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Sustainable Hydrogen Production, Storage, and Distribution – A Systematic Review for Newfoundland and Labrador

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Abstract

Growing concerns over climate change and reliance on fossil fuels bring further attention towards sustainable energy sources. This has been amplified by the recent Russia-Ukraine war. Hydrogen from renewable sources is a promising response to the existing concerns. Newfoundland and Labrador (NL) is an encouraging location for producing hydrogen due to its natural resources. Furthermore, its geopolitical situation positions NL to be superbly situated to help alleviate the current energy crisis in Europe. To have sustainable hydrogen production and supply from NL it is essential to utilize the available resources. Therefore, this paper systematically reviews all scientific papers on NL hydrogen production, storage, and distribution. The papers are reviewed from hydrogen sources, production methods and technologies, storage methods, transportation, transmission, optimization, and sustainability perspectives across NL. Finally, some insights for academics, government, and industry sectors are provided based on our results.

Keywords: hydrogen, energy, hydrogen production, hydrogen storage, hydrogen distribution, optimization, sustainability, Newfoundland and Labrador, Canada

1. Introduction

Global warming and the limited, uneven fossil fuels distribution have brought the policymakers around world to the table to find a solution for the future of the planet. The onset of the Russia-Ukraine war in early 2022 has significantly added to the requirement for renewable fuels. To address these concerns, the European Union further emphasized the need for renewable energy production (Misˇ´ık and Nosko, 2023), which was also stressed in the 2015 Paris Agreement (Naganuma and Ueno, 2022). However, the enormous challenges of achieving net zero emissions and energy security remain to be further addressed.

Recognizing the urgent need to reduce emissions and establish energy independence, European unions and the Canadian government are collaborating to resolve the issue (Risley and Kaufmann, 2023). This is in addition to Canadian plans for net zero emissions by 2050, e.g., Powering the Economy with Renewable Electricity (Government of Canada, 2022). In this vein, Germany has established a partnership with Canada, particularly in the area of renewable hydrogen (Prys-Hansen and Kaack, 2023).

The Province of Newfoundland and Labrador (NL), in Canada, has been recognized by governments and the energy industry as having significant potential for renewable hydrogen production (Government of Newfoundland and Labrador, 2023*e*). Because of the constancy of wind available throughout the province Government of Newfoundland and Labrador (2023*b*) opened crown land bids for wind-hydrogen production. About 20 companies from around the globe participated in the bid; however, just four of them were awarded lands in August 2023 (Government of Newfoundland and Labrador, 2023*d*). To utilize the available resources in the province while pursuing net zero emissions, the provincial government has launched several funds for research and development projects, e.g., the Green Transition Fund (Government of Newfoundland and Labrador, 2023*c*). Therefore, the purpose of this study is to analyze all the scientific papers linked to sustainable hydrogen production, storage, and distribution from NL in order to offer guidance to government, business, and academia on where to focus their resources.

To meet the objective of this study, the rest of this paper is organized as follows: Section 2 compares this paper with other review papers (1) exclusively focused on NL, (2) that include NL in their study, and (3) recent literature. The methodology in Section 3 represents the framework of this review and analyzes the papers within the framework from various perspectives, i.e., (1) the distribution of papers by year and journal and (2) their keywords co-occurrence, strength, and relationship. Section 4 examines the papers within the framework by focusing on hydrogen sources, production methods and technologies, storage methods, transportation, transmission, optimization, and sustainability. Accordingly, Section 5 provides insights for government, industry, and academia.

2. Literature Review

Our search for review papers regarding the Province of Newfoundland and Labrador (NL) shows no review paper has exclusively focused on NL, despite its significant potential for renewable hydrogen production, especially from wind. Furthermore, to the best of our knowledge, NL has not been included in other review papers. Table 1 further clarifies how this paper covers all the existing research gaps in the other nine review papers published about hydrogen production after the beginning of the Russia-Ukraine war in February 2022, which opened a new chapter in sustainable energy for the globe.

We categorize Table 1 into six main classes: (1) Production, (2) Storage, (3) Distribution, (4) Optimization, (5) Sustainability, and (6) Location; this classification is based on a recent study by Azadnia et al. (2023). However, to have a more comprehensive study we extend their focus on renewable hydrogen sources (wind, solar, hydro, biomass, geothermal) to the full spectrum of hydrogen production, adding non-renewable sources (diesel, coal, oil, nuclear, gas). To provide further information we looked into production technologies and methods of hydrogen production; for further details please see Dash et al. (2023) and Amin et al. (2023) respectively. Following the production of hydrogen it may go through storage, and distribution (Azadnia et al., 2023); for storage: battery and hydrogen tanks (Amin et al., 2023), for transportation: pipeline, trucks, ships, and railways (Riera et al., 2023), and for grid: it may be transmitted as electricity through the grid to remote locations, making them grid connected; for communities not connected to the grid, we refer to this as stand-alone consumption in the nearby communities. (Herdem et al., 2023). To ensure hydrogen production, storage, and distribution are taking place properly, optimization software packages, mainly HOMER and MATLAB are employed, please see Herdem et al. (2023). These optimization software packages are able to provide sustainability insights while evaluating economic, environmental, and social aspects of hydrogen production, storage, and distribution in various locations (Azadnia et al., 2023).

