

# Hydrogen Supply Chains Downstream – A Systematic Analysis of The Western U.S.

Farzam Farahmand<sup>1</sup>, James King<sup>1</sup>, Davoud Ghahremanlou<sup>1</sup> & Mohammadreza Moghaddas Jafari<sup>2</sup>

<sup>1</sup>Faculty of Business Administration, Memorial University of Newfoundland, Canada

<sup>2</sup>Faculty of Science, Memorial University of Newfoundland, Canada

Correspondence: Farzam Farahmand, Faculty of Business Administration, Memorial University of Newfoundland, Canada. Tel: 1-709-864-2615. E-mail: farzamf@mun.ca

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## Abstract

This paper delves into the critical exploration of hydrogen supply chains downstream (HSCD) in the Western U.S., responding to the nation's prioritization of hydrogen as a clean alternative and its ambitious Hydrogen Program Plan for net-zero emissions and enhanced exports. We develop a conceptual model which is utilized to identify gaps in the existing 116 regional and global review papers published from March 2020, the beginning of the COVID-19 pandemic, to November 2023. This leads us to HSCD segments, decision levels, research properties, and sustainability as the necessary criteria to analyze 48 peer-reviewed original journal papers published about HSCD in the Western U.S. until November 2023. Accordingly, we offer future research directions and contribute to the development of effective strategies for a sustainable hydrogen-based future.

**Keywords:** hydrogen supply chain, downstream, decision levels, COVID-19, sustainability, systematic review, Western U.S

## 1. Introduction

The United States, responsible for 20% of the world's oil consumption, is prioritizing a shift towards hydrogen as a promising clean alternative to combat global warming. The U.S. launched its Hydrogen Program Plan, focusing on developing a robust hydrogen supply chain for net-zero emissions and enhanced hydrogen exports (U.S. Energy Information Administration, 2023). Notably, the Western U.S., with abundant natural resources like solar power for hydrogen production (refer to subplot (a) in Figure 1), holds significance in this transition. Canada, too, is exploring the use of existing natural gas pipelines to tap into the hydrogen market in the Western U.S. (Bloom et al., 2022). Investigating the downstream hydrogen supply chain, where both export and import occur, in the Western U.S. is crucial, aligning with the objectives of this research. To achieve our research objective, Section 2 outlines a conceptual structure for systematic analysis. This structure is then applied in Section 3 to review relevant literature and create a knowledge base. Section 4 systematically analyzes the literature, highlighting the need for further exploration into emission components, economic factors, and social dimensions. Section 5 proposes future perspectives for researchers, emphasizing holistic understanding and effective strategies. Finally, Section 6 provides a summary of the paper.

## 2. Conceptual structure and background

Figure 1's Subplot (a) delineates the Western U.S. into three regions, WI, EI, and Texas, according to Bloom et al. (2022). WI comprises 13 states: Alaska, Arizona, California, Colorado, Hawaii, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming. Subplots (b) and (c) highlight biomass and geothermal energy in the Western U.S., showcasing their potential for hydrogen production. This paper underscores its significance by thoroughly examining prior systematic reviews on Hydrogen Supply Chains Downstream (HSCD). To ensure coherence and minimize bias, we structure our analysis across three sections (2.1, 2.2, and 2.3), addressing HSCD segments, decision levels, research properties, and sustainability. This structural framework is inspired by the downstream hydrogen supply chain model proposed by Farahmand et al. (2024). Each subsection follows a dual approach: firstly, laying a robust foundation for assessment, and secondly, reviewing 116 studies conducted between the official announcement of the Covid-19 pandemic in March 2020 and November 2023, marking a

transformative period for the global energy supply chain (International Energy Agency, 2021; Ghahremanlou and Kubiak, 2023; 2020<sub>b</sub>).

