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A Systematic Review and Bibliometric Analysis of Sustainable Hydrogen Production and Distribution in Canada

Priya Sakthi[1*], Davoud Ghahremanlou[1]

Faculty of Business Administration, Memorial University of Newfoundland, NL A1C 5S7 St. John's, Canada

[*] Correspondence: Priya Sakthi (psakthi@mun.ca)

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Abstract: In light of the intricate interconnection of current global challenges, energy security concerns, and global warming, the strategic pursuit of renewable hydrogen has emerged as a beacon of promise. Consequently, Canada, in alignment with its global environmental commitments and supported by partnerships with entities such as the European Union, is actively working to harness its significant potential in sustainable hydrogen production and distribution. This study undertakes a systematic review and bibliometric analysis of 55 scientific papers focused on hydrogen production and distribution in Canada, published up to September 2023. Firstly, a comprehensive synthesis of these papers is provided across four key dimensions: production, distribution, optimization, and sustainability. Secondly, critical insights into the evolution of hydrogen research and the collaborations shaping the field are unveiled through bibliometric analysis, employing Bibliometrix, an R-package designed for comprehensive science mapping and bibliometric analysis. The findings are intended to offer valuable insights to academic, public, and business communities, enabling them to better utilize available resources, enhance teamwork, and contribute to a more sustainable global energy landscape.

Keywords: Hydrogen; Energy; Bibliometric analysis; Optimization; Renewable energy; Sustainability; Canada

1 Introduction

Global warming and the uneven distribution of fossil fuels have galvanized policymakers worldwide into urgent action to address these challenges humanity faces through renewable energies. In response to these pressing issues, the European Union has redoubled its commitment to renewable energy production [1], aligning with the goals set forth in the 2015 Paris Agreement [2] and the sustainable development goals of the United Nations [3]. Nevertheless, the monumental challenges of achieving net-zero emissions and ensuring energy security loom large, demanding even greater attention and sustainable solutions.

In recognition of the pressing imperative to attain further energy security and reduce emissions, collaborative efforts between the European Union and the Canadian government have taken center stage as they jointly address these critical challenges [4]. This strategic alliance complements Canada's ambitious commitment to achieve net-zero emissions by 2050, exemplified by initiatives like "Helping industries develop and adopt clean technology in their journey to net-zero emissions" [5]. Germany, likewise, has forged a pivotal partnership with Canada, with a particular emphasis on advancing the frontier of renewable hydrogen technologies [6]. These national policies and international collaborations demonstrate the capabilities and efforts of Canada to develop a robust economy by utilizing its resources to shape a sustainable and resilient energy future.

Canada encompasses a bountiful and diverse energy landscape, which serves as a robust foundation for powering its thriving economy. The study [7] announces that in 2020, Canada held the position of the fourth-largest oil producer globally by producing 4.66 million barrels per day, and stood as the sixth-largest natural gas producer worldwide, consistently generating an average daily production of $15.5 billion cubic feet. Furthermore, Canada has hydro, nuclear, wind, coal, biomass, and solar energy sources that are utilized to produce electricity. To further accelerate the momentum towards net zero emissions, in December 2020, the Canadian government unveiled its Hydrogen Strategy, with a focus on the production and distribution of hydrogen. To reinforce this strategy, the federal government has committed a sizeable sum of $1.5 billion to promote low-carbon and zero-emission fuels, coupled with an extra

$287 million set aside for a comprehensive zero-emission vehicle program [8]. This paper addresses gaps in the understanding of sustainable hydrogen production and distribution in Canada, focusing on underexplored areas such as the integration of renewable energy sources and the economic viability of hydrogen supply chains. It uniquely contributes by providing a comprehensive bibliometric analysis and proposing actionable strategies for future research and implementation.

To satisfy the goal of this research: Section 2 compares this paper with both systematic and bibliometric analysis review papers. Section 3 represents the search approach used for finding relevant papers for review in this paper. Two types of analyses are conducted on the found papers, in Section 4: (1) Bibliometric, in which three main components: paper (year and journal of publication), authors (collaboration, productivity, and affiliation), and keywords (thematic map and word cloud) are analyzed, and (2) systematic, which focuses on the contents of the papers (i.e., hydrogen sources, production methods and technologies, storage options, transport and transmission techniques, optimization, and sustainability considerations). According to analyses, Section 5 offers our findings and directions for the public sector, private sector, and academic community for further attention. Section 6 concludes the entire paper.

2 Background

The main goal of this paper is to be the primary source of systematic distillation of all papers dealing with hydro-gen production and distribution in Canada and their corresponding bibliometric information. This will provide a solid ground for further efforts towards alleviating global warming and energy insecurity through utilizing Canada's resources. To that end, first, this paper represents how it contributes in (1) systematic review papers in Canada and around the globe in Section 2.1 through comparison with the other 40 recent relevant systematic review papers, and (2) bibliometric analysis review papers by filling the research gaps in seven recent relevant bibliometric analysis review papers, in Section 2.2. Finally, all the contributions and the way forward are outlined in Section 2.3.

2.1 Former Systematic Review Papers

A systematic review paper is a thorough summary of primary studies that contains a precise statement of its goal, sources, and repeatable methodology. Systematic review papers have swiftly and progressively supplanted traditional narrative reviews as the primary means of delivering and maintaining the latest research findings [9]. The study [10] claims that most journals have started to change their policy in acceptance of review papers, they have been giving priority to systematic review papers.

Table 1 compares 41 relevant systematic review papers with this paper based on five major categories: (1) Pro-duction, (2) Distribution, (3) Optimization, (4) Sustainability, and (5) Location; these categories are selected based on their significance, please see study [11]. Table 1 represents all 41 review papers related to hydrogen production and distribution published in February 2022, ushering in a new era in the global energy landscape. In the table, only review paper #34 [12] focuses on Canada. The study [12] has not: (1) considered algae and coal as the source of production, while Canada has abundant algae [13] and coal [14], (2) evaluated storage and transportation methods, which are vital for managing a complete spectrum of hydrogen businesses, and (3) demonstrated the opti-mization software, which ensures sustainable hydrogen production and distribution. Hence, this paper contributes to Canada's systematic review literature about hydrogen production and distribution by incorporating these issues.

The other 40 systematic review papers, excluding those focused on Canada, listed in Table 1, mostly form a matrix where elements below the counter-diagonal are largely unchecked. This shows the review papers are progressing to-wards covering all segments of hydrogen production and distribution, as the papers are sorted in reverse chronological order. The most complete and recent systematic review paper is #1, in which: algae, nuclear, standalone systems, and optimization software are not evaluated as the review criteria; however, Canada is recognized for its amount of algae [13], Canada is the sixth largest nuclear producer in the world [15], $1/9$ Canadians live in remote communities for which stand-alone systems are vital for fair access to energy [16], and optimization software plays a key role in ensuring a sustainable energy sector. Therefore, this paper also contributes to global systematic review literature about hydrogen production and distribution by addressing all the research gaps in the 39 systematic review papers [17–56].

This paper has broadened the focus of the study [11] on renewable hydrogen sources (wind, solar, hydro, biomass, and geothermal) to include the complete spectrum of hydrogen production, including algae and non-renewable sources (natural gas, coal, oil, and nuclear) in order to enrich our analyses. Please see studies [57, 58] for further information on the various hydrogen production technologies and methods, respectively.

Hydrogen goes through procedures pertaining to storage, transportation, and grid integration after the production phase. Battery and hydrogen tanks are two storage solutions, as described in study [58]. According to study [59], transportation methods include pipeline, truck, ship, and railroad. Hydrogen can be integrated into the grid by being sent as energy to remote sites for consumption; also, it can be what is called stand-alone consumption, in which it is produced in an area and consumed in surrounding communities that are not connected to the main grid [18].

Table 1. Comparison of this paper with relevant systematic review papers published since February 2022

		Production												Distribution											Sustainability	Location
		Energy Sources R						NR				P		St		Tr				ET		Software				
No.	**Reference**	W	S	H	B	G	A	Na	C	O	N	T	M	Ba	HT	P	T	S	R	GC	SA	Ho	Ma	O		
1	[17]	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	Europe
2	[18]	✓	✓	✓		✓		✓	✓	✓		✓	✓		✓	✓	✓	✓	✓						✓	Europe
3	[19]	✓	✓	✓								✓	✓		✓	✓					✓					
4	[20]	✓	✓	✓					✓			✓	✓													
5	[21]	✓	✓	✓		✓		✓	✓																	
6	[22]	✓	✓						✓	✓	✓	✓	✓			✓	✓	✓	✓					✓		
7	[23]																									
8	[24]	✓	✓	✓		✓		✓	✓						✓	✓	✓	✓				✓	✓	✓		
9	[25]	✓	✓									✓	✓													
10	[26]														✓											Latvia
11	[27]																									
12	[28]	✓	✓	✓								✓	✓		✓	✓					✓					
13	[29]																									
14	[30]	✓	✓	✓		✓		✓		✓	✓	✓														Philippines
15	[31]	✓	✓						✓	✓		✓	✓		✓	✓										Djibouti
16	[32]																									
17	[33]	✓	✓	✓		✓		✓	✓						✓											
18	[34]			✓	✓			✓																		
19	[35]	✓	✓	✓						✓	✓	✓	✓	✓				✓						✓		
20	[36]	✓	✓	✓		✓					✓															Egypt
21	[37]	✓						✓																		UK
22	[38]		✓	✓																						
23	[39]	✓	✓	✓		✓																				
24	[40]	✓																								
25	[41]	✓	✓		✓	✓																				
26	[42]																									
27	[43]	✓	✓	✓												✓										
28	[44]	✓		✓														✓			✓					Europe
29	[45]	✓	✓			✓	✓						✓													
30	[46]	✓	✓	✓																						
31	[47]	✓	✓		✓			✓	✓																	Australia
32	[48]	✓													✓											Italy
33	[49]	✓	✓	✓	✓	✓		✓	✓		✓	✓	✓		✓	✓							✓			
34	[12]	✓	✓	✓	✓	✓		✓			✓	✓		✓							✓				✓	Canada
35	[50]																									
36	[51]	✓	✓	✓		✓	✓	✓	✓	✓		✓	✓	✓										✓	✓	Northern Netherlands
37	[52]	✓						✓			✓															Gulf of Mexico
38	[53]	✓	✓					✓			✓				✓											Western Europe
39	[54]	✓	✓									✓	✓		✓	✓										
40	[55]																									
41	[56]	✓	✓	✓				✓	✓	✓	✓	✓	✓		✓	✓										China
This paper		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	Canada

Abbreviations: R: Renewable, NR: Non-Renewable, P: Production, W: Wind, S: Solar, H: Hydro, B: Biomass, G: Geo-thermal, A: Algae, Na: Natural gas, C: Coal, O: Oil, N: Nuclear, T: Technology, M: Method, St: Storage, Tr. Transportation, Ba: Battery, S: Ship, ET: Electricity Transmissisn, HT: Hydrogen Tank, P: Pipeline, T: Truck, R: Railway, GC: Grid Connected, SA: Stand Alone, Ma: MATLAB, Ho: HOMER.