Following the five main classes, Table 1 shows the gaps in the nine hydrogen review papers. In energy sources, only Shah et al. (2022) and Meloni et al. (2022) focus on geothermal energy; however, currently, they are demonstrating a significant potential for producing renewable hydrogen (Halder et al., 2023). Only Modu et al. (2023) evaluate the papers that use batteries as a form of energy storage; they place a focus on the necessity of batteries in order to meet the demand for electricity generated by hydrogen. Trucks and ships have been modes of transportation for centuries, and enable the transportation of hydrogen from, for example, NL to Europe; however, Panchenko et al. (2023) and Ghorbani, Zendehboudi, Saady, and Dusseault (2023) just reviewed the papers from these points respectively. There are many remote communities that require access to energy, especially in NL (Agu et al., 2023), in which stand-alone systems are preferred (Sarker et al., 2023); however, it is only Van et al. (2023) emphasize their significance. Modu et al. (2023) and Herdem et al. (2023) are the only review papers to study optimization software and sustainability, although these are significant issues, especially in the field of energy (Perna et al., 2023). Finally, although Agaton et al. (2022), Amin et al. (2022), Capurso et al. (2022), Razi and Dincer (2022), and Spezakis and Xydis (2022) review papers related to a specific region, none focus on NL. This paper, therefore, aims to address all aforementioned gaps.

To meet the aim of this paper, we contribute by (1) collecting and analyzing all the papers related to hydrogen production, storage, and distribution in NL by year, journal, and keywords, in Sections 3.2, 3.3, and 3.1 respectively, (2) reviewing all the papers from production (energy sources, technologies, and methods) point of view in Section 4.1, (3) comparing all papers from storage (battery and hydrogen tanks), distribution (transportation, electricity transmission) and optimization points in Section 4.2, (4) making a comparison between all the papers from a sustainability point of view and the location of study with the Province of NL in Section 4.3, and (5) providing insights for academic, government, and industry sectors in Section 5.

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

	Energy Sources								Production		St		Distribution						Software			Sustainability	Location
	R					NR							Tr				ET						
Reference	W	S	H	B	G	Na	C	N	T	M	Ba	HT	P	T	S	R	GC	SA	Ho	Ma	O		
Herdem et al. (2023)	✓	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓						✓	Europe
Hossain et al. (2023)	✓	✓	✓		✓				✓	✓	✓	✓	✓										
Okere and Sheng (2023)	✓	✓				✓			✓	✓													
Toure et al. (2023)	✓					✓			✓	✓		✓		✓			✓		✓				
Agaton et al. (2022)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓												Philippines
Amin et al. (2022)	✓	✓	✓		✓	✓	✓	✓	✓	✓							✓						Djibouti
Capurso et al. (2022)	✓	✓		✓	✓	✓	✓	✓	✓	✓							✓						Germany and Nepal
Razi and Dincer (2022)	✓	✓	✓	✓		✓	✓	✓	✓	✓							✓					✓	Canada
Spezakis and Xydis (2022)	✓					✓	✓		✓	✓			✓		✓							✓	Gulf of Mexico
This paper	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	NL

Abbreviations – R: Renewable, NR: Non-Renewable, St: Storage, Tr: Transportation, ET: Electricity Transmission, Software, W: Wind, S: Solar, H: Hydro, B: Biomass, G: Geo-thermal, Na: Natural gas, C: Coal, N: Nuclear, T: Technology, M: Method, Ba: Battery, HT: Hydrogen Tank, P: Pipeline, T: Trucks, S: Ships, R: Railway, GC: Grid Connected, SA: Stand Alone, Ho: HOMER, Ma: MATLAB

3. Methodology

To review the sustainability of NL hydrogen production, storage, and distribution, we looked for all papers in scientific publishing portals, e.g., ScienceDirect, Wiley, 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, sustainability, and engineering. The following keyword searches were employed: “hydrogen production”, “hydrogen distribution”, “hydrogen storage”, “hydrogen transportation”, “hydrogen optimization”, or “hydrogen sustainability” which was separately combined with “Newfoundland and Labrador”, “Newfoundland”, “Labrador”, or “NL”. Furthermore, the references of the studied papers and those works cited in the studied papers served as a secondary source to search relevant literature. To develop a more comprehensive study we searched for all available papers regardless of their publication time. This led to 16 papers, which will be analyzed from the keywords, years, and journals in the coming three subsections respectively.

3.1 Keyword Co-Occurrence Strength and Relationship

Figure 1 presents a keyword co-occurrence network map that visualizes the relationships between pertinent keywords extracted from the analyzed 16 papers. The map clusters keywords that frequently occur together in the papers into eight distinct groups, represented with eight different colors. Larger and bolded keywords that occur more regularly are placed towards the center of their respective clusters. The clusters and their frequently repeated keywords are as follows:

1) Combined Heat and Power (violet color) – “accessibility problems” and “combined heat and power system”;

2) Cost Benefits (dark green color) – “costs”, “cost-benefits analysis”, and “electric fault current”;

3) Conventional Methods (dark blue color) – “steam methane reforming”, “oil reforming”, and “coal gasification”;

4) Digital Control and Simulation (light blue color) – “wind power”, “hydrogen storage”, “control systems”,

"digital simulation", "control", and "control systems synthesis";

5) Computational Modeling and Control (ink blue color) – "renewable energy", "energy conversation", "computer simulation", "control systems", and "MATLAB";

6) Energy Systems (red color) – "energy storage", "economic analysis", and "energy utilization";

7) Sustainable Energy Systems (orange color) – "carbon storage", "battery technology", "conventional battery", "alternative energy", "coastal community", "battery storage", and "hybrid system";

8) Optimization of Biogas Upgrading and Fuel Cell (green color) – "biogas upgrading", "CO2 emission", "carbon dioxide", "fuel cell", "exergy", and "liquified gases".

The proximity of clusters above signifies stronger relationships between the constituent keywords. For instance, the Digital Control and Simulation, Computational Modeling and Control, energy systems, Sustainable Energy Systems, and Optimization of Biogas Upgrading and Fuel Cell clusters are placed closely together, indicating the use of computer technology to design, control, and optimize sustainable energy systems. Overall, this keyword network map provides a helpful visualization of common research areas and their interlinkages explored within the analyzed body of literature.