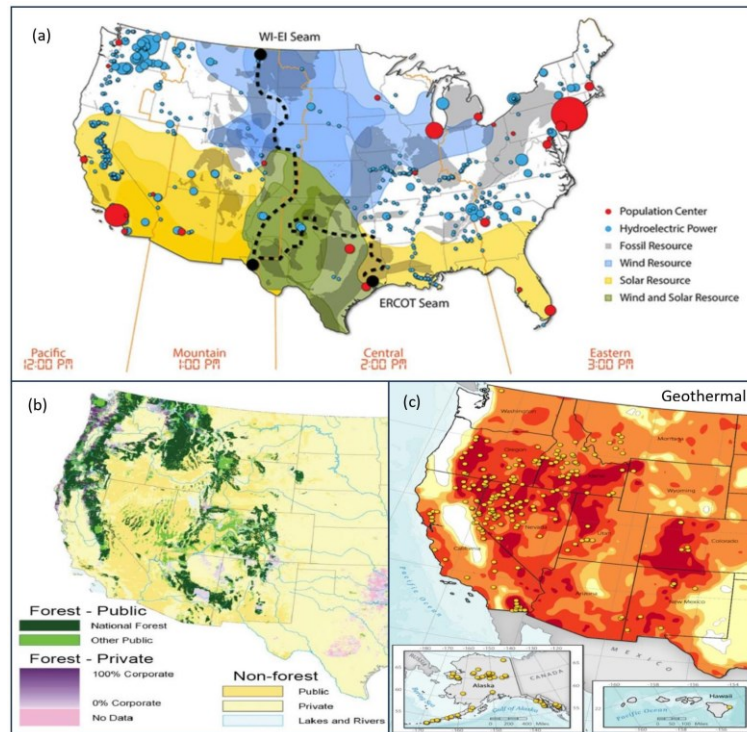


Figure 1. (a)National Renewable Energy Laboratory (2021)

(b)National Climate Assessment (2018)

(c)National Renewable Energy Laboratory (2018)

### 2.1 Hydrogen Supply Chain Downstream (HSCD) Segments

Subplot 1 in Figure 2 delineates the structure of Hydrogen Supply Chain Downstream (HSCD) segments, employing special codes for components in parentheses and color categories for enhanced analysis convenience. The four primary HSCD components: Transportation (TR), Storage (ST), Distribution (DI), and End-User (EU), are highlighted in yellow, aligning with the categorization by Perna et al. (2023). Transportation methods, including rail (RL), vessel (VS), truck (TK), and pipeline (PL), are presented in blue, referencing Clematis et al. (2023<sub>a</sub>). The subsequent component, storage (ST), is further classified into three categories in blue: Physical (PE), Chemical (CH), and Technical (TE), following Hren et al. (2023). Physical storage includes gaseous hydrogen ( $GH_2$ ), liquid hydrogen ( $LH_2$ ), and a combination of both ( $GH_2+LH_2$ ), showcased in orange based on He et al. (2021). Similarly, the two subcategories of the Chemical category, Liquid (LI) and Solid (SO), are identified in the color orange, encompassing chemical components like  $NH_3$ ,  $CH_3OH$ ,  $MCH$ , and  $H_18DBT$  presented in purple, mirroring Usman (2022). In the context of storage, Techniques (T) include Tank (TA), Cylinder (CY), and Salt Caverns (SC), according to Amirthan and Perera (2023). The distribution of hydrogen products can be achieved through Pipeline (PL) and Truck (TK), represented in blue, echoing Reuß et al. (2019). Genovese et al. (2023) categorize transportation (TR), industries (IN), and residential (RE) as end-users (EU) for hydrogen.

