proceedings of PICMET '12: technology management for emerging technologies. IEEE; 2012. p. 829–35. https://api.semanticscholar.org/CorpusID:24379387.
[151] Shi J, Chang Y, Khan F, Zhu Y, Chen G. Methodological improvements in the risk analysis of an urban hydrogen fueling station. J Clean Prod 2020;257:120545. https://doi.org/10.1016/j.jclepro.2020.120545.
[152] Qolipour M, Mostafaeipour A, Tousi OM. Techno-economic feasibility of a photovoltaic-wind power plant construction for electric and hydrogen production: a case study. Renew Sustain Energy Rev 2017;71:113–23. https://doi.org/10.1016/j.rser.2017.04.088.
[153] Cormos A-M, Cormos C-C. Techno-economic assessment of combined hydrogen & power co-generation with carbon capture: the case of coal gasification. Appl Therm Eng 2019;147:29–39. https://doi.org/10.1016/j.applthermaleng.2018.10.064.
[154] Kang L, Jiang Y, Liu Y. Impacts of synthesis schemes on economy and flexibility of hydrogen networks. Chem Eng Sci 2019;207:1159–74. https://doi.org/10.1016/j.ces.2019.07.041.
[155] Sun K, Li Z. Quantitative risk analysis of life safety and financial loss for road accidents of fuel cell vehicles. Int J Hydrog Energy 2019;44:8791–8. https://doi.org/10.1016/j.ijhydene.2018.10.065.
[156] Yukesh Kannah R, Kavitha S, Preethi Parthiba Karthikeyan O, Kumar G, Dai-Viet NV, Rajesh Banu J. Techno-economic assessment of various hydrogen production methods: a review. Bioresour Technol 2021;319:124175. https://doi.org/10.1016/j.biortech.2020.124175.
[157] Cormos C-C, Cormos A-M, Petrescu L, Dragan S. Techno-economic assessment of decarbonised biogas catalytic reforming for flexible hydrogen and power production. Appl Therm Eng 2022;207:118218. https://doi.org/10.1016/j.applthermaleng.2022.118218.
[158] Zhang T. Techno-economic analysis of a nuclear-wind hybrid system with hydrogen storage. J Energy Storage 2022;46:103807. https://doi.org/10.1016/j.est.2021.103807.
[159] Liu R, He G, Wang X, Mallapragada D, Zhao H, Shao-Horn Y, Jiang B. A cross-scale framework for evaluating flexibility values of battery and fuel cell electric vehicles. Nat Commun 2024;15:280. https://doi.org/10.1038/s41467-023-43884-x.
[160] El-Taweel NA, Khani H, Farag HE. Hydrogen storage optimal scheduling for fuel supply and capacity-based demand response program under dynamic hydrogen pricing. IEEE Trans Smart Grid 2018;4:4531–42. https://doi.org/10.1109/TSG.2018.2863247.
[161] Correa-Jullian C, Groth KM. Opportunities and data requirements for data-driven prognostics and health management in liquid hydrogen storage systems. Int J Hydrog Energy 2022;43:18748–62. https://doi.org/10.1016/j.ijhydene.2022.04.048.
[162] Han Z, Yuan S, Dong Y, Ma S, Bian Y, Mao X. Research on the flexibility margin of an electric–hydrogen coupling energy block based on model predictive control. Front Energy Res 2022;10:879244. https://doi.org/10.3389/fenrg.2022.879244.
[163] Sharifpour M, Ameli MT, Ameli H, Strbac G. A resilience-oriented approach for microgrid energy management with hydrogen integration during extreme events. Energies 2023;24:8099. https://doi.org/10.3390/en16248099.
[164] Valverde L, Ali D, Abdel-Wahab M, Guerra J, Hogg DF. A technical evaluation of Wind-Hydrogen (WH) demonstration projects in Europe. In: 4th international conference on power engineering, energy and electrical drives; 2013. p. 1098–104. https://doi.org/10.1109/PowerEng.2013.6635764.
[165] Sardashti Birjandi MR, Shahraki F, Razzaghi K. Hydrogen network retrofit via flexibility analysis: the steady-state flexibility index. Chem Eng Res Des 2017;117:83–94. https://doi.org/10.1016/j.cherd.2016.10.017.
[166] De Corato AM, Riaz S, Mancarella P. Assessing the flexibility of electricity-gas-hydrogen distribution systems with P2G units. In: 2021 IEEE PES innovative smart grid technologies - asia (ISGT Asia). IEEE; 2021. p. 1–5. https://doi.org/10.1109/ISGTAsia49270.2021.9715573.
[167] Yang F, Tian X, Tong X, Wang X. Adaptability assessment of hydrogen energy storage system based on proton exchange membrane fuel cell under the scenarios of peaking shaving and frequency regulation. In: 2021 4th asia conference on energy and electrical engineering (ACEEE). IEEE; 2021. p. 84–90. https://doi.org/10.1109/ACEEE51855.2021.9575144.
[168] Chau K, Djire A, Khan F. Review and analysis of the hydrogen production technologies from a safety perspective. Int J Hydrog Energy 2022;47:13990–4007. https://doi.org/10.1016/j.ijhydene.2022.02.127.
[169] Bigestans D, Cardin M-A, Kazantzis N. Economic performance evaluation of flexible centralised and decentralised blue hydrogen production systems design under uncertainty. Appl Energy 2023;121944. https://doi.org/10.1016/j.apenergy.2023.121944.
[170] Cai W, Mansouri SA, Rezaee Jordehi A, Tostado-Véliz M, Ahmarinejad A, Jurado F. Resilience of hydrogen fuel station-integrated power systems with high penetration of photovoltaics. J Energy Storage 2023;73:108909. https://doi.org/10.1016/j.est.2023.108909.
[171] Zheng W, Li J, Shao Z, Lei K, Li J, Xu Z. Optimal dispatch of hydrogen/electric vehicle charging station based on charging decision prediction. Int J Hydrog Energy 2023;69:26964–78. https://doi.org/10.1016/j.ijhydene.2023.03.375.
[172] Yin Y, Yang H, Duan P, Li L, Zio E, Liu C, Li Y. Improved quantitative risk assessment of a natural gas pipeline considering high-consequence areas. Reliab Eng Syst Saf 2022;225:108583. https://doi.org/10.1016/j.ress.2022.108583.
[173] Zio E. Critical infrastructures vulnerability and risk analysis. Eur J Futures Secur Res 2016;2:97–114. https://doi.org/10.1007/s41125-016-0004-2.
[174] Abedi A, Gaudard L, Romerio F. Review of major approaches to analyse vulnerability in power system. Reliab Eng Syst Saf 2019;183:153–72. https://doi.org/10.1016/j.ress.2018.11.019.