According to study [18], optimization software, with a particular emphasis on HOMER and MATLAB, has emerged as crucial instruments for ensuring the efficacy of hydrogen production and delivery. Utilizing these soft-ware programs, it is possible to do a thorough examination of the social, economic, and environmental aspects of hydrogen generation and distribution, providing vital sustainability insights. Therefore, this paper aims to systemati-cally analyze all the scientific papers regarding hydrogen production and distribution published in Canada from four main aspects: (1) Production, (2) Distribution, (3) Optimization, and (4) Sustainability. Furthermore, to offer addi-tional insights about the trends, core contributors, and research hotspots for hydrogen production and distribution in Canada, we employ bibliometric analysis, which is an emerging method for literature review [60]. This may enhance collaboration on addressing the current significant challenges in the field and accelerate the response to the existing energy crisis in Europe. Therefore, we show how this paper stands among other bibliometric analysis review papers in the following section.

2.2 Former Bibliometric Analysis Papers

Bibliometric analysis refers to the quantitative analysis of publications and citations in academic literature [61]. It pro-vides an objective way to visualize and evaluate the growth of literature in a given field over time. By tracking various characteristics of papers, including keywords, authors, publications, citations, and collaborative networks, it enables visualization of how a research topic or domain is evolving [62]. This helps identify emerging trends, intellectual structures, and paradigm shifts. Furthermore, bibliometric analysis, through citation analysis, determines which pa-pers are highly cited and widely influence the work of others, providing a measure of relative significance and scientific impact [63]. Additionally, bibliometric data is crucial for research evaluation and informed policymaking. For instance, many funding agencies and institutions now use bibliometric indicators to assess research performance and allocate grants and resources [61]. Moreover, comparative bibliometric analysis helps benchmark research standards identify areas for improvement, and assist strategic planning [64].

Table 2 demonstrates how this paper stands among seven other relevant bibliometric analysis review papers pub-lished since February 2022. There are three main categories for conducting bibliometric analysis in the table: (1) paper: distribution of papers annually and by journals, (2) authors: collaboration, production, and affiliation, and (3) keywords: thematic map, and word cloud. Only studies [65] and [66], items #6 and 7, respectively, have just one column unchecked. Study [65] do not investigate green hydrogen (i.e., hydrogen produced from renewable sources) from a collaboration network point of view; however, this network shows the most active authors in the field and their teams. Study [66] do not compare the papers from a word cloud point of view; however, this is significant for identifying the hotspots of the research. Therefore, this paper analyzes all papers found for hydrogen production and distribution in Canada from author collaboration and word cloud as well.

Table 2. Comparison of this paper with relevant bibliometric analysis review papers published since February 2022

No.	Ref.	Analysis							Focus	Research Gaps
		Paper		Author			Keyword			
		Year	Journal	Collaboration	Production	Affiliation	Thematic Map	Word Cloud		
1	[67]	✓	✓		✓	✓	✓		Production	Distribution, Optimization, Sustainability.
2	[68]	✓	✓	✓	✓	✓			Production	Distribution, Optimization, Sustainability.
3	[69]	✓	✓		✓	✓	✓		Green hydrogen	Non-renewable sources, Optimization, Sustainability.
4	[43]	✓	✓	✓	✓		✓		Economics	Production, Distribution, Optimization, Sustainability.
5	[70]	✓	✓	✓	✓	✓			Green hydrogen	Non-renewable sources, Optimization, Sustainability.
6	[65]	✓	✓		✓	✓	✓	✓	Green hydrogen	Non-renewable sources, Optimization, Sustainability.
7	[66]	✓	✓	✓	✓	✓	✓		Green hydrogen	Non-renewable sources, Optimization, Sustainability.
	This paper	✓	✓	✓	✓	✓	✓	✓	Production, Distribution, Optimization, Sustainability	We cover all these gaps.

To further clarify the significance of this paper, we distilled the seven relevant bibliometric analysis review papers by identifying their research focus and research gaps in Table 2. The table demonstrates papers #3, 5, 6, and 7 are about green hydrogen, while Canada held the position of the fourth-largest oil producer and the sixth-largest natural gas producer worldwide in 2020 [7]. Papers #1, 2, and 4 have not considered distribution, optimization, and sustainability in their studies; however, these are significant for sustainable hydrogen production and distribution in Canada. Our paper has addressed all of these gaps in the bibliometric analysis. Furthermore, this paper is the first to provide both a systematic review and bibliometric analysis of the same set of papers to provide a more comprehensive study; please note that none of the papers in Table 2 are repeated in Table 1.

2.3 Contributions and Structure

In order to fulfill the purpose of this work, it expands the body of knowledge in the field by: (1) designing a search approach and employing it for identifying all the papers related to hydrogen production and distribution in Canada in Section 3, (2) analyzing the found papers from both systematic and bibliometric points of view in Section 4; Section 4.1 synthesizes the found papers from energy sources (renewable and non-renewable), production methods and technologies, transportation and transmission techniques, optimization software, sustainability, and their particular attention within Canada, and Section 4.2 focuses on bibliometric analysis, in which three main components of the found papers: paper (year and journal of publication), author (collaboration, productivity, and affiliation), and keyword (thematic map and word cloud) are analyzed, and (3) compiling the results of analyses and offering insights for academic, government, and industry communities in Section 5.

3 Methodology

Study [71] strongly advises authors to be transparent about the methodology they employ to choose the materials as the review's sources. They mention that the methodology should include the publishing portals, e.g., ScienceDirect, used as the sources for searching for materials to review. Furthermore, the search employs keywords and Boolean operators (AND, OR, and NOT). Additionally, it's important to be clear about the time range and its selection's motivations.

To systematically review sustainable hydrogen production and distribution in Canada, we looked for all papers in publishing portals, e.g., ScienceDirect, Elsevier, Scopus, IEEE Xplore, and SpringerLink. These reputable sources were selected due to their wide coverage of high-quality, peer-reviewed journals across the fields of energy, sustain-ability, and engineering. The following keyword searches were employed along with Boolean operators (AND, OR): "hydrogen production", "hydrogen distribution", "hydrogen storage", "hydrogen transportation", "hydrogen optimiza-tion", or "hydrogen sustainability", which was separately combined with "Canada", and provinces and territories in Canada (e.g., "Alberta", "British Columbia", "Manitoba", "New Brunswick", "Newfoundland & Labrador", or "Que-bec"). Furthermore, references to the studied papers and the works cited within them were utilized as secondary sources for identifying relevant literature. In order to create a more thorough analysis, we looked for all relevant journal papers (theses, conference papers, and other types of documents were excluded) until September 2023 to en-sure our analysis covered the most recent advancements in the field, aligning with the latest technological and policy developments, considering a year and a half passed since the beginning of the Russian-Ukraine conflict in February 2022, leading to efforts to manage the energy crisis in Europe. This led to 55 papers, which will be analyzed from bibliometric and content points of view in the coming section.

4 Analyses

To provide a comprehensive review, we analyze the papers from the bibliometric and content points of view. To that end, the 55 papers selected about hydrogen production and distribution in Canada are analyzed, respectively, following some of the most recent works in the field by studies [72] and [73] for bibliometric analysis and [11] for systematic analysis. Section 4.1 reviews the 55 papers from (1) Production, (2) Distribution, (3) Optimization, and (4) Sustainability aspects. Section 4.2 provides bibliometric analysis with a focus on paper (year and journal of publication), author (collaboration, productivity, and affiliation), and keyword (thematic map and word cloud).

4.1 Systematic Analysis

Study [74] highlighted that a systematic review is an important process that helps researchers synthesize all available empirical evidence that fits pre-specified eligibility criteria explained in the Methodology Section. In this section, we distill the contents of the 55 papers that meet the eligibility criteria from: (1) the production aspect in Section 4.1.1, (2) the distribution and optimization aspect in Section 4.1.2, and (3) sustainability in Section 4.1.3.

4.1.1 Production aspect

Table 3 reviews the 55 papers, about hydrogen production and distribution in Canada, from two main categories: (1) production sources, and (2) production methods and technologies. In production sources, we have divided sources into two classes: (1) renewable: wind, solar, hydro, biomass, geothermal, and algae, and (2) non-renewable: natural gas, coal, oil, and nuclear.

Table 3 indicates that renewable sources of hydrogen production have been studied further relative to non-renewable sources. Wind power has been the predominant focus of research over the years, with 58.1% of studies exploring its optimization and integration within hydrogen production systems. This aligns well with Canada's substantial wind energy potential; except for Nunavut, every province and territory in Canada produced some wind energy in 2015 [75]. Ontario, Quebec, Alberta, British Columbia, and Nova Scotia are five provinces of Canada (out of ten provinces) with the highest wind potential [75]. Additionally, study [76] demonstrates that, compared to many other Canadian regions, Newfoundland has a higher average wind speed. On the other hand, less than 10% of the papers studied hydro, geothermal, and algae as the sources of hydrogen production. However, Canada has abundant water resources; it has access to up to 20% of the world's freshwater surface and 7% of the world's renewable water flow, making it one of the largest renewable freshwater supplies in the world [77]. Furthermore, Alberta, Saskatchewan, the Northwest Territories, and British Columbia have significant potential for geothermal energy and have received fundings from the government for further development, e.g., a $25.6 million investment in 2019 [78]. Only 29% of papers studied biomass as the source of hydrogen, while Canada is the second-most forested country globally [79]. Quebec, Ontario, British Columbia, the Northwest Territories, Alberta, Saskatchewan, Manitoba, and Newfoundland and Labrador are provinces and territories with over 10,000 hectares of forest [80].

On the other hand, oil has been considered as the non-renewable source of hydrogen production in 30.9% of the papers. Followed by 21.8% of the papers including natural gas in their study. However, according to study [7], Canada was the sixth-largest producer of natural gas and ranked fourth in the world for oil production in 2020. Just 16.3% and 7.2% of the papers included coal and nuclear in their research, respectively. Despite, the fourth-largest exporter of metallurgical coal worldwide is Canada, mainly coming from Alberta and British Columbia [81]. In 2016, Canada ranked sixth in the world for production of nuclear energy output [82]. Finally, we noticed that papers published over 2018 have mainly considered the methods and technologies of hydrogen production in their studies; however, in total, they count for 32.7% and 23.6% of the papers. Considering the significance of technologies and methods for hydrogen production, as strategic decisions [83], they require further attention.