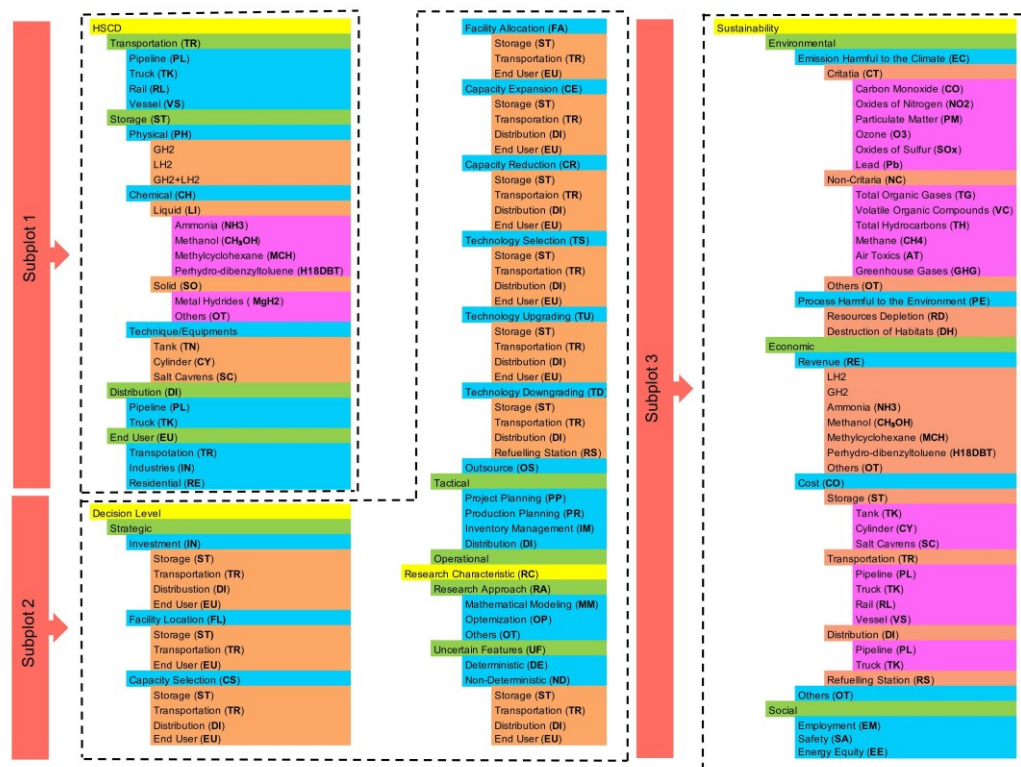


Figure 2. Progressive Trend of Examined Papers

Table 1 offers an overview of 116 systematic review publications published post-2020, coinciding with the significant disruption of the global energy supply chain after the COVID-19 pandemic, as per Piya et al. (2022). According to Table 1's results, no study has covered all aspects of HSCD, with none of the criteria reviewed by more than 55% of review papers. This paper addresses all current research gaps comprehensively. Effectively managing the hydrogen supply chain downstream (HSCD) is essential for fully utilizing hydrogen as a clean energy source. Transportation is a critical component in the hydrogen supply chain context. Table 1 indicates that pipeline and truck methods were the most prevalent focus, with 44% and 34% of studies, respectively, while rail and vessel were focused on by only 22% and 25%, respectively. Despite the emphasis on certain methods, all components must be well-studied due to the extensive infrastructure in the Western U.S., including 338,520 miles of pipeline in the 13 states and a considerable number of ports (Andrade-California, Eureka-California, Fresno-California, Blaine-Washington, Anacortes-Washington, Astoria-Oregon, and Douglas-Arizona), as per U.S. Customs and Border Protection (2023). Similarly, pipeline and truck methods in the distribution aspect of HSCD were reviewed by 35% and 28% of papers, respectively. Regarding hydrogen storage, each method has its pros and cons. Gaseous hydrogen (GH<sub>2</sub>) and the liquefaction process of hydrogen (LH<sub>2</sub>) had the lowest study percentages at 22% and 33%, respectively, according to Zhang et al. (2023). On the other hand, chemical forms of storage, particularly Ammonia (NH<sub>3</sub>) and Methanol (CH<sub>3</sub>OH), received the highest attention, with 49% and 39% of review papers, respectively. However, there was no study conducted on other methods of storage, such as GH<sub>2</sub> + LH<sub>2</sub>, Methylcyclohexane (MCH), Perhydro-dibenzyltoluene (H18DBT), and MgH<sub>2</sub>. Insufficient investigations were conducted on both cylinder and salt cavern, by only 24% and 30%, respectively. However, the significance of these two storage methods is clear, with the cylinder being a lightweight and cost-effective method Rohit et al. (2023), and salt cavern being a proven technique of hydrogen storage due to its low hydrogen loss and contamination, according to Minougou et al. (2023). Hydrogen's application as a source of energy in transportation, industry, and residential sectors has garnered attention, with transportation being the most focused area by 47% of review papers, followed by 31% in industry and 20% in residential. However, more research is needed across all three applications of hydrogen, considering U.S. government policy The White House (2022) to become net-zero by 2050.

Table 1. Examination of Relevant Systematic Review Papers in the HSCD Segments (published from January 2020 to October 2023)

elements like Project Planning (PP), Production Planning (PR), Inventory Management (IM), and Distribution (DI) are presented in blue. In Figure 2, Subplot 2, a comprehensive review of the research characteristics (RC) in the hydrogen supply chain is depicted, focusing on the research approach (RA) and uncertain features (UF) highlighted in a green color scheme. The foundation of the Research Approach (RA) is formed by Mathematical Modelling (MM), Optimization (OP), and other qualitative and quantitative techniques (OT), all shown in blue within Subplot 2. The domain of Uncertain Features (UF) is emphasized with a green tint, underscoring its importance in understanding and mitigating uncertainties in the hydrogen supply chain. UF encompasses both deterministic and nondeterministic. Table 2 provides an overview of the attention given by review papers to the HSCD decision level since 2020. Notably, none of the decision level segments were studied more than 44%, as indicated in the row before the last. However, the intention is to thoroughly investigate all aspects of the decision level in this realm, as highlighted in the last row of the table. Strategic investments in HSCD are highlighted in Table 2, with percentages allocated to ST (18%), TP (20%), DI (9%), and EU (14%).

Table 2. Examination of Relevant Systematic Review Papers in HSCD Decision Levels and Research Properties (published from January 2020 to October 2023)

[illegible]