[175] Koh SCL, Suresh K, Ralph P, Saccone M. Quantifying organisational resilience: an integrated resource efficiency view. Int J Prod Res 2023;62:5737–56. https://doi.org/10.1080/00207543.2023.2296018.

[176] Teichmann FMJ, Wittmann C, Sergi BS. Operational resilience in light of the war in Ukraine: the disruptive effect of implementing economic sanctions on financial service providers. J Financ Crime 2023. https://doi.org/10.1108/JFC-01-2023-0005. ahead-of-print.

[177] Kantur D, Say AI. Measuring organisational resilience: a scale development. J Bus Econ Finance 2015;3:1–21. https://doi.org/10.17261/Pressacademia.2015313066.

[178] Fuerst MJ, Luetge C. The conception of organizational integrity: a derivation from the individual level using a virtue-based approach. Bus Ethics Environ Responsib 2023;1:25–33. https://doi.org/10.1111/beer.12401.

[179] Gil-Vilda F, Yagüe-Fabra JA, Sunyer A. From lean production to lean 4.0: a systematic literature review with a historical perspective. Appl Sci 2021;11:10318. https://doi.org/10.3390/app112110318.

[180] Sadollah A, Nasir M, Geem ZW. Sustainability and optimization: from conceptual fundamentals to applications. Sustain 2020;12:2027. https://doi.org/10.3390/su12052027.

[181] Ivanov D, Guo Z, Shen B, Chang QC. Analysis, optimization, and collaboration in digital manufacturing and supply chain systems. Int J Prod Econ 2023;269:109130. https://doi.org/10.1016/j.ijpe.2023.109130.

[182] Piercy N, Rich N. The relationship between lean operations and sustainable operations. Int J Oper Prod Manag 2015;35:282–315. https://doi.org/10.1108/IJOPM-03-2014-0143.

[183] Åhlström P, Danese P, Hines P, Netland TH, Powell D, Shah R, Thürer M, van Dun DH. Is lean a theory? Viewpoints and outlook. Int J Oper Prod Manag 2021;12:1852–78. https://doi.org/10.1108/IJOPM-06-2021-0408.

[184] Silva J da, Fernandes V, Limont M, Dziedzic M, Andreoli CV, Rauen WB. Water sustainability assessment from the perspective of sustainable development capitals: conceptual model and index based on literature review. J Environ Manag 2020:109750. https://doi.org/10.1016/j.jenvman.2019.109750.