3.2 Distribution of Reviewed Papers by Year

Figure 2 displays how the 16 reviewed papers regarding hydrogen production, storage, and distribution in NL are distributed in four various time spans between 2005 to 2023. The bar graph displays years on the x-axis and the number of publications on the y-axis. Accordingly, the volume of research on the topic has steadily increased through the years. From 2021 to 2023, eight papers (or 50% of the total) were published, indicating a rise in research interest during that time.

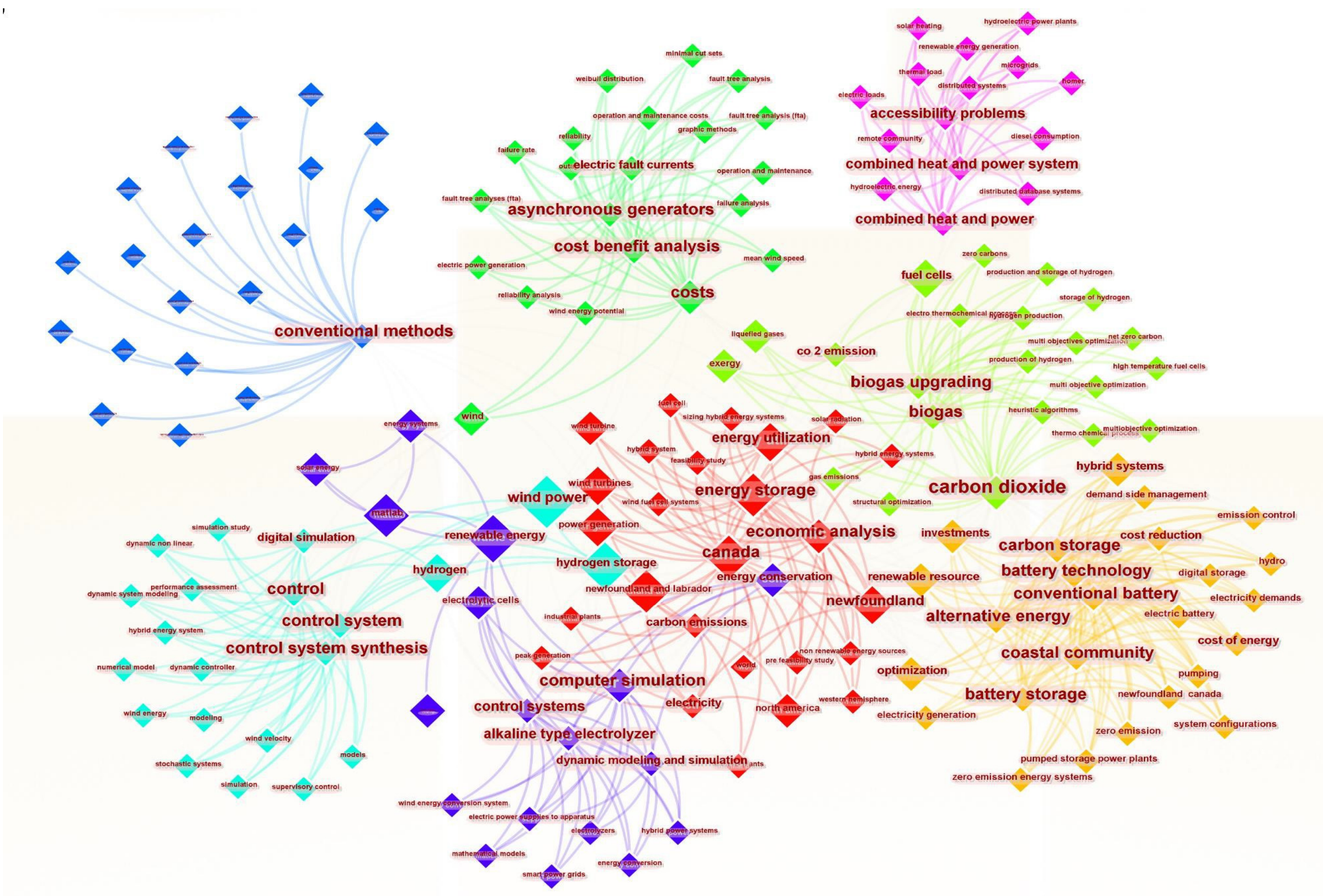

Figure 1. A map visualizing keyword co-occurrence strength and relationship

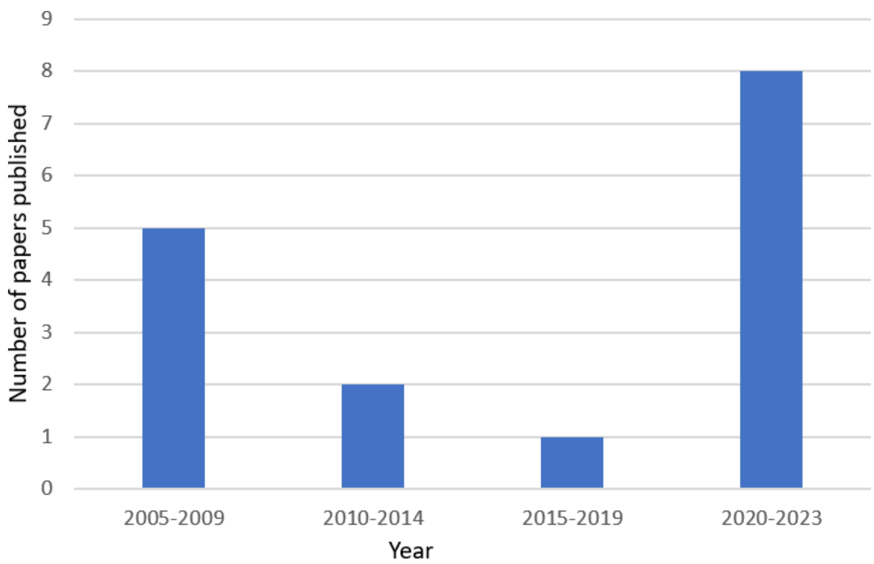

Figure 2. Distribution of reviewed papers by year

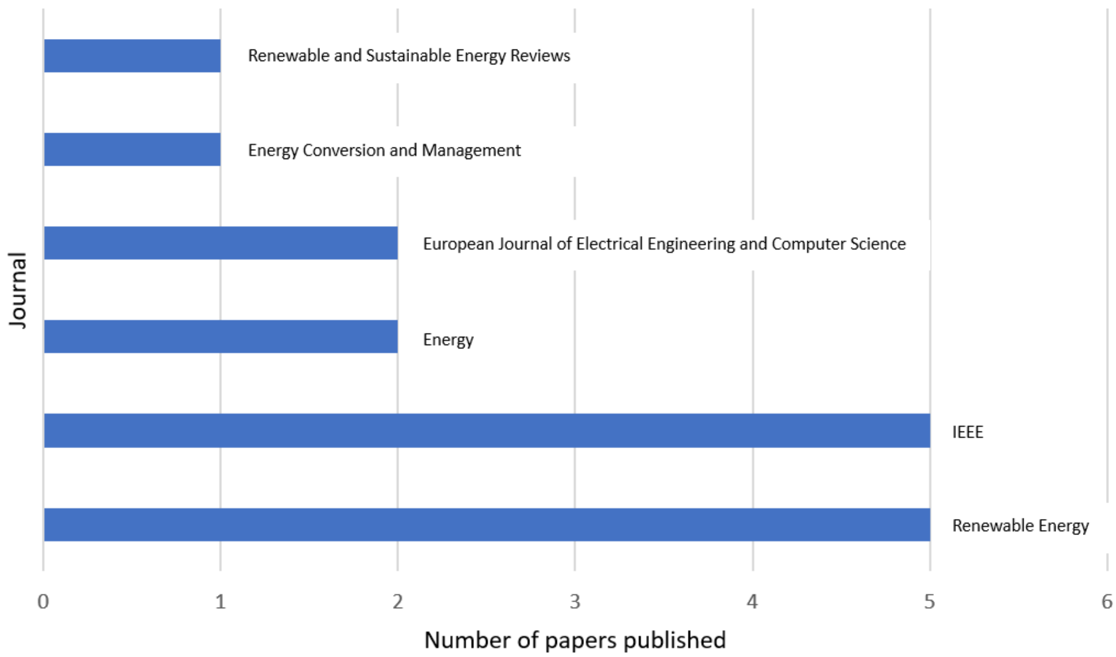

Figure 3. Distribution of reviewed papers by journal

The second half of the reviewed papers were published between 2005 to 2020. Six reviewed papers, 75% of this half, were published between 2005 to 2011 and can be associated with the government fund for hydrogen production (Government of Newfoundland and Labrador, 2007). This is followed by 2 reviewed papers published from 2012 to 2020. These show the significance of government support for hydrogen production, storage, and distribution.

Overall, the rising trend illustrated on the bar graph demonstrates that the body of knowledge on hydrogen production, storage, and distribution in NL has expanded substantially over the last two decades. Though initial studies were limited, there is now more extensive research. The upwards trajectory in publications also aligns well with growing global sustainability priorities in the reviewed hydrogen domain (Wang et al., 2023).

3.3 Distribution of Reviewed Papers by Journal

The bar graph in Figure 3 demonstrates the distribution of the 16 reviewed papers published on sustainable hydrogen production, storage, and distribution in Newfoundland and Labrador across various academic journals. The graph shows the number of publications on the x-axis and the journal titles listed on the y-axis. The graph illustrates 16 reviewed papers published in six different journals, from top to bottom of the graph: *Renewable and Sustainable Energy Reviews*, *Energy Conversion