The investment decision level in the hydrogen supply chain is crucial in determining the optimal location, size, and type of hydrogen storage, transportation, and refueling facilities, aligning with the insights of Erazo-Cifuentes et al. (2023). Facility location aspects, including ST (16%), TP (9%), and EU (19%), have been studied by review papers, emphasizing the impact of facility location on the affordability, sustainability, and accessibility of hydrogen infrastructure, as per Ryu et al. (2023). Notably, facility allocation at the decision level has not received attention from review papers. Table 2 further reveals that among decisions related to capacity, only capacity selection has been the focus, with percentages assigned to ST (44%), TP (18%), DI (5%), and EU (9%). Additionally, no study has addressed capacity decision levels, including capacity expansion and reduction, since 2020. Similarly, among decisions regarding technology, only technology selection has been explored, with percentages attributed to ST (37%), TP (23%), DI (9%), and EU (10%). There has been no study on the other two aspects of technology at the decision level, namely, technology upgrading and technology downgrading. Outsourcing is another component that has not been studied in the context of HSCD decision levels. Factors, represented in blue, with non-deterministic factors (ND) further categorized into distribution (DIS), storage (ST), transportation (TP), and end-user (EU) based on Lingefj rd (2006). The tactical decision stage within the HSCD decision level has received



insufficient research attention. Among the components of tactical distribution, review papers primarily focused on 14%. The other three components; project planning, production planning, and inventory management, and distribution; received attention from 5%, 9%, and 8% of the review papers, respectively. Additionally, only 38% of the papers delved into the operational segment of the HSCD decision level. Table 2 reveals that only 33% of studies in the research context utilized mathematical modeling. This method, as outlined by Forghani et al. (2023), employs mathematical formulas to model intricate systems, including hydrogen supply networks, enabling precise forecasting, varied scenario analysis, and well-informed decision-making. Furthermore, only 28% of papers focused on optimization, a crucial aspect for finding the optimum design or solution for problems with multiple goals or constraints, following the research optimization approach, as discussed by Ebbs-Picken et al. (2023). A majority of papers, constituting 66%, employed other methodologies in their research, encompassing both qualitative and quantitative methods. Qualitative research explores and understands the meanings and experiences of individuals or events, while quantitative research utilizes techniques such as surveys, trials, or statistics to measure and test the effects and correlations of variables, aligning with the insights of Schoonenboom (2023). Moreover, only 28% of papers devoted attention to deterministic modeling, a numerical methodology extracting parameters from experimental data using mathematical manipulation and optimization approaches, according to Xu et al. (2023). The non-deterministic research method, which considers the probability distributions of unknown factors and assesses how randomness affects system performance, received attention from only 4%, 5%, 2%, and 3% of papers concerning storage, transportation, distribution, and end-user components, respectively, as discussed by Lopez-Ramirez et al. (2023).

### 2.3 HSCD Sustainability

Subplot 3 in Figure 2 illustrates the sustainability aspect of the hydrogen supply chain, encompassing environmental, economic, and social dimensions in green Sakthi et al. (2024); Ghahremanlou and Kubiak (2020<sub>a</sub>). The environmental aspect is further divided into Emission Harmful to the Climate (EC) and Process Harmful to the Environment (PE), both colored in blue (Wang et al., 2022). Emission Harmful to the Climate (EC) is then subdivided into Criteria (CT), Non-Criteria (NC), and Others (OT), presented in orange. Criteria (CT) includes Carbon Monoxide ( $CO$ ), Oxides of Nitrogen ( $NO_2$ ), Particulate Matter (PM), Ozone ( $O_3$ ), Oxides of Sulfur ( $SO_3$ ), and Lead ( $Pb$ ), all depicted in purple. Non-Criteria (NC) emissions comprise Total Organic Gases (TG), Volatile Organic Compounds (VC), Total Hydrocarbons (TH), Methane ( $CH_4$ ), Air Toxics (AT), and Greenhouse Gases (GHG), also in purple. The two components of processes harmful to the Environment are resource depletion (RD) and Destruction of Habitats (DH), both shown in orange (Wang et al., 2022). The economic aspect of sustainability is divided into Revenue (RE), Cost (CO), and Others (OT), presented in blue. Revenue includes various hydrogen products such as  $LH_2$ ,  $GH_2$ ,  $NH_3$ ,  $CH_3OH$ ,  $MCH$ ,  $H_{18}DBT$ , and other products (OT), all colored in orange. Dong et al. (2023) consider the cost of storage (ST), including tank (TK), cylinder (CY), and salt caverns (SC). Similarly, for transportation (TR), costs are associated with pipeline (PL), truck (TK), rail (RL), and vessel (VS). For distribution (DI), costs are related to pipeline (PL) and truck (TK). The social aspect of sustainability includes employment (EM), safety (SA), and energy equity (EE), following the insights of Mneimneh et al. (2023). Table 3 presents a comprehensive comparison of this paper to relevant systematic reviews concerning the sustainability aspect of HSCD. Regarding environmental criteria,  $CO$  emissions were reviewed by 23% of papers, while GHG, a non-criteria emission, was studied by 52%. However, none of the papers examined processes harmful to the environment. Similarly, none of the papers reviewed any aspect of revenue. However, different components of cost, as an economic aspect of sustainability, were considerably focused by review papers. In storage (ST), tank (TK), cylinder (CY), and salt caverns (SC) were studied by 29%, 13%, and 14%, respectively. Furthermore, transportation (TP), pipeline (PL), truck (TK), rail (RL), and vessel (VS) were focused on by 27%, 21%, 13%, and 11%, respectively. Refueling station was researched by 14% of the papers. Lastly, 41% of papers contributed to safety (SA) in the social aspect of sustainability. Employment (SA) was focused on by 13%, and only 4% studied energy equity (EE).

