Journal of Sustainable Development; Vol. 17, No. 2; 2024
ISSN 1913-9063 E-ISSN 1913-9071
Published by Canadian Center of Science and Education

A Comprehensive Systematic Overview of Canadian Hydrogen Supply Chains Downstream

Farzam Farahmand[1], James King[1], Davoud Ghahremanlou[1], Priya Sakthi[2] & Mohammad Reza Moghadas Jafari[3]

[1] Faculty of Business Administration, Memorial University of Newfoundland, Canada

[2] Faculty of Engineering and Applied Science, Memorial University of Newfoundland, Canada

[3] 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

Received: November 16, 2023 Accepted: December 26, 2023 Online Published: December 27, 2023

doi:10.5539/jsd.v17n2p1 URL: https://doi.org/10.5539/jsd.v17n2p1

Abstract

This paper investigates Canada's endeavor for carbon neutrality by 2050 and its strategic response to the European energy crisis resulting from the Russia-Ukraine war. With a significant potential for hydrogen production, Canada's hydrogen exports to Europe are poised to reshape its hydrogen supply chains downstream (HSCD). Through a systematic review of 39 papers published before October 2023, our examination explores HSCD components, decision levels, and sustainability perspectives. Consequently, we offer recommendations for scientific, legislative, and industrial sectors for forward horizons. Additionally, this study proposes future research avenues for similar systematic review papers.

Keywords: hydrogen supply chain, downstream, decision levels, sustainability, systematic review, Canada.

1. Introduction

Supply chain management has taken center stage in this era where businesses must integrate all operations from raw materials to end user to take advantage of every opportunity for staying competitive. Among the supply chains it is vital to study energy supply chains, the backbone of contemporary civilization, as it supports economic activity, technical developments, as well as the general well-being of civilizations. Hydrogen as an ecofriendly renewable energy carrier is gaining increasing attention, as nations, including Canada, are working to meet environmental targets, leading to the formation of Hydrogen Supply Chains (HSCs). Additionally, efforts for development of HSCs have drastically escalated since the initiation of the Russia-Ukraine war (Steffen and Patt, 2022). Canada has been recognized as a reliable source of supplying hydrogen to Europe due to its natural resources, while satisfying its global environmental commitments, please see Dolata (2022). Europe as a new customer will radically change the downstream of the Canadian HSCs. Furthermore, Gordon et al. (2023*b*) emphasize the significance of addressing HSC downstream challenges, e.g., pipeline repurposing, for expansion of HSCs. Thus, investigation into Canada's HSC downstream forms the essence of this paper.

To satisfy the goal of this research, and maintaining the consistency in our systematic analysis, we introduce the framework of this study through which we examine the former review papers regarding the downstream HSCs in Section 2. Then, Section 3 presents the methodology for compiling relevant literature. In Section 4 the same framework is utilized again to synthesize the selected body of knowledge and discuss the existing gaps. Accordingly, we offer recommendations for scholars, regulators, and corporations in Section 5. Finally, we conclude the paper in Section 6.

2. Framework and Prior Review Studies

To highlight the significance of this paper, we comprehensively examine previous systematic review works relevant to the Hydrogen Supply Chain Downstream (HSCD). To that end, we first establish a framework to minimize bias in our analysis, i.e., HSCD components, HSCD decision levels and research characteristics, sustainability and geographical domain in the following three Subsections 2.1, 2.2, and 2.3, respectively; this framework is a customization of the one used by Sahebi et al. (2014) for oil supply chains, due to the similarity of both oil and hydrogen supply chain downstreams. Furthermore, providing the framework first improves the paper's streamlining. Each of the subsections offers their contents in two sequences: (i) developing a solid ground for evaluation, and (ii) studying the relevant review papers, published from the onset of the Russia-Ukraine conflict, February 2022 to October 2023, changing the global energy supply chain (International Energy Agency, 2023). This section will be devoted to our investigation of the 43 pertinent review papers that we found.

2.1 Hydrogen Supply Chain Downstream (HSCD) Components

Figure 1 shows the structure for the HSCD components. In this figure, there are letters written in bold, mainly in parentheses, representing the code we considered for the corresponding term, e.g., (TP) stands for Transportation. The reason for coding the terms is keeping the analysis manageable considering number of aspects we investigate. We employ the same convention throughout of this study, e.g., Table 1, to enhance readability.

The HSCD, colored in dark pink, consists of four main components shown in blue, from left to right: transportation, storage, distribution, and end user, which follows Riera et al. (2023). Each component has different subcomponents, represented in green color. Transportation can take place through pipeline (PL), truck (TRK), vessel (VSL), and rail (RL), reflecting the categorization of Oh et al. (2023). The next component from left is storage (ST), which includes physical (PS), chemical (CH), and techniques (T), mirroring Zhang et al. (2023). Descending through the breakdown, physical encompasses gaseous hydrogen (GH_2), liquid hydrogen (LH_2), and a combination of both ($GH_2 + LH_2$), replicating Noh et al. (2023). Likewise, chemical has two subcategories: liquid (LI) and solid (SO), colored in yellow, where liquid includes NH_3 (ammonia), CH_3O (methanol), MCH (methylcyclohexane), and $H_{18}DBT$ (perhydro-dibenzyltoluene) which are colored light pink, and solid includes MgH_2 and Others (OTH), i.e., dodecahydro-N-ethylcarbazole and dibenzylmethane, which are colored in light pink as well, echoing Hampp et al. (2023). In a similar vein, storage techniques (T) are tank (TA), cylinder (CY), and salt caverns (SC) based on Vishal et al. (2023). These products are distribution (DIS) by pipeline (PL) and truck (TRK) (Vijayakumar et al., 2023). Yue et al. (2021) conclude transportation (TP), industries (ID), and residential (RE) as end user (EU) for hydrogen.

Figure 1. Structure and codes for the HSCD components

Table 1 demonstrates how the 43 former systematic review papers, rows #1 to 43, address various components of the HSCD, explained in Figure 1. According to the table, none of the papers has investi- gated all the components of HSCD (no row has × sign under all the columns). Furthermore, none of the criteria has been studied by over 75% of the review papers, please see the row before the last, including the percentages. However, this paper addresses all existing research gaps regarding HSCD components, please see the last row of the table.

To use hydrogen fuel in a wide range of industrial applications, it is imperative to discover an ap-propriate method of transportation for hydrogen. To that end, understanding the chemical properties of hydrogen is crucial to prevent explosions and leaks. Furthermore, hydrogen exists in many states based on temperature and pressure, which adds additional constraint for selecting the transportation means (Faye et al., 2022). Table 1 illustrates pipeline, trucks, and vessels have been studied by 53%, 56%, and 51% of the papers, while the study of rail transportation has been incorporated in only 29% of the papers. All of these options should be well studied since Canada is second largest country in the world and has 840,000 kilometers of pipelines Natural Resources Canada (2023), over 30 million kilometers of heavy truck roads (Transport Canada, 2021*b*), over 550 ports (Chircop, 2023), and over 46,000 kilometers of railway tracks (Streiner, 2019). Similar rationale holds for distribution within a short distance, for which pipeline and trucks are used and these have been studied by 66% and 56% of the papers.

Transportation of gaseous hydrogen over a long distance is challenging due to its chemical properties, e.g., high reactivity (Hampp et al., 2023). Therefore, other forms of hydrogen (e.g., the liquid and solid forms in Table 1) like ammonia (NH_3) are recognized as more promising options for transportation (Cui and Aziz, 2023), which explains why LH_2, NH_3, and CH_3OH, with higher energy density, have been studied by 54%, 60%, and 54% of the review papers, respectively. On the other hand, GH_2, $GH_2 + LH_2$, MCH, $H_{18}DBT$, and MgH_2 have been considered in a minimum number of studies; however, GH_2 has quick charge and discharge rates, making it simpler to industrialize. Stable liquids with significant storage capacities, i.e., MCH and $H_{18}DBT$, are appropriate for long range transportation. MgH_2 is often employed in lab research because of its great volumetric storage capacity and safety (Chu et al., 2023).

Likewise, chemical properties of hydrogen impacts its storage. Tanks are studied by 73% of the reviewed papers; however, this number is due to tanks being an umbrella term for various types of tanks used for hydrogen transportation; for example, compressed H_2 storage systems use pressurized cylinders to store GH_2. In contrast, cryogenic tanks are used in liquid hydrogen storage systems to hold hydrogen in a liquid form. Lastly, solid materials that can absorb and release hydrogen reversibly are used in metal hybrid storage systems, making them ideal for solid hydrogen storage (Qureshi et al., 2023). Cylinders and salt caverns have been investigated by 53% and 47% of the papers; however, a proven method for storing compressed hydrogen gas is cylinders. With entirely composite containers, they may attain high gravimetric density and handle a range of pressure. They may be used in fixed, on-board, and ground transportation applications because of their versatility (Yang et al., 2023). Furthermore, because salt caves have self-healing capabilities and little permeability they are advantageous for storing hydrogen. They are easy to mine and monitor, sustain high flow rates, and need less cushion gas. They are an easily accessible resource due to their abundance in nature (Abreu et al., 2023). According to Hui et al. (2023), Ontario's geological features make it a province with substantial potential for salt cavern storage.

Hydrogen can be used as energy for transportation, industries, and in residential use. 73% of the review papers have studied the application of hydrogen in industries, e.g., oil and gas. However, transportation and residential use have been studied by 67% and 33% of the review papers. Between 2005 and 2018, greenhouse gas emissions from road transportation have grown 19% in Canada (Transport Canada, 2021*a*). Furthermore, Canada is one of the coldest countries in the world (Health Canada, 2019). Therefore, it is crucial to utilize hydrogen as a renewable source of energy for transportation and residential use, considering Canada's global environmental commitments to net zero emissions by 2050 (Government of Canada, 2020).

2.2 HSCD Decision Levels and Research Characteristics

Figure 2 illustrates the HSCD decision levels with same coloring convention we used in the former section. The HSCD decision levels, colored in dark pink, is divided into three components: strategic, tactical, and operational, shown in blue (Azadnia et al., 2023). To highlight the significance of strategic decisions in supply chains, we placed it in the center of figure. To develop the branches in the figure, we have projected the frameworks of Alizadeh and Karimi (2023) and Sahebi et al. (2014) regarding oil supply chain on the framework in Li et al. (2019) focused to HSCs.

Table 1. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from HSC components dimension

#	Ref.	Transportation				Storage									Technique			Distribution		End User		
						Physical			Chemical													
									Liquid				Solid									
		PL	TK	RL	VL	GH_2	LH_2	GH_2+LH_2	NH_3	CH_3OH	MCH	$H_{18}DBT$	MgH_2	OTH	TA	CY	SC	PL	TK	TP	ID	RE
1	Alsaba et al. (2023)	x	x		x	x	x		x	x					x			x	x	x	x	x
2	Amirthan and Perera (2023)																x			x	x	x
3	Aslannezhad et al. (2023)														x	x	x	x			x	
4	Beschkov and Ganev (2023)								x	x												
5	Chen et al. (2023)	x													x	x	x	x	x	x	x	x
6	Clematis et al. (2023)	x	x		x		x		x	x	x	x	x		x	x	x	x	x	x	x	x
7	Feng et al. (2023)	x	x	x	x	x	x		x						x	x				x	x	
8	Ghorbani and Zendehboudi (2023)					x	x			x					x	x	x	x	x	x	x	x
9	Gorji (2023)	x	x		x		x		x	x					x			x	x	x	x	
10	Hren et al. (2023)	x	x	x	x	x	x		x	x	x	x			x			x	x	x	x	
11	Kim et al. (2023)														x	x		x	x			
12	Kindra et al. (2023)	x	x	x	x	x	x		x						x	x	x	x	x	x	x	
13	Kumar et al. (2023)	x				x	x		x	x	x				x	x		x	x	x	x	x
14	Lagioia et al. (2023)	x	x			x	x		x	x			x		x	x	x	x	x	x	x	x
15	M et al. (2023)												x		x	x	x		x	x	x	x
16	Ma, Sun, Xue, Zhang and Chen (2023)	x	x		x				x	x					x		x					
17	Ma, Zhao, Wang, Li and Zhou (2023)	x	x		x	x	x	x	x	x		x			x	x	x	x	x	x	x	x
18	Muthukumar et al. (2023)					x	x		x				x		x							
19	Negro et al. (2023)	x	x		x				x								x	x				
20	Qureshi et al. (2023)	x	x		x	x	x	x	x	x	x	x			x					x	x	x
21	Riera et al. (2023)	x	x						x	x	x	x			x	x	x	x	x		x	
22	Sgarbossa et al. (2023)	x	x	x	x				x	x								x				
23	Stöhr et al. (2023)	x	x	x	x	x	x		x	x	x	x	x			x		x	x	x		
24	Tan et al. (2023)	x	x		x	x	x		x	x	x	x			x		x	x	x	x	x	x
25	Zhang et al. (2023)	x	x		x	x	x	x	x	x	x	x			x	x	x	x	x	x	x	x
26	Berstad et al. (2022)					x	x								x							
27	de las Nieves Camacho et al. (2022)	x	x	x	x													x	x			
28	Kim et al. (2022)	x		x													x	x		x	x	
29	Lee et al. (2022)	x				x	x	x	x	x	x	x			x	x	x	x	x	x	x	
30	Li et al. (2022)								x	x							x	x		x	x	
31	Otto et al. (2022)	x	x	x	x				x	x	x	x	x									
32	Raad et al. (2022)	x													x	x				x		x
33	Rasul et al. (2022)	x	x	x	x	x	x	x	x	x	x	x	x			x	x					
34	Schrotenboer et al. (2022)								x	x					x	x		x	x	x	x	
35	Shi et al. (2022)	x											x									
36	Shin (2022)		x						x				x					x	x			
37	Simanullang and Prost (2022)					x	x	x					x		x		x	x		x	x	
38	Tahan (2022)	x	x		x	x	x						x									
39	Tarkowski and Uliasz-Misiak (2022)														x							
40	Thiyagarajan et al. (2022)														x	x	x	x	x			
41	Ustolin et al. (2022)	x	x	x	x	x	x								x	x	x	x	x	x		
42	Xu et al. (2022)					x	x		x	x	x	x	x					x	x		x	
43	Zhang et al. (2022)														x			x	x			
	Total (%)≈	53	56	29	51	40	54	13	60	51	26	26	27	0	73	50	44	66	56	67	73	33
	This paper	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

At the Tactical level (TCL) of the HSCD decisions regarding project planning (PJP), production planning (POP), inventory management (INM), and distribution (DIS) are considered. More longer term, and often financially heavier decisions focus on investment (INV), facility location (FLC), capacity selection (CSC), facility allocation (FAL), capacity expansion (CAE), capacity reduction (CAR), technology selection (TES), technology upgrading (TEU), technology downgrading (TED), and outsourcing (OUT). The INV decisions affect storage (ST), transportation (TP), distribution (DIS), and end user (EU), which here means building/purchasing refueling stations. The FLC decisions address the location for refueling stations (EU), transportation (TP), and storage (ST). The best places for facilities are chosen to provide a smooth flow of hydrogen by minimizing transportation costs, streamlining distribution networks, and increasing end-user accessibility (Kumar et al., 2023). The next are CSC decisions, which involves choosing the best capacities for ST, TP, DIS, and EU. The FAL is the next group of decisions. The allocation of resources to ST, TP, and EU is managed under the FAL. Strategies for capacity expansion, or CAE, entails the deliberate addition of capacity in the ST, TP, DIS, and EU segments. These choices involve making capital-intensive strategic decisions that will affect the supply chain's performance over the long run (Oliveira et al., 2013). The subcategory of capacity reduction (CAR) involves the strategic determination of capacity reductions in the following areas: DIS, ST, TP, and EU. Demand variations, operational effectiveness, and cost optimization are factors that impact these choices, making it possible to distribute resources wisely and minimize unnecessary capabilities sensibly, thereby eliminating surplus capacity. Strategic decisions about the use of technologies for ST, TP, DIS, and EU are made under TES. These decisions, which are influenced by market preferences, environmental concerns, and technology breakthroughs, keep the supply chain at the forefront of innovation and sustainability. Strategic choices are made regarding TEU to improve the technologies that are currently being used in ST, TP, DIS, and EU. Strategic choices to downgrade technologies in the ST, TP, DIS, and EU sectors may need to be made in order to preserve operational efficiency for a variety of reasons, including cost-effectiveness, market demands, or the need to switch to more sustainable alternatives. Finally, the strategic level of outsourcing decisions (OUT) includes the thoughtful choice of outside partners and service providers for specific aspects of the operation.