Table 3. Analysis of reviewed papers from production perspective

		Energy Sources											
		Renewable						**Non-renewable**				**Production**	
No.	**Ref.**	Wind	Solar	Hydro	Biomass	Geothermal	Algae	Natural Gas	Coal	Oil	Nuclear	Method	Technology
1	[84]	✓	✓					✓	✓			✓	✓
2	[85]		✓		✓	✓		✓	✓	✓		✓	
3	[86]		✓									✓	✓
4	[87]							✓				✓	✓
5	[88]		✓									✓	✓
6	[89]	✓	✓	✓	✓			✓	✓	✓		✓	
7	[90]	✓	✓					✓	✓			✓	✓
8	[91]							✓				✓	✓
9	[92]	✓	✓					✓		✓		✓	✓
10	[93]	✓	✓									✓	
11	[94]	✓											
12	[95]	✓	✓	✓									
13	[96]	✓	✓	✓				✓	✓	✓		✓	✓
14	[97]				✓			✓	✓	✓		✓	✓
15	[98]										✓	✓	✓
16	[99]	✓	✓	✓							✓		✓
17	[100]	✓	✓					✓				✓	
18	[101]	✓	✓	✓								✓	
19	[102]	✓										✓	
20	[103]	✓	✓					✓					✓
21	[104]		✓		✓			✓	✓	✓		✓	✓
22	[105]	✓	✓										
23	[106]	✓								✓			
24	[107]	✓								✓			
25	[108]	✓				✓							
26	[109]	✓							✓		✓		
27	[110]	✓								✓			
28	[111]	✓	✓							✓			
29	[112]	✓											
30	[113]	✓								✓	✓		
31	[114]	✓				✓				✓			
32	[115]	✓											
33	[116]				✓								

		Energy Sources											
		Renewable						Non-renewable				Production	
No.	Ref.	Wind	Solar	Hydro	Biomass	Geothermal	Algae	Natural Gas	Coal	Oil	Nuclear	Method	Technology
34	[117]												
35	[118]				✓				✓	✓			
36	[119]	✓											
37	[120]												
38	[121]												
39	[122]	✓											
40	[123]				✓								
41	[124]				✓								
42	[125]												
43	[126]												
44	[127]				✓								
45	[128]						✓						
46	[129]				✓								
47	[130]	✓			✓					✓			
48	[131]	✓			✓								
49	[132]	✓					✓			✓			
50	[133]	✓										✓	
51	[134]	✓											
52	[135]	✓			✓		✓			✓			
53	[136]				✓	✓							
54	[137]		✓		✓	✓							
55	[138]				✓					✓			
	Total (%)	58.1	32.7	9	29	9	5.4	21.8	16.3	30.9	7.2	32.7	23.6

4.1.2 Distribution and optimization aspect

Table 4 depicts the 55 reviewed papers from two major categories: (1) distribution, and (2) optimization software packages. In the distribution category we consider three main sub-categories: (1) storage, which can be done through utilizing batteries for electricity and hydrogen tanks, (2) the transportation of hydrogen through: pipeline, truck, ship, and railway, and (3) transmission, by which electricity from hydrogen can be transmitted through connection to a grid; or off-grid, referred to as stand-alone, by which hydrogen produced electricity is transported to, converted and consumed by communities. In the optimization software packages, HOMER and MATLAB serve as the primary sub-categories, and additional packages, i.e., GAMBIT, Simulink, ASPEN, and MS Excel, fall under sub-category named Others.

Table 4. Analysis of reviewed papers from distribution and optimization perspective

		Distribution								Software		
		Storage		Transportation				Electricity Transmission				
No.	Ref.	Battery	Hydrogen Tank	Pipeline	Truck	Ship	Railway	Grid-connected	Stand-alone	HOMER	MATLAB	Others
1	[84]		✓					✓				
2	[85]		✓	✓	✓					✓		
3	[86]		✓								✓	
4	[87]											✓
5	[88]							✓			✓	
6	[89]		✓	✓	✓							
7	[90]	✓		✓								
8	[91]	✓		✓	✓			✓				✓
9	[92]	✓		✓	✓			✓				
10	[93]							✓	✓			
11	[94]		✓					✓			✓	
12	[95]	✓										
13	[96]			✓								
14	[97]		✓	✓				✓				

No.	Ref.	Storage		Distribution Transportation				Electricity Transmission		Software		
		Battery	Hydrogen Tank	Pipeline	Truck	Ship	Railway	Grid-connected	Stand-alone	HOMER	MATLAB	Others
15	[98]											
16	[99]			✓								
17	[100]		✓	✓	✓	✓	✓	✓				
18	[101]	✓	✓						✓	✓	✓	
19	[102]	✓	✓					✓				
20	[103]							✓			✓	
21	[104]		✓			✓						
22	[105]		✓					✓				
23	[106]					✓						
24	[107]		✓									
25	[108]	✓				✓						
26	[109]		✓					✓	✓	✓		
27	[110]	✓										
28	[111]		✓					✓				
29	[112]		✓					✓				
30	[113]		✓					✓				
31	[114]		✓					✓				
32	[115]	✓										
33	[116]			✓								
34	[117]		✓					✓				
35	[118]			✓								
36	[119]	✓										
37	[120]		✓					✓				
38	[121]		✓					✓				
39	[122]	✓										
40	[123]			✓								
41	[124]		✓					✓				
42	[125]		✓					✓				
43	[126]		✓					✓				
44	[127]		✓					✓				
45	[128]		✓					✓				
46	[129]		✓					✓				
47	[130]	✓										
48	[131]		✓					✓				
49	[132]	✓										
50	[133]	✓			✓							
51	[134]	✓										
52	[135]	✓		✓			✓					
53	[136]		✓					✓				
54	[137]		✓					✓				
55	[138]	✓										
	Total (%)	30.9	52.7	23.6	10.9	7.2	3.6	50.9	5.4	5.4	9	3.6

Study [138] claim that the creation of a high-density, safe, inexpensive, and efficient hydrogen storage and transportation technology is one of the major obstacles to the widespread use of hydrogen and the creation of a worldwide hydrogen economy. Both storage methods mentioned in Table 4, battery and tank, respectively, have been considered in 30.9% and 52.7% of the reviewed papers. Likewise, none of the four transportation modes has been considered in more than 25% of the reviewed papers. Therefore, hydrogen storage and transportation require additional attention. Furthermore, grid connected and stand-alone are included in 50.9% and 5.4% of the reviewed papers, respectively. However, 1/9 Canadians live in remote communities for which stand-alone systems are vital for fair access to energy [16]. Additionally, optimization of hydrogen is vital for establishing a sustainable hydrogen economy [139]; however, less than 10% of the reviewed papers have considered them in their studies.

4.1.3 Sustainability aspect

In order to achieve the UN Sustainable Development Goals, study [140] emphasize the importance of sustainable hydrogen generation and delivery. Thus, Table 5 illustrates the 55 reviewed papers from economic, environmental, and social aspects, which is the framework of sustainability [141]. A basic summation of the numbers shows 27 papers out of 55 reviewed papers studied different aspects of sustainability. The majority of papers, 16 of them, focused on the economic aspect, while study [142] emphasize on the need to determine the extent and cost of the viability and practicability of moving to a hydrogen energy economy. It is apparent that economy and environment together have been included in four reviewed papers, and environment alone has just been studied in two reviewed papers. However, global warming was is the key factor for moving towards hydrogen energy as a substitution for fossil fuel sources of energy. No reviewed paper has considered all the aspects of sustainability or solely the social aspect in their study, please see zeros in Table 5. Furthermore, the socio-economic aspect has received more attention from researchers relative to socio-environment, three and two reviewed papers included them in their research, respectively.

Table 5. Analysis of reviewed papers from sustainability perspective

No.	Ref.	**Economic**						**Environment**			**Social**	
		LCOE	OC	CF	LCOH	COP	Others	Greenhouse Gases	Renewable Fraction	Fuel Consumption	Job	Energy Access
1	[84]		✓									
2	[85]		✓		✓	✓	✓	✓	✓			
3	[86]						✓					
4	[87]		✓	✓					✓	✓		
5	[88]						✓	✓				
6	[89]	✓					✓					
7	[90]											
8	[91]						✓					
9	[92]								✓		✓	
10	[93]											
11	[94]								✓		✓	
12	[95]	✓	✓								✓	
13	[96]	✓	✓									
14	[97]											
15	[98]											
16	[99]											
17	[100]											
18	[101]	✓			✓							
19	[102]											
20	[103]	✓	✓	✓	✓							
21	[104]							✓	✓			
22	[105]											
23	[106]											
24	[107]	✓										
25	[108]						✓					
26	[109]		✓						✓			
27	[110]	✓										
28	[111]											
29	[112]											
30	[113]											
31	[114]											
32	[115]	✓										
33	[116]				✓							
34	[117]											
35	[118]				✓							
36	[119]	✓										
37	[120]											
38	[121]											
39	[122]	✓										

No.	Ref.	Economic						Environment			Social	
		LCOE	OC	CF	LCOH	COP	Others	Greenhouse Gases	Renewable Fraction	Fuel Consumption	Job	Energy Access
40	[123]				✓							
41	[124]											
42	[125]											
43	[126]											
44	[127]											
45	[128]											
46	[129]											
47	[130]	✓										
48	[131]											
49	[132]	✓										
50	[133]					✓					✓	
51	[134]											
52	[135]	✓			✓						✓	
53	[136]											
54	[137]											
55	[138]											
	Total (%)	23.6	12.7	3.6	12.7	3.6	10.9	5.4	10.9	1.8	9	0

Abbreviations: LCOE: Levelized Cost Of Energy, OC: Operating Cost, CF: Capacity Factor, LCOH: Levelized Cost Of Hydrogen, COP: Coefficient of Performance.