[185] Huan N, Yamamoto T, Sato H, Sala R, Goncalves L. Perceptions to connections: a multidimensional investigation of hydrogen acceptance. Renew Sustain Energy Rev 2024;200:114612. https://doi.org/10.1016/j.rser.2024.114612.

[186] Gordon JA, Balta-Ozkan N, Nabavi SA. Price promises, trust deficits and energy justice: public perceptions of hydrogen homes. Renew Sustain Energy Rev 2023;188:113810. https://doi.org/10.1016/j.rser.2023.113810.

[187] Yu Y, Ma D, Wang Y. Structural resilience evolution and vulnerability assessment of semiconductor materials supply network in the global semiconductor industry. Int J Prod Econ 2024;270:109172. https://doi.org/10.1016/j.ijpe.2024.109172.

[188] Tang J, Han S, Wang J, He B, Peng J. A comparative analysis of performance-based resilience metrics via a quantitative-qualitative combined approach: are we measuring the same thing? Int J Disaster Risk Sci 2023;15:736–50. https://doi.org/10.1007/s13753-023-00519-5.

[189] Bode C, Wagner SM. Structural drivers of upstream supply chain complexity and the frequency of supply chain disruptions. J Oper Manag 2015;1:215–28. https://doi.org/10.1016/j.jom.2014.12.004.

[190] Lu G, Shang G. Impact of supply base structural complexity on financial performance: roles of visible and not-so-visible characteristics. J Oper Manag 2017;53–56:23–44. https://doi.org/10.1016/j.jom.2017.10.001.

[191] Ellis B, Herbert S. Complex adaptive systems (CAS): an overview of key elements, characteristics and application to management theory. J Innov Health Inform. 2010;1:33–7. https://doi.org/10.14236/jhi.v19i1.791.

[192] Shishodia A, Sharma R, Rajesh R, Munim ZH. Supply chain resilience: a review, conceptual framework and future research. Int J Logist Manag 2021;4:879–908. https://doi.org/10.1108/IJLM-03-2021-0169.

[193] Gunasekaran A, Subramanian N, Rahman S. Supply chain resilience: role of complexities and strategies. Int J Prod Res 2015;53:6809–19. https://doi.org/10.1080/00207543.2015.1093667.

[194] Juan SJ, Li EY, Hung WH. An integrated model of supply chain resilience and its impact on supply chain performance under disruption. Int J Logist Manag 2022;1:339–64. https://doi.org/10.1108/IJLM-03-2021-0174.

[195] Dubey R, Gunasekaran A, Childe SJ, Fosso Wamba S, Roubaud D, Foropon C. Empirical investigation of data analytics capability and organizational flexibility as complements to supply chain resilience. Int J Prod Res 2021;1:110–28. https://doi.org/10.1080/00207543.2019.1582820.

[196] Alaedini AH, Tourani HK, Saidi M. A review of waste-to-hydrogen conversion technologies for solid oxide fuel cell (SOFC) applications: aspect of gasification process and catalyst development. J Environ Manag 2023;329:117077. https://doi.org/10.1016/j.jenvman.2022.117077.

[197] Zhao J, Lee JY, Camenzind D, Wolcott M, Lewis K, Gillham O. Multi-component resilience assessment framework for a supply chain system. Sustain 2023;7:6197. https://doi.org/10.3390/su15076197.

[198] Bø E, Hovi IB, Pinchasik DR. COVID-19 disruptions and Norwegian food and pharmaceutical supply chains: insights into supply chain risk management, resilience, and reliability. Sustain Futures 2023;5:100102. https://doi.org/10.1016/j.sftr.2022.100102.

[199] Cheng Y, Elsayed EA, Huang Z. Systems resilience assessments: a review, framework and metrics. Int J Prod Res 2022;2:595–622. https://doi.org/10.1080/00207543.2021.1971789.

[200] Macdonald JR, Zobel CW, Melnyk SA, Griffis SE. Supply chain risk and resilience: theory building through structured experiments and simulation. Int J Prod Res 2018;12:4337–55. https://doi.org/10.1080/00207543.2017.142178.

[201] Kyriakopoulos GL. Should low carbon energy technologies be envisaged in the context of sustainable energy systems?. In: Low carbon energy technologies in sustainable energy systems. first ed. Academic Press; 2021. p. 357–89. https://doi.org/10.1016/B978-0-12-822897-5.00015-8.

[202] Kyriakopoulos GL. Energy communities overview: managerial policies, economic aspects, technologies, and models. J Risk Financ Manag 2022;15:521. https://doi.org/10.3390/jrfm15110521.