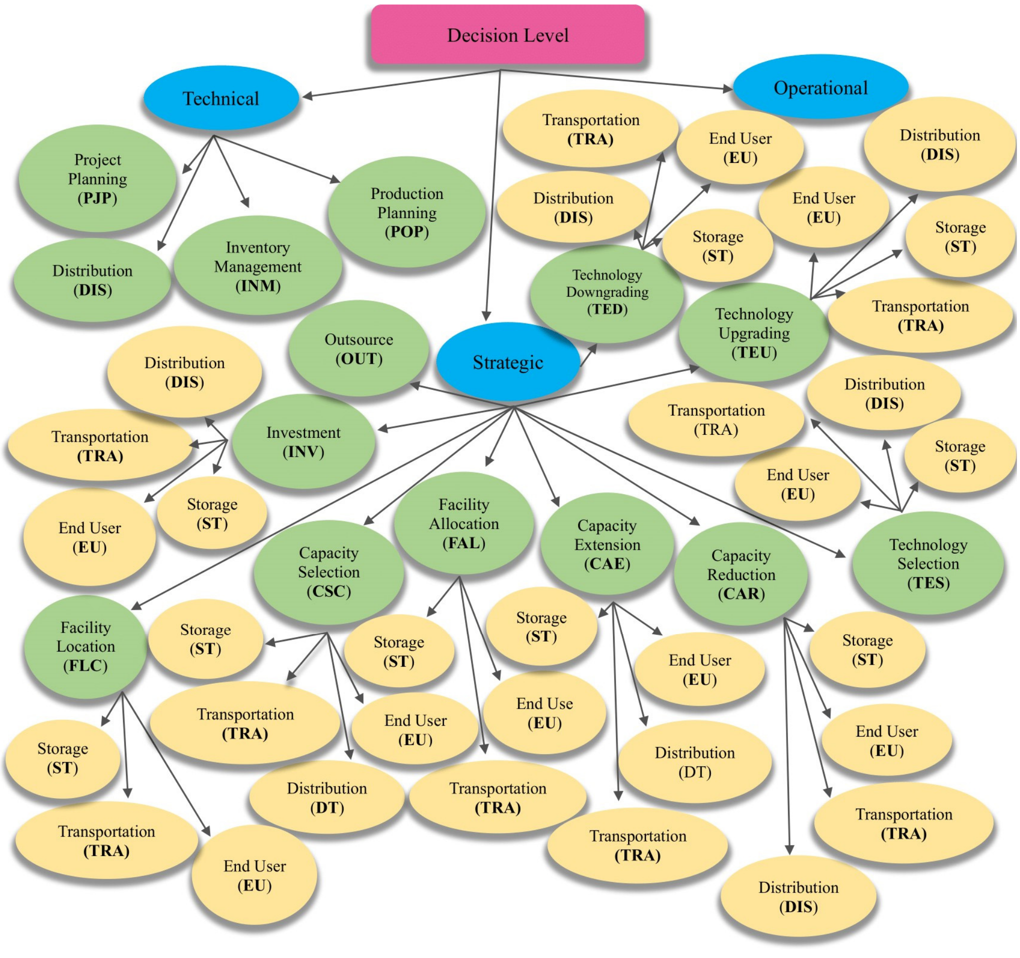

Figure 2. HSCD decision levels and codes

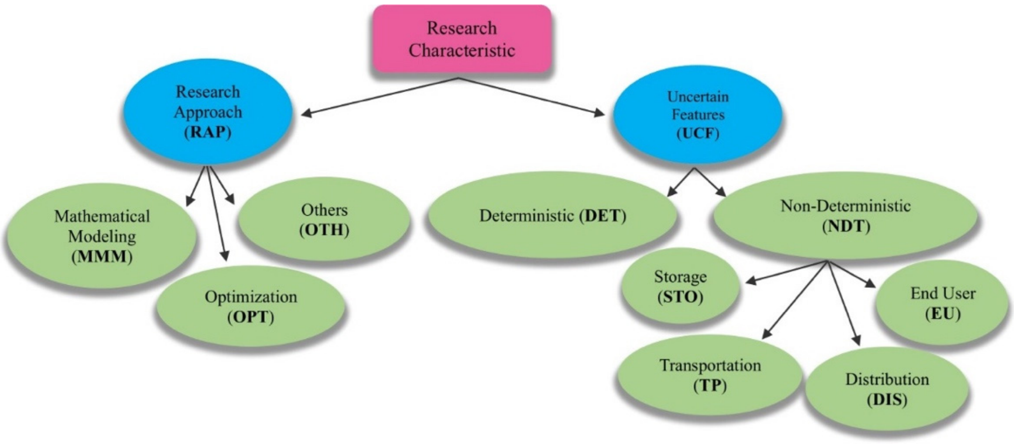

Figure 3. HSCD research characteristic

Figure 3 outlines a range of research characteristics used in the HSCD: research approach (RAP) and uncertain features (UCF), shown in blue. The foundation of the RAP includes mathematical modelling (MMM), optimization (OPT), and others (OTH), i.e., qualitative and quantitative approaches. The UCF is further detailed into deterministic (DET) and non-deterministic (NDT) elements to cover all the factors in HSCD. The NDT breaks down into four sections, ST, TP, DIS, and EU. This classification is based on Li et al. (2019).

Table 2 compares this work to pertinent systematic review studies published since February 2022 from the viewpoints of research characteristics and decision levels. None of the decision levels are studied by more than 70% of the papers. Investment decisions are pivotal to HSCD, however, Table 2 displays disparities in this category: ST (49%), TP (38%), DIS (33%), and EU (31%) considerations. The feasibility of HSCD depends on investments made across these components. A strong infrastructure, a smooth supply chain, and the broad adoption of hydrogen technologies all depend on adequate finance and the planned deployment of resources. One major obstacle to making well-informed decisions and accelerating the shift to hydrogen-based energy is the paucity of thorough research in these areas (Gordon et al., 2023*a*).

There has not been considerable study completed about location of facilities, only 33% in storage, 20% in transportation, and 24% end user. Determining the best sites for facilities is essential for cutting costs, minimizing transit distances, and guaranteeing prompt access to hydrogen; nevertheless, these fac- tors are notably absent from the literature assessment (Sgarbossa et al., 2023). Furthermore, decisions regarding capacity show inequalities in the following areas: end user capabilities (16%), distribution (13%), transportation (24%), and storage (53%). One reason for disregarding end user capacity and distribution might be the difficulty in forecasting future needs. However, ignoring these factors might lead to less-than-ideal capacity planning, which would impede the smooth integration of hydrogen. Additionally, optimizing the HSCD requires making judgements on FAL, including storage, transportation, and refueling station facilities. Nonetheless, there are gaps in the study of this field particularly when it comes to refueling stations (13%). The effective integration of hydrogen into diverse applications is impeded by appropriate localized facility allocation.

Making decisions on capacity expansion (CAE) for ST, TP, DIS, EU is essential to meet rising demand. However, there are still research shortages, particularly in the areas of distribution (13%) and end user capacity (11%). On the other hand, although it is sometimes ignored, capacity reduction is essential for guaranteeing economic sustainability. However, this feature receives little, if any, attention in the literature that is currently available. Furthermore, although there is a significant focus on initial technology selection, particularly in the areas of storage (56%) and transportation (51%), refueling station technology exploration results reflect a 20% research focus. This basic lack of knowledge regarding refueling station technology choices is impeding the smooth integration of hydrogen applications across many sectors. Moreover, there is a clear lack of study on technology upgrading, especially with regard to refueling station technologies (4%). This disparity is a result of the industry's inability to keep up with the quick speed of innovations, which hinders the adoption of creative solutions and reduces the efficiency benefits that may be attained through technological improvements. Conversely, decisions on technology downgrade, which are essential for retiring obsolete technologies, are remarkably understudied, as seen by the scant attention they receive in all industries. Comprehending the technology downgrade process is essential for facilitating a seamless shift to more effective substitutes. Finally, outsourcing received just 2% of the attention in the current literature. Making judgements on outsourcing is essential for assuring specialized knowledge, cutting expenses, and simplifying processes (Lahiri, 2016).

Table 2. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from decision level and research characteristics dimension

#	Reference	Decision Level																																						Research Characteristic							
		Strategic																																									UCF				
		INV				FLC			CSC				FAL			CAE				CAR				TES				TEU				TED					Tactical					RAP				NDT			
		ST	TP	DIS	EU	ST	TP	EU	ST	TP	DIS	EU	ST	TP	EU	ST	TP	DIS	EU	ST	TP	DIS	EU	ST	TP	DIS	EU	ST	TP	DIS	EU	ST	TP	DIS	RFS	OUT	PJP	POP	INM	DIS	Operational	MMM	OPT	OTH	DET	ST	TP	DIS	EU
1	Alsaba et al. (2023)																							X	X	X	X														X			X					
2	Amirthan and Perera (2023)	X				X			X		X		X																												X	X							
3	Aslannezhad et al. (2023)								X			X																										X	X	X		X	X						X
4	Beschkov and Ganev (2023)																							X				X	X													X							
5	Chen et al. (2023)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X	X											X	X				X	X						
6	Clematis et al. (2023)	X	X		X	X	X	X	X	X	X			X	X	X	X		X						X		X	X	X		X							X		X	X			X		X	X		X
7	Feng et al. (2023)								X								X							X			X																X	X					
8	Ghorbani and Zendehboudi (2023)																							X	X	X	X										X	X	X	X		X	X						
9	Gorji (2023)	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X					X	X	X		X	X	X							X	X	X	X	X	X	X	X	X	X	X		
10	Hren et al. (2023)	X	X	X	X	X	X	X					X	X	X	X	X	X						X	X			X	X							X	X	X	X	X	X	X	X		X				
11	Kim et al. (2023)								X																																X	X	X		X				
12	Kindra et al. (2023)	X	X	X		X	X	X	X	X			X	X		X	X			X	X			X	X			X	X	X		X	X				X	X	X	X	X	X	X		X				
13	Kumar et al. (2023)		X	X	X	X	X	X	X	X			X	X	X	X	X							X	X												X	X	X	X	X	X	X		X	X	X	X	X
14	Lagioia et al. (2023)	X	X		X	X	X	X	X	X	X	X				X	X	X	X					X	X			X	X												X			X					
15	M et al. (2023)	X	X	X	X																			X	X	X	X											X		X	X			X		X	X	X	X
16	Ma, Sun, Xue, Zhang and Chen (2023)	X						X																																X	X		X						
17	Ma, Zhao, Wang, Li and Zhou (2023)	X	X	X		X		X	X			X	X	X	X		X							X	X																X	X	X		X	X	X		
18	Muthukumar et al. (2023)																																									X							
19	Negro et al. (2023)	X	X			X			X					X										X	X	X	X														X								
20	Qureshi et al. (2023)	X			X	X																																			X	X	X						
21	Riera et al. (2023)								X							X			X								X	X	X	X	X								X	X	X	X		X					
22	Sgarbossa et al. (2023)																																								X	X				X	X	X	X
23	Stöhr et al. (2023)								X	X														X	X																								
24	Tan et al. (2023)			X																				X	X	X	X	X	X	X											X	X	X						
25	Zhang et al. (2023)	X	X	X	X																							X		X											X	X	X		X				
26	Berstad et al. (2022)								X																																X	X	X						
27	de las Nieves Camacho et al. (2022)																							X	X																	X	X						
28	Kim et al. (2022)	X	X	X	X	X	X	X																X																				X					
29	Lee et al. (2022)								X	X														X																X			X						
30	Li et al. (2022)	X				X			X				X											X		X																		X					
31	Otto et al. (2022)																																									X	X						
32	Raad et al. (2022)	X	X	X	X																			X	X	X					X											X	X						
33	Rasul et al. (2022)																																									X	X						
34	Schrotenboer et al. (2022)								X															X	X																	X	X		X				
35	Shi et al. (2022)																																											X					
36	Shin (2022)																							X	X				X															X					
37	Simanullang and Prost (2022)							X	X			X				X			X																							X		X					
38	Tahan (2022)																																											X			X		
39	Tarkowski and Uliasz-Misiak (2022)																																									X	X						
40	Thiyagarajan et al. (2022)	X																																								X	X						
41	Ustolin et al. (2022)	X	X	X					X				X																													X	X						
42	Xu et al. (2022)																																									X	X						
43	Zhang et al. (2022)								X																																	X	X						
	Total (%)≈	49	38	33	31	33	20	24	53	24	13	16	20	18	13	24	22	13	11	2	2	0	0	56	51	27	20	20	20	11	4	2	2	0	0	2	18	27	18	31	47	69	64	27	24	18	20	11	13
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Differences may be seen in the tactical choices that are crucial to HSCD operations, PJP (18%), POP (27%), INM (18%), and DIS (31%). Project planning and inventory management may be neglected because of their alleged subordinate status. These elements, however, are essential for efficient HSCD operation. While ineffective inventory management upsets supply networks, inadequate project planning causes delays. Furthermore, about 47% of the papers reviewed detail operational choices, which highlight the industry's emphasis on daily productivity. Still, it is necessary to further investigate these points to guarantee efficient execution of daily activities.

Finally, in the Research Characteristic, using mathematical models is the most common study strategy for HSCD, covering a significant 69% of the examined publications. Through mathematical modeling decision-making procedures can be optimized, as a variety of scenarios may be analyzed (Lingefj¨ard, 2006). Furthermore, 64% of the studies make use of optimization methods, e.g., stochastic optimization. Two thirds of the studies use both qualitative and quantitative approaches. In-depth investigation of phenomena, frequently via case studies or interviews, qualitative approaches offer important insights into environmental variables and human behavior. The use of numerical data analysis, quantitative approaches provide study conclusions and statistical validity. The knowledge of the HSCD dynamics is enhanced by the distinct views offered by both qualitative and quantitative methodologies (Riera et al., 2023). Moreover, 24% of the studies are devoted to deterministic models, representing situations with well-specified parameters and no uncertainty. Deterministic models are useful for comprehending baseline circumstances and for forecasting future events. Diverse phases of the HSCD exhibit variable amounts, falling into the non-deterministic category, e.g., demand. Uncertainties related to ST, TP, DIS, and EU are investigated by 18%, 20%, 11%, and 13% of studies, respectively. These differences underscore the necessity for robust models that can account for these uncertainties.

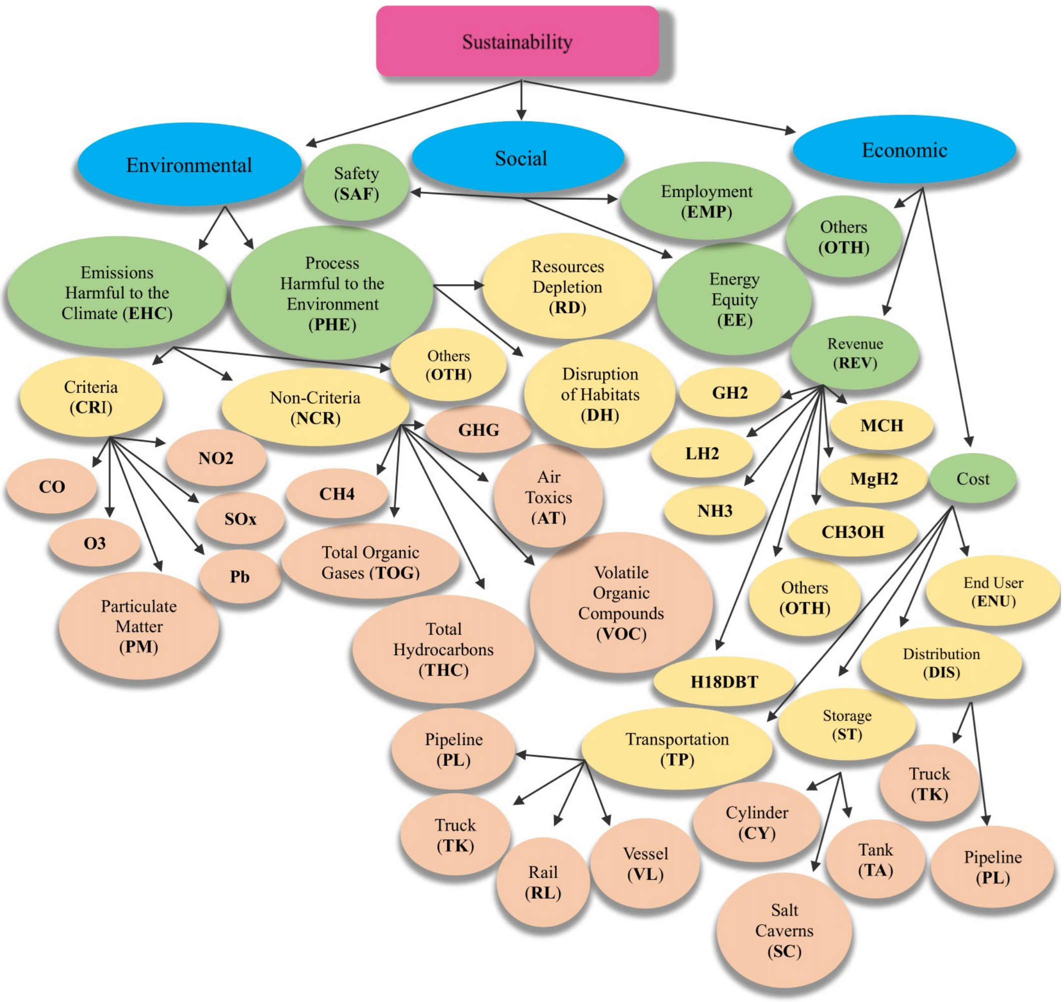

Figure 4. Structure and codes for hydrogen supply chain downstream sustainability

2.3 HSCD Sustainability

Figure 4 shows sustainability includes environmental, social, and economic aspects (Ghahremanlou and Kubiak, 2020). Subsequently, the environmental aspect encompasses both emission harmful to the cli- mate (EHC) and process harmful to the environment (PHE) (Wang et al., 2022). The EHC entails criteria (CRI), i.e., carbon monoxide (CO), oxides of nitrogen (NO_2), particulate matter (PM), ozone (O_3), oxides of sulfur (SO_x), and Lead (Pb) and non-criteria (NCR), i.e., total organic gases (TOG), volatile organic compounds (VOC), total hydrocarbons (THC), methane (CH_4), air toxics (AT), and greenhouse gases (GHG); the rest of the EHC is considered under others (OTH), i.e., fuel consumption, (U.S. Department of Energy, 2023*a*). Wang et al. (2022) categorize PHE into resource depletion (RD) and destruction of habitats (DH).

Blohm and Dettner (2023) divide social aspect into three factors, employment (EMP), safety (SAF), and energy equity (EE). On the other hand, the economic element is analyzed from cost, revenue (REV), and others (OTH), i.e., profit and net present value (Ogumerem et al., 2018). The sources of revenue in the HSCD are selling metal hydrolysis (M_gH_2), methylcyclohexane (MCH), methanol (CH_3OH), gaseous hydrogen (GH_2), ammonia (NH_3), and perhydro-dibenzyltoluene ($H_{18}DBT$). Moreover, the costs involved are transportation (TP), storage (ST), distribution (DIS), and end user (EU) (Le Duigou et al., 2017). Lahnaoui et al. (2018) further detail TP into pipelines (PL), trucks (TK), rails (RL), and vessels (VL). Likewise, for storage (STO) they consider tanks (TA), cylinders (CY), and salt caverns (SC), and for distribution (DIS) just pipelines (PL) and trucks (TK).

Table 3 provides a comparative analysis of this paper with relevant systematic reviews from the sustainability point of view. With 27% and 29%, respectively, CO and NO_2 make considerable contributions among CRI subcategories. However, CH4 and GHGs, in particular, are the NCR that accounts for 38% and 56% review papers, respectively. Nevertheless, there is still a significant knowledge gap regarding the effects of process related emissions considering none of the CRI and NCR have been studied in more than 60% of the review papers. Furthermore, RD and DH being incorporated in 7% and 4% respectively, indicates a significant research gap in the current body of the PHE.

Remarkably, studying revenue generation from hydrogen and its various forms, e.g., LH_2 is not being addressed by any of the papers. However, this is the primary motive for for-profit companies to invest in HSCD. None of the storage, transportation, distribution, end user, and other costs are studied by more that 40% of the papers, while their analysis provides insights towards competitiveness of hydrogen in comparison to other energies. Additionally, 27% of the conversations that center on employment opportunities and energy equity, the major social benefits, suggests the hydrogen industry has a significant ability to support job and energy access development. One of the main concerns is safety, which has received 60% of the researchers' attention. In order to ensure the hydrogen sector creates job opportunities as well as supports safe working conditions, and promotes fair access to clean energy supplies, it is imperative that these social factors be addressed as they have a direct impact on communities (Almaraz et al., 2023).

To accomplish what we aimed in the last row of Tables 1, 2, and 3 accumulatively, and add to the body of knowledge related to systematic review, we: (i) consolidate the entire body of research focusing on the HSCD in Canada, (ii) carry out bibliometric analysis to evaluate the performance of papers and their hosting journals, (iii) conduct a systematic examination of the selected papers from: (a) the HSCD components and geographical focus, (b) decision levels and research characteristics, and (c) sustainability dimensions, (iv) conclude our findings by providing forward horizons and recommendations for further investigations from academic, policymaking, and practitioner standpoints.