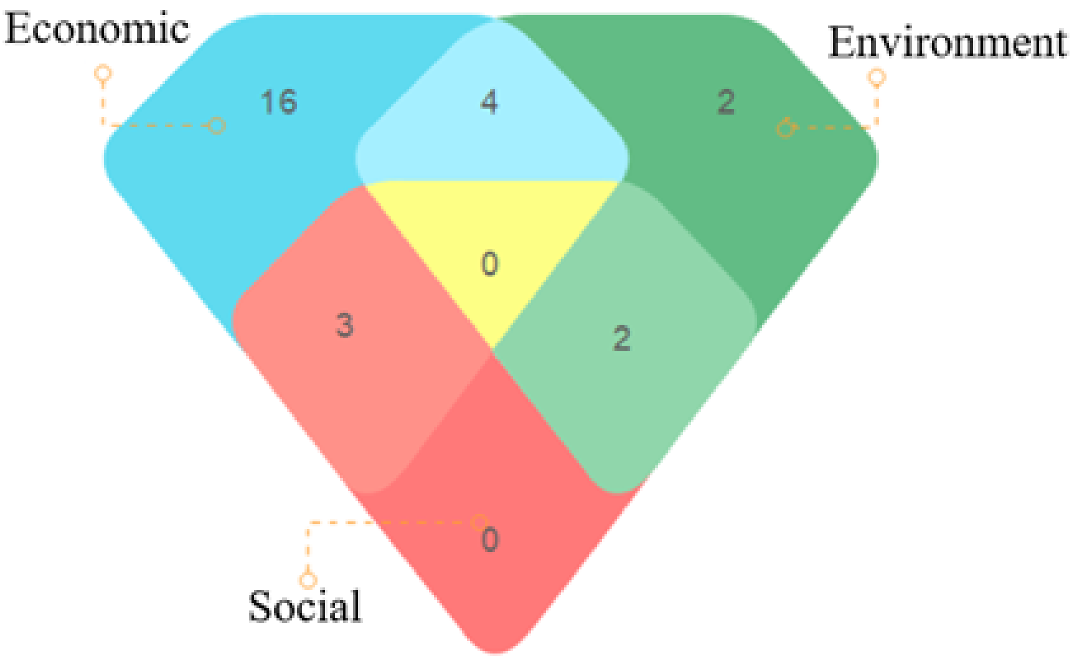

Figure 1. Analysis of reviewed papers within framework of sustainability

Figure 1 goes into further detail to outline the indicators investigated under each sustainability aspect and their precise area of investigation. We look into three different aspects of sustainability: (1) economic: levelized cost of energy, operating cost, capacity factor, levelized cost of hydrogen, coefficient of performance, and others (i.e., levelized cost of ammonia, electricity production cost, excess electricity cost, unmet electricity load cost, and payback period); (2) environment: greenhouse gases, renewable fraction, and fuel consumption; and (3) social: job creation and energy access. Overall, none of the criteria in any of the three aspects of sustainability have been studied in more than 25% of the reviewed papers.

As for the economic aspect, the levelized cost of energy, operating cost, and levelized cost of hydrogen have received the most attention from researchers. On the other hand, the capacity factor and coefficient of performance have received the least attention from the academic community. This is despite the significance of a higher capacity factor [143] and coefficient of performance leading to lower hydrogen production costs [144]. Finally, further attention towards the economic aspect of renewable hydrogen production and distribution enhances energy security [145].

Regarding environmental and social aspects, renewable fraction and job creation have been considered in 10.9% and 9% of the reviewed papers, respectively. While climate change was the initial force for moving towards sustainable hydrogen, greenhouse gases and fuel consumption have been studied, respectively, in just 5.4% and 1.8% of the reviewed papers. Study [146] claim that the challenge of the 21st century is climate change, which has resulted from an accumulation of greenhouse gases. 1/9 Canadians live in remote communities, for which stand-alone systems are vital for fair access to energy. Study [16] demonstrated that one out of every nine Canadians lives in remote communities for which fair access to energy is vital; however, none of the 55 reviewed papers has considered this criterion in their research.

4.2 Bibliometric Analysis

Bibliometric analysis aims to quantitatively analyze the 55 papers found about hydrogen production and distribution in Canada from the publication and citation dimensions. There are various software packages for bibliometric analysis, such as pyBibX, Bibliometrix, CiteSpace, and VOSviewer, that offer unique features. The pyBibX is known for its flexibility in data manipulation, CiteSpace excels in visualizing citation networks, VOSviewer is user-friendly for mapping bibliometric data, and Bibliometrix, an open-source R-package, is among the most comprehensive tools for quantitative research in the field of bibliometrics and scientometrics [147]. The Bibliometrix tool enables users to import bibliographic data from various databases, e.g., Scopus, which can be stored as a Bibtex (.bib) or Plain Text (.txt) file. Bibliometrix is increasingly being used in academic research for conducting descriptive analyses, such as identifying the most cited authors, the most published journals, and the most relevant keywords in a specific field. While pyBibX, CiteSpace, and VOSviewer offer various bibliometric analysis capabilities, Bibliometrix was chosen for its comprehensive science mapping features and user-friendly interface, which facilitated detailed and systematic analysis. Therefore, to provide further insights and enhance replicability of analyses, we employ Bibliometrix for this research to represent: (1) paper in Section 4.2.1 (visualized by Microsoft Excel), which includes distribution of papers by year in Section 4.2.1 and distribution of papers by journal of publication in Section 4.2.2, (2) author in Section 4.2.2 encompasses collaboration, productivity, and affiliation in Sections 4.2.1, 4.2.2, and 4.2.3, and (3) keyword in Section 4.2.3, including thematic map word cloud are analyzed.

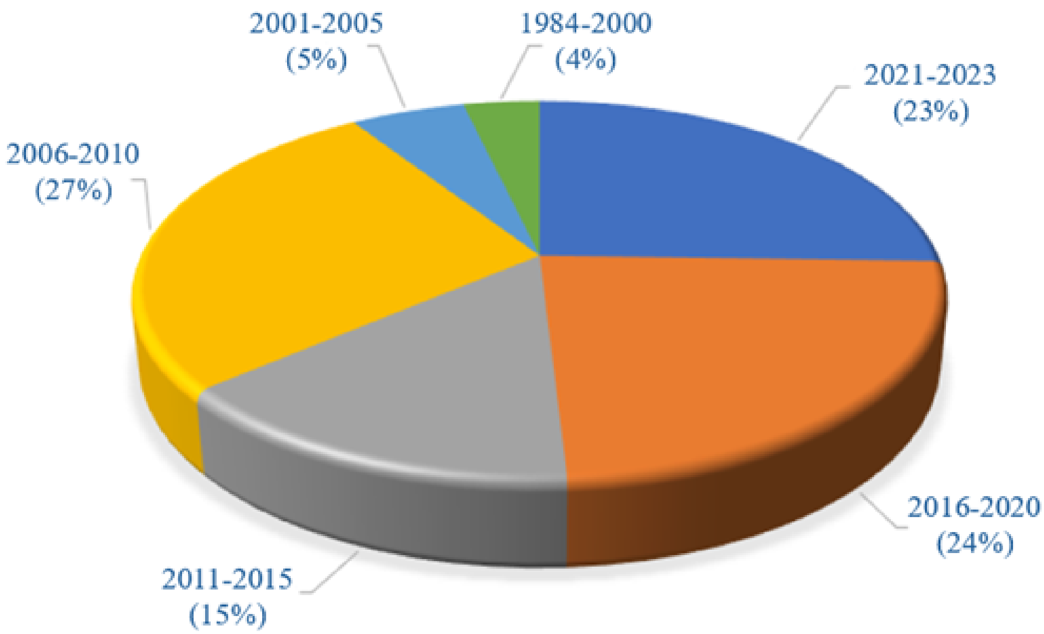

Figure 2. Distribution of reviewed papers by year

4.2.1 Paper

(1) Distribution of reviewed papers by year

Pie chart in Figure 2 demonstrates how the 55 reviewed papers regrading hydrogen production and distribution in Canada are synthesized in six various time spans between 1984 and 2023, along with the proportion of publications within that span in parentheses: (1) 1984 to 2000 (4%), (2) 2001 to 2005 (5%), (3) 2006 to 2010 (27%), (4) 2011 to 2015 (16%), (5) 2016 to 2020 (24%), and (6) 2021 to 2023 (25%). The time spans are mainly distributed uniformly (every 5 years), except for spans #1 and 6. Accordingly, more than 95% of hydrogen production and distribution research in Canada has taken place since 2000. Furthermore, the volume of research on the topic has generally increased through the years, except from 2011 to 2015, which is almost similar to the global trend, please see study [73]. From 2021 to 2023 (September 2023), 25% of the total papers were published, indicating a serious rise in research interest in the last three years. This attraction towards hydrogen is attributed to the Canada Hydrogen Strategy, announced in 2020, please see study [148].

(2) Distribution of reviewed papers by journal

Figure 3 illustrates the distribution of the 55 reviewed papers published on sustainable hydrogen production and distribution in Canada across various academic journals. The bar chart indicates the journal titles on the x-axis and the number of publications listed on the y-axis. The chart demonstrates that reviewed papers are published in nine main different journals, from top to bottom of the graph: International Journal of Hydrogen Energy, Renewable and Sustainable Energy Reviews, Energy, Energy Storage, Global Energy Interconnection, Journal of Electronic Science and Technology, Energy Reports, IEEE, and Energy Policy. We have merged six other journals with one publication in each in a category called Others (i.e., Journal of Energy Chemistry, Current Opinion in Chemical Engineering, Journal of Cleaner Production, Journal of Power and Energy Systems, Energy Conversion and Management, and Environmental Science and Pollution Research). This demonstrates that the International Journal of Hydrogen Energy and Renewable and Sustainable Energy Reviews have been the main gates for Canada's research in this field, publishing over half of the reviewed papers together. Furthermore, the International Journal of Hydrogen Energy is the source for over 1/3 of the reviewed papers. Both Energy and Energy Storage published 8 papers out of 55 reviewed papers. Each of the five main journals has published two papers.

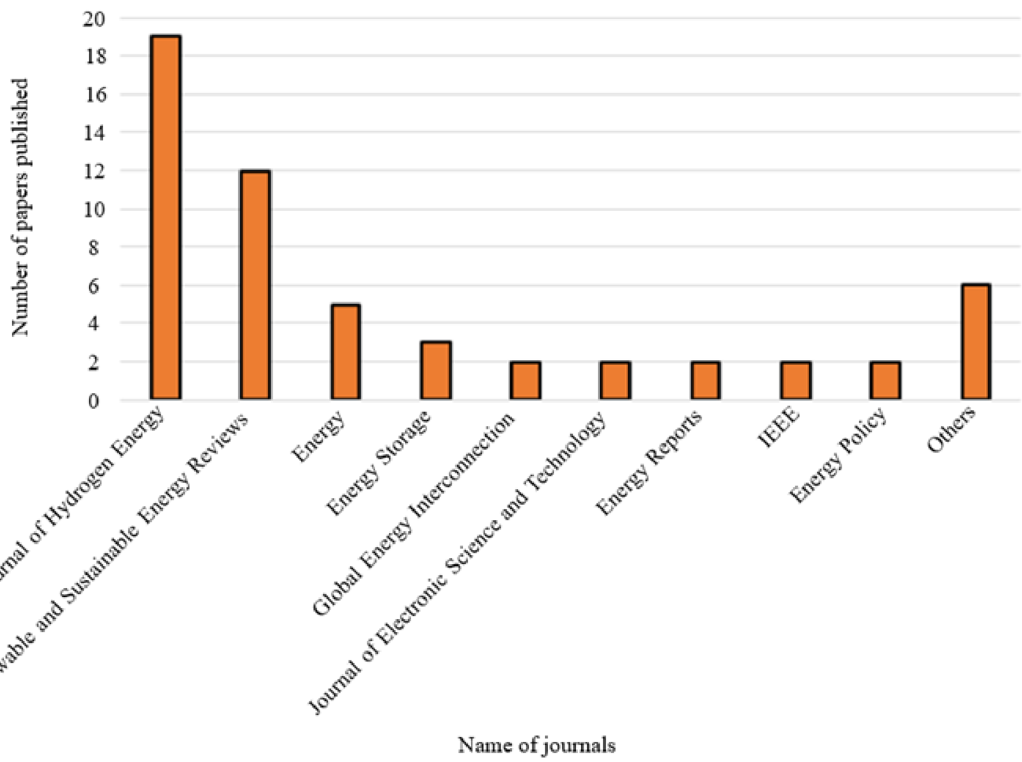

Figure 3. Distribution of reviewed papers by journal

4.2.2 Author

(1) Collaboration network

Bibliometrix generates author collaboration networks by analyzing patterns of joint authorship among researchers. Analyzing these collaboration patterns reveals the influential researchers who bring together many collaborators. It also identifies academic communities and subgroups based on dense interconnected clusters of co-authors. To develop a collaboration network, Bibliometrix extracts author data from the publications being analyzed. It then examines each paper's list of authors to find instances where two or more authors have jointly authored one or more works. Each unique pairing of co-authors that Bibliometrix identifies becomes a connected node on the network graph. The more times a pair of authors collaborate on papers together, the stronger their connection will be represented on the map, through thicker lines or closer proximity between their nodes. Authors who have co-written frequently with many others will appear more centrally located. Furthermore, the size of nodes indicates the number of papers each author has published.