and Management*, *European Journal of Electrical Engineering and Computer Science*, *Energy*, *IEEE*, and *Renewable Energy*. Based on the published papers, we can divide these journals into three categories: (1) Minimum: *Renewable and Sustainable Energy Reviews* and *Energy Conversion and Management*, (2) median: *European Journal of Electrical Engineering and Computer Science* and *Energy*, and (3) maximum: *IEEE* and *Renewable Energy*; there are 1, 2, and 5 papers published in each journal in each class, respectively. This indicates that the *IEEE* and *Renewable Energy* have been significant platforms for Newfoundland and Labrador-based research on this subject.

4. Framework–Driven Analysis of Reviewed Papers

We apply the same approach proposed by Azadnia et al. (2023), to assess the 16 papers selected for review in this paper, just as we did when creating 1 in Section 2. As a consequence, we examine the 16 publications from the perspectives of (1) Production, (2) Storage, (3) Distribution, (4) Optimization, (5) Sustainability, and (6) Location perspectives. The three sections that follow, 4.1, 4.2, and 4.3 will convey this information with an emphasis on Production, Storage, Distribution, and Optimization, and finally, Sustainability and Location, respectively.

4.1 Production Perspective

Table 2 reviews the 16 papers 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, and geothermal, and (2) non-renewable: natural gas, coal, and nuclear.

Table 2. Analysis of reviewed papers from a production perspective

References	Energy Sources								Production	
	R					NR				
	W	S	H	B	G	Na	C	N	M	T
Al Mahbub et al. (2023)	✓	✓	✓	✓	✓					
Ghorbani, Zendehboudi and Afrouzi (2023)		✓		✓	✓	✓	✓	✓	✓	
Li et al. (2023)	✓	✓								
Kotian et al. (2022)	✓	✓								
Omidi and Iqbal (2022)	✓	✓								
Elsaraf et al. (2021)	✓	✓	✓	✓						
Ghorbani et al. (2021)	✓									
Islam et al. (2021)	✓	✓	✓							
Ahadi et al. (2017)	✓									
Harrison et al. (2010)	✓									
Maruf-ul Karim and Iqbal (2010)	✓									
Iqbal (2009)	✓		✓							
Flynn and Iqbal (2007)	✓									
Blackler and Iqbal (2006)		✓								
Khan and Iqbal (2005a)	✓									
Khan and Iqbal (2005b)	✓									
Total (%)	87.5	50	25	18.75	18.75	6.25	6.25	6.25	6.25	0