3. Methodology

To gather the body of literature for this review, we focus on peer-reviewed journals in the domains of supply chain, energy, sustainability, and engineering through searching publication portals, i.e., ScienceDirect, Elsevier, Scopus, IEEE Xplore, and SpringerLink. The wide reach of these platforms serve as a justification for this approach. We applied "Hydrogen Supply Chain", "Hydrogen Distribution", "Hydrogen Supply Chain Transportation", "Hydrogen Supply Chain Storage", "Hydrogen Supply Chain Network Design", "Refueling Station", "Hydrogen Supply Chain Sustainability", as well as "Decision Level" as keywords to perform our systematic searches. To direct our search to Canada, geographical names e.g., Ontario, Alberta, British Columbia, that denote Canadian provinces and territories were paired with the keywords through using the Boolean operator AND. To further enhance our search, we looked through the references of papers we found in our primary search where we used keywords and locations. Then, documents like theses, conference papers, reports, were excluded to maintain the concentration on English peer-reviewed journals. Our search resulted in a total of 39 original papers, which will be analyzed using the framework we employed in Section 2 for evaluating the review pa- pers. However, we provide some insights about the trends in the Canadian HSCD by conducting a brief bibliometric analysis on the 39 papers in this section.

Table 3. Analysis of relevant systematic review papers (published from February 2022 to October 2023) from sustainability dimension

#	Reference	Sustainability														
		Environmental														
		EHC													PHE	
		CRI						NCR								
		CO	NO_2	PM	O_3	SO_x	Pb	TOG	VOC	THC	CH_4	AT	GHG	OTH	RD	DH
1	Alsaba et al. (2023)															
2	Amirthan and Perera (2023)															
3	Aslannezhad et al. (2023)												X		X	
4	Beschkov and Ganev (2023)							X	X	X	X		X	X	X	X
5	Chen et al. (2023)															
6	Clematis et al. (2023)															
7	Feng et al. (2023)		X													
8	Ghorbani and Zendehboudi (2023)												X			
9	Gorji (2023)	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
10	Hren et al. (2023)	X	X	X	X	X	X	X	X	X	X		X			
11	Kim et al. (2023)	X	X													
12	Kindra et al. (2023)													X		
13	Kumar et al. (2023)	X	X	X	X	X	X	X	X	X	X	X	X	X		
14	Lagioia et al. (2023)							X			X	X	X			
15	M et al. (2023)												X			
16	Ma, Sun, Xue, Zhang and Chen (2023)	X	X			X				X	X		X			
17	Ma, Zhao, Wang, Li and Zhou (2023)												X	X		
18	Muthukumar et al. (2023)										X		X			
19	Negro et al. (2023)							X	X	X	X	X	X			
20	Qureshi et al. (2023)	X	X			X				X	X		X	X		
21	Riera et al. (2023)	X			X		X				X					
22	Sgarbossa et al. (2023)	X	X	X	X	X	X	X	X	X	X	X	X			
23	Stöhr et al. (2023)		X							X	X		X			
24	Tan et al. (2023)												X			
25	Zhang et al. (2023)		X										X			
26	Berstad et al. (2022)		X							X	X		X			
27	de las Nieves Camacho et al. (2022)												X			
28	Kim et al. (2022)															
29	Lee et al. (2022)													X		
30	Li et al. (2022)												X			
31	Otto et al. (2022)															
32	Raad et al. (2022)			X		X					X		X			
33	Rasul et al. (2022)															
34	Schrotenboer et al. (2022)															
35	Shi et al. (2022)															
36	Shin (2022)															
37	Simanullang and Prost (2022)	X	X		X	X	X				X		X			
38	Tahan (2022)															
39	Tarkowski and Uliasz-Misiak (2022)	X												X		
40	Thiyagarajan et al. (2022)												X			
41	Ustolin et al. (2022)										X		X			
42	Xu et al. (2022)															
43	Zhang et al. (2022)	X														
	Total (%)≈	27	29	11	18	16	16	18	16	22	38	13	56	18	7	4
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

#	Reference	Sustainability																					
		Economic																			Social		
		REV								Cost													
										ST			TP				DT						
		LH_2	GH_2	NH_3	CH_3OH	MCH	$H_{18}DBT$	MgH_2	OTH	TA	CY	SC	PL	TK	RL	VL	PL	TK	ENU	OTH	EMP	SAF	EE
1	Alsaba et al. (2023)									X						X							
2	Amirthan and Perera (2023)											X										X	
3	Aslannezhad et al. (2023)									X		X	X	X			X	X				X	
4	Beschkov and Ganev (2023)												X	X	X	X	X	X		X			
5	Chen et al. (2023)										X		X	X		X			X		X	X	
6	Clematis et al. (2023)																				X	X	X
7	Feng et al. (2023)									X	X	X										X	
8	Ghorbani and Zendehboudi (2023)																				X	X	
9	Gorji (2023)																				X	X	
10	Hren et al. (2023)									X	X	X	X	X	X	X	X	X	X		X	X	
11	Kim et al. (2023)																					X	
12	Kindra et al. (2023)									X	X	X	X	X	X	X	X	X	X		X	X	X
13	Kumar et al. (2023)									X	X	X	X	X	X	X	X	X	X		X	X	X
14	Lagioia et al. (2023)									X	X	X	X	X	X	X	X	X	X	X			
15	M et al. (2023)																				X		
16	Ma, Sun, Xue, Zhang and Chen (2023)																				X	X	
17	Ma, Zhao, Wang, Li and Zhou (2023)									X	X	X	X	X	X								
18	Muthukumar et al. (2023)									X									X			X	
19	Negro et al. (2023)																						
20	Qureshi et al. (2023)									X	X	X	X					X	X			X	
21	Riera et al. (2023)																					X	
22	Sgarbossa et al. (2023)																						
23	Stöhr et al. (2023)																					X	
24	Tan et al. (2023)									X			X	X								X	
25	Zhang et al. (2023)																						
26	Berstad et al. (2022)																					X	
27	de las Nieves Camacho et al. (2022)																				X	X	X
28	Kim et al. (2022)																						
29	Lee et al. (2022)									X	X	X	X	X		X			X				
30	Li et al. (2022)												X										
31	Otto et al. (2022)																						
32	Raad et al. (2022)									X									X			X	
33	Rasul et al. (2022)																						
34	Schrotenboer et al. (2022)																				X	X	
35	Shi et al. (2022)																						
36	Shin (2022)																					X	X
37	Simanullang and Prost (2022)																					X	
38	Tahan (2022)												X									X	
39	Tarkowski and Uliasz-Misiak (2022)									X						X			X				
40	Thiyagarajan et al. (2022)																						
41	Ustolin et al. (2022)																						
42	Xu et al. (2022)																						
43	Zhang et al. (2022)																						
	Total (%)≈	0	0	0	0	0	0	0	0	36	27	29	36	27	18	27	16	13	22	4	27	60	27
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 5 illustrates patterns in the temporal order of the 39 selected papers, utilizing four blocks, each representing a distinct time period. The green block, showing the years 2006-2008, is the least published period for the Canadian HSCD researchers with 8% of the total papers. During 2009-2013 and 2014-2018 there are same amount of publications, 28% of the papers, which is over three times more than publications from 2006 to 2008. There is another growth in the quantity of papers between the years 2019-2023, making up 36% of all publications. Overall, as demonstrated, over the past 18 years there has been a discernible increase in academic publishing regarding the Canadian HSCD. This is a sign of the intensive efforts towards further understanding the HSCD in Canada.

Figure 6 demonstrates which journals have published the 39 selected papers by exhibiting the information as cylinders, with each cylinder denoting a distinct journal. The *International Journal of Hydrogen Energy*, symbolized by an orange cylinder, accounts for a sizable 64% of the selected papers. Then, under the heading Others, a number of journals are gathered, *Mining*, *Journal of Power Sources*, *Energies*, *Energy Policy*, *Renewable and Sustainable Energy Reviews*, and *Renewable Energy Focus*, each of which just published one of the papers. This group, which is represented in yellow, makes up about 17% of the papers. The *Journal of Cleaner Production* makes up 13% of the total publications. Finally, *Energy Conversion Management* with just 6% of the papers, represents the smallest amount of publications.

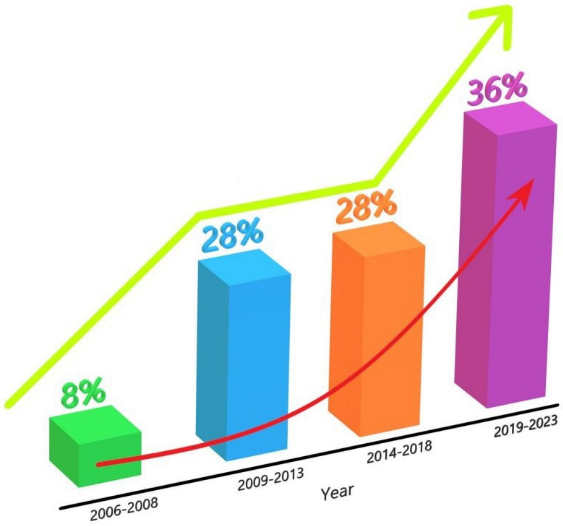

Figure 5. Chronological pattern in the selected papers

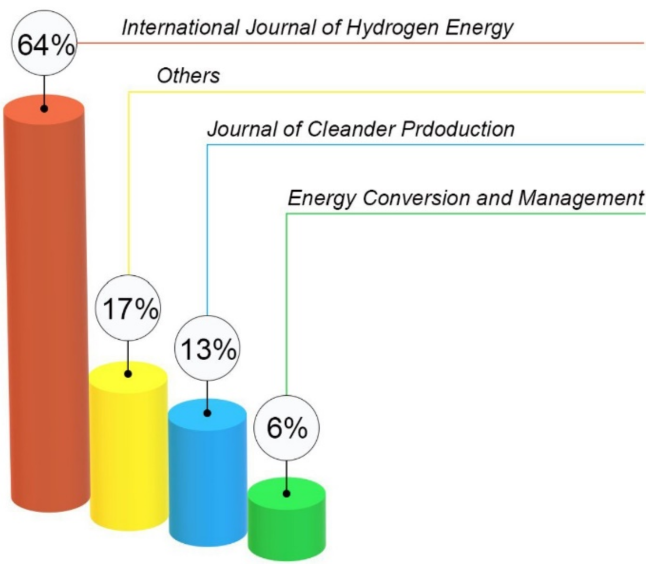

Figure 6. Dispersion of selected papers across their corresponding journals

4. Results and Discussion

4.1 Hydrogen Supply Chain Downstream (HSCD) Dimension

Table 4 presents the results of an analysis of 39 selected papers that focus on the HSCD in Canada. 74% of the publications examined pipeline transportation, making it the most studied mode. The reason for the lack of research may be due to the high initial construction costs of pipelines (Kim et al., 2022). However, due to the importance of pipelines as the most secure and ecologically friendly with a delivery efficiency of more than 99%, this makes them an excellent choice for transporting substantial amounts of hydrogen over long distances (Kim et al., 2022). The majority of large Canadian cities are served by significant crude oil and natural gas pipelines, which are typically subterranean and operate in both inhabited and isolated locations (Natural Resources Canada, 2023). For example, British Columbia include major pipelines, e.g., Trans Mountain Pipeline, Coastal GasLink Pipeline, Pembina's NEBC/Western Pipeline system, Enbridge's Westcoast Pipeline; please see Canada Energy Regulator (2021) for a complete list of pipelines in Canada. Therefore, more research needs to be conducted on pipelines, especially to enable evaluation of available pipelines in the country for hydrogen transportation.

According to Table 4, only 49%, just under half of the examined papers, have reviewed trucking as one of the methods for hydrogen transportation. This lack of study might be due to its limited capacity for energy transmission that prevents scalability, being more sensitive to distance travelled, which raises costs (Cui and Aziz, 2023). However, trucking is a particularly advantageous mode of transportation for hydrogen because it can reach remote areas with limited transportation access, lowering storage costs (Oh et al., 2023). Transport Canada (2021*b*) announces the primary means of transporting both freight and people throughout Canada is by roads, which links every region from coast to coast. British Columbia, Alberta, Ontario, and Quebec are the primary hubs for this industry Statistics Canada (2021). Therefore, further research, with focus on employing existing roads, e.g., Alberta 1 and 2, is required.

Only 18% of the analyzed papers, focused on railway as the transportation mode for hydrogen. The lack of research may be due to the fact that transporting hydrogen via a railway tube trailer results in higher carbon emissions than those of tanker trucks, and has restricted availability between certain grids (Seo et al., 2020; Erdoğan et al., 2023). However, Seo et al. (2020) claims that railway transportation of hydrogen has a lower cost than road transportation. The two major freight rail companies in Canada, Canadian National Railway Company and Canadian Pacific Railway, own the majority of the country's 46,000 miles of rails, e.g., Algoma Central Railway in Ontario. Therefore, it is essential for researchers to evaluate the potential of rail infrastructure in various provinces, regions, and territories in Canada.

Vessels are considered solely in 26% of papers. Navigating environmental effects of burning marine diesel oil and energy-intensive procedures for preserving carrier conditions may be the reason behind this lack of research (Noh et al., 2023). However, large cargo capacities and transport of significant volumes of hydrogen can be considered as advantages of vessels. They are, therefore, a cost-effective option for bulk transportation. Transporting hydrogen can be realized through a variety of forms, including liquid or compressed gas, depending on the infrastructure and particular needs (Aglen and Hofstad, 2022). According to Transport Canada (2019), over 550 port facilities exist in Canada, with 17 of them being Canada Port Authorities, which manage over 60% of the country's tonnage of commercial cargo. Furthermore, in terms of performance, nearly $200 billion of Canada's imports and exports were processed by ports in 2017, and during the previous ten years, container throughput has increased by 35%. Thus, future research endeavors could focus more closely on advancing vessel technologies to utilize various ports across Canada, e.g., in Nova Scotia, the port of Halifax, and in Newfoundland and Labrador, the port of Argentia.

Table 4 shows that of 39 papers, only 5% of the papers delved into the gaseous form of hydrogen, while 3% of papers focused on liquid hydrogen storage. A notable research gap in this field is highlighted by the surprising lack of studies that have examined the combination of gaseous and liquid storage (0%). This gap in research may be due to the low density of gaseous hydrogen, even when compressed to high pressures of up to 700 bar (Seo et al., 2023). However, according to Klopčič et al. (2023), gaseous hydrogen has a faster filling and extraction time than metal hydride storage and a high gravimetric storage capacity of 100% at ambient conditions that requires less energy for compression than liquid hydrogen storage. Likewise, there is a huge gap in research on liquid hydrogen, which may be due to its extremely low liquefaction temperature under atmospheric pressure (Moradi and Groth, 2019).

Table 4. Analysis of the reviewed papers from HSCD components dimension

		Transportation				Storage													Distribution		End User			
						Physical			Chemical						Technique									
									Liquid				Solid											
#	Reference	PL	TK	RL	VL	GH_2	LH_2	GH_2+LH_2	NH_3	CH_3OH	MCH	$H_{18}DBT$	MgH_2	OTH	TA	CY	SC	PL	TK	TP	ID	RE	Location
1	Davis et al. (2023)	x																					Alberta
2	Ghorbani et al. (2023)	x	x		x																		Newfoundland and Labrador
3	Hui et al. (2023)	x																					Ontario
4	Maynard and Abdulla (2023)	x	x			x												x		x			Ontario
5	Wu and Zhong (2023)														x			x	x	x		x	Canada
6	Cunanan et al. (2022)	x			x										x			x	x	x		x	Nova Scotia
7	Okunlola et al. (2022)	x			x																		Canada
8	Yaïci and Longo (2022)	x	x	x														x	x	x			Ontario
9	Aydin et al. (2021)								x						x		x	x		x	x		Ontario
10	Shamsi et al. (2021)	x	x															x		x	x		Ontario
11	Talebian et al. (2021)	x	x												x			x				x	British Columbia
12	Herdem et al. (2020)																x						Ontario
13	Al-Zakwani et al. (2019)	x											x		x	x		x	x	x	x		Ontario
14	Talebian et al. (2019)	x													x	x				x		x	Alberta
15	Sorgulu and Dincer (2018)								x						x							x	Ontario
16	Talebian et al. (2018)		x	x											x			x	x	x			British Columbia
17	Mukherjee et al. (2017)	x			x				x					x			x	x		x		x	Ontario
18	Perera et al. (2017)	x	x	x																			British Columbia
19	Bicer et al. (2016)	x													x				x	x	x		Ontario
20	Ghandehariun and Kumar (2016)	x			x				x											x	x	x	Alberta
21	Khalid et al. (2016)	x																		x			Ontario
22	Olateju et al. (2016)	x								x					x			x	x	x			Alberta
23	Sean B. Walker and Elkamel (2016)	x	x																				Ontario
24	Sean B. Walker and Mukherjee (2016)	x	x						x	x					x			x	x	x			Ontario
25	Ahmadi and Kjeang (2015)		x		x										x			x	x	x			British Columbia/Alberta
26	Cetinkaya et al. (2012)	x			x										x	x		x		x		x	Ontario
27	Cuda et al. (2012)			x																x		x	Ontario
28	Hacatoglu et al. (2012)		x						x				x			x		x	x	x	x		Ontario
29	Liu et al. (2012)	x	x												x				x	x			Ontario
30	Hajimiragha et al. (2011)	x	x												x			x	x	x	x	x	Ontario
31	J. Adam Holbrook and Cassidy (2010)								x	x					x			x	x	x	x		British Columbia
32	Gnanapragasam et al. (2010)	x													x					x	x		Ontario
33	Marin et al. (2010a)	x	x	x											x			x	x	x	x		Ontario
34	Marin et al. (2010b)	x	x	x	x								x		x			x	x	x			Ontario
35	Naterer et al. (2010)	x	x	x	x		x		x	x			x					x	x	x	x		Ontario
36	Lubis et al. (2009)					x											x	x	x	x		x	Ontario
37	Taljan et al. (2008)	x	x		x				x						x	x		x		x	x		Ontario
38	Granovskii et al. (2006)	x	x										x		x			x	x	x	x		Ontario
39	Zamel and Li (2006)	x	x						x	x										x			Ontario
	Total (%)≈	74	49	18	26	5	3	0	26	13	0	0	13	3	54	13	10	59	46	77	33	28	
	This paper	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	

Furthermore, there is a considerable gap in research regarding different types of hydrogen carriers, such as ammonia being most preferred and studied by 26% of the papers. This lack of research could be because of NH_3 high toxicity, which prevents it from being used for hydrogen storage (Klerke et al., 2008). However, a variety of energy sources, such as natural gas, coal, biomass, and renewable energy, can be used to manufacture ammonia (Moradi and Groth, 2019). Furthermore, only 13% of the studies discussed methanol-based storage, suggesting a consistent but rather low level of attention to this chemical solution. However, CH_3OH has the highest density of the four liquid hydrogen carriers. Also, methanol can be transported and kept in liquid form at ambient temperature, unlike ammonia, which must be held at low temperatures (Song et al., 2022). The lack of specialized studies examining storage solutions incorporating methylcyclohexane (*MCH*) and perhydro-dibenzyltoluene ($H_{18}DBT$) suggests uncharted ground and research gaps in these particular chemical storage media for hydrogen. However, *MCH* may be easily incorporated into the current liquid fuel infrastructure (Obara, 2019). Furthermore, the substantial gap in research regarding $H_{18}DBT$ may be due to its high kinematic viscosity under ambient circumstances. However, the advantage of $H_{18}DBT$ is a high hydrogen storage capacity (Kwak et al., 2021). Moreover, entirely 13% of reviewed papers studied metal hydrides as a method of hydrogen storage. However, higher volumetric energy densities and improved safety characteristics make M_gH_2 a superior hydrogen storage solution when compared to other methods Klopˇciˇc et al. (2023). Other chemical compounds of hydrogen, ammonia borane (NH_3BH_3), are less popular; perhaps explained in part by only 3% of the reviewed papers focusing on them (Moradi and Groth, 2019). Therefore, there are needs for further study in order to identify the benefits and drawbacks of every hydrogen carrier from various aspects, e.g., cost and storage density.