Table 3. Examination of Relevant Systematic Review Papers in HSCD Sustainability (published from January 2020 to October 2023)

distribution of original papers. The second section of the chart outlines the percentage of review papers and their distribution among 13 journals. The “Others” category leads with 29%, followed by the International Journal of Hydrogen Energy at 23%. Renewable and Sustainable Energy Reviews (17%), Energies (9%), and other journals each contribute to the distribution of review papers. This chart provides insights into the distribution of publications across journals in the field of hydrogen supply chain research in the Western United States.

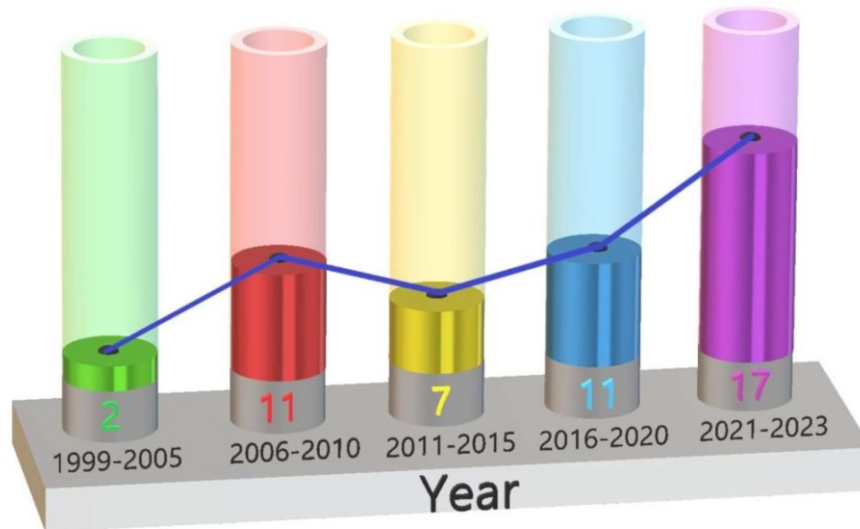


Figure 3. Progressive Trend of Examined Papers

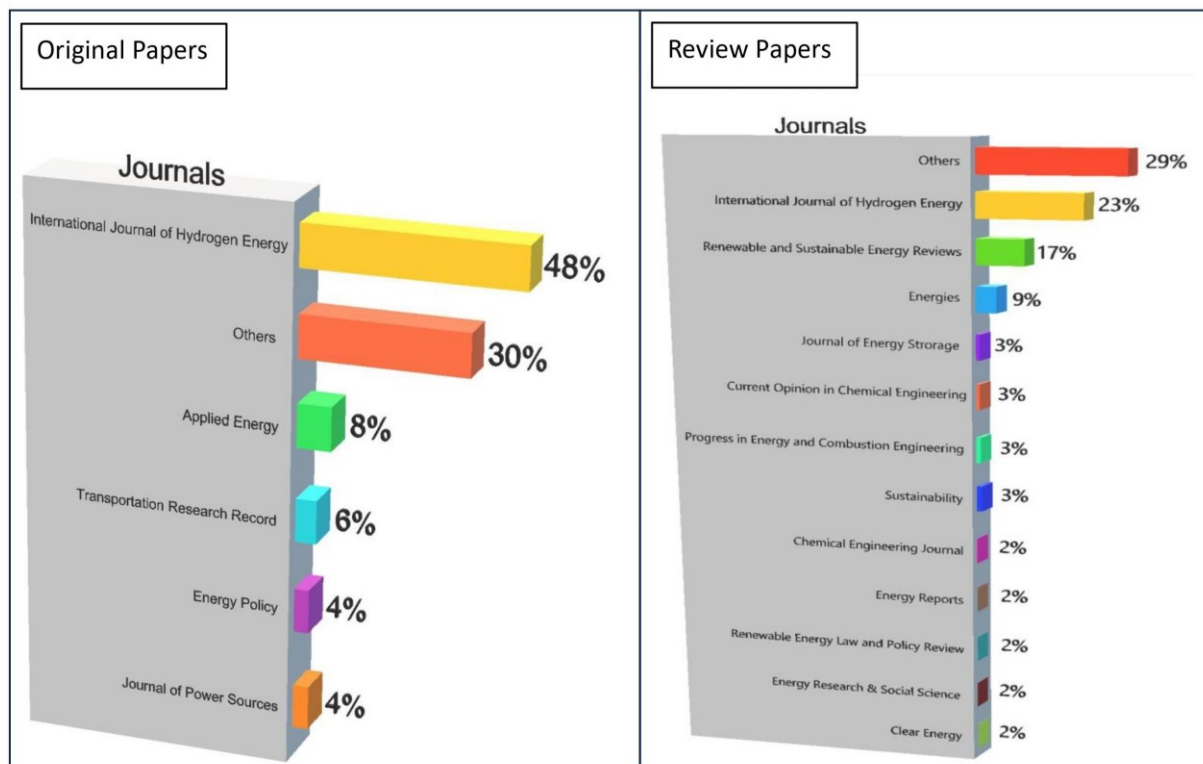


Figure 4. An Analysis Comparing Original Papers with Review Papers, Focused on Journals