Abbreviations – R: Renewable, NR: Non-Renewable, W: Wind, S: Solar, H: Hydro, B: Biomass, G: Geo-thermal, Na: Natural gas,C: Coal, N: Nuclear, T: Technology, M: Method

Table 2 indicates that wind power has been the predominant focus of research over the years, with 87.5% of studies exploring its optimization and integration within hydrogen production systems. This aligns well with NL's substantial wind energy potential, please see the Government of Newfoundland and Labrador (2023*e*). On the other hand, geothermal and biomass sources have been minimally investigated for hydrogen production; however, NL has a considerable amount of geothermal energy potential (Grasby et al., 2012), and forestry and its residues are abundant in NL (Newfoundland and Education, 2010). Additionally, NL has significant hydroelectric projects, e.g., Muskrat Falls, but only 25% of the studies incorporated these in their research (Elsaraf, 2022). Only Ghorbani, Zendehboudi and Afrouzi (2023) considered non-renewable sources and their methods for hydrogen production, despite the Province having abundant access to fossil fuels (Doe, 2022).

4.2 Storage, Distribution, and Optimization Perspective

Table 3 examines the 16 articles from three major categories: (1) storage, (2) distribution, and (3) optimization software packages, with HOMER and MATLAB serving as the primary sub-categories, and additional packages, such as Simulink, GAMBIT, ASPEN, and MS Excel, falling under Others. Then, in the storage category: batteries for electricity and hydrogen tanks are considered, and in the distribution category we consider two main sub-categories: (1) the transportation of hydrogen through: pipeline, truck, ship, and railway, and (2) 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.

Table 3 demonstrates that batteries for storage, connection to grids for electricity transmission, and HOMER for optimization have gained substantial research interest over the years. The underlying reason for this may be that there are many remote communities in NL that can access energy through batteries or there is an ongoing effort to connect them to grids. As for utilizing HOMER, the reason may be its power in modeling, simulation, and comparing different hybrid energy systems that generate, store, and consume hydrogen. On the other hand, the following have received minimum or no attention from the researchers: (1) hydrogen tank, (2) pipeline, truck, and railway, while gasoline is stored in tanks and transported by trucks in the Province currently (Energy NL, 2020), (3) stand-alone systems, which are vital for meeting energy demand for many communities in remote areas in NL, and (4) other optimization packages, e.g., Fichtner H2-Optimizer, can provide optimal insights (Klumpp, 2022). Therefore, addressing these under-explored aspects will be essential for accomplishing the net zero emissions journey NL is on currently.

Table 3. Analysis of reviewed papers from storage, distribution, and optimization perspective

References	St		Distribution						Software		
			Tr				ET				
	Ba	HT	P	T	S	R	GC	SA	Ho	Ma	Others
Al Mahbub et al. (2023)	✓				✓				✓		
Ghorbani, Zendehboudi and Afrouzi (2023)											
Li et al. (2023)							✓	✓	✓	✓	
Kotian et al. (2022)	✓						✓		✓	✓	
Omidi and Iqbal (2022)		✓					✓		✓		
Elsaraf et al. (2021)	✓								✓		✓
Ghorbani et al. (2021)		✓					✓			✓	
Islam et al. (2021)	✓						✓		✓		
Ahadi et al. (2017)		✓								✓	
Harrison et al. (2010)	✓									✓	
Maruf-ul Karim and Iqbal (2010)	✓								✓		✓
Iqbal (2009)							✓	✓	✓		
Flynn and Iqbal (2007)	✓										
Blackler and Iqbal (2006)		✓									
Khan and Iqbal (2005a)									✓		
Khan and Iqbal (2005b)	✓						✓	✓			
Total (%)	50	25	0	0	6.25	0	43.7	18.75	56.25	31.25	12.5

Abbreviations – D: Distribution, St: Storage, Tr: Transportation, ET: Electricity Transmission, So: Software, Ba: Battery, HT: Hydrogen Tank, P: Pipeline, T: Truck, S: Ship, R: Railway, GC: Grid Connected, SA: Stand Alone, Ho: HOMER, Ma: MATLAB

4.3 Sustainability and Location Perspective

Mneimneh et al. (2023) emphasize the significance of sustainable hydrogen production, storage, and distribution in meeting the Sustainable Development Goals of the United Nations. Therefore, in Figure 4 we analyze and demonstrate the 16 papers from economic, environmental, and societal perspectives, which is the framework of sustainability (Ghahremanlou and Kubiak, 2020). It is apparent economic and environmental areas have drawn substantial research focus, while only one paper out of 16 focuses on all three dimensions of sustainability. Furthermore, just four studies focus on environmental and social dimensions. However, Leduchowicz-Municio et al. (2023) emphasize the significance of fair energy access for prosperous societies, especially remote communities, and according to Natural Resources Canada (2013) there are respectively 16 and 12 aboriginal and non-aboriginal remote communities with populations over 8000 in NL.

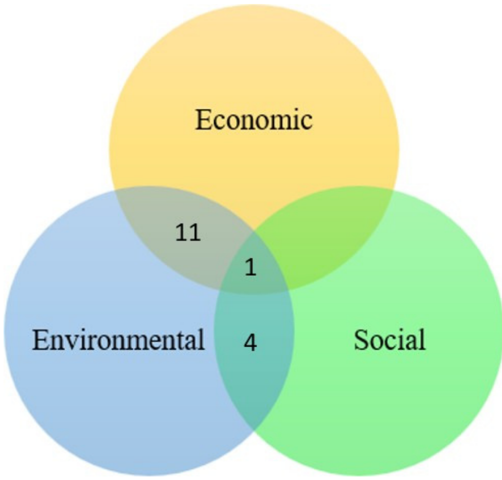

Figure 4. Analysis of reviewed papers within the framework of sustainability

Table 4 delves further to delineate indicators explored under each dimension of sustainability and their exact location of study. Within the framework of sustainability, we investigate under: (1) economic: levelized cost of energy, operating cost, net present cost, levelized cost of hydrogen, coefficient of performance, and others (i.e., levelized cost of ammonia, capacity factor, electricity production, excess electricity, unmet electricity load, and payback period), (2) environment: greenhouse gases, renewable fraction, and fuel consumption, and (3) social: job creations and energy access.