Regarding methods of storage, storage in tanks was the focus of 54% of the reviewed papers. However, according to Sens et al. (2022), tanks are essential for storing hydrogen because they can be customized to meet different needs at varying points in the supply chain. On the other hand, only 13% and 10% examined storage in cylinders and salt caves, respectively. The reason for this huge lack of research on cylinders may be due to low efficiency (Züttel, 2004). However, flexibility and extensive use of high-pressure gas cylinders make them a desirable option for hydrogen storage. Furthermore, the gap in research on salt caverns may be due to the complex geomechanical analysis needed to design them. However, according to Abreu et al. (2023), high injection and withdrawal rates are provided by salt caverns, which make storage operations more effective. Moreover, the gap in research on salt caverns may be due to the complex geomechanical analysis needed to design them. However, high injection and withdrawal rates are provided by salt caverns, which make storage operations more effective (Abreu et al., 2023). Hence, additional research is required on these three storage methods.

A total of 77% of reviewed papers studied the application of hydrogen in transportation. Hydrogen has enormous potential to transform many forms of transportation, e.g., vehicles, trains, ships, aircraft. Hydrogen may be consumed in internal combustion engines to power cars or used in fuel cells to produce electricity. Vehicles running on hydrogen are very effective and produce very little pollution, which helps to lessen the need for fossil fuels (Sharma and Ghoshal, 2015). Furthermore, only 33% of studies focused on the application of hydrogen in industries. However, hydrogen is needed in various industries, e.g., in the aerospace sector as rocket propellant, in the pharmaceutical industry to help in drug development, in metallurgy to cut and weld metals, in the electronics industry to make semiconductor materials (Okolie et al., 2021). In Canada, industrial activity is a major contributor to air pollution. It releases a range of pollutants, e.g., carbon monoxide, contributing to global warming. Moreover, 28% of the studies focused on the use of hydrogen in the residential sector. This minimal attention from researchers may be due to significant costs, including a levelized energy price that is higher than ordinary grid rates Maestre et al. (2022). Yet, a variety of specifically designed residential buildings can be supplied with heat and power in both grid-connected and off-grid locations. Therefore, the recommended future direction of hydrogen application is to evaluate hydrogen, especially renewable hydrogen, as a substitution fuel in most air pollutants applications, especially in remote and indigenous Canadian communities that mainly consume diesel as residential fuel (Government of Canada, 2023).

To provide a clear insight as to the focus of the reviewed papers geographically, we projected the information under location column in Table 4, on the map in Figure 7. This figure illustrates that solely British Columbia, Alberta, Ontario, Nova Scotia, and Newfoundland and Labrador have been studied by 4, 4, 26, 1, and 1 papers (excluding papers #5, 7, and 25 not focusing just on province), respectively. Hydrogen generation from biomass, natural gas with carbon capture and storage, and renewable electricity have great promise in British Columbia. Also, the province has established a network of hydrogen refueling stations, a low-carbon fuel standard, and a mandate for zero-emission vehicles. In addition to having the largest carbon capture and storage facility in the world, Alberta is a significant producer of hydrogen from natural gas. The province can service both domestic and international markets by utilizing its current hydrogen infrastructure and knowledge. Hydrogen production from renewable electricity, particularly from offshore wind and tidal energy, has great potential in Nova Scotia. A high potential for hydrogen production from renewable electricity, particularly from wind and hydropower, exists in Newfoundland and Labrador. However, none of the other Canadian provinces and territories has been studied, while Saskatchewan is a leading producer of hydrogen from coal, natural gas, and renewable electricity. Similarly, Manitoba and Quebec can use biomass and hydroelectricity to produce hydrogen. In contrast, New Brunswick can utilize renewable electricity to produce hydrogen. Hydrogen may be produced in Prince Edward Island employing biomass and wind energy. Finally, the Yukon, the Northwest Territories, and Nunavut can generate hydrogen from biomass and renewable electricity. Please see Figure 8 for the significant role considered for each province to meet the global environmental commitments of Canada in the national hydrogen strategy (Natural Resources Canada, 2020).

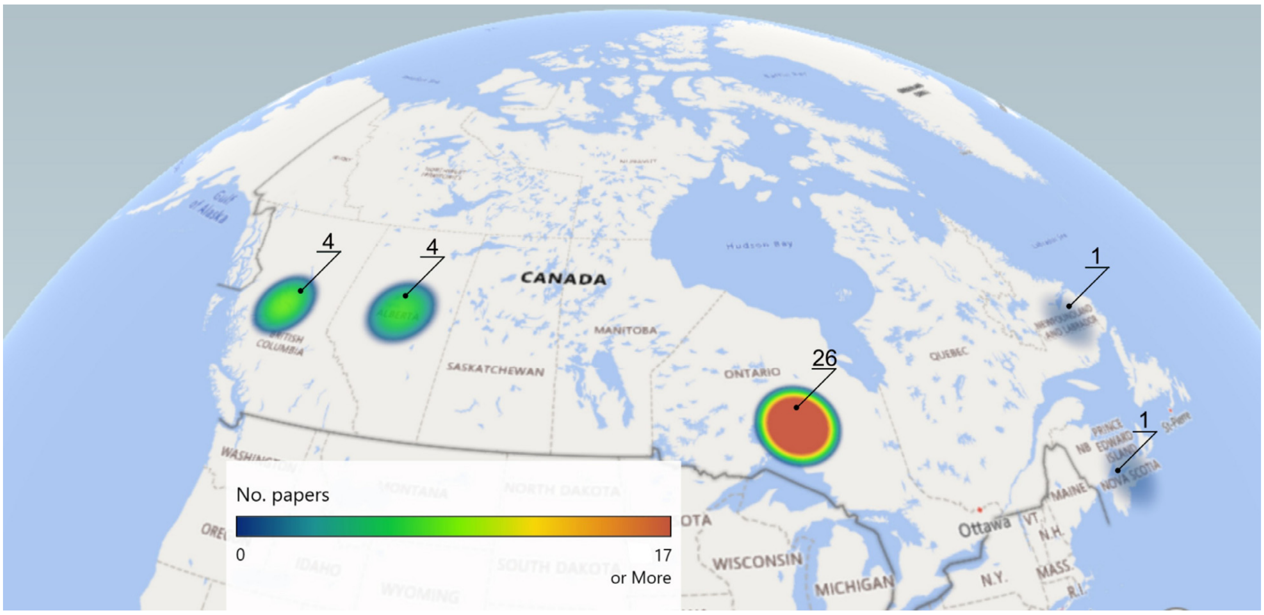

Figure 7. Province-specific distribution of reviewed papers

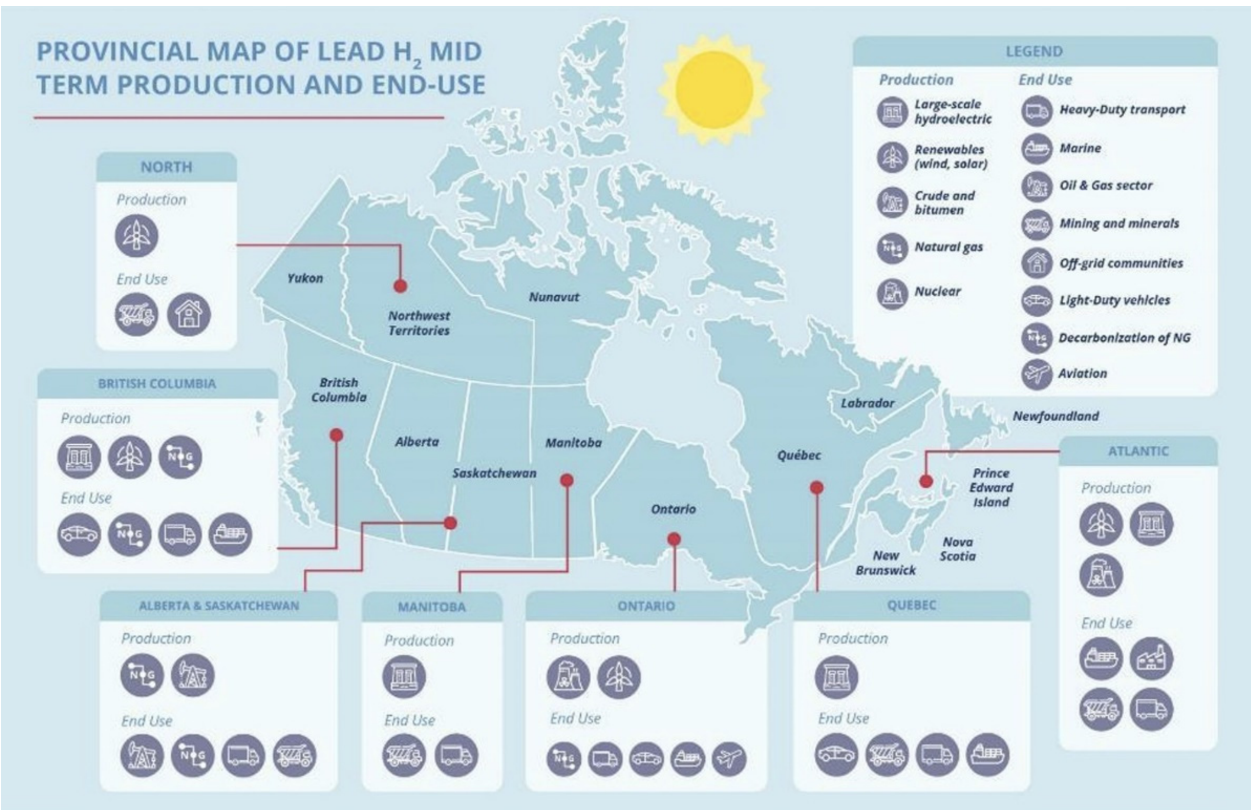

Figure 8. Hydrogen Strategy of Canada (Natural Resources Canada, 2020)

Table 5. Analysis of the reviewed papers from decision level and research characteristics dimension

#	Reference	Decision Level																	
		Strategic																	
		INV				FLC			CSC				FAL			CAE			
		ST	TP	DIS	EU	ST	TP	EU	ST	TP	DIS	EU	ST	TP	EU	ST	TP	DIS	EU
1	Davis et al. (2023)																		
2	Ghorbani et al. (2023)																		
3	Hui et al. (2023)																		
4	Maynard and Abdulla (2023)	X	X				X		X			X							
5	Wu and Zhong (2023)			X		X		X	X	X		X					X		
6	Cunanan et al. (2022)					X			X					X					
7	Okunlola et al. (2022)																		
8	Yaïci and Longo (2022)	X	X			X		X	X										
9	Aydin et al. (2021)	X			X	X		X	X										
10	Shamsi et al. (2021)		X		X			X	X			X							
11	Talebian et al. (2021)	X																	
12	Herdem et al. (2020)	X		X				X	X										
13	Al-Zakwani et al. (2019)	X			X	X	X							X		X	X	X	
14	Talebian et al. (2019)	X		X		X		X					X						
15	Sorgulu and Dincer (2018)	X			X				X			X					X		
16	Talebian et al. (2018)	X			X	X	X	X	X			X	X						
17	Mukherjee et al. (2017)					X	X	X	X	X	X	X						X	X
18	Perera et al. (2017)					X													
19	Bicer et al. (2016)						X		X										
20	Ghandehariun and Kumar (2016)	X			X			X	X			X							
21	Khalid et al. (2016)	X																	
22	Olateju et al. (2016)																		
23	Sean B. Walker and Elkamel (2016)	X				X		X				X							
24	Sean B. Walker and Mukherjee (2016)							X											
25	Ahmadi and Kjeang (2015)	X	X			X			X										
26	Cetinkaya et al. (2012)	X	X		X	X		X		X	X	X							
27	Cuda et al. (2012)	X	X	X		X											X		
28	Hacatoglu et al. (2012)	X	X	X		X			X			X							X
29	Liu et al. (2012)		X																
30	Hajimiragha et al. (2011)					X										X			
31	J. Adam Holbrook and Cassidy (2010)				X		X	X	X			X							
32	Gnanapragasam et al. (2010)	X		X		X		X		X									
33	Marin et al. (2010a)	X				X			X										
34	Marin et al. (2010b)							X				X							
35	Naterer et al. (2010)	X			X			X	X		X	X							
36	Lubis et al. (2009)	X										X							X
37	Taljan et al. (2008)	X	X				X	X	X			X							
38	Granovskii et al. (2006)	X						X	X	X							X	X	
39	Zamel and Li (2006)							X	X										
	Total (%)≈	56	23	15	23	44	18	49	51	13	8	38	5	5	0	5	13	8	8
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

#	Reference	Decision Level																
		Strategic																
		CAR				TES				TEU				TED				
		ST	TP	DIS	EU	ST	TP	DIS	EU	ST	TP	DIS	EU	ST	TP	DIS	RFS	OUT
1	Davis et al. (2023)																	
2	Ghorbani et al. (2023)																	
3	Hui et al. (2023)																	
4	Maynard and Abdulla (2023)							X										
5	Wu and Zhong (2023)							X										
6	Cunanan et al. (2022)			X		X		X										
7	Okunlola et al. (2022)																	
8	Yaïci and Longo (2022)					X	X	X										
9	Aydin et al. (2021)																	
10	Shamsi et al. (2021)					X		X	X									
11	Talebian et al. (2021)																	
12	Herdem et al. (2020)					X												
13	Al-Zakwani et al. (2019)	X	X			X	X		X									
14	Talebian et al. (2019)			X														
15	Sorgulu and Dincer (2018)																	
16	Talebian et al. (2018)					X	X	X	X									
17	Mukherjee et al. (2017)					X												
18	Perera et al. (2017)		X															
19	Bicer et al. (2016)			X			X											
20	Ghandehariun and Kumar (2016)	X							X									
21	Khalid et al. (2016)																	
22	Olateju et al. (2016)				X				X									
23	Sean B. Walker and Elkamel (2016)																	
24	Sean B. Walker and Mukherjee (2016)	X				X	X											
25	Ahmadi and Kjeang (2015)					X	X	X										
26	Cetinkaya et al. (2012)	X			X		X		X									
27	Cuda et al. (2012)				X													
28	Hacatoglu et al. (2012)					X		X										
29	Liu et al. (2012)								X									
30	Hajimiragha et al. (2011)				X	X			X									
31	J. Adam Holbrook and Cassidy (2010)	X	X			X												
32	Gnanapragasam et al. (2010)		X		X		X											
33	Marin et al. (2010a)						X											
34	Marin et al. (2010b)																	
35	Naterer et al. (2010)					X												
36	Lubis et al. (2009)																	
37	Taljan et al. (2008)	X																
38	Granovskii et al. (2006)		X		X		X											
39	Zamel and Li (2006)	X					X											
	Total (%)≈	18	13	8	15	33	28	21	21	0	0	0	0	0	0	0	0	0
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

#	Reference	Decision Level					Research Characteristic							
		Tactical				Operational				UCF				
							RAP				NDT			
		PJP	POP	INM	DIS		MMM	OPT	OTH	DET	ST	TP	DIS	EU
1	Davis et al. (2023)													
2	Ghorbani et al. (2023)													
3	Hui et al. (2023)													
4	Maynard and Abdulla (2023)		X				X	X				X	X	
5	Wu and Zhong (2023)				X	X	X	X		X				
6	Cunanan et al. (2022)						X	X		X				
7	Okunlola et al. (2022)								X					
8	Yaïci and Longo (2022)				X		X	X						
9	Aydin et al. (2021)				X	X			X					
10	Shamsi et al. (2021)				X	X	X	X		X				
11	Talebian et al. (2021)					X	X	X		X				
12	Herdem et al. (2020)								X					
13	Al-Zakwani et al. (2019)				X	X			X					
14	Talebian et al. (2019)		X			X			X					
15	Sorgulu and Dincer (2018)				X	X			X					
16	Talebian et al. (2018)				X	X	X	X		X				
17	Mukherjee et al. (2017)				X	X	X	X		X				
18	Perera et al. (2017)						X	X		X				
19	Bicer et al. (2016)				X		X			X				
20	Ghandehariun and Kumar (2016)				X	X			X					
21	Khalid et al. (2016)				X	X	X	X		X				
22	Olateju et al. (2016)				X	X			X					
23	Sean B. Walker and Elkamel (2016)								X					
24	Sean B. Walker and Mukherjee (2016)				X				X					
25	Ahmadi and Kjeang (2015)				X				X					
26	Cetinkaya et al. (2012)				X	X		X						
27	Cuda et al. (2012)	X							X					
28	Hacatoglu et al. (2012)				X			X	X					
29	Liu et al. (2012)				X				X					
30	Hajimiragha et al. (2011)				X	X			X					
31	J. Adam Holbrook and Cassidy (2010)				X	X			X					
32	Gnanapragasam et al. (2010)				X				X					
33	Marin et al. (2010a)				X	X			X					
34	Marin et al. (2010b)				X				X					
35	Naterer et al. (2010)				X	X	X	X		X				
36	Lubis et al. (2009)				X				X					
37	Taljan et al. (2008)				X	X			X					
38	Granovskii et al. (2006)		X		X	X			X					
39	Zamel and Li (2006)				X	X			X					
	Total (%)≈	3	8	0	69	51	31	33	59	26	0	3	3	0
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X

4.2 HSCD Decision Levels and Research Characteristics Dimension

Table 5 presents a comparison between the reviewed papers from decision level and research characteristics perspectives. This indicates 56% of papers studied storage in the domain of investment. This may be due to the challenges associated with hydrogen storage, including the requirement for substantial space and infrastructure, safety issues arising from flammability and leakage, and energy losses during the process of converting back to electricity. However, storage is essential to the hydrogen economy because it helps to stabilize the supply of hydrogen and manage the erratic nature of renewable energy (Gordon et al., 2023*a*). There are opportunities for innovation and cooperation in hydrogen storage despite the industry's technological, financial, and environmental difficulties. Next, our research shows that only 23% and 15% of the research highlighted investment on transportation and distribution, which may be due to high costs and complicated infrastructure needs, e.g., specialized vessels, trucks, and pipelines, that may prevent hydrogen from being widely available and inexpensive. Although Gordon et al. (2023*a*) claim that in the hydrogen economy, transportation plays a crucial role in determining the cost, environmental effect, and delivery of hydrogen. It indicates a balanced strategy to fulfill market needs and guarantee timely supply to customers. Finally, just 23% of papers focused on financial commitment to developing refueling stations where customers' demand is met, which may be due to the lack of societal acceptance and customer buy-in. However, utilizing low-carbon hydrogen applications can result in lower energy expenses and emissions. Therefore, conducting research about investment in the HSCD in Canada is a fertile research avenue.