Figure 4 provides an authors collaboration network for 55 papers considered for reviewing in this paper. The nodes, represented as circles, correspond to individual authors, while the edges, depicted as lines, signify the connections between them. The nodes or authors, e.g., "kaye mh" (Matthew H. Kaye from Faculty of Energy Systems and Nuclear Science, University of Ontario Institute of Technology), "rosen ma" (Mark A. Rosen from Faculty of Engineering and Applied Science, University of Ontario Institute of Technology), "gabriel k" (Kamiel S. Gabriel from Faculty of Engineering and Applied Science, University of Ontario Institute of Technology), "suppiah h" (Sam Suppiah from Technical Manager, Hydrogen and Tritium Technologies Directorate, Canadian Nuclear Laboratories), and "fowler m" (Michael W. Fowler from Department of Mechanical and Mechatronics Engineering, University of Waterloo) are differentiated by blue color as they collaborate with each other (they are in one cluster); these five authors have done maximum publications about hydrogen production and distribution in Canada. Likewise, the edge connecting them, are colored blue, and form a dense network in the center of the graph, indicating a high degree of interconnection among these authors and most of other researchers in the field. The thicker edge between "gabriel k" and "fowler m" represents a relatively higher collaboration between these two among the five authors, as is in "kumar a" (Amit Kumar from Mechanical Engineering Department, University of Alberta) and "olateju b" (Babatunde Olateju from Mechanical Engineering Department, University of Alberta). Additionally, there are seven more clusters (pairs) of authors, shown in different colors, who are also active in the field.

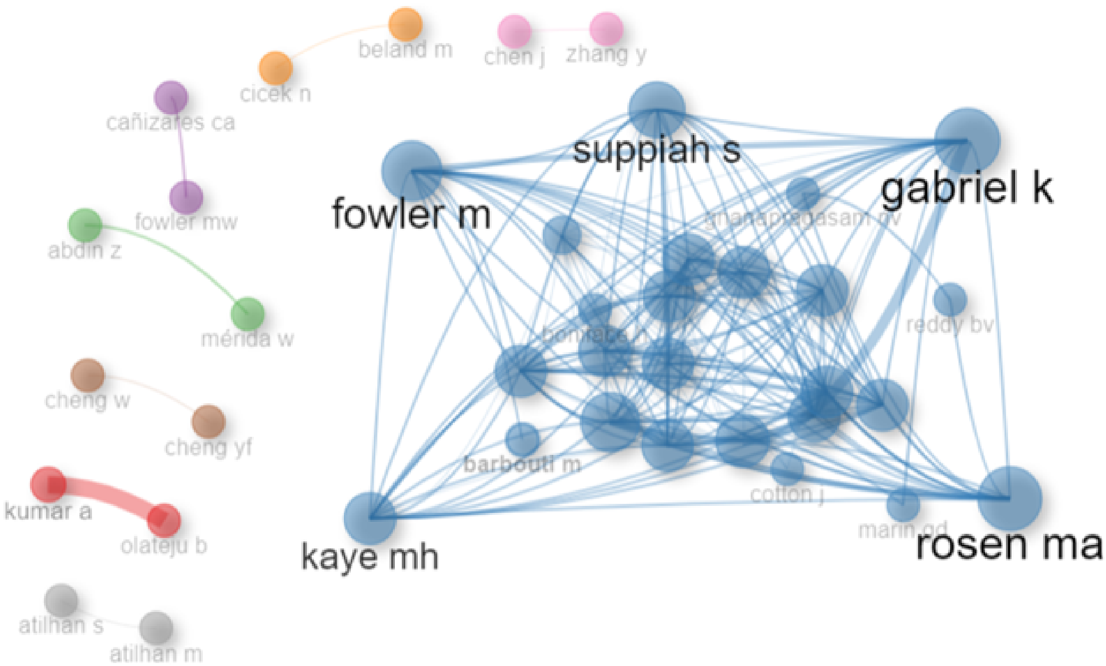

Figure 4. Authors collaboration network for the reviewed papers

(2) Authors' production over time

Tracking author publication counts over time provides valuable insights and is an important bibliometric analysis. In Bibliometrix, this is represented through the "authors' production over time" visualization. To generate this, Bibliometrix first identifies all unique authors in the imported publication data. It then examines the publication metadata for each paper an author is linked to. This allows it to tally the number of works published by that author within each discrete time period, whether it be annually, or broken down further. Plotting these publication counts per time interval for each author reveals trends in individual and collective research productivity. Spikes or plateaus in output for high-publishing authors may signify particularly active periods or completed projects. The graphs also contextualize researchers' careers and allow easy comparisons of progression. At the systemic level, this view offers insights into the long-term publishing volumes, tempos, and flows within the studied research domain. Aggregated author counts per year act as a proxy for the field's expansion or contraction. Periods of unusually high cohort productivity may point to emerging topic clusters.

Authors' production over time in Figure 5 provides a comprehensive overview of the significant scholarly output of authors over time in the 55 reviewed papers. The x-axis represents the timeline, denoting the years, while the y-axis represents the author names. Each horizontal line in front of each author's name indicates the timeline for that author; for example, "KUMAR A" begins the publication in the field of hydrogen production and distribution in Canada between 2011 and 2022. The size of each circle shows the number of papers published by that particular author; thus, "KUMAR A" published three papers in 2016, which seems like the end of a project as there were other publications in the former years, but nothing for a couple of years after that. The color of each circle quantifies the Total Citations (TC) per year, a key metric in assessing the impact of an author's work. For instance, "Abdin Z" has a publication in 2019 that has made a significant contribution in the field. "KUMAR A", "FOWLER M", and "SUPPIAH S" are the authors for being active over the longest period in this research area.

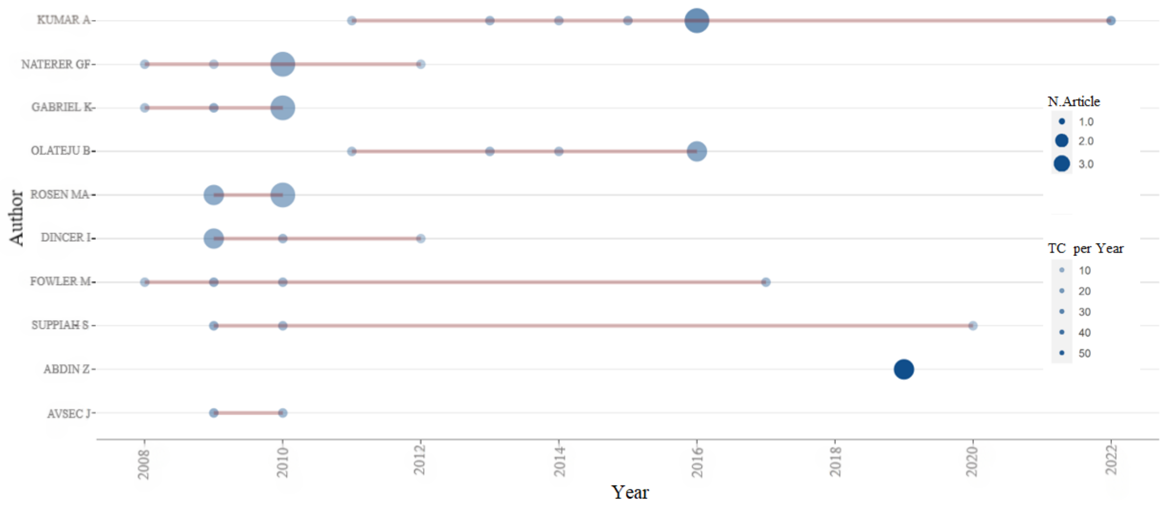

Figure 5. Authors' production over time for the reviewed papers

(3) Authors' affiliation over time

An analysis of author affiliations over time provides important strategic intelligence for research evaluation and resource allocation. To generate this, Bibliometrix first extracts affiliation information for all authors included in the imported publication dataset. It then categorizes this affiliation data, such as grouping universities by country or region. Bibliometrix is able to tally the number of publications attributed to authors from each affiliation category across discrete time periods. This allows trends in research output by university, department, institute, or other organizational designations to be tracked longitudinally. Plotting changes in the relative publication counts of different affiliations over the time span reveals how productive leadership within the field is shifting. For example, the growth of Canadian universities relative to others in the word would indicate strengthening national competitiveness. At the micro level, emerging or declining affiliations within specific word cloud categories pinpoint institutions increasing or decreasing their footprint. This informs strategic funding to reinforce rising excellence or remedy declining centers of knowledge production.

The line graph in Figure 6 represents the trend of articles published by various universities over a period of 29 years, from 1984 to 2023. The x-axis represents the timeline, denoting the years, while the y-axis represents the number of published papers. Each university is represented by a different colored line on the graph. From a cursory glance at the graph, it's evident that there's an overall increase in the number of articles published by all these universities over the years. This could be indicative of several factors, such as increased funding for research, a growing number of research scholars, or a strategic emphasis on research output by these institutions. According to the graph, the University of Waterloo leads the pack with 8 articles published in 2023. This is followed by the University of Alberta, which has published 7 articles in the same year. The University of Ontario comes in the third with 5 articles in 2023. While the majority of the papers are published by Canadian institutions, some top universities from other countries have shown interest in hydrogen production and distribution in Canada, e.g., the University of Oxford and the University of Science and Technology Beijing.