On the economic front, a majority of the works (43.75%) have analyzed operation costs (OC). However, the levelized cost of energy (LCOE), levelized cost of hydrogen (LCOH), and coefficient of energy (COE), received minimum attention from researchers (43.75%). This underscores the emphasis on conducting thorough techno-economic assessments of proposed solutions. Environmental impacts are also well represented, with at least 50% of papers reporting on various parameters, i.e., greenhouse gases, renewable fraction, and fuel consumption. Also, it is apparent that priority is given to quantifying the reduction in greenhouse gas footprint. However, with regard to social impacts just 25% of the papers focused on measuring the number of jobs created and 25% on energy access, requiring further contributions.

While 50% of the studies have employed a macro-view and studied the entire province, very few have focused on towns/islands across the province. However, focusing on towns/islands or micro-views can provide feasibility and sustainability insight about the hydrogen projects in those communities and help tailor solutions to unique geographical and socio-economic conditions. Furthermore, these micro-level studies can shed light on how communities can contribute to the bigger picture of achieving sustainability and net zero emissions.

Table 4. Analysis of reviewed papers from sustainability and location perspective

References	Sustainability											Location
	Economic						Environmental			Social		
	LCOE	OC	NPC	LCOH	COP	Others	GHG	RF	FC	Job	EA	
Al Mahbub et al. (2023)		✓					✓		✓	✓		Mccallum
Ghorbani, Zendehboudi and Afrouzi (2023)							✓		✓	✓		NL
Li et al. (2023)	✓	✓				✓	✓		✓			St. Lewis
Kotian et al. (2022)								✓				Ramea Island
Omidi and Iqbal (2022)	✓	✓	✓			✓	✓		✓			Paradise River
Elsaraf et al. (2021)		✓		✓		✓	✓	✓				NL
Ghorbani et al. (2021)								✓		✓		NL
Islam et al. (2021)			✓	✓		✓	✓	✓	✓			NL
Ahadi et al. (2017)									✓			St.John’s
Maruf-ul Karim and Iqbal (2010)						✓	✓	✓				NL
Harrison et al. (2010)		✓				✓	✓		✓			NL
Iqbal (2009)						✓	✓	✓		✓	✓	Ramea Island
Flynn and Iqbal (2007)						✓	✓	✓			✓	Ramea Island
Blackler and Iqbal (2006)	✓	✓	✓		✓		✓	✓	✓			Holyrood
Khan and Iqbal (2005a)						✓	✓	✓			✓	NL
Khan and Iqbal (2005b)		✓	✓	✓		✓	✓	✓			✓	NL
Total (%)	18.75	43.75	25	18.75	6.25	62.5	81.25	62.25	50	25	25	

Abbreviations – LCOE: Levelized Cost Of Energy, OC: Operating Cost, NPC: Net Present Cost, LCOH: Levelized Cost Of Hydrogen, COP: Coefficient of Performance, GHG: Green House Gases, RF: Renewable Fraction, FC: Fuel Consumption, EA: Energy Access, L: Location

5. Future Directions, Challenges, and Barriers

Yap and McLellan (2023) reveal that academic, government, and industry communities have been moving in the direction of net zero emissions, and emphasize hydrogen as being the solution. To assist these three communities in utilizing their resources to support NL on its net zero emissions journey, we summarize the gaps in the reviewed papers in Table 5, and provide insights to academic, government, and industry communities in Sections 5.1, 5.2, and 5.3 respectively. This will also help to further enhance the synergy between these three communities. Finally, we discuss some of the challenges and barriers on the way of Newfoundland and Labrador to reaching sustainable hydrogen development in Section 5.4.

5.1 Academic Insights

Karaca and Dincer (2021) reveal significant contributions of Canadian academics towards net zero emissions through hydrogen production, storage, and consumption. To enhance the level of contributions, Table 5 recommends some research directions, based on the research gaps found in the 16 reviewed papers, in four classes:

1) *Production* – In the pursuit of sustainable hydrogen production in Newfoundland and Labrador, we found four pivotal research directions. These include optimizing energy pathways by incorporating all available energy

sources, integrating hydrogen production with the forestry sector, harnessing surplus energy from hydroelectric plants for hydrogen production (83 megawatts≈ 15, 091 cubic meters of hydrogen per hour through an electrolyzer operating at 75% efficiency, planned to be transmitted to Nova Scotia (CBC News, 2021)), and exploring efficient methods for geothermal-based hydrogen production in Southern Newfoundland (Yukon Energy, Mines and Resources, 2018).