hydrogen at high pressures Manurung et al. (2023), and salt caverns are deemed relatively cost-effective to develop and operate, requiring minimal cushion gas and surface installations (Tackie-Otoo and Haq, 2024). Regarding applications, only 63% of papers explored hydrogen's application in the transportation industry, highlighting its potential as a promising alternative fuel to reduce greenhouse gas emissions and enhance energy security (Zhang et al., 2024). Hydrogen's versatility extends to various vehicles, including cars, buses, trucks, trains, ships, and airplanes. Furthermore, 27% of papers investigated hydrogen usage in various industries, emphasizing its role in electricity generation and manufacturing (Genovese et al., 2023). In the residential sector, only 17% of papers focused on hydrogen applications, but Zakaria et al. (2023) underscore the potential of hydrogen fuel cells for residential power generation systems.

Table 5. Examination of the Reviewed Papers from HSCD Decision Levels and Research Properties Aspect

#	Reference	Decision Level																								Research Characteristics																			
		Strategic												Tactical												Operational						Research Properties													
		IS				FS				CS				CB				ES				EU				ED				OS				PP		PM		LT		Operational		RA		TD	
ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET	ST	TH	DI	ET						
1	Beagle et al. (2021)																																												
2	Chen, Ma, Nussle, Chen, Shihana and Yu Wip (2021)																																												
3	Pinto-Vaz et al. (2021)																																												
4	Reid et al. (2021)																																												
5	Banati-Park et al. (2021)																																												
6	Vijayakumar et al. (2021)																																												
7	Bernag et al. (2021)																																												
8	de Fiores and Wu (2021)																																												
9	Nagado et al. (2021)																																												
10	Okunola et al. (2021)																																												
11	Reid et al. (2021)																																												
12	Frank et al. (2021)																																												
13	Genovese et al. (2021)																																												
14	Hernandez and Genger (2021)																																												
15	Papadimitriou et al. (2021)																																												
16	Staka and Broyko (2021)																																												
17	Vijayakumar et al. (2021)																																												
18	Kelly et al. (2020)																																												
19	Lau et al. (2020)																																												
20	Lin, Yu, Guo and Wu (2020)																																												
21	Toussier (2020)																																												
22	Collopy et al. (2019)																																												
23	Lopez-Jaramila et al. (2019)																																												
24	Oguzmenen et al. (2019)																																												
25	Bordano and Tai (2019)																																												
26	Lipman et al. (2018)																																												
27	Wang et al. (2018)																																												
28	Lau et al. (2017)																																												

#### 4.2 HSCD Decision Levels and Research Properties Aspect

Decision-Level and Research Characteristics: Table 5 provides a comparative analysis of the examined papers, focusing on decision-level perspectives and research characteristics. Notably, 10% of the scrutinized papers pertain to storage within the investment domain. The significance of storage in the hydrogen economy lies in its role in stabilizing hydrogen supply and addressing the unpredictability of renewable energy, as emphasized by Elaouzy and Fadar (2024). However, our research indicates that only 6% and 8% of the studies highlight investment in transportation and distribution. In contrast, Risco-Bravo et al. (2024) argue that transportation plays a pivotal role in determining costs, environmental impact, and timely hydrogen delivery, suggesting a well-balanced strategy to meet market demands. Examining financial commitments to developing refueling stations, a mere 15% of papers focus on this aspect. Nevertheless, Genovese et al. (2021) stress the crucial nature of determining optimal investment strategies for individual hydrogen refueling stations, crucial for minimizing production costs and mitigating financial risks. Facility location, known as facility allocation, determines optimal locations and sizes for hydrogen refueling stations. However, Table 5 reveals that storage, transportation, and end-user considerations were studied by only 19%, 21%, and 31%, respectively. In the long-term decision-making realm, capacity expansion and reduction decisions significantly impact economic viability, operational efficiency, and environmental impact, as noted by Isaac and Saha (2023). However, our study indicates that in the domain of capacity selection, only 29%, 17%, 6%, and 21% of papers focused on storage, transportation, distribution, and end-user, respectively. Notably, only 4% of papers reviewed capacity expansion involving storage, transportation, and distribution, with no study conducted on capacity reduction. Facility allocation, a strategic decision determining how to assign facilities, was not studied in our systematic review. However, this decision aims to maximize the overall cost or profit of the supply chain by considering demand, transportation, manufacturing, and inventory (Farahmand et al., 2024). Technology upgrading and downgrading were also not studied extensively, with none of the aspects of technology selection investigated by more than 17%. Nonetheless, Farahmand et al. (2024) highlights the technology section as a key factor contributing to the sustainability of Hydrogen Supply Chains Downstream (HSCD). Additionally, outsourcing, leveraging external suppliers' expertise and capabilities, enhances the performance of HSCD. Mid-Term and Operational Decision Levels: The mid-term decision level in Hydrogen Supply Chains Downstream (HSCD) contributes to tactical decision levels, involving operational and distribution decisions, as well as project planning, production planning, and inventory management (Farahmand