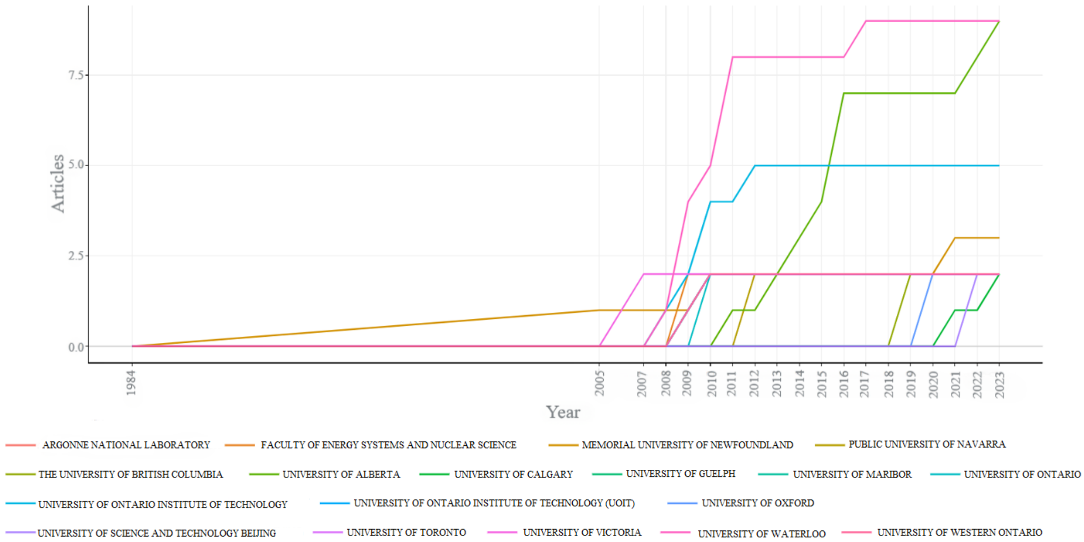

Figure 6. Author's affiliation overtime for the reviewed papers

4.2.3 Keyword

(1) Thematic map

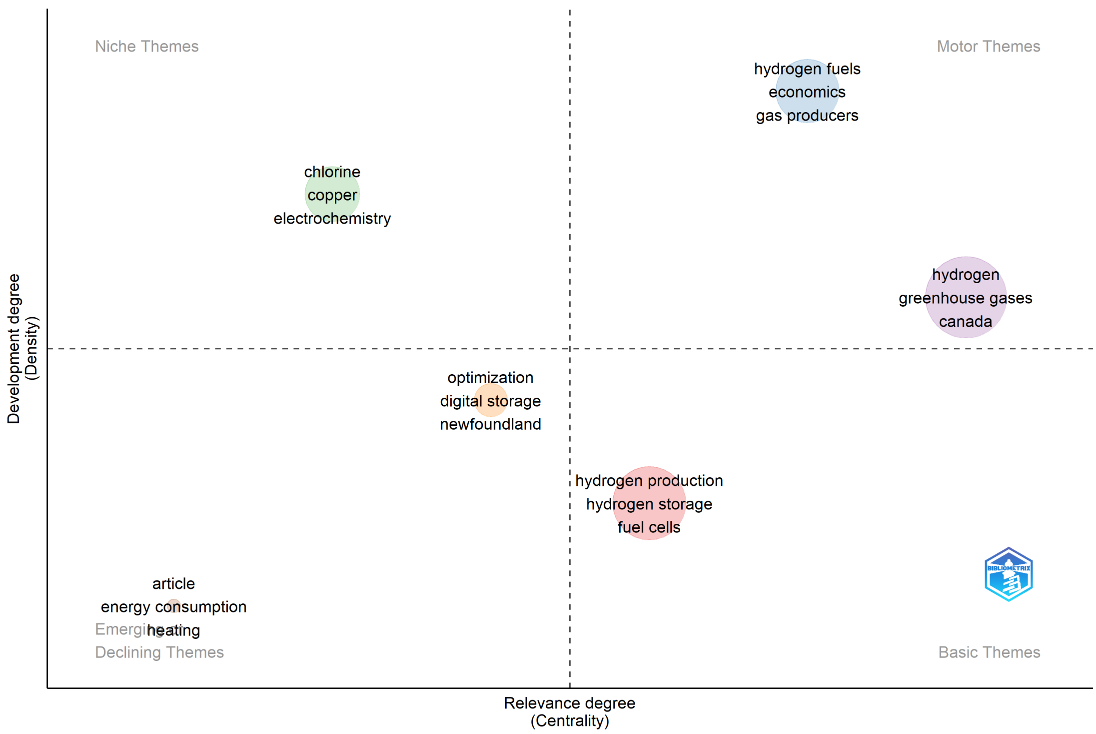

Figure 7. Thematic map for the reviewed papers

Thematic maps generated by Bibliometrix's co-keyword analysis provide strategic insights into the key topics and themes driving a research domain. Identifying trends in co-occurring keywords over time helps stakeholders under-stand the evolving intellectual structure and cognitive framework of that field. To develop a co-keyword thematic map, Bibliometrix extracts keyword metadata from all publications in the imported data set. It then systematically analyzes each paper's keyword list to detect instances where two or more keywords are used together within the same work. Each bubble (cluster) in the map represents a theme, and size of the bubble is determined with word occurrences. Thematic map includes four quadrants: motor themes, which are well-developed and essential for the field; niche themes, which include specialized topics like 'chlorine', 'copper', and 'electrochemistry' relevant to catalyst devel-opment and electrolysis processes; emerging and declining themes, which are underdeveloped but have potential; and basic themes, which form the foundation of the research, such as ‘hydrogen production’, ‘hydrogen storage’, and ‘fuel cells’, please see Figure 7:

-First quadrant (top-right) – This is called motor themes and encompasses keywords with high centrality (rele-vance degree on x-axis) and density (development degree on y-axis); for details of the concepts please see study [149]. There are two clusters in motor themes, emphasizing these are the well-developed and significant for hydrogen production and distribution in Canada, please see Figure 7. The first cluster including “hydrogen”, green-house gases”, and “Canada” has higher centrality than “hydrogen fuels”, “economics”, and “gas procedure” second cluster, while density of the clusters follow the reverse relationship. This shows the first cluster has higher cohesion in the network, and second cluster more ties with other clusters.

-Second quadrant (top-left) - This is called niche themes and includes keywords with low centrality and high density. There is one cluster in that quadrant, “chlorine”, “copper”, and “electrochemistry” representing limited relevance. The niche themes such as “chlorine”, “copper”, and “electrochemistry”, pertain to specific aspects of hydrogen research, including catalyst development and electrolysis processes. These themes are considered niche due to their specialized focus on chemical aspects and relatively limited scope within the broader field of hydrogen production.

-Third quadrant (bottom-left) – This is called emerging and declining themes and encompasses keywords with lower centrality and density. There two themes in this quadrant: first, “optimization”, “digital storage”, and “newfoundland”, and second, “article”, “energy consumption”, and “heating”. The second theme has less cen-trality and density, signifying less developed relative to the first theme.

-Fourth quadrant (bottom-right) – This is called basic themes and includes keywords with high centrality and low density. There is one bubble in this quadrant “hydrogen production”, “hydrogen storage”, and “fuel cells”. This theme is crucial for multidisciplinary research topics since it forms foundation of the research in the field.

Overall, technology (i.e., hydrogen fuels), economic and environmental aspects of hydrogen production and dis-tribution in Canada are the current focus of research. However, energy consumption and hydrogen application for heating are disappearing topics.

(2) Word cloud

An analysis of the most frequently occurring keywords in a word cloud visualization, such as that generated by Bibliometrix, provides strategic insights into the core topics and concepts driving a research field. To produce the keyword word cloud, Bibliometrix first extracts all keywords assigned to publications in the imported dataset. It then counts the frequency of each unique keyword, calculating how many times it is tagged across all papers. Keywords appearing most regularly are positioned prominently in the center of the word cloud and rendered in a larger font size proportional to their frequency count. Less common keywords are placed towards the periphery in smaller text.

Figure 8 illustrates the word cloud for the 55 papers reviewed in this study. The most frequent word is “hydrogen production”, shown with maximum size in the center; this word was in the basic theme, the fourth quadrant in the thematic map in Figure 7. Likewise, “hydrogen storage”. The keywords “hydrogen”, “greenhouse gases”, and “hydrogen fuels” in the first quadrant of Figure 7, motor themes, are also written in relatively larger size in the word cloud.