Table 5. Recommended directions

Categories	Recommended directions
Production	• Incorporating all renewable and non-renewable energy sources along with hydrogen production methods and technologies in the hydrogen models to provide optimal energy pathways. • Integrating hydrogen production process with existing NL forestry sector, i.e., Sexton Lumber Co., Cottles Island Lumber Co., Burton's Cove Logging & Lumber, and Corner Brook Pulp and Paper Co., to utilize forestry residues. • Utilizing partial surplus energy of existing NL hydro plants, which is planned to be transmitted to Nova Scotia, for hydrogen production up to 15,091 cubic meters per hour. • Investigating into efficient and commercial methods for utilizing geothermal for hydrogen production in Southern Newfoundland.
Storage, distribution, and optimization	• Considering possible hydrogen storage, transportation, and electricity transmission options to enable the models to select optimal combination(s). • Investigating drop-in hydrogen distribution, utilizing available transportation modes, e.g., existing heating oil delivery trucks. • Putting additional attention to stand-alone and grid connection methods of electricity to provide NL remote communities, e.g., Nain, Hopedale, Ramea, and Port Hope Simpson, with fair access to energy, and comparing their results to select the best option. • Comparing the quality of the solution and computation time for various software to identify the best optimization software package.
Sustainability	• Evaluating all dimensions of sustainability: economic, environmental, and social, for hydrogen projects before their implementation. • Comparing the results of different combinations of sustainability dimensions with each other to provide further insights. • Measuring various economic factors, e.g., return on investment and cash flow analysis.
Location	• Assessing the impact of hydrogen production on its neighboring communities, e.g., Leading Tickles, Botwood, Grand Falls-Windsor, St. George's, St. Alban's, Francois, Fortune, and St. Lawrence. • Exploring NL offshore sites for hydrogen production, and evaluating their capacity for meeting the energy demand of NL offshore oil platforms and/or hydrogen export.

2) *Storage, distribution, and optimization* – we encourage researchers to address the following four key aspects: exploring hydrogen storage, transportation, and electricity transmission options for optimal combinations, investigating drop-in hydrogen distribution (e.g., existing heating oil delivery trucks), ensuring equitable energy access for NL remote communities (e.g., Nain, Hopedale, Ramea, and Port Hope Simpson (Government of Canada, Year of Dataset Publication)), and comparing optimization software from efficiency perspectives.

3) *Sustainability* – we recommend a comprehensive evaluation of sustainability dimensions—economic, environmental, and social—for hydrogen systems. We further encourage the researchers to enhance their insights by comparing the outcomes of different combinations of these dimensions. Additionally, we suggest including return on investment and cash flow analysis to measure economic factors in the hydrogen assessment process.

4) *Location* – Two prominent research gaps exist: firstly, the unexplored assessment of the impact of hydrogen production on neighboring communities such as Leading Tickles, Botwood, Grand Falls-Windsor, St. George's,

St. Alban's, Francois, Fortune, and St. Lawrence, and secondly, the untapped potential of Newfoundland and Labrador's offshore sites for hydrogen production, along with their capacity to meet the energy needs of offshore oil platforms or facilitate hydrogen export.

5.2 Government Insights

Lee et al. (2023) emphasize the vital role of governments in leading and enhancing both strong hydrogen economy leadership and hydrogen risk management policy. In this vein and the refection of information in Table 5, the following directions are suggested for further attention to the government of NL:

1) Diversifying energy portfolio – Reducing reliance on any single source through investigating geothermal, biomass, and hydro sources for hydrogen production.

2) Efficient energy transition – Supporting feasibility analysis of employing the existing infrastructure for non-renewable energy storage and transportation for hydrogen distribution.

3) Fair energy access – Encouraging research on stand-alone and grid-connected methods for providing fair energy access for NL remote communities.

4) New revenue streams – Identifying potential offshore wind farms and announcing a call for bids for the farms to enhance royalties' revenue. This also may help in meeting the NL offshore oil platforms' energy requirements and/or helping towards mitigating the energy crisis in Europe; for a similar case in the Bohai Sea of China please see Hu et al. (2023). Figure 5 demonstrates NL offshore locations and may help in identifying the best potential locations for offshore wind farms.

5) Impact assessment – Evaluating the impact of hydrogen production on neighboring communities, for example, please see Figure 6 for high wind areas in NL shown in green color and some of the neighboring communities.

6) Sustainability – Encouraging any hydrogen development projects is assessed from a sustainability point before implementation.

Additionally, we conducted research to identify strategies for the government of NL to attract Foreign Direct Investment, especially for the crown land and potential offshore wind farms. To the best of our knowledge there is no document publicly available. Therefore, this might be another direction for the government to further explore to enhance its revenues from royalties.

5.3 Industry Insights

In the former section we explained how policymakers in NL can create new opportunities for industries interested in the hydrogen sector. On the other hand, industries should ensure sustainable industrialization and infrastructure, which is emphasized in the