Within the strategic domain, just 49% of the papers investigated locations of refueling stations, which can be the result of a significant level of uncertainty in the adoption of hydrogen technologies and market development. It is critical to position hydrogen refueling stations strategically for safety, environmental effect, market growth, and customer satisfaction, which entails being close to customers (Sgarbossa et al., 2023). Following this, 44% of the papers examined locations for storage facilities, an important factor, because the management of demand fluctuation can be easier handled by strategically located storage facilities that efficiently store inventory. Finally, the transportation domain of facility location was analyzed by only 18% of the total papers, although, the benefits of strategically placing transportation facilities leads to reduced distribution costs, enhanced environmental performance, and increased market penetration. Therefore, further research attention is required to address this class of strategic decisions.

Capacity selection for storage systems is studied by 51% of the papers, albeit storage capacity can provide stable support for both production level and human resource level (Isaac and Saha, 2023). The next most preferred capacity evaluation is of hydrogen refueling stations, studied in 38% of papers; however, by considering end-user demand, the capacity selection process for stations should utilize the capital for the development projects. Transportation and distribution capacities are explored by 13% and 8% of the papers, respectively. Nonetheless, it is important to reduce travel expenses and environmental emissions related to it. Furthermore, only 5%, 5%, and 0% of the papers delved into the decisions regarding allocation to storage facilities, transportation means, and refueling stations, respectively. In contrast, these decisions are significant to balancing the supply and demand for hydrogen. Likewise, it is vital to adjust the capacity for storage, transportation, distribution, and refueling stations according to the demand to enhance HSCD responsiveness, while none of them has been studied by over 18% of the papers. In a similar manner, technology selection, upgrading, and downgrading are not investigated by over 33% of the studies, despite the fact that technological adjustment enhance the HSCD sustainability. Therefore, additional research is needed to address capacity and technology selection and fluctuation, and facility allocations for the HSCD in Canada. Finally, decision regarding outsourcing various activities in the HSCD, e.g., transportation, has not been the focus of any of the papers. However, through the use of external suppliers' specialized expertise and capabilities, outsourcing may enhance a the HSCD's performance (Lahiri, 2016). Therefore, more research needs to be conducted on outsourcing aspects of the HSCD in Canada.

As for operational and distribution tactical decisions, they are addressed by 51% and 69% of the papers, respectively. On the other hand, tactical decisions about project planning, production planning, and inventory management are responded by 3%, 8%, and 0% of the studies. The viability of these decisions are impacted by data availability and quality, especially in large-scale HSCs. Conversely, the benefits of tactical and operational planning may lead to improved coordination and integration, lowering costs and risks through resource optimization, and more flexibility in responding to market circumstances. Thus, it is critical for additional attention to these levels of decisions.

Mathematical modeling and optimization are used by 31% and 33% of papers, respectively. However, mathematical modeling is a flexible tool that simplifies complicated phenomena through the practical applications of mathematics by enabling scenario analysis (Lingefj¨ard, 2006). Linear programming can address problems in resource allocation, production planning, transportation, and scheduling. Non-linear programming, e.g., demand fluctuations, and mixed integer non-linear programming, e.g., refueling station locations along with the amount delivered to them and the amount of demand in each station, would be helpful. Looking at the models closer, we realized 26% and 3% of the papers are deterministic and non-deterministic, respectively. Along this line, optimization helps making data-driven decisions. Furthermore, qualitative and quantitative, under others, are used by only 59% of the papers. When it comes to analyzing the HSCD, both qualitative and quantitative models have advantages. While quantitative models offer numerical solutions and optimization for weighing the costs, benefits, and effects of different alternatives, qualitative models offer insights into the structure and interactions of the system, which is helpful in generating scenarios (Riera et al., 2023). Therefore, there is a gap for more research in qualitative and quantitative studies, mathematical modeling and optimization, especially non-deterministic (e.g., stochastic, robust, and fuzzy) as this is inherent to the HSCD, being as yet in its infancy stage in Canada. Moreover, utilizing optimization and simulation software packages, e.g., CPLEX, GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), EIO-LCA (Economic Input-Output Life Cycle Assessment), and RETScreen (Renewable-energy and Energy-efficiency Technology Screening) would propose some future direction.

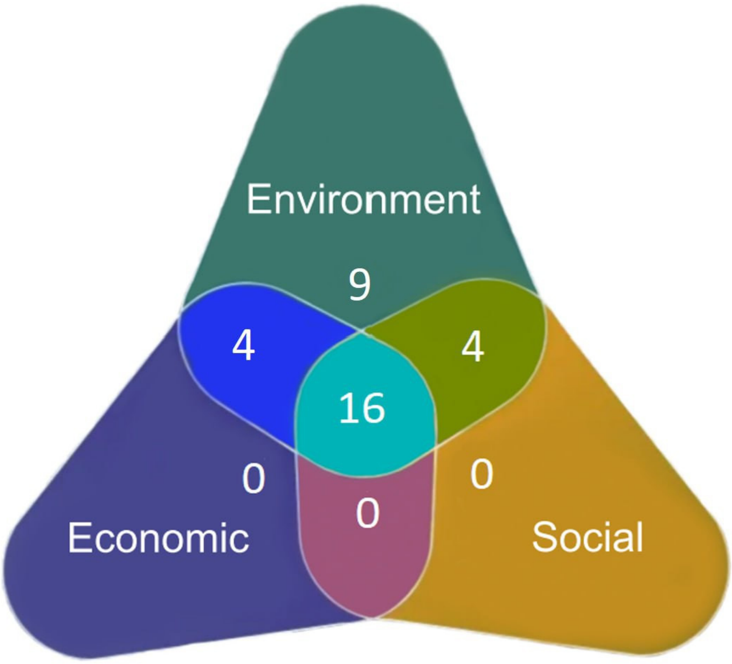

Figure 9. Analysis of reviewed papers from sustainability dimension

4.3 HSCD Sustainability Dimension

Figure 9 demonstrates the analysis of the 39 papers within the framework of sustainability, i.e., environ- mental, social, and economic (Ghahremanlou and Kubiak, 2020). All three dimensions of sustainability are evaluated by just 16 papers (written in the center of the figure), which is less than half of the total number of reviewed papers. The next most studied dimension is environment, 9 of the papers. The environmental-social, economic-social, and environmental-economic dimensions are investigated by 4, 0, and 4 papers, respectively. Furthermore, papers #1, 2, 3, 7, 11, and 23 did not consider sustainability at all, please see Table 6 for further details. However, Sakthi et al. (2024) emphasize studying all dimensions of sustainability, clarifying how significant it is to investigate each dimension and their combinations, and which are open directions for additional examinations in the HSCD in Canada.

Table 6 shows different components of the criteria air emissions that are harmful to the climate, CO, NO_2, Particulate Matter (PM), O_3, SO_x, Pb, are investigated by 28%, 41%, 8%, 13%, 23%, 10%, respectively. This means that criteria emissions were not sufficiently studied in the reviewed papers. However, criteria pollutants are important to the extent that the U.S. Environmental Protection Agency has regulated them in order to safeguard public health. These pollutants generated by sources such as cars have a variety of negative effects on human health and the environment; thus, efforts to minimize their levels are necessary (U.S. Department of Energy, 2023*b*). On the other hand, the non-criteria air emissions harmful to the climate including total organic gases, volatile organic compounds, total hydrocarbons, methane (CH_4), air toxics, and Greenhouse Gases (GHG), are examined by 74%, 21%, 23%, 72%, 3%, and 77% of the papers, respectively. Although scrutinizing non-criteria pollutants in the Canadian HSCD are highlighted by the U.S. Department of Energy (2023b) due to their contribution to the creation of ozone, being classified as air toxics with consequences for respiratory health and cancer, and greenhouse gasses' negative impact on climate change. Finally, both resource depletion and destruction of habitats were not reviewed at all. Therefore, further research needs to be conducted on various factors of criteria and non-criteria emissions along with the processes harmful to environment in HSCD in Canada.

No study has been done on the revenue generation within the economic aspect of sustainability. However, the revenue generated by hydrogen products plays a crucial role in shaping the economic viability of hydrogen energy in various sectors. Furthermore, none of the cost items has been examined by over 23% of the papers. The cost of tanks, cylinders, and salt caverns for storage, pipelines, trucks, railways, and vessels for transportation, pipelines and tanks for distribution, and refueling stations are studied, respectively, by 23%, 3%, 5%, 21%, 13%, 3%, 0%, 15%, 10%, and 23% of the papers. However, Le Duigou et al. (2017) claim these costs have a great impact on the viability and profitability of hydrogen as an energy vector. Lastly, social factors, employment creation, safety, and energy equity are investigated by 8%, 49%, and 0% of the papers, while employment is significant for regional economic development, safety is a critical social component, and energy equity is emphasized in Canada's hydrogen strategy due to number of remote communities in the country (Sakthi et al., 2024).

5. Forward Horizons

5.1 Academic Recommendations

Figure 10 offers recommendations to academic communities for further studies in three different categories: (i) Hydrogen Supply Chain Downstream (HSCD) components, (ii) decision levels and research characteristics, shortly written as decision levels, and (iii) sustainability, derived from Tables 4, 5, and 6. Development of the HSCD in Canada requires the assessment of various available transportation means in Canada, including rail (e.g., Mackenzie Northern Railway), trucking (e.g., Alberta 1), pipelines (e.g., Trans Mountain), and vessels (e.g., port of Vancouver). Examination of GH_2, LH_2, and other chemical storage alternatives considers cost, safety, environmental impact, and density as another horizon for further investigation. Techno-economic studies focusing on customized tanks, and research aiming to reduce hydrogen cylinder costs and enhance energy density are other open research avenues. Exploration of existing salt caverns, establishing multifuel refueling stations, and substituting hydrogen (especially green hydrogen) in polluting industries is also open for additional research. Conducting research on hydrogen as a household fuel in regions such as Newfoundland and Labrador and hydrogen generation from wind energy for isolated settlements, particularly in jurisdictions where limited research has been conducted seem promising research avenues.

In the decision levels of the HSCD, critical factors such as storage, transportation, distribution, and refueling stations need extra attention from scientific community from investment, facility location, capacity selection/reduction/expansion, allocation, and technology selection/upgrading/and downgrading aspects. Incorporating inventory control, operational decisions, and project and production planning in mathematical models, e.g., multiperiod, multi-objective, deterministic, and non-deterministic, and optimization, may provide new insights. The use of optimization and simulation software packages, e.g., CPLEX and GREET, to ensure efficiency and accuracy in decision-making processes across all decision levels in the HSCD seems another direction for research. On the other hand, the sustainability assessment of the HSCD, examining environment, social, and economic dimensions are needed. Environmental assessment should be focused on criteria pollutants, non-criteria pollutants, and harmful processes to the environment. Economic factors require attention of researchers on revenue from sell of hydrogen energy, storage, transportation, and distribution expenses, along with other economic performance measures, e.g., net present value. The social component should narrow the studies on employment, safety, and energy fairness. For detailed recommendations, please see Figure 10.

5.2 Policymaking Recommendations

We offer recommendations for policymakers in Figure 11. The HSCD infrastructure development in Canada entails collaboration between provinces and territories to create a seamless hydrogen distribution system. This project explores cutting-edge technological developments while making use of the current transportation networks. Therefore, financial incentives are recommended, including grants and tax exemptions, to encourage the stakeholders toward creation and application of various hydrogen storage and delivery options. With an emphasis on technology and energy transition, resources should be allocated to the study of various hydrogen storage options and the evaluation of their effects on expenses, security, and the environment. Furthermore, support for research and development, especially focused on creating specialized tanks for different energy carriers and technologies is required. Establish procedures for monitoring optimization of the performance of hydrogen distribution and storage networks, demonstrating a dedication to the advancement of efficient and sustainable energy solutions.

Table 6. Analysis of the reviewed papers from sustainability dimension

		Sustainability																																				
		Environmental															Economic																			Social		
		EHC													PHE		REV								Cost													
		CRI						NCR																	ST			TP				DT						
#	Reference	CO	NO_2	PM	O_3	SO_x	Pb	TOG	VOC	THC	CH_4	AT	GHG	OTH	RD	DH	LH_2	GH_2	NH_3	CH_3OH	MCH	$H_{18}DBT$	MgH_2	OTH	TA	CY	SC	PL	TK	RL	VL	PL	TK	ENU	OTH	EMP	SAF	EE
1	Davis et al. (2023)																																					
2	Ghorbani et al. (2023)																																					
3	Hui et al. (2023)																																					
4	Maynard and Abdulla (2023)		X								X		X																			X	X				X	
5	Wu and Zhong (2023)		X			X		X			X		X												X			X	X				X	X				
6	Cunanan et al. (2022)								X	X	X		X												X			X						X				
7	Okunlola et al. (2022)																																					
8	Yaïci and Longo (2022)							X																	X													
9	Aydin et al. (2021)		X					X		X	X		X														X					X					X	
10	Shamsi et al. (2021)		X				X	X			X		X																									
11	Talebian et al. (2021)																																					
12	Herdem et al. (2020)							X			X		X														X										X	
13	Al-Zakwani et al. (2019)	X	X								X																	X	X	X							X	
14	Talebian et al. (2019)	X	X		X	X			X		X		X																							X		
15	Sorgulu and Dincer (2018)	X						X					X																									
16	Talebian et al. (2018)	X						X			X		X												X			X				X					X	
17	Mukherjee et al. (2017)	X	X					X			X		X												X			X				X					X	
18	Perera et al. (2017)							X			X																											
19	Bicer et al. (2016)	X	X		X	X		X	X	X	X	X	X																									
20	Ghandehariun and Kumar (2016)							X		X	X		X																					X		X	X	
21	Khalid et al. (2016)							X					X															X	X									
22	Olateju et al. (2016)						X	X			X		X												X			X	X								X	
23	Sean B. Walker and Elkamel (2016)																																					
24	Sean B. Walker and Mukherjee (2016)							X	X		X		X																									
25	Ahmadi and Kjeang (2015)	X	X	X	X	X		X	X		X		X																									
26	Cetinkaya et al. (2012)							X	X				X																					X			X	
27	Cuda et al. (2012)		X	X				X			X		X																									
28	Hacatoglu et al. (2012)				X	X		X	X		X		X													X						X	X				X	
29	Liu et al. (2012)				X	X		X		X			X																					X			X	
30	Hajimiragha et al. (2011)							X		X	X		X												X												X	
31	J. Adam Holbrook and Cassidy (2010)						X	X			X		X															X	X					X				
32	Gnanapragasam et al. (2010)	X	X	X				X	X		X		X																								X	
33	Marin et al. (2010a)							X			X		X																			X	X	X			X	
34	Marin et al. (2010b)	X	X			X	X	X		X	X		X																					X			X	
35	Naterer et al. (2010)	X	X			X		X		X	X		X																								X	
36	Lubis et al. (2009)							X			X		X												X											X	X	
37	Taljan et al. (2008)		X					X			X		X																								X	
38	Granovskii et al. (2006)		X					X			X		X	X											X									X			X	
39	Zamel and Li (2006)	X	X			X		X		X	X		X																									
	Total (%)≈	28	41	8	13	23	10	74	21	23	72	3	77	3	0	0	0	0	0	0	0	0	0	0	23	3	5	21	13	3	0	15	10	23	0	8	49	0
	This paper	X	X	X	X	X	X	X	X	X	X	X	X	X X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

With an emphasis on technology and energy transition, resources should be allocated to the study of various hydrogen storage options and the evaluation of their effects on expenses, security, and the environment. Furthermore, support for research and development, especially focused on creating specialized tanks for different energy carriers and technologies is required. Establish procedures for monitoring optimization of the performance of hydrogen distribution and storage networks, demonstrating a dedication to the advancement of efficient and sustainable energy solutions.

A multifaceted approach to reducing environmental impact is part of the sustainability assessment process. This requires legislation to encourage the use of green hydrogen in sectors of the economy that produce air pollutions, with the goal of drastically lowering emissions. The economic viability of hydrogen as a propane or heating oil substitute should be examined, taking into account the financial impact on households. So too, encouraging incorporating hydrogen-generated electricity from renewable sources to support energy sustainability, especially in remote communities that rely on diesel fuels.

5.3 Industry Recommendations

Figure 12 recommends eight directions to practitioner communities to help towards building the HSCD in Canada. Establishing a comprehensive HSCD requires building partnerships between construction companies, logistics companies, and energy corporations to create the infrastructure development and integration. Industry participants must simultaneously think about adapting current infrastructure or allocating particular resources for hydrogen transport in order to optimize hydrogen mobility. Sustainable development still depends on funding research and development (R&D) projects, especially those that address storage issues like developing tank technologies and making hydrogen cylinders more efficient.

Additionally, enterprises are urged to investigate the implementation of hydrogen-based processes, which offer fresh revenue opportunities and complement sustainability goals. This tactical change has the potential to significantly reduce air pollution and further global environmental objectives. Companies should think about regional hydrogen growth in unexplored regions and forming alliances with research institutions in order to strategically position themselves in the changing energy landscape. In the quickly changing field of hydrogen technologies, this cooperative approach promotes innovation, strengthens market leadership, and guarantees a competitive advantage. In order to ensure that hydrogen efforts remain viable over the long term, special emphasis should also be made on creating customized solutions for streamlining operations and carrying out sustainability analyses.

HSCD Components

1. Developing real-life HSCD through horizontal integration including all existing and potential resources in various provinces/territories/regions in Canada.
2. Evaluating utilization of existing transportation and distribution resources in development of case studies for HSCD:
   - Pipeline – In British Columbia, e.g., Trans Mountain and Coastal GasLink, in Alberta, e.g., Alberta Clipper and Alliance, and in Ontario, e.g., TransCanada Mainline and TransNorthern.
   - Truck- In British Columbia, e.g., 5m Wide and North Peace, in Alberta, e.g., Alberta 1 and 2, in Ontario, e.g., Highway 2 and 3, in Nova Scotia, e.g., Schedule B and C, and in Newfoundland, e.g., Trans Canada Highway and Salmon Cove Road West.
   - Rail – In British Columbia, e.g., Kelowna Pacific Railway and Englewood Railway, in Alberta, e.g., Mackenzie Northern Railway and Forty Mile Rail, in Ontario, e.g., Algoma Central Railway and Essex Terminal Railway, in Nova Scotia, e.g., Cape Breton and Central Nova Scotia Railway and Sydney Coal Railway, and in Newfoundland and Labrador, e.g., Wabush Lake Railway.
   - Vessel – In British Columbia, e.g., port of Vancouver and Imperial Oil Co terminal, in Nova Scotia, e.g., port of Halifax and Sydney Harbour, and in Newfoundland and Labrador, e.g., Come By Chance and port of Argentia.
3. Exploring physical, (e.g., GH2, LH2, and Gh2+LH2), and chemical (e.g., Ammonia, Methanol, Methylcyclohexane, Perhydro-dibenzyltoluene, Metal Hydrolysis) storage options from various aspects, e.g., cost, safety, environmental impacts, storage density, utilization, and transportation.
4. Conducting techno-economic analysis for tanks specialized for each energy carrier.
5. Examining technologies to reduce hydrogen cylinder cost and enhance energy density.
6. Exploring existing slat caverns for hydrogen storage, e.g., caverns located in Alberta's Industrial Heartland.
7. Investigating multi-purpose fuel stations for light and heavy vehicle, rail, vessel, and aviation.
8. Evaluating hydrogen, especially green hydrogen, as a substitution fuel in most air pollutants producing industries in Canada, e.g., electricity generation, aluminum, alumina, Iron and steel, to drastically reduce air pollution.
9. Investigating application of hydrogen, especially green hydrogen, as fuel for provinces/territories/regions using heating oil or propane as the most common fuel, e.g., Newfoundland and Labrador, Nova Scotia, and New Brunswick for residential purposes.
10. Studying hydrogen-produced electricity from wind for remote and indigenous Canadian communities, mainly consuming diesel as residential fuel and mostly are situated on coastlines, e.g., Ramea, Forteau, Hopedale, Mary's Harbour, Red Bay, St Lewis, Black Tickle, and St. Brendan's.
11. Investigating establishment of HSCD, i.e., renewable and non-renewable for provinces/territories/regions with no studies in the field, excluding British Columbia, Alberta, Ontario, Nova Scotia, and Newfoundland and Labrador.
12. Evaluating expanding renewable HSCD, i.e., wind, biomass, solar, geothermal, and algae in provinces with further hydrogen production opportunities and limited studies, i.e., British Columbia, Alberta, Ontario, Nova Scotia, and Newfoundland and Labrador.

Decision Levels

1. Addressing following decisions regarding storage, transportation, distribution, and refueling stations:
   - Investment, facility location, capacity, allocation, and capacity expansion and reduction.
   - Technology selection, upgrading, downgrading, and outsourcing.
2. Incorporating project and production planning, inventory management, and operational decisions.
3. Developing mathematical models and optimization:
   - Linear: Linear Programming (e.g., transportation and distribution costs), Mixed Integer Linear Programming (e.g., location-allocation)
   - Non-linear: Non-linear Programming (e.g., including demand fluctuations), Mixed Integer Non-linear Programming (e.g., refueling station locations along with amount delivered to them and amount of demand in each station)
   - Mono-objective optimization models: for various objectives (e.g., maximization of revenue, profit, jobs created, safety, energy access, and minimization of costs and greenhouse gases).
   - Multi-objective optimization models: for trade-offs between two (e.g., maximization of profit and maximization of jobs), or more conflicting objectives (e.g., maximization of revenue, minimization of greenhouse gases, and maximization of energy access).
   - Deterministic models: assuming exact information available (e.g., known demand and costs).
   - Non-deterministic models: for real-life cases (e.g., capital costs for setting up refueling stations, storage, and transportation costs) utilizing stochastic programing and robust optimization.
   - Single and multi-period models: single period for ease of computationally tractability in identifying configuration of HSCD in the beginning (which is as same as the last period), and multi-period for more realistic cases (e.g., enabling reflection of technology upgrading/downgrading and demand fluctuation).
   - Superstructures: horizontal (i.e., storage, transportation, distribution, and end user) and vertical integration (i.e., strategic, tactical, and operational decisions) of all potential options (e.g., locations, capacities, and technologies).
4. Utilizing off-the-shelf optimization/simulation software packages (e.g., CPLEX, GREET (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation), EIO-LCA (Economic Input Output Life Cycle Assessment), RETScreen (Renewable-energy and Energy-efficiency Technology Screening).

Sustainability

1. Evaluating sustainability of potential configurations and operations of HSCD (i.e., environment, economic, and society).
2. Investigating various combination of pillars of sustainability (i.e., economic & environment, economic & society, and environment & society).
3. Exploring various factors in each dimension of sustainability:
   - Environment: (1) criteria pollutants (e.g., Carbon Monoxide, Oxides of Nitrogen, Particulate Matter, Ozone, Oxides of Sulfur, Lead), (2) non-criteria pollutants (e.g., Volatile Organic Compounds, Total Hydrocarbons, Air Toxics), and (3) harmful environmental process (e.g., resources depletion, destruction of habitats).
   - Economic: (1) revenue (from selling e.g., LH2, GH2, Ammonia, Methanol, Methylcyclohexane, Perhydro-dibenzyltoluene, Metal Hydrolysis), (2) cost of storage (i.e., tank, cylinder, salt cavern), transportation and distribution (i.e., pipeline, truck, rail, vessel), refueling stations, and (3) other economic performance measures (e.g., net present value).
   - Social: employment, safety, and energy equity.

Figure 10. Academic horizons for the HSCD in Canada

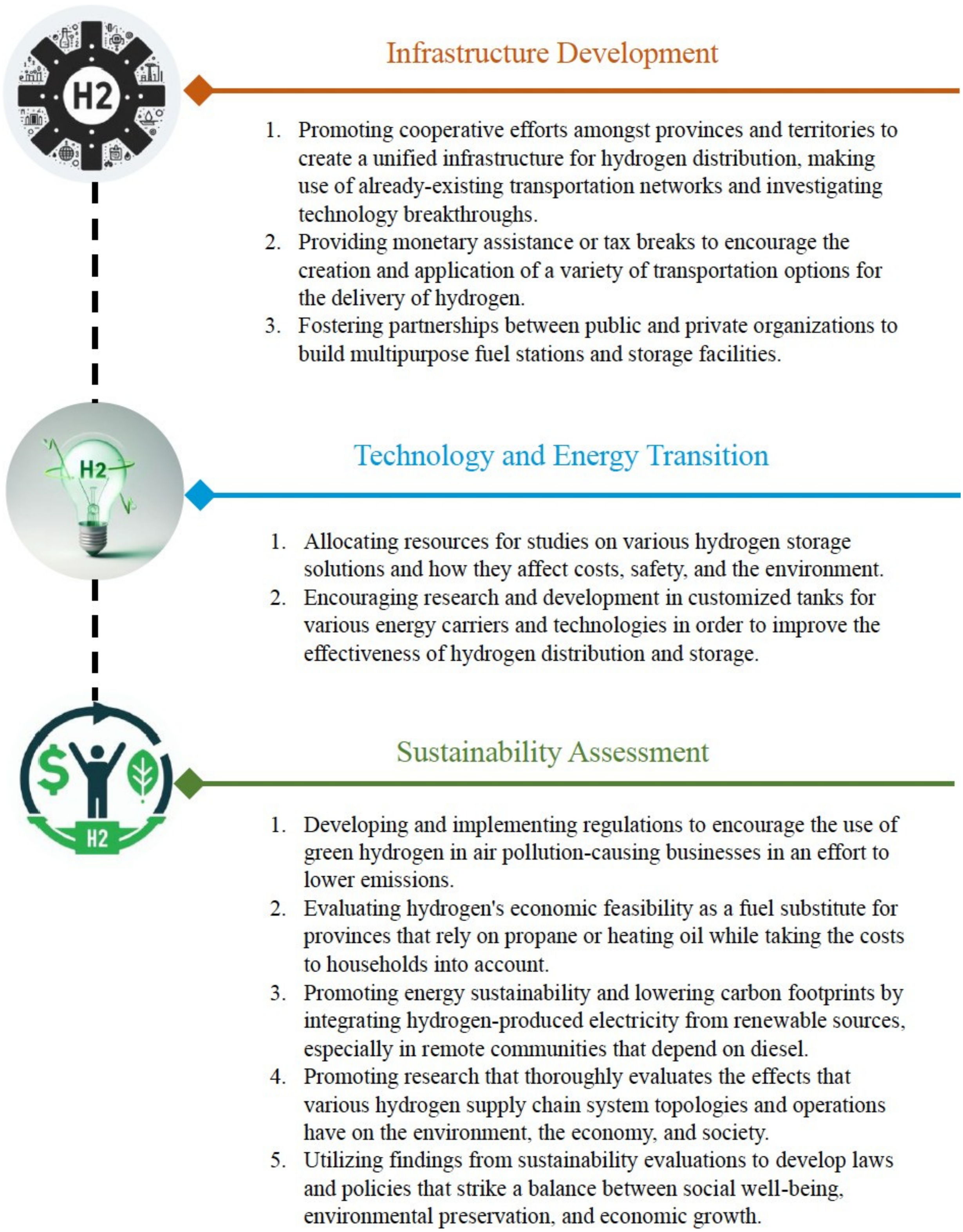

Figure 11. Government horizons for the HSCD in Canada

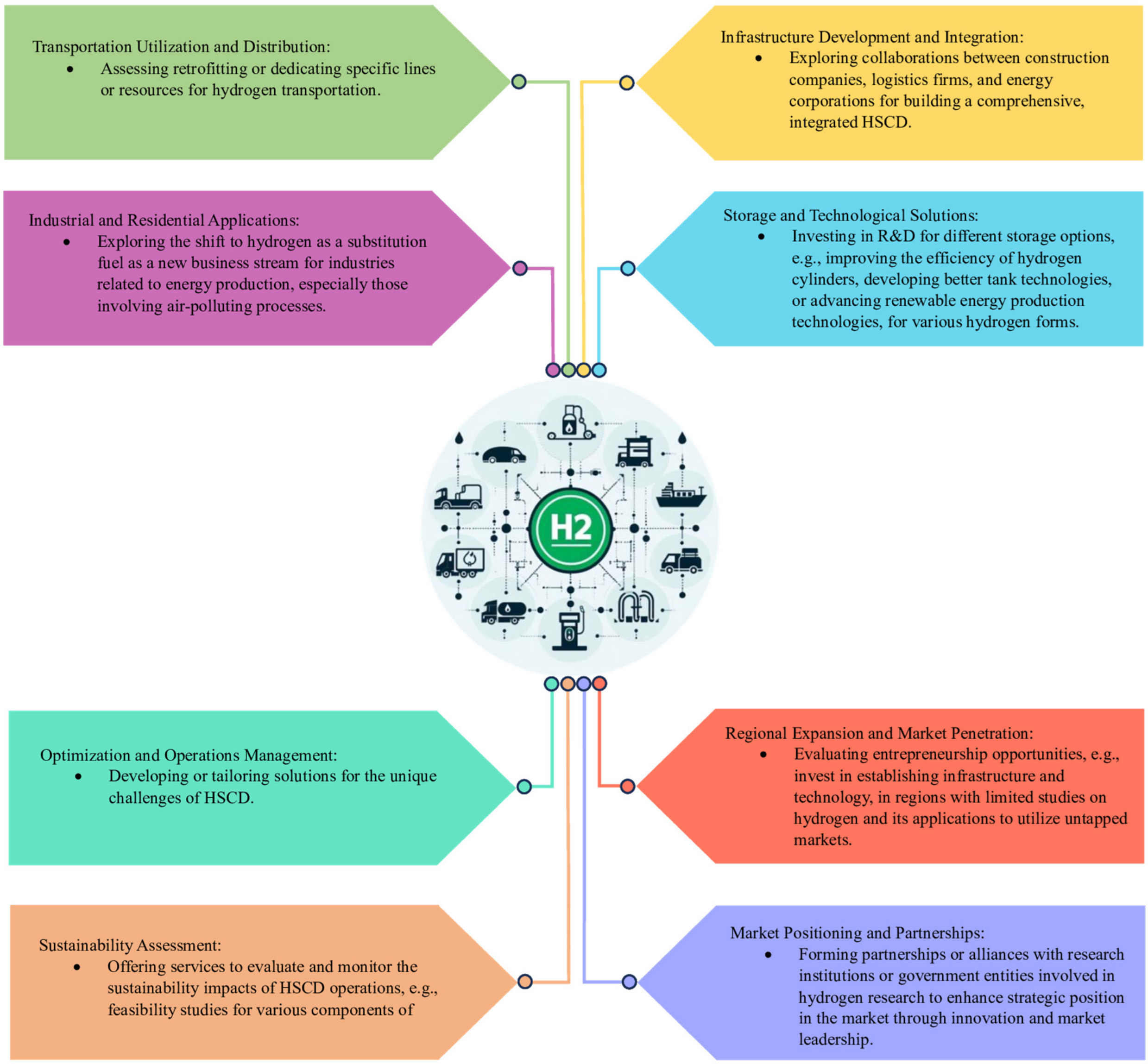

Figure 12. Industry horizons for the HSCD in Canada

6. Conclusions

Canada is pursuing being carbon-free by 2050. Furthermore, it is advantageously situated to respond to the energy crisis in Europe escalated by the Russia-Ukraine war due to its natural resources to produce hydrogen. With Europe importing hydrogen from Canada it will change the configuration of the hydrogen supply chains downstream (HSCD) in Canada. Therefore, this paper compiled and analyzed all the relevant 39 papers published prior to October 2023, systematically. Our investigation extracted insights through examining the papers from (1) the HSCD components and geographical focus, (2) decision levels and research characteristics, and (3) sustainability standpoints. Accordingly, we contributed by recommending forward horizons for scientific, legislative, and practitioner societies in Figures 10, 11, and 12. Furthermore, we performed a bibliometric analysis reflecting a growing emphasis on research and scholarly publishing in Canada and *International Journal of Hydrogen Energy* being the main cornerstone.

Firstly, forward academic horizons outlined in the scientific sector underscore a holistic approach to the HSCD, covering transportation means, storage alternatives, and sustainability assessments. This comprehensive strategy aims to establish an efficient and sustainable hydrogen supply chain in Canada. The decision levels of the HSCD are required additional attention from academic community. Extra sustainability assessments, focusing on environmental, social, and economic dimensions of the HSCD, promotes a responsible development and distribution of hydrogen in Canada and beyond.

Secondly, in the government sector, the emphasis should be on incentives for encouraging collaborative infrastructure development, utilizing existing transportation networks and supporting the establishment of adaptable refueling stations and storage facilities. Financial incentives, public-private partnerships, and a commitment to technology and energy transition ensure the dedication to creating an effective hydrogen distribution system in Canada. Additionally, a multifaceted approach to sustainability through regulations encouraging the use of hydrogen and studies on the economic viability of hydrogen as a substitute energy, reflect a commitment to reducing emissions and promoting energy sustainability. Thirdly, the industry sector ought to concentrate on partnerships between construction companies, logistics firms, and energy corporations for the establishment of a sustainable HSCD. Furthermore, sponsoring research and development initiatives for storage technologies can add to the competitive advantages of corporations in the field.

This research has some limitations which can be utilized as future research directions for researchers interested in performing a systematic review analysis in HSCD. Further details of end users of hydrogen energy, e.g., heavy vehicles and light vehicles, may provide additional insights. Another direction is breaking down the operational decisions as well as breaking down the mathematical models, optimization, and qualitative research methods into their subcategories, e.g., linear models, stochastic optimization, and survey.

References

Abreu, J. F., Costa, A. M., Costa, P. V., Miranda, A. C., Zheng, Z., Wang, P., Ebecken, N. F., de Car- valho, R. S., dos Santos, P. L., Lins, N., de Melo, P. R., Goulart, M. B., Bergsten, A., Bittencourt, C. H., Assi, G., Meneghini, J. R., & Nishimoto, K. (2023). Carbon net zero transition: A case study of hydrogen storage in offshore salt cavern. *Journal of Energy Storage, 62*, 106818. https://doi.org/10.1016/j.est.2023.106818

Aglen, T., & Hofstad, A. (2022). Designing the hydrogen supply chain for maritime transportation, PhD thesis, Master's thesis, Department of industrial economics and technology.

Ahmadi, P., & Kjeang, E. (2015). Comparative life cycle assessment of hydrogen fuel cell passenger vehicles in different canadian provinces. *International Journal of Hydrogen Energy, 40*, 12905-12917. https://doi.org/10.1016/j.ijhydene.2015.07.147

Alizadeh, M., & Karimi, B. (2023). A trio of resiliency, reliability, and uncertainty to design and plan the downstream oil supply chain. *Computers & Chemical Engineering, 176*, 108281. https://doi.org/10.1016/j.compchemeng.2023.108281

Almaraz, S. D.-L., Kocsis, T., Azzaro-Pantel, C., & Szántó, Z. O. (2023). Identifying social aspects related to the hydrogen economy: Review, synthesis, and research perspectives. *International Journal of Hydrogen Energy*.