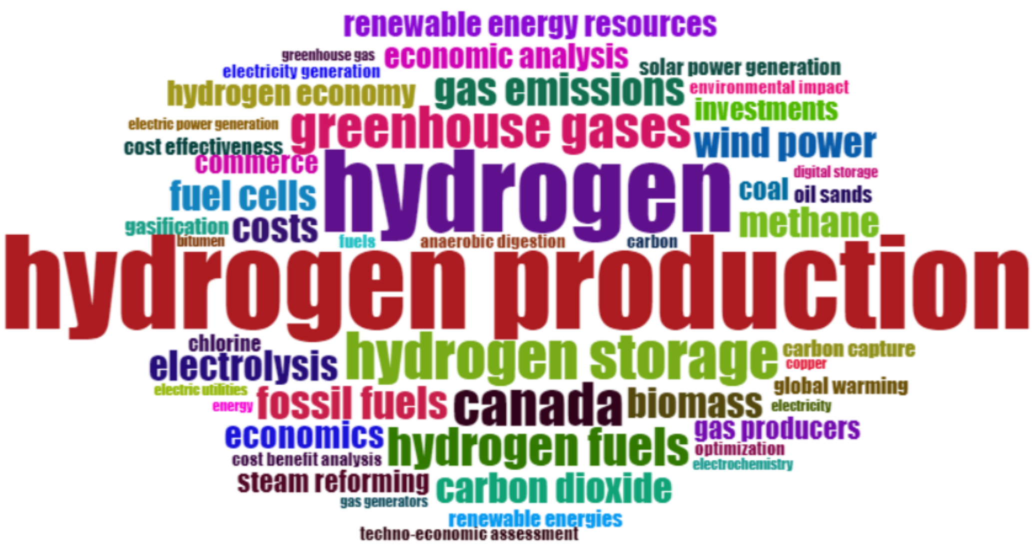

Figure 8. Word cloud for the reviewed papers

5 Results and Discussions

Table 6. Recommended directions

Categories	**Sub-Categories**	**Recommended Directions**
Systematic Review	Production	- Including all available hydrogen sources (i.c., renewable and non-renewable), as well as methods and technologies for producing hydrogen, in the hydrogen models to offer the optimal possible hydrogen production paths. Current hydrogen models often lack accuracy in predicting the economic viability and environmental impact of large-scale hydrogen projects. For example, models may underestimate the costs associated with infrastructure development in remote areas. Case studies from remote communities in Northem Canada show that hydrogen-based solutions can reduce dependence on diesel fuel, though challenges such as harsh weather conditions and logistical issues must be addressed. - Analyzing wind in various windy provinces/regions onsbore and offshore, e.g., Ontario, Quebec, Alberta, British Columbia, Nova Scotia, and Newfoundland and Labrador, to accelerate production of green hydrogen. - Utilizing forestry residues in the Canadian provinces with the existing robust and sustainable forestry business, e.g., Quebec, Ontario, British Columbia, Northwest Territories, Alberta, Saskatchewan, Manitoba, and Newfoundland and Labrador, to produce hydrogen. - Generating hydrogen using extra energy from existing hydroelectric facilities in various Canadian provinces, eg., Quebec, Ontario, Manitoba, and British Columbia. - Exploring practical and effective ways to produce hydrogen utilizing geothermal energy available in Canada's provinces, e.g. Alberta, Saskatchewan, and Northwest Territories, and British Columbia. - Investigating use of Canadian algal resources, e.g., in, Lake Champlain, Lake Ontario, Lake Erie, Lake of the Woods, Lake Winnipeg, Bay of Quinte, and lakes in Vietoria and throughout British Columbia, to produce hydrogen sustainably. - Examining use of non-renewable hydrogen generation sourees in Canada to respond to high hydrogen demand, for example: — Natural gas in Alberta, British Columbia, Saskatchewan, New Brunswick, Ontario, and the Northwiest Territories. — Coal in Alberta, British Columbia, and Saskatchewan. — Oil in Alberta, Saskatchewan, and Newfoundland and Labrador. — Nuclear in British Columbia, Manitola, New Brunswick, and Ontario.
	Distribution and optimization	- Enabling the hydrogen models to choose the best paths for a particular province/region through taking into account all hydrogen storage, transportation, and electricity transmission altematives. - Examining the storage and distribution of hydrogen or chemical compounds including hydrogen, e.g., ammonia, methanol, and methyleyclobexane, through utilizing available infrastructure in Canada, for example: — Pipeline - Trans-Northern Pipeline, Enbridge's Canadian Mainline, TC Energy's Keystone, Trans Mountain, and Enbridge's Express, Enbridge's Southern Lights, Pembina's Cochin, TC Energy's Canadian Mainline, Alliance, Westcoast, Foothills, Trans-Quebec and Maritimes, Maritimes and Northeast, and Emera Brunswick. — Truck - It can be utilized in any province and territory. — Ship - The Port of Vancouver, the Port of Montreal, Port de Quebec, Newfoundland Offshore, Come by Chance, Port Saint John, and Port Hawkesbury, and Nova Scotia. - Railway - Alberta, British Columbia, Saskatchewan, Manitoba, Ontario, Quebec, and New Brunswick. - Exploring stand-alone and grid connection hydrogen produced electricity generation methods in order to ensure that remote communities in Canada, e.g., some with over 1,500 population and diesel and natural gas consumption include Les lles-de-la-Madeleine, Iqaluit, Jasper, Inuvik, Rankin Inlet, Kuujijuq, Pikangikum, Arviat, Sandy Lake, Baker Lake, Obedjiwan, Puvirnituq, Cambridge Bay, Inukjuak, Igloolik, Pond Inlet, and Fort Hope, have equitable access to energy, and evaluating outcomes of both systems in order to choose the optimal alternative. - Employing various optimization software packages, e.g. HOMER and MATLAB, to ensure sustainability of hydrogen business through obtaining efficiently optimal solutions.

Categories	Sub-Categories	Recommended Directions
	Sustainability	- Assessing economic, environment, and social aspects for enhancing sustainability of hydrogen projects before making them operational. - Evaluating the outcomes of combinations of various sustainability aspects, e.g-, socio-economic and socio-ervironmental, in order to gain additional understanding. - Measuring various factors under each aspect of sustainability, for examples — Economic - Levelized cost of energy, operating cost, capacity factor, levelized cost of hydrogen, coefficient of performance, return on imestment, cash flow analysis, revenue from selling hydrogen or chemical compounds including hydrogen (e.g, ammonia, methanol, and methylcyclohexane), and detailed breakdown of cost items. — Environment - Greenhouse gases, renewable fraction, and fuel consumption. — Social - Job creation and energy access.
Bibliometric Review	Paper	- Studying relevant papers continuously to ensure novelty since there has been an ongoing high attention to hydrogen production and distribution in the last three years in Canada. Current hydrogen production methods, such as steam methane reforming and electrolysis, face significant challenges including high energy consumption, carbon emissions, and infrastructure costs. Diversifying production methods to include renewable energy sources is essential to overcome these limitations and achieve sustainable hydrogen production. - Following papers from various journals, e.g, International Journal of Hydrogen Energy and Renewable and Sustainable Energy Reviews as two main outlets of research regarding hydrogen production and distribution in Carada, to ensure exposure to maximum volume of studies, enabling speedy growth and success of the field.
	Author	- Considering collaboration with the following authors with maximum publications — University Of Ontario Instinte Of Technology - Mathew H. Kaye, Mark A. Rosen, and Kamiel S. Gabriel. — Canadian Nuclear Laboratories - Sam Suppiah. — University of Waterloo - Michael W. Fowlet — University of Alberra - Amit Kumar and Babatunde Olateju. - Proposing two following types of projects between interested parties at: — Narional - Educational institutions, ic., University Of Ontario Institute Of Technology, University of Waterloo, and University of Alberta, and crown corporation, i.e., Canadian Nuclear Laboratories. — International - Europe, i.c., University of Oxford, and Asia, i.e., University of Science and Technology Beijing, with Canadian institutions with high level of activity in the field, i.e., University Of Ontario Institute Of Technology, Canadian Nuclear Laboratonies, University of Waterloo, and University of Alberta.
	Keyword	- Developing research projects regarding the hydrogen production and distribution in Canada utilizing well-developed themes, i.c., “hydrogen”, “greenhouse gases”, “hydrogen fuels”, “economics”, and “gas procedure” to accelerate the research progress. - Defining multidisciplinary research projects through employing fundamental themes, i.e., “hydrogen production”, “hydrogen storage”, and “fuel cells”.

Study [150] highlighted communities in academia, government, and industry that have been advancing toward net zero emis-sions in Canada through focusing on hydrogen production and consumption. To further assist them, this paper offers insights to the academic, governmental, and business communities in Sections 5.1, 5.2, and 5.3, respectively. These insights are aimed to enhance the synergy and help these three communities utilize their resources to support Canada as it moves further toward net zero. The source of the insights are a summary of the distillation of the 55 reviewed papers presented in terms of recommended directions in Table 6.

Table 6 encompasses two main categories: systematic review and bibliometric review, following the analyses in Sections 4.1 and 4.2, respectively. Then, the systematic review category is further divided into three main sub-categories: (1) production, (2) distribution and optimization, and (3) sustainability, according to analyses in Sections 4.1.1, 4.1.2, and 4.1.3. Likewise, bibliometric review categories includes: paper, author, and keyword, as the sub-categories, following Sections 4.2.1, 4.2.2, and 4.2.3.

5.1 Academic Insights

We demonstrated significant contributions of academic institutions towards net zero in Canada through hydrogen pro-duction and consumption in Section 4.2.2. To enhance the level of contributions, Table 6 recommends some research avenues, based on the synthesis of the 55 reviewed papers, in six categories, three of which are from systematic review, and the remaining three are from bibliometric analysis:

-Production - We identified numerous significant research gaps in the area of hydrogen production in Canada in this paper. In order to select the optimal hydrogen production pathway(s) in the country/province/region, we first emphasize the necessity of incorporating all currently accessible hydrogen sources, both renewable and non-renewable, as well as a wide range of production methods and technologies. Second, we highlight the possibility for producing hydrogen from forestry residues in provinces with well-established and sustainable forestry sectors, for example, Quebec, Ontario, British Columbia, Northwest Territories, Alberta, Saskatchewan, Manitoba, and Newfoundland and Labrador [80]. Thirdly, we draw attention to the potential for generating hydrogen using excess energy from existing hydroelectric plants in provinces, for instance, Quebec, Ontario, Manitoba, and British Columbia [151]. In addition, we recommend evaluation of the practical and efficient exploitation of geothermal energy resources for hydrogen generation in British Columbia, Alberta, Saskatchewan, and the Northwest Territories [152]. Additionally, we propose the environmentally friendly production of hydrogen using Canadian algal resources found in lakes like Lake Champlain, Lake Ontario, Lake Erie, Lake of the Woods, Lake Winnipeg, Bay of Quinte, and numerous lakes in Victoria and throughout British Columbia [153]. The incorporation of non-renewable hydrogen generation sources in Canada (natural gas, oil, coal, and nuclear energy), for example in, Alberta, British Columbia, and Ontario, is the final topic we offer for further exploration, for more potential locations for hydrogen production in Canada via natural gas and oil, please see study [7], and for coal and nuclear, respectively, please see studies [82, 154].

-**Distribution and optimization** - First, it is necessary to improve hydrogen models by taking into account storage, transportation, and power transmission choices to enable them to identify the best route(s) for the country/province/region. The future studies should also consider the transportation, storage, and distribution of hydrogen or related chemical compounds, for instance, ammonia, methanol, and methylcyclohexane [155], using the country's current infrastructure, which includes pipelines like the Trans-Northern Pipeline, Enbridge's Canadian Mainline, TC Energy's Keystone, and Trans Mountain, as well as truck, ship, and railway transportation methods [7]. In order to ensure equitable energy access for remote communities in Canada, such as Les Iles-de-la-Madeleine, Iqaluit, and Jasper, many of which currently rely on diesel and natural gas, it is also imperative to investigate stand-alone and grid-connected hydrogen-based electricity generation methods; for a more comprehensive list of remote communities and their energy sources, please see study [156]. Comparing stand-alone and grid-connected options for remote communities to find the best option is another direction for research. Finally, to maintain the longevity and effectiveness of the hydrogen sector in Canada, it is crucial to apply numerous optimization software packages like HOMER and MATLAB, which enable the development of optimal solutions.

-**Sustainability** - Prior to operationalization, it is crucial to conduct a thorough assessment of hydrogen projects' viability from an economic, environmental, and social standpoint. To better understand the impact of the initiatives, this necessitates a comprehensive examination of sustainability factors, pairwise, such as socio-economic and socio-environmental issues. Several elements within each sustainability dimension need to be painstakingly measured in order to accomplish this. These variables fall under the economic dimension and include the levelized cost of energy, operating cost, capacity factor, levelized cost of hydrogen, coefficient of performance, return on investment, cash flow analysis, revenue from the sale of hydrogen or related chemical compounds (such as ammonia, methanol, and methylcyclohexane), as well as a thorough breakdown of cost components. The evaluation should take into account factors like greenhouse gas emissions, the percentage of renewable energy sources, and fuel usage from an environmental point of view. Finally, from a societal standpoint, it is critical to look at the projects' contributions to greater access to energy and job creation. Addressing these research gaps may provide insights, helping to ensure that projects are not only financially feasible but also ethically and environmentally sound.