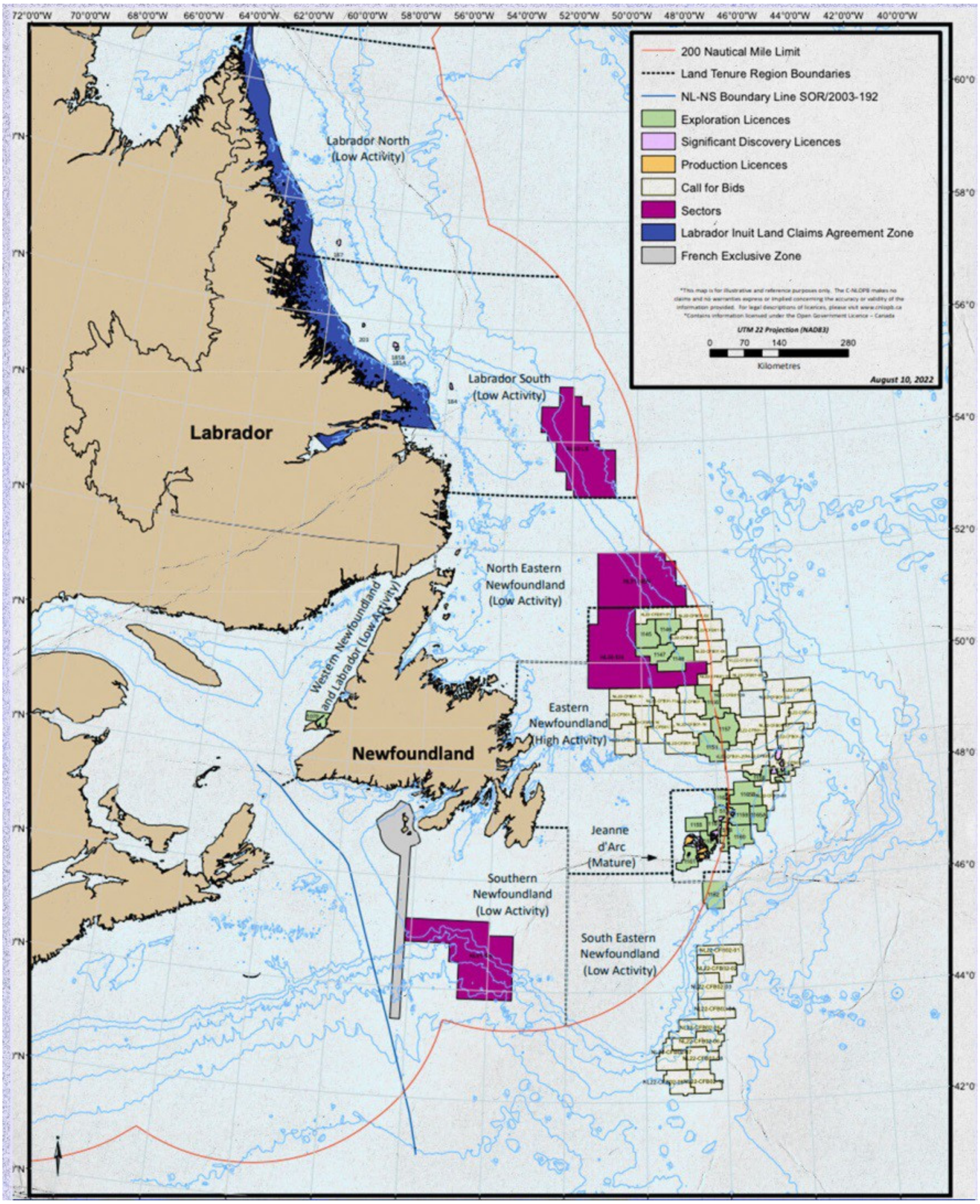

Figure 5. Newfoundland and Labrador offshore oil (Woodside and Logan, 2022)

Sustainable Development Goals of the United Nations (Genovese et al., 2023), for their hydrogen businesses. In this vein, for example, they can refer to Table 4 and accordingly analyze the results of the available studies from sustainability for any specific communities within the Province; this may also lead to some feasibility study cost savings.

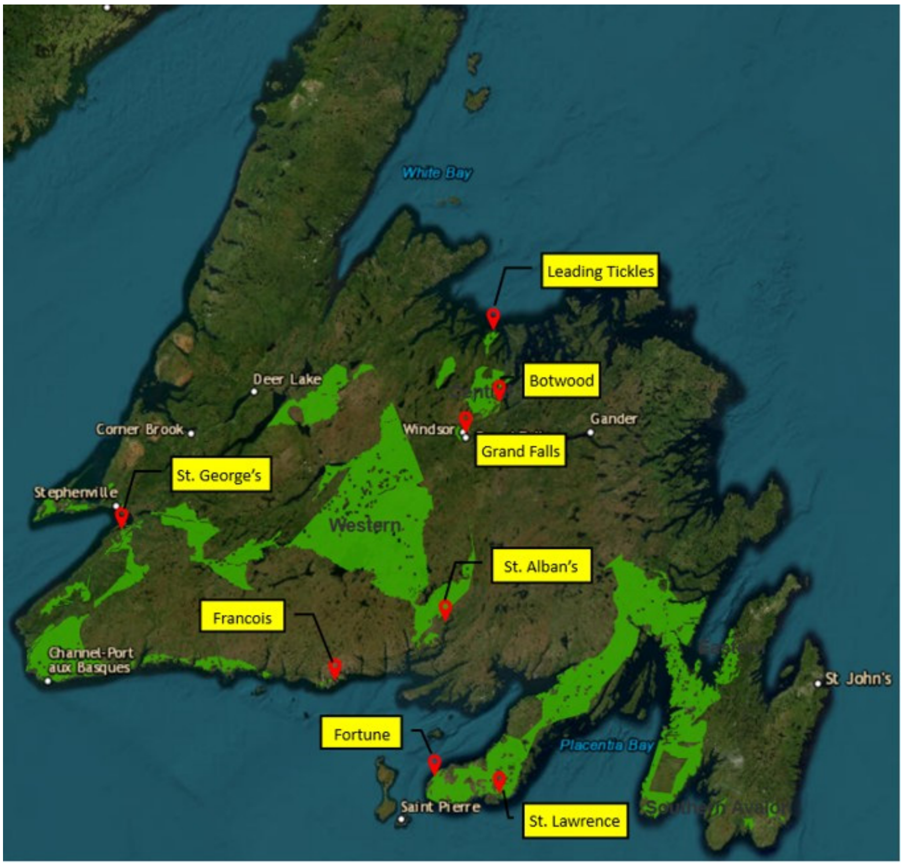

Figure 6. Newfoundland and Labrador communities close to potential hydrogen production plants (Roberts, 2022)

The Province of Newfoundland and Labrador has abundant opportunities for renewable energy industries due to its geography and natural resources (Mercer et al., 2017). There are still lots of potential locations for wind farms to produce hydrogen onshore, e.g., near Leading Tickles, Botwood, Grand Falls-Windsor, St. George's, St. Alban's, Francois, Fortune, and St. Lawrence. Furthermore, the province's offshore is a virgin territory from the hydrogen production perspective. This may lead to business partnerships with other operational offshore oil businesses to meet their energy demand, please see Figure 5. Additionally, they can analyze the feasibility of investment in unexplored sources of hydrogen production, e.g., biomass, hydro, and geothermal, while utilizing existing resources for the storage and distribution of non-renewable energy in the province.

5.4 Challenges and Barriers

There are several technical obstacles to the development of a robust and sustainable hydrogen infrastructure in Newfoundland