et al., 2024). However, our systematic review reveals that distribution is the sole aspect of the tactical decision level studied by 42%, with no research conducted on Project Planning, Production Planning, and Inventory Management. Moving to the operational decision level, which encompasses short-term planning and daily operations execution Kim et al. (2024), only 17% of papers focused on this aspect. Mathematical modeling and optimization techniques were utilized in merely 17% of papers. Despite this, mathematical modeling proves to be a valuable tool across various disciplines, enabling the study of phenomena in science, engineering, economics, and the environment (Chen, Sabir, Raja, Gao and Baskonus, 2023; Kotian and Ghahremanlou, 2024). Optimization techniques, while employed in a limited number of papers, play a crucial role in enhancing efficiency, effectiveness, robustness, and solution quality, as well as reducing costs, time, and resource requirements (Cura, 2012). In contrast, 81% of total papers employed other research approaches, including qualitative and quantitative methods. The deterministic approach, used in only 15% of papers, is noted by Kentli and Alkaya (2009) for providing accurate and consistent solutions comparable or superior to techniques such as evolutionary algorithms and hybrid approaches. Transportation is the sole aspect of the nondeterministic approach employed by 4% of the papers. The significance of non-deterministic techniques lies in their ability to capture uncertainty and unpredictability in activity duration, influenced by variables such as human error, environmental circumstances, and resource availability (Kentli and Alkaya, 2009).

#### 4.3 HSCD Sustainability Aspect

Figure 5 provides an overview of the 48 papers using the sustainability framework. Only 5 papers considered all three aspects of sustainability; environmental, social, and economic. Additionally, environmental-social, environmental-economics, and economic-social were the focus of 1, 22, and 3 papers, respectively.

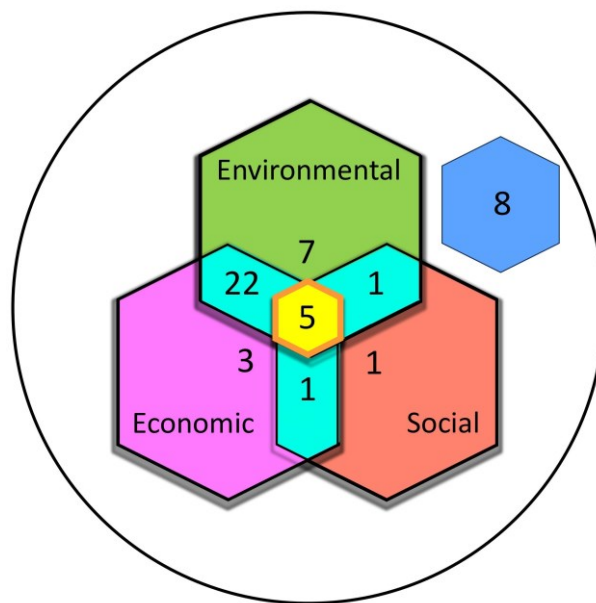


Figure 5. Examination of Sustainability Aspects within the Reviewed Papers

Environmental, economic, and social aspects were reviewed by only 7, 3, and 1 papers, while 8 papers did not consider the sustainability aspect of Hydrogen Supply Chains Downstream (HSCD) in their studies. Table 6 presents various components of criteria emissions harmful to the climate. Among all air emissions, CO is the only component reviewed, focused on by 19% of the papers. The U.S. Department of Energy (2023b) emphasizes the toxicity of these emissions, highlighting significant impacts on human health and the environment. GHG is the sole reviewed component in noncriteria emissions, with 52% of papers addressing it. However, other non-criteria pollutants can lead to health issues, such as headaches, dizziness, respiratory irritation, nausea, cancer, brain and nervous system damage, blood disorders, impaired fertility, and contribute to climate change. Therefore, monitoring and reducing emissions of non-criteria pollutants from vehicles and other sources are crucial The U.S. Department of Energy (2023b). In the economic aspect of sustainability, no study focused on any revenue components. However, the cost dimension was examined by some papers, including tank, cylinder, and salt caverns in storage, pipeline, truck, rail, and vessels in transportation, pipeline and truck in distribution, and end-user; by 17%, 2%, 10%, 25%, 23%, 2%, 2%, 17%, 10%, 23%, respectively. Cost is a vital factor affecting the viability and

competitiveness of renewable energy technologies (Saeedmanesh et al., 2018). Other economic factors, such as NPV, were focused on by 13% of the papers. In the social aspect, only employment and safety were the focus of papers by 4% and 15%, respectively. However, social sustainability, which relates to social risks like working conditions, health and safety, fair pay, social acceptance, and local development Zafar et al. (2024), is one of the three pillars of sustainability.