-**Paper** - In light of the ongoing and increasing attention towards hydrogen production and distribution in Canada over the past three years, it is vital to keep an active involvement with the most recent literature in the field. To ensure the novelty and relevance of research works, a diligent and continuous study of pertinent papers is encouraged. This includes a commitment to monitoring and synthesizing the latest research findings published in various journals, especially outlets such as the International Journal of Hydrogen Energy and Renewable and Sustainable Energy Reviews. By staying abreast of the latest developments and insights, the academic community can further contribute to the rapid advancement and success of the hydrogen production and distribution field in Canada, leading to fostering innovation and data-driven decision-making in this dynamic and evolving domain.

-**Author** - To further advance research in the field of hydrogen production and distribution, it is recommended to consider collaboration with accomplished authors who have demonstrated notable contributions. Remarkably, potential collaborative partners include scholars from institutions such as the University of Ontario Institute of Technology, Canadian Nuclear Laboratories, the University of Waterloo, and the University of Alberta, including experts like Matthew H. Kaye, Mark A. Rosen, Kamiel S. Gabriel, Sam Suppiah, Michael W. Fowler, Amit Kumar, and Babatunde Olateju. Collaborative projects can lead to growth and success in both national and international areas. Nationally, collaboration with Canadian educational institutions and a crown corporation, including the University of Ontario Institute of Technology, the University of Waterloo, the University of Alberta, and Canadian Nuclear Laboratories, can be pursued to investigate and optimize hydrogen production, distribution, and sustainability in Canada. Internationally, forging partnerships with already involved institutions in Canadian hydrogen production and distribution from Europe and Asia, such as the University of Oxford and the University of Science and Technology Beijing, is recommended to gain diverse perspectives and global relevance. These international collaborations can result in Canadian institutions actively engaging in hydrogen research, establishing comprehensive and globally impactful studies to move the field forward.

-**Keyword** - It is proposed to develop research projects based on well-established themes such as "hydrogen", "greenhouse gases", "hydrogen fuels", "economics", and "gas procedures". These themes can serve as a cornerstone for planning research works, making sure a focused and cohesive approach is utilized to respond to the multidisciplinary opportunities in the field. Furthermore, it is vital to define integrative research projects that involve fundamental themes like "hydrogen production", "hydrogen storage", and "fuel cells". These kinds of projects will enable comprehensive investigations, drawing expertise from various fields to address the complexities of hydrogen research impactfully. By directing research works with these thematic frameworks, researchers can speed up the progress and innovation in hydrogen production and distribution within the Canadian context.

5.2 Government Insights

Governments play a crucial role in establishing and strengthening policies for a hydrogen-based economy and net zero emissions [157]. The government of Canada announced its Hydrogen Strategy, aiming to position Canada as a global leader in the production, usage, and export of hydrogen and related technologies [8]. In this regard, based on the information in Table 6, the following recommendations are offered to the government of Canada for further attention:

1. Optimizing potential resources - Enhancing energy security through looking at various sources for hydrogen production, e.g., biomass and hydro, in each province/region. For example, on the west of Canada, utilizing abundant wind, biomass, hydropower, geothermal, algal, natural gas, coal, and nuclear, in British Columbia. On the other hand, on the east of Canada, in Newfoundland and Labrador, oil can be employed for hydrogen production, in addition to the province's wind, biomass, and hydropower.

2. Catalyzing hydrogen evolution - Facilitating hydrogen production and consumption through: (1) funding hydrogen research and development, especially through joint collaboration between well-experienced institutions nationally and internationally, e.g., the University of Ontario Institute of Technology, the University of Waterloo, the University of Alberta, and Canadian Nuclear Laboratories, and, the University of Oxford and University of Science and Technology Beijing. Also, incentivizing collaboration with knowledgeable experts, e.g., Matthew H. Kaye, Mark A. Rosen, Kamiel S. Gabriel, Sam Suppiah, Michael W. Fowler, Amit Kumar, and Babatunde Olateju, to address fundamental domains, i.e., "hydrogen production", "hydrogen storage", and "fuel cells", (2) subsidizing private sector for establishing hydrogen infrastructure through various means, e.g., tax credits, utilizing various hydrogen sources, i.e., renewable and non-renewable, in different provinces/regions, and (3) streamlining permitting processes and regulatory support for deployment of hydrogen infrastructure, e.g., allocation of crown land for wind-hydrogen projects [158], and trade, e.g., hydrogen export to European countries like Germany [6].

3. Equalizing energy accessibility - Addressing the energy requirements of remote communities in Canada, which mainly rely on diesel and natural gas for power generation, through supporting feasibility studies to identify the most suitable energy solutions for each specific remote community, taking into account factors such as grid connection vs. stand-alone, resource availability, e.g., hydrogen production resource, population size, and energy demand; some of the high priority communities are Les Iles-de-la-Madeleine, Iqaluit, Jasper, Inuvik, Rankin Inlet, Kuujjuaq, Pikangikum, Arviat, Sandy Lake, Baker Lake, Obedjiwan, Puvirnituq, Cambridge Bay, Inukjuak, Igloolik, Pond Inlet, and Fort Hope. These studies would help establish a clear policy to transition away from diesel and natural gas in favor of green hydrogen.

4. Diversifying revenue avenues - The government can utilize and extend its partnerships and export agreements to become a major global hydrogen exporter. Also, the government can increase its hydrogen transportation capabilities and generate revenue through usage fees and pipeline tariffs. Furthermore, identifying potential onshore and offshore hydrogen resources, and announcing a call for bids to enhance royalty revenue.

5. Sustainability - Developing policies that solely fund projects aligning with sustainability goals should be granted government support or approval. Therefore, there is a need for establishing a framework for assessing proposed hydrogen projects based on the measured sustainability factors, their economic viability (through e.g., return on investment and cash flow analysis), environmental impact (through e.g., Greenhouse gases, renewable fraction, and fuel consumption), and social advantages (through e.g., job creation and energy access).

5.3 Industry Insights

We discussed in the prior section how Canadian politicians can construct new opportunities for the private sector interested in the hydrogen sector. However, as highlighted by the Sustainable Development Goals of the United Nations [3], firms should provide sustainable industrialization and infrastructure for their hydrogen operations. In keeping with this, they can, for instance, consult Table 5 and evaluate the findings of the sustainability studies that are already accessible; doing so may also result in some cost savings for feasibility studies.

The research [159] demonstrates current hydrogen production in Canada is based on oil and gas and is located in the provinces of British Columbia, Quebec, Ontario, and Alberta. However, Canada has a abundant and varied energy portfolio, e.g., hydro, nuclear, wind, coal, biomass, and solar; for a brief about resources available in each province for hydrogen production please see Table 6. Private sectors are encouraged to explore renewable resources in different provinces/regions for hydrogen production as hydrogen production from non-renewable resources is not be sustainable. Furthermore, to the best of our knowledge there is no hydrogen production on the offshore of Canada currently. However, there are plans for offshore hydrogen production in Canada, especially in Nova Scotia. Therefore, exploring offshore hydrogen production and consumption opportunities may be another avenue for companies to pursue since it may help towards emissions reduction on offshore oil activities and easier access to foreign hydrogen market.

Companies are recommended to focus on developing and implementing hydrogen-based energy solutions, particularly for remote communities with limited access to traditional energy sources in Canada. These projects may be supported by the government of Canada, for example, please see study [160] for $300 million dollars fund. Furthermore, to optimize hydrogen storage and distribution, the private sector should consider employing existing infrastructure, e.g., pipeline, truck, ship, and railway. Moreover, businesses are advised to utilize optimization software packages like HOMER and MATLAB to ensure the sustainability of hydrogen projects through conducting comprehensive assessments of hydrogen projects, considering economic, environmental, and social aspects.

6 Conclusions

Global warming and the unequal distribution of fossil fuels have pushed governments to prioritize renewable energy sources in order to improve energy security while also being more environmentally friendly. Thus, hydrogen produced from renewable resources is considered a promising direction. Canada's worldwide environmental commitment, along with the European Union and Canada's green alliance, led to a pursuit of the production of renewable hydrogen to both expedite the net zero emission process in Canada and also support Europe through its present energy crisis.

To support Canada in addressing both the aforementioned global challenges through hydrogen production and distribution, this paper systematically searched and found all 55 scientific papers published in the field. Then, we analyzed the papers from two main perspectives: contents through systematic review, and paper carriers through bibliometric review. The contents of the reviewed papers were synthesized employing four lenses: (1) production, (2) distribution, (3) optimization, and (4) sustainability. As for reviewed paper carriers, three main criteria were utilized for analysis: (1) distribution of reviewed papers by year and journal, (2) collaboration, productivity, and affiliation of authors, and (3) thematic map and word cloud. For our bibliometric analysis, we relied on Bibliometrix, which is among the most powerful software packages available for this purpose. Stakeholders can pursue immediate actions such as investing in pilot projects for renewable hydrogen production and forming public-private partnerships to share knowledge and resources, for example, please refer to the Hydrogen Strategy of Canada, which involved over 1000 stakeholders, leading to a development of hydrogen hubs in Edmonton, Vancouver, and Southern Ontario.

Despite our efforts to provide a comprehensive systematic review and bibliometric analysis regarding Canada's hydrogen production and distribution in this paper, we had to leave some avenues for future review papers to maintain the tractability of this paper. Some of the avenues we recommend to other colleagues interested in this domain are: (1) a detailed focus on hydrogen production technologies and methods, (2) considering various products, e.g., liquid hydrogen, gaseous hydrogen, and ammonia, generated in the process, and (3) categorizing the literature into two main categories, i.e., qualitative and quantitative, and approaching each one accordingly. These research directions may reveal insights, that may be different from our findings summarized in Table 6.

We have systemized our findings in Table 6, and accordingly offered insights for academic institutions, public bodies, and industries involved in hydrogen production in Canada and its distribution, aiming to enhance joint efforts, utilizing the available resources. For instance, academic institutions can lead the way by conducting comprehensive research that includes all hydrogen production sources, methods and technologies, storage and transportation modes, ultimately enabling optimal and sustainable hydrogen production and distribution. Government bodies can support these efforts by promoting provincial and regional analysis and ensuring equitable access to hydrogen-based energy solutions. Businesses, in turn, can contribute by investing in the development of infrastructure for sustainable hydrogen production and distribution, for instance, through offshore wind-hydrogen production. Collaboration with active experts and institutions in the field, both nationally, e.g., the University of Ontario Institute of Technology, the University of Waterloo, and internationally, e.g., the University of Oxford, can drive innovation and accelerate the growth process.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

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Conflicts of Interest

The authors declare no conflict of interest.

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