Alsaba, W., Al-Sobhi, S. A., & Qyyum, M. A. (2023). Recent advancements in the hydrogen value chain: Opportunities, challenges, and the way forward-middle east perspectives. *International Journal of Hydrogen Energy, 48*(68), 26408-26435. https://doi.org/10.1016/j.ijhydene.2023.05.160

Al-Zakwani, S. S., Maroufmashat, A., Mazouz, A., Fowler, M., & Elkamel, A. (2019). Allocation of ontario's surplus electricity to different power-to-gas applications. *Energies, 12*, 2675. https://doi.org/10.3390/en12142675

Amirthan, T., & Perera, M. S. (2023). Underground hydrogen storage in australia: A review on the feasibility of geological sites. *International Journal of Hydrogen Energy, 48*, 4300-4328. https://doi.org/10.1016/j.ijhydene.2022.10.218

Aslannezhad, M., Ali, M., Kalantariasl, A., Sayyafzadeh, M., You, Z., Iglauer, S., & Keshavarz, A. (2023). A review of hydrogen/rock/brine interaction: Implications for hydrogen geo-storage. *Progress in Energy and Combustion Science, 95*, 101066. https://doi.org/10.1016/j.pecs.2022.101066

Aydin, M. I., Dincer, I., & Ha, H. (2021). Development of oshawa hydrogen hub in canada: A case study. *International Journal of Hydrogen Energy, 46*, 23997-24010. https://doi.org/10.1016/j.ijhydene.2021.05.011

Azadnia, A. H., McDaid, C., Andwari, A. M., & Hosseini, S. E. (2023). Green hydrogen supply chain risk analysis: A european hard-to-abate sectors perspective. *Renewable and Sustainable Energy Reviews, 182*, 113371. https://doi.org/10.1016/j.rser.2023.113371

Berstad, D., Gardarsdottir, S., Roussanaly, S., Voldsund, M., Ishimoto, Y., & Neksā, P. (2022). Liquid hydrogen as prospective energy carrier: A brief review and discussion of underlying assumptions applied in value chain analysis. *Renewable and Sustainable Energy Reviews, 154*, 111772. https://doi.org/10.1016/j.rser.2021.111772

Beschkov, V., & Ganev, E. (2023). Perspectives on the development of technologies for hydrogen as a carrier of sustainable energy. *Energies, 16,* 6108. https://doi.org/10.3390/en16176108

Bicer, Y., Dincer, I., Zamfirescu, C., Vezina, G., & Raso, F. (2016). Comparative life cycle assessment of various ammonia production methods. *Journal of Cleaner Production, 135*, 1379-1395. https://doi.org/10.1016/j.jclepro.2016.07.023

Blohm, M., & Dettner, F. (2023). Green hydrogen production: Integrating environmental and social criteria to ensure sustainability. *Smart Energy, 11*, 100112. https://doi.org/10.1016/j.segy.2023.100112

Canada Energy Regulator. (2021). *Crude oil pipeline transportation system.* Retrieved from https://www.cer-rec.gc.ca/en/data-analysis/facilities-we-regulate/canadas-pipeline-system/2021/crude-oil-pipeline-transportation-system.html

Cetinkaya, E., Dincer, I., & Naterer, G. F. (2012). Life cycle assessment of various hydrogen production methods. *International Journal of Hydrogen Energy, 37*, 2071-2080. https://doi.org/10.1016/j.ijhydene.2011.10.064

Chen, Y., Jin, X., Zeng, L., Zhong, Z., Mehana, M., Xiao, W., Pu, W., Regenauer-Lieb, K., & Xie, Q. (2023). Role of large-scale underground hydrogen storage and its pathways to achieve net-zero in china. *Journal of Energy Storage, 72*, 108448. https://doi.org/10.1016/j.est.2023.108448

Chircop, A. (2023). Understanding port jurisdiction in Canadian law, Technical report, WWF Canada.

Chu, C., Wu, K., Luo, B., Cao, Q., & Zhang, H. (2023). Hydrogen storage by liquid organic hydrogen carriers: Catalyst, renewable carrier, and technology - a review. *Carbon Resources Conversion, 6*, 334-351. https://doi.org/10.1016/j.crcon.2023.03.007

Clematis, D., Bellotti, D., Rivarolo, M., Magistri, L., & Barbucci, A. (2023). Hydrogen carriers: Scien- tific limits and challenges for the supply chain, and key factors for techno-economic analysis. *Energies, 16*(16). https://doi.org/10.3390/en16166035

Cuda, P., Dincer, I., & Naterer, G. F. (2012). Hydrogen utilization in various transportation modes with emissions comparisons for ontario, Canada. *International Journal of Hydrogen Energy, 37*, 634-643. https://doi.org/10.1016/j.ijhydene.2011.09.076

Cui, J., & Aziz, M. (2023). Techno-economic analysis of hydrogen transportation infrastructure using ammonia and methanol. *International Journal of Hydrogen Energy, 48*, 15737-15747. https://doi.org/10.1016/j.ijhydene.2023.01.096

Cunanan, C. J., Casas, C. A. E., Yorke, M., Fowler, M., & Wu, X. Y. (2022). Design and analysis of an offshore wind power to ammonia production system in nova scotia. *Energies, 15*, 9558. https://doi.org/10.3390/en15249558

Davis, M., Okunlola, A., Lullo, G. D., Giwa, T., & Kumar, A. (2023). Greenhouse gas reduction potential and cost-effectiveness of economy-wide hydrogen-natural gas blending for energy end uses. *Renewable and Sustainable Energy Reviews, 171*, 112962. https://doi.org/10.1016/j.rser.2022.112962

de las Nieves Camacho, M., Jurburg, D., & Tanco, M. (2022). Hydrogen fuel cell heavy-duty trucks: Review of main research topics. *International Journal of Hydrogen Energy, 47*(68), 29505-29525. https://doi.org/10.1016/j.ijhydene.2022.06.271

Dolata, P. (2022). Canada, the eu and energy security: a historical perspective. *Canadian Foreign Policy Journal, 28*(3), 216-233. https://doi.org/10.1080/11926422.2022.2125411

Erdoğan, A., Geçici, E., & Güler, M. G. (2023). Design of a future hydrogen supply chain: A multi- objective model for turkey. *International Journal of Hydrogen Energy, 48*(31), 11775-11789. https://doi.org/10.1016/j.ijhydene.2022.12.071

Faye, O., Szpunar, J., & Eduok, U. (2022). A critical review on the current technologies for the generation, storage, and transportation of hydrogen. *International Journal of Hydrogen Energy, 47*(29), 13771-13802. https://doi.org/10.1016/j.ijhydene.2022.02.112

Feng, S., Ngo, H. H., Guo, W., Chang, S. W., Nguyen, D. D., Bui, X. T., Zhang, X., Ma, X. Y., & Hoang, B. N. (2023). Biohydrogen production, storage, and delivery: A comprehensive overview of current strategies and limitations. *Chemical Engineering Journal, 471*, 144669. https://doi.org/10.1016/j.cej.2023.144669

Ghahremanlou, D., & Kubiak, W. (2020). Sustainable petroleum supply chains created during economic crisis in response to us government policies. *International Journal of Sustainable Economy, 12*, 205-232. https://doi.org/10.1504/IJSE.2020.111535

Ghandehariun, S., & Kumar, A. (2016). Life cycle assessment of wind-based hydrogen production in western canada. *International Journal of Hydrogen Energy, 41*, 9696-9704. https://doi.org/10.1016/j.ijhydene.2016.04.077

Ghorbani, B., & Zendehboudi, S. (2023). Strategies to improve the performance of hydrogen storage systems by liquefaction methods: A comprehensive review. *ACS Omega, 8*, 18358-18399. https://doi.org/10.1021/acsomega.3c01072

Ghorbani, B., Zendehboudi, S., & Afrouzi, Z. A. (2023). Thermo-economic optimization of a novel hybrid structure for power generation and portable hydrogen and ammonia storage based on magne- sium-chloride thermochemical process and liquefied natural gas cryogenic energy. *Journal of Cleaner Production, 403*, 136571. https://doi.org/10.1016/j.jclepro.2023.136571

Gnanapragasam, N. V., Reddy, B. V., & Rosen, M. A. (2010). Feasibility of an energy conversion system in canada involving large-scale integrated hydrogen production using solid fuels. *International Journal of Hydrogen Energy, 35*, 4788-4807. https://doi.org/10.1016/j.ijhydene.2009.10.047

Gordon, J. A., Balta-Ozkan, N., & Nabavi, S. A. (2023*a*). Gauging public perceptions of blue and green hydrogen futures: Is the twin-track approach compatible with hydrogen acceptance?. *International Journal of Hydrogen Energy.* https://doi.org/10.1016/j.ijhydene.2023.06.297

Gordon, J. A., Balta-Ozkan, N., & Nabavi, S. A. (2023*b*). Socio-technical barriers to domestic hydrogen futures: Repurposing pipelines, policies, and public perceptions. *Applied Energy, 336*, 120850. https://doi.org/10.1016/j.apenergy.2023.120850

Gorji, S. (2023). Challenges and opportunities in green hydrogen supply chain through metaheuristic optimization. *academic.oup.com, 10.* https://doi.org/10.1093/jcde/qwad043

Government of Canada (2020). *A healthy environment and a healthy economy: Canada's strengthened climate plan to create jobs and support people, communities and the planet.* Retrieved from https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

Government of Canada (2023). *Greenhouse gas emissions by economic sector, Canada, 1990 to 2019.* Retrieved from https://open.canada.ca/data/en/dataset/0e76433c-7aeb-46dc-a019-11db10ee28dd

Granovskii, M., Dincer, I., & Rosen, M. A. (2006). Life cycle assessment of hydrogen fuel cell and gasoline vehicles. *International Journal of Hydrogen Energy, 31*, 337-352. https://doi.org/10.1016/j.ijhydene.2005.10.004

Hacatoglu, K., Rosen, M. A., & Dincer, I. (2012). Comparative life cycle assessment of hydrogen and other selected fuels. *International Journal of Hydrogen Energy, 37*, 9933-9940. https://doi.org/10.1016/j.ijhydene.2012.04.020

Hajimiragha, A. H., Cañizares, C. A., Fowler, M. W., Moazeni, S., Elkamel, A., & Wong, S. (2011). Sustainable convergence of electricity and transport sectors in the context of a hydrogen economy. *International Journal of Hydrogen Energy, 36*, 6357-6375. https://doi.org/10.1016/j.ijhydene.2011.02.070

Hampp, J., Düren, M., & Brown, T. (2023). Import options for chemical energy carriers from renewable sources to germany. *PLOS ONE, 18*, e0262340. https://doi.org/10.1371/journal.pone.0281380

Health Canada. (2019). *Extreme cold.* Retrieved from https://www.canada.ca/en/health-canada/services/healthy-living/your-health/environment/extreme-cold.html

Herdem, M. S., Mazzeo, D., Matera, N., Wen, J. Z., Nathwani, J., & Hong, Z. (2020). Simulation and modeling of a combined biomass gasification-solar photovoltaic hydrogen production system for methanol synthesis via carbon dioxide hydrogenation. *Energy Conversion and Management, 219*, 113045. https://doi.org/10.1016/j.enconman.2020.113045

Hren, R., Vujanović, A., Fan, Y. V., Klemeš, J. J., Krajnc, D., & Čuček, L. (2023). Hydrogen produc- tion, storage and transport for renewable energy and chemicals: An environmental footprint assessment. *Renewable and Sustainable Energy Reviews, 173*, 113113. https://doi.org/10.1016/j.rser.2022.113113

Hui, S., Yin, S., Pang, X., Chen, Z., & Shi, K. (2023). Potential of salt caverns for hydrogen storage in southern ontario, canada. *Mining, 3,* 399-408. https://doi.org/10.3390/mining3030024

International Energy Agency. (2023). *Analysing the impacts of russia's invasion of ukraine on global energy markets and international energy security.* Retrieved from https://phys.org/news/2023-07-korean-team-room-temperature-ambient-pressure-superconductor.html

Isaac, N., & Saha, A. K. (2023). A review of the optimization strategies and methods used to locate hydrogen fuel refueling stations. *Energies, 16,* 2171. https://doi.org/10.3390/en16052171

J. Adam Holbrook, D. A., & Cassidy, E. (2010). Understanding the vancouver hydrogen and fuel cells cluster: A case study of public laboratories and private research‡. *European Planning Studies, 18*(2), 317-328. https://doi.org/10.1080/09654310903491648

Khalid, F., Dincer, I., & Rosen, M. A. (2016). Analysis and assessment of an integrated hydrogen energy system. *International Journal of Hydrogen Energy, 41*, 7960-7967. https://doi.org/10.1016/j.ijhydene.2015.12.221

Kim, C., Cho, S. H., Cho, S. M., Na, Y., Kim, S., & Kim, D. K. (2022). Green, turquoise, blue, or grey? environmentally friendly hydrogen production in transforming energy systems. *Progress in Energy and Combustion Science, 90*, 100996. https://doi.org/10.1016/j.pecs.2022.100996

Kim, C., Cho, S. H., Cho, S. M., Na, Y., Kim, S., & Kim, D. K. (2023). Review of hydrogen in- frastructure: The current status and roll-out strategy. *International Journal of Hydrogen Energy, 48*, 1701-1716. https://doi.org/10.1016/j.ijhydene.2022.10.053

Kindra, V., Maksimov, I., Oparin, M., Zlyvko, O., & Rogalev, A. (2023). Hydrogen technologies: A critical review and feasibility study. *Energies, 16,* 5482. https://doi.org/10.3390/en16145482

Klerke, A., Christensen, C. H., Nørskov, J. K., & Vegge, T. (2008). Ammonia for hydrogen storage: challenges and opportunities. *Journal of Materials Chemistry, 18*, 2304-2310. https://doi.org/10.1039/b720020j

Klopčič, N., Grimmer, I., Winkler, F., Sartory, M., & Trattner, A. (2023). A review on metal hydride materials for hydrogen storage. *Journal of Energy Storage, 72*, 108456. https://doi.org/10.1016/j.est.2023.108456

Kumar, S., Arzaghi, E., Baalisampang, T., Garaniya, V., & Abbassi, R. (2023). Insights into decision- making for offshore green hydrogen infrastructure developments. *Process Safety and Environmental Protection, 174*, 805-817. https://doi.org/10.1016/j.psep.2023.04.042

Kwak, Y., Kirk, J., Moon, S., Ohm, T., Lee, Y. J., Jang, M., Park, L. H., il Ahn, C., Jeong, H., Sohn, H., Nam, S. W., Yoon, C. W., Jo, Y. S., & Kim, Y. (2021). Hydrogen production from homocyclic liquid organic hydrogen carriers (lohcs): Benchmarking studies and energy-economic analyses. *Energy Conversion and Management, 239*, 114124. https://doi.org/10.1016/j.enconman.2021.114124

Lagioia, G., Spinelli, M. P., & Amicarelli, V. (2023). Blue and green hydrogen energy to meet euro- pean union decarbonisation objectives. an overview of perspectives and the current state of affairs. *International Journal of Hydrogen Energy, 48*, 1304-1322. https://doi.org/10.1016/j.ijhydene.2022.10.044

Lahiri, S. (2016). Does outsourcing really improve firm performance? empirical evidence and research agenda. *International Journal of Management Reviews, 18*, 464-497. https://doi.org/10.1111/ijmr.12075

Lahnaoui, A., Wulf, C., Heinrichs, H., & Dalmazzone, D. (2018). Optimizing hydrogen transportation system for mobility by minimizing the cost of transportation via compressed gas truck in north rhine- westphalia. *Applied Energy, 223*, 317-328. https://doi.org/10.1016/j.apenergy.2018.03.099

Le Duigou, A., Bader, A.-G., Lanoix, J.-C., & Nadau, L. (2017). Relevance and costs of large scale underground hydrogen storage in france. *International Journal of Hydrogen Energy, 42*(36), 22987-23003. https://doi.org/10.1016/j.ijhydene.2017.06.239

Lee, J. S., Cherif, A., Yoon, H. J., Seo, S. K., Bae, J. E., Shin, H. J., Lee, C., Kwon, H., & Lee, C. J. (2022). Large-scale overseas transportation of hydrogen: Comparative techno-economic and environmental investigation. *Renewable and Sustainable Energy Reviews, 165*, 112556. https://doi.org/10.1016/j.rser.2022.112556

Li, L., Manier, H., & Manier, M. A. (2019). Hydrogen supply chain network design: An optimization- oriented review. *Renewable and Sustainable Energy Reviews, 103*, 342-360. https://doi.org/10.1016/j.rser.2018.12.060

Li, Y., Shi, X., & Phoumin, H. (2022). A strategic roadmap for large-scale green hydrogen demonstra- tion and commercialisation in china: A review and survey analysis. *International Journal of Hydrogen Energy, 47*, 24592-24609. https://doi.org/10.1016/j.ijhydene.2021.10.077

Lingefjärd, T. (2006). Faces of mathematical modeling. *ZDM, 38*, 96-112. https://doi.org/10.1007/BF02655884

Liu, H., Almansoori, A., Fowler, M., & Elkamel, A. (2012). Analysis of ontario's hydrogen economy demands from hydrogen fuel cell vehicles. *International Journal of Hydrogen Energy, 37*, 8905-8916. https://doi.org/10.1016/j.ijhydene.2012.03.029

Lubis, L. I., Dincer, I., Naterer, G. F., & Rosen, M. A. (2009). Utilizing hydrogen energy to reduce greenhouse gas emissions in canada's residential sector. *International Journal of Hydrogen Energy, 34*, 1631-1637. https://doi.org/10.1016/j.ijhydene.2008.12.043

M, A., V, M. K., Hariharan, V. S., Narahari, T., P, A. K., K, M., G, P. K. and Prabakaran, R. (2023). Fuelling the future: A review of non-renewable hydrogen production and storage techniques. *Renewable and Sustainable Energy Reviews, 188*, 113791. https://doi.org/10.1016/j.rser.2023.113791

Ma, H., Sun, Z., Xue, Z., Zhang, C., & Chen, Z. (2023). A systemic review of hydrogen supply chain in energy transition. *Frontiers in Energy, 17*(1), 102-122. https://doi.org/10.1007/s11708-023-0861-0

Ma, Zhao, W., Wang, W., Li, X., & Zhou, H. (2023). Large scale of green hydrogen storage: Oppor- tunities and challenges. *International Journal of Hydrogen Energy.* https://doi.org/10.1016/j.ijhydene.2023.09.021

Maestre, V. M., Ortiz, A., & Ortiz, I. (2022). The role of hydrogen-based power systems in the energy transition of the residential sector. *Journal of Chemical Technology & Biotechnology, 97*, 561-574. https://doi.org/10.1002/jctb.6938

Marin, G. D., Naterer, G. F., & Gabriel, K. (2010*a*). Rail transportation by hydrogen vs. electrification - case study for ontario canada, i: Propulsion and storage. *International Journal of Hydrogen Energy, 35*, 6084-6096. https://doi.org/10.1016/j.ijhydene.2010.03.098

Marin, G. D., Naterer, G. F., & Gabriel, K. (2010*b*). Rail transportation by hydrogen vs. electrification case study for ontario, canada, ii: Energy supply and distribution. *International Journal of Hydrogen Energy, 35*, 6097-6107. https://doi.org/10.1016/j.ijhydene.2010.03.095

Maynard, I., & Abdulla, A. (2023). Assessing benefits and costs of expanded green hydrogen production to facilitate fossil fuel exit in a net-zero transition. *Renewable Energy Focus, 44*, 85-97. https://doi.org/10.1016/j.ref.2022.12.002

Moradi, R., & Groth, K. M. (2019). Hydrogen storage and delivery: Review of the state of the art technologies and risk and reliability analysis. *International Journal of Hydrogen Energy, 44*, 12254-12269. https://doi.org/10.1016/j.ijhydene.2019.03.041

Mukherjee, U., Maroufmashat, A., Ranisau, J., Barbouti, M., Trainor, A., Juthani, N., El-Shayeb, H., & Fowler, M. (2017). Techno-economic, environmental, and safety assessment of hydrogen powered community microgrids; case study in canada. *International Journal of Hydrogen Energy, 42*, 14333-14349. https://doi.org/10.1016/j.ijhydene.2017.03.083

Muthukumar, P., Kumar, A., Afzal, M., Bhogilla, S., Sharma, P., Parida, A., Jana, S., Kumar, E. A., Pai, R. K., & Jain, I. P. (2023). Review on large-scale hydrogen storage systems for better sustainability. *International Journal of Hydrogen Energy, 48*, 33223-33259. https://doi.org/10.1016/j.ijhydene.2023.04.304

Naterer, G. F., Suppiah, S., Stolberg, L., Lewis, M., Wang, Z., Daggupati, V., Gabriel, K., Dincer, I., Rosen, M. A., Spekkens, P., Lvov, S. N., Fowler, M., Tremaine, P., Mostaghimi, J., Easton, E. B., Trevani, L., Rizvi, G., Ikeda, B. M., Kaye, M. H., Lu, L., Pioro, I., Smith, W. R., Secnik, E., Jiang, J., & Avsec, J. (2010). Canada's program on nuclear hydrogen production and the thermochemical cu-cl cycle. *International Journal of Hydrogen Energy, 35*, 10905-10926. https://doi.org/10.1016/j.ijhydene.2010.07.087

Natural Resources Canada. (2020). *The hydrogen strategy for Canada: Seizing the opportunities for hydrogen.* Retrieved from https://natural-resources.canada.ca/climate-change-adapting-impacts-and-reducing-emissions/canadas-green-future/the-hydrogen-strategy/23080

Natural Resources Canada. (2023). Pipelines across Canada. Retrieved from https://natural-resources.canada.ca/our-natural-resources/energy-sources-distribution/fossil-fuels/pipelines/pipelines-across-canada/18856

Negro, V., Noussan, M., & Chiaramonti, D. (2023). The potential role of ammonia for hydrogen storage and transport: A critical review of challenges and opportunities. *Energies, 16,* 6192. https://doi.org/10.3390/en16176192

Noh, H., Kang, K., & Seo, Y. (2023). Environmental and energy efficiency assessments of offshore hydrogen supply chains utilizing compressed gaseous hydrogen, liquefied hydrogen, liquid organic hydrogen carriers and ammonia. *International Journal of Hydrogen Energy, 48*, 7515-7532. https://doi.org/10.1016/j.ijhydene.2022.11.085

Obara, S. (2019). Energy and exergy flows of a hydrogen supply chain with truck transportation of ammonia or methyl cyclohexane. *Energy, 174*, 848-860. https://doi.org/10.1016/j.energy.2019.01.103

Ogumerem, G. S., Kim, C., Kesisoglou, I., Diangelakis, N. A., & Pistikopoulos, E. N. (2018). A multi- objective optimization for the design and operation of a hydrogen network for transportation fuel. *Chemical Engineering Research and Design, 131*, 279-292. https://doi.org/10.1016/j.cherd.2017.12.032

Oh, H. X., Ng, D. K. S., & Andiappan, V. (2023). Decision support model for planning optimal hydrogen supply chains. *Industrial & Engineering Chemistry Research.* https://doi.org/10.1021/acs.iecr.3c01088

Okolie, J. A., Patra, B. R., Mukherjee, A., Nanda, S., Dalai, A. K., & Kozinski, J. A. (2021), 'Fu- turistic applications of hydrogen in energy, biorefining, aerospace, pharmaceuticals and metallurgy. *International Journal of Hydrogen Energy, 46*, 8885-8905. https://doi.org/10.1016/j.ijhydene.2021.01.014

Okunlola, A., Giwa, T., Lullo, G. D., Davis, M., Gemechu, E., & Kumar, A. (2022). Techno-economic assessment of low-carbon hydrogen export from western canada to eastern canada, the usa, the asia- pacific, and europe. *International Journal of Hydrogen Energy, 47*, 6453-6477. https://doi.org/10.1016/j.ijhydene.2021.12.025

Olateju, B., Kumar, A., & Secanell, M. (2016). A techno-economic assessment of large scale wind- hydrogen production with energy storage in western canada. *International Journal of Hydrogen Energy, 41*, 8755-8776. https://doi.org/10.1016/j.ijhydene.2016.03.177

Oliveira, F., Gupta, V., Hamacher, S., & Grossmann, I. E. (2013). A lagrangean decomposition ap- proach for oil supply chain investment planning under uncertainty with risk considerations. *Computers & Chemical Engineering, 50*, 184-195. https://doi.org/10.1016/j.compchemeng.2012.10.012

Otto, M., Chagoya, K. L., Blair, R. G., Hick, S. M., & Kapat, J. S. (2022). Optimal hydrogen carrier: Holistic evaluation of hydrogen storage and transportation concepts for power generation, aviation, and transportation. *Journal of Energy Storage, 55*, 105714. https://doi.org/10.1016/j.est.2022.105714

Perera, P., Hewage, K., & Sadiq, R. (2017). Are we ready for alternative fuel transportation systems in canada: A regional vignette. *Journal of Cleaner Production, 166*, 717-731. https://doi.org/10.1016/j.jclepro.2017.08.078

Qureshi, F., Yusuf, M., Arham Khan, M., Ibrahim, H., Ekeoma, B. C., Kamyab, H., Rahman, M. M., Nadda, A. K., & Chelliapan, S. (2023). A state-of-the-art review on the latest trends in hydrogen production, storage, and transportation techniques. *Fuel, 340*, 127574. https://doi.org/10.1016/j.fuel.2023.127574

Raad, S. M. J., Leonenko, Y., & Hassanzadeh, H. (2022). Hydrogen storage in saline aquifers: Oppor- tunities and challenges. *Renewable and Sustainable Energy Reviews, 168*, 112846. https://doi.org/10.1016/j.rser.2022.112846

Rasul, M. G., Hazrat, M. A., Sattar, M. A., Jahirul, M. I., & Shearer, M. J. (2022). The future of hydrogen: Challenges on production, storage and applications. *Energy Conversion and Management, 272*, 116326. https://doi.org/10.1016/j.enconman.2022.116326

Riera, J. A., Lima, R. M., & Knio, O. M. (2023). A review of hydrogen production and supply chain modeling and optimization. *International Journal of Hydrogen Energy, 48*, 13731-13755. https://doi.org/10.1016/j.ijhydene.2022.12.242

Sahebi, H., Nickel, S., & Ashayeri, J. (2014). Strategic and tactical mathematical programming models within the crude oil supply chain context—a review. *Computers & Chemical Engineering, 68*, 56-77. https://doi.org/10.1016/j.compchemeng.2014.05.008

Sakthi, P., Ghahremanlou, D., & Lardi, A. B. A. Q. (2024). Sustainable hydrogen production, stor- age, and distribution-a systematic review for Newfoundland and Labrador. *Journal of Sustainable Development, 17*(1), 1-15. https://doi.org/10.5539/jsd.v17n1p1

Schrotenboer, A. H., Veenstra, A. A., uit het Broek, M. A., & Ursavas, E. (2022). A green hydrogen energy system: Optimal control strategies for integrated hydrogen storage and power generation with wind energy. *Renewable and Sustainable Energy Reviews, 168*, 112744. https://doi.org/10.1016/j.rser.2022.112744

Sean B. Walker, Daniel Van Lanen, M. F., & Mukherjee, U. (2016). Economic analysis with respect to power-to-gas energy storage with consideration of various market mechanisms. *International Journal of Hydrogen Energy, 41*, 7754-7765. https://doi.org/10.1016/j.ijhydene.2015.12.214

Sean B. Walker, Ushnik Mukherjee, M. F., & Elkamel, A. (2016). Benchmarking and selection of power-to-gas utilizing electrolytic hydrogen as an energy storage alternative. *International Journal of Hydrogen Energy, 41*, 7717-7731. https://doi.org/10.1016/j.ijhydene.2015.09.008

Sens, L., Neuling, U., Wilbrand, K., & Kaltschmitt, M. (2022). Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 - a techno-economic well-to-tank assessment of various supply chains. *International Journal of Hydrogen Energy.*

Seo, S. K., Yun, D. Y., & Lee, C. J. (2020). Design and optimization of a hydrogen supply chain using a centralized storage model. *Applied Energy, 262*, 114452. https://doi.org/10.1016/j.apenergy.2019.114452

Seo, Y., Park, H., Lee, S., Kim, J., & Han, S. (2023). Design concepts of hydrogen supply chain to bring consumers offshore green hydrogen. *International Journal of Hydrogen Energy, 48*, 15126-15142. https://doi.org/10.1016/j.ijhydene.2023.01.030

Sgarbossa, F., Arena, S., Tang, O., & Peron, M. (2023). Renewable hydrogen supply chains: A planning matrix and an agenda for future research. *International Journal of Production Economics, 255*, 108674. https://doi.org/10.1016/j.ijpe.2022.108674

Shamsi, H., Tran, M. K., Akbarpour, S., Maroufmashat, A., & Fowler, M. (2021). Macro-level opti- mization of hydrogen infrastructure and supply chain for zero-emission vehicles on a canadian corridor. *Journal of Cleaner Production, 289*, 125163. https://doi.org/10.1016/j.jclepro.2020.125163

Sharma, S., & Ghoshal, S. K. (2015). Hydrogen the future transportation fuel: From production to applications. *Renewable and Sustainable Energy Reviews, 43*, 1151-1158. https://doi.org/10.1016/j.rser.2014.11.093

Shi, R., Chen, X., Qin, J., Wu, P., & Jia, L. (2022). The state-of-the-art progress on the forms and modes of hydrogen and ammonia energy utilization in road transportation. *Sustainability, 14,* 11904. https://doi.org/10.3390/su141911904

Shin, J.-E. (2022). Hydrogen technology development and policy status by value chain in south korea. *Energies, 15*(23). https://doi.org/10.3390/en15238983

Simanullang, M., & Prost, L. (2022). Nanomaterials for on-board solid-state hydrogen storage appli- cations. *International Journal of Hydrogen Energy, 47*, 29808-29846. https://doi.org/10.1016/j.ijhydene.2022.06.301

Song, Q., Tinoco, R. R., Yang, H., Yang, Q., Jiang, H., Chen, Y., & Chen, H. (2022). A comparative study on energy efficiency of the maritime supply chains for liquefied hydrogen, ammonia, methanol and natural gas. *Carbon Capture Science & Technology, 4*, 100056. https://doi.org/10.1016/j.ccst.2022.100056

Sorgulu, F., & Dincer, I. (2018). A renewable source based hydrogen energy system for residential applications. *International Journal of Hydrogen Energy, 43*, 5842-5851. https://doi.org/10.1016/j.ijhydene.2017.10.101

Stöhr, T., Wohlmuth, B., Kutz, J., Lesemann, L., Pletz, S., Zimmermann, F., & Hujer, J. (2023). Analysis and installation of h2 value chains in rural areas. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2023.09.209

Statistics Canada. (2021). *Consumer price index, april 2021.* Retrieved from https://www150.statcan.gc.ca/n1/daily-quotidien/220524/dq220524a-eng.htm

Steffen, B., & Patt, A. (2022). A historical turning point? early evidence on how the russia-ukraine war changes public support for clean energy policies. *Energy Research & Social Science, 91*, 102758. https://doi.org/10.1016/j.erss.2022.102758

Streiner, S. (2019). *Chair and CEO scott streiner addresses the RBC Canadian automotive.* Retrieved from https://otc-cta.gc.ca/eng/content/chair-and-ceo-scott-streiner-addresses-rbc-canadian-automotive-transportation-and

Tahan, M. R. (2022). Recent advances in hydrogen compressors for use in large-scale renewable energy integration. *International Journal of Hydrogen Energy, 47*, 35275-35292. https://doi.org/10.1016/j.ijhydene.2022.08.128

Talebian, H., Herrera, O. E., & Mérida, W. (2019). Spatial and temporal optimization of hydrogen fuel supply chain for light duty passenger vehicles in british columbia. *International Journal of Hydrogen Energy, 44*, 25939-25956. https://doi.org/10.1016/j.ijhydene.2019.07.218

Talebian, H., Herrera, O. E., & Mérida, W. (2021). Policy effectiveness on emissions and cost reduction for hydrogen supply chains: The case for british columbia. *International Journal of Hydrogen Energy, 46*, 998-1011. https://doi.org/10.1016/j.ijhydene.2020.09.190

Talebian, H., Herrera, O. E., Tran, M., & Mérida, W. (2018). Electrification of road freight transport: Policy implications in british columbia. *Energy Policy, 115*, 109-118. https://doi.org/10.1016/j.enpol.2018.01.004

Taljan, G., Fowler, M., Cañizares, C., & Verbič, G. (2008). Hydrogen storage for mixed wind-nuclear power plants in the context of a hydrogen economy. *International Journal of Hydrogen Energy, 33*, 4463-4475. https://doi.org/10.1016/j.ijhydene.2008.06.040

Tan, K. C., Chua, Y. S., He, T., & Chen, P. (2023). Strategies of thermodynamic alternation on organic hydrogen carriers for hydrogen storage application: A review. *Green Energy and Resources, 1*, 100020. https://doi.org/10.1016/j.gerr.2023.100020

Tarkowski, R., & Uliasz-Misiak, B. (2022). Towards underground hydrogen storage: A review of bar- riers. *Renewable and Sustainable Energy Reviews, 162*, 112451. https://doi.org/10.1016/j.rser.2022.112451

Thiyagarajan, S. R., Emadi, H., Hussain, A., Patange, P., & Watson, M. (2022). A comprehensive review of the mechanisms and efficiency of underground hydrogen storage. *Journal of Energy Storage, 51*, 104490. https://doi.org/10.1016/j.est.2022.104490

Transport Canada. (2019). *Backgrounder: Canada's port system.* Retrieved from https://tc.canada.ca/en/marine/backgrounder-canada-s-port-system

Transport Canada. (2021*a*). *Green transportation.* Retrieved from https://tc.canada.ca/en/corporate-services/transparency/corporate-management-reporting/transportation-canada-annual-reports/green-transportation

Transport Canada. (2021*b*). *Road transportation.* Retrieved from https://tc.canada.ca/en/corporate-services/road-transportation

U.S. Department of Energy. (2023*a*). *Emissions from hybrid and plug in electric vehicles.* Retrieved from https://afdc.energy.gov/vehicles/emissionspollutants.html

U.S. Department of Energy. (2023*b*). *Vehicle emissions and air quality.* Retrieved from https://afdc.energy.gov/vehicles/emissions pollutants.html

Ustolin, F., Campari, A., & Taccani, R. (2022). An extensive review of liquid hydrogen in transportation with focus on the maritime sector. *Journal of Marine Science and Engineering, 10,* 1222. https://doi.org/10.3390/jmse10091222

Vijayakumar, V., Jenn, A., & Ogden, J. (2023). Modeling future hydrogen supply chains in the western united states under uncertainties: an optimization-based approach focusing on California as a hydrogen hub. *Sustainable Energy & Fuels, 7*(5), 1223-1244. https://doi.org/10.1039/D3SE00043E

Vishal, V., Verma, Y., Sulekh, K., Singh, T. N., & Dutta, A. (2023). A first-order estimation of underground hydrogen storage potential in indian sedimentary basins. *Geological Society, London, Special Publications, 528*, 123-137. https://doi.org/10.1144/SP528-2022-24

Wang, H., Wang, Z., Liang, C., Carriveau, R., Ting, D. S., Li, P., Cen, H., & Xiong, W. (2022). Under- water compressed gas energy storage (uwcges): Current status, challenges, and future perspectives. *Applied Sciences, 12,* 9361. https://doi.org/10.3390/app12189361

Wu, Y., & Zhong, L. (2023). An integrated energy analysis framework for evaluating the application of hydrogen-based energy storage systems in achieving net zero energy buildings and cities in canada. *Energy Conversion and Management, 286*, 117066. https://doi.org/10.1016/j.enconman.2023.117066

Xu, Z., Zhao, N., Hillmansen, S., Roberts, C., & Yan, Y. (2022). Techno-economic analysis of hydrogen storage technologies for railway engineering: A review. *Energies, 15*, 6467. https://doi.org/10.3390/en15176467

Yaïci, W., & Longo, M. (2022). Feasibility investigation of hydrogen refuelling infrastructure for heavy- duty vehicles in canada. *Energies, 15*, 2848. https://doi.org/10.3390/en15082848

Yang, M., Hunger, R., Berrettoni, S., Sprecher, B., & Wang, B. (2023). A review of hydrogen storage and transport technologies. *Clean Energy, 7*, 190-216. https://doi.org/10.1093/ce/zkad021

Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews, 146*, 111180. https://doi.org/10.1016/j.rser.2021.111180

Zamel, N., & Li, X. (2006). Life cycle analysis of vehicles powered by a fuel cell and by internal combustion engine for canada. *Journal of Power Sources, 155*, 297-310. https://doi.org/10.1016/j.jpowsour.2005.04.024

Zhang, C., Cao, X., Bujlo, P., Chen, B., Zhang, X., Sheng, X., & Liang, C. (2022), 'Review on the safety analysis and protection strategies of fast filling hydrogen storage system for fuel cell vehicle application. *Journal of Energy Storage, 45*, 103451. https://doi.org/10.1016/j.est.2021.103451

Zhang, T., Uratani, J., Huang, Y., Xu, L., Griffiths, S., & Ding, Y. (2023). Hydrogen liquefaction and storage: Recent progress and perspectives. *Renewable and Sustainable Energy Reviews, 176*, 113204. https://doi.org/10.1016/j.rser.2023.113204

Züttel, A. (2004). Hydrogen storage methods. *Naturwissenschaften, 91*, 157-172. https://doi.org/10.1007/s00114-004-0516-x

Acknowledgments

We would like to extend our gratitude to Mr. Charlie Oliver, owner and CEO of Martek Morgan Finch Inc., for directing us during our meetings with energy companies to receive practical feedback from the business community to reinforce the insights we provided for the industries interested in the field of energy, especially hydrogen.

Authors contributions

Farzam Farahmand contributed to investigation, research methodology, conceptualization, and writing – original draft. James King conducted investigation on evaluation criteria, analysis, conceptualization, and data collection. Davoud Ghahremanlou proposed the research idea, and performed investigation, research methodology, conceptualization, writing – original draft – review & editing, supervision, and project administration. Priya Sakthi contributed to investigation and visualization. Mohammad Reza Moghadas Jafari helped in data collection and visualization. All authors have thoroughly read and given their approval for the final manuscript to be published.

Funding

We also wish to express our gratitude for the financial support received from the Faculty of Business Administration at Memorial University of Newfoundland's Start-up fund grant number 216576 40500 2000.

Competing interests

The authors confirm that there are no known conflicts of interest, including financial interests or personal relationships, that might be perceived to have influenced the work presented in this paper.

Informed consent

Obtained.

Ethics approval

The Publication Ethics Committee of the Canadian Center of Science and Education.

The journal's policies adhere to the Core Practices established by the Committee on Publication Ethics (COPE).

Provenance and peer review

Not commissioned; externally double-blind peer reviewed.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Data sharing statement

No additional data are available.