## 5. Future Perspectives

In this section, we summarize all the research gaps identified in Section 4 for the HSCD in the Western U.S. The exploration of hydrogen pipelines, considering their cost-effectiveness and high capacity, is recommended for further scrutiny. In addition, there's a call to enhance the understanding of truck transportation methods and optimize railway transportation for hydrogen distribution networks. The potential of maritime hydrogen transport is highlighted, suggesting research into its dynamics and global feasibility. Addressing significant research gaps in physical and chemical forms of hydrogen storage, including ammonia, methanol, and various carriers, is emphasized. The study suggests diversifying storage techniques beyond tanks, exploring cylinders and salt caverns, and integrating hydrogen applications in transportation, industries, and residential sectors. Public awareness and policy implications are also considered crucial for a smooth transition to a hydrogen-based economy, creating a comprehensive roadmap for future research endeavours in this dynamic field.

Furthermore, future research directions emphasize the need for comprehensive exploration of strategic decision domains, especially in investment and technology aspects, to optimize hydrogen supply chains. Facility location studies should extend to transportation and storage, while capacity-related decision levels, including expansion and reduction, demand a thorough investigation. The tactical level, comprising project planning, production planning, inventory management, and distribution, presents a notable research gap that requires attention. Operational decision levels, particularly research characteristics, warrant further exploration to enhance understanding. Additionally, the academic community is urged to delve into optimization and non-deterministic modeling, especially in storage, transportation, distribution, and end-user domains, addressing the limited attention these areas have received.

The examination of emission components reveals a need for a broader investigation beyond  $CO$  and GHG, urging researchers to explore various criteria and non-criteria pollutants associated with hydrogen supply chains. A comprehensive understanding of the toxicity and environmental impact of diverse emissions is essential. In the economic dimension, the absence of studies on revenue components emphasizes the need for future research to explore potential income sources and economic benefits associated with hydrogen supply chain activities. Furthermore, a deeper exploration of economic factors influencing viability, including life cycle cost analysis and return on investment, is warranted. In the social dimension, beyond employment and safety, researchers are encouraged to investigate broader social risks, fostering socially responsible practices within the hydrogen supply chain.

## 6. Conclusions

This paper extensively examined the downstream hydrogen supply chains (HSCD) in the Western U.S. We developed a conceptual model, which was employed to identify gaps in the existing 116 regional and global review papers published from March 2020, at the onset of the COVID-19 pandemic, to November 2023. This process enabled us to identify segments of HSCD, decision levels, research properties, and sustainability as essential criteria for analyzing 48 peer-reviewed original journal papers pertaining to HSCD in the Western U.S. up to November 2023. The temporal distribution of publications highlighted a significant upward trajectory in research interest and publication activity over time, emphasizing the evolving importance of HSCD studies in the western U.S. Furthermore, the International Journal of Hydrogen Energy emerged as a leading contributor in the field.

Our findings show that future research should comprehensively explore strategic decision domains, especially in investment and technology, to optimize the HSCD. Facility location studies should extend to transportation and storage, while capacity-related decision levels demand thorough investigation. The tactical level, including project and production planning, inventory management, and distribution, presents a notable research gap. Operational decision levels, particularly research characteristics, warrant further exploration to enhance understanding. Additionally, the academic community is urged to delve into optimization and non-deterministic modeling, particularly in storage, transportation, distribution, and end-user domains, addressing the limited attention these areas have received.

Moreover, the exploration of hydrogen pipelines requires further investigation. Additionally, optimizing truck transportation methods and enhancing railway networks for hydrogen distribution are recommended. The potential of maritime hydrogen transport highlights the need for research into its dynamics and global feasibility. Addressing

significant research gaps in hydrogen storage, including ammonia, methanol, and various carriers, is crucial. Diversifying storage techniques beyond tanks, exploring cylinders and salt caverns, and integrating hydrogen applications across transportation, industries, and residential sectors are suggested. Furthermore, the need for broader investigations into emission components, economic factors, and social dimensions associated with the HSCD is highlighted. Beyond CO<sub>2</sub> and GHG, exploring various pollutants, understanding the toxicity and environmental impact, and delving into revenue components and economic benefits will contribute to a more comprehensive understanding of sustainability.

Finally, there are some directions for researchers interested in writing HSC review papers. Firstly, extending this review to include upstream and midstream of the HSCD. Secondly, apply the same structure as this paper in other regions of the U.S. and world. Thirdly, include detail qualitative studies of the HSCD in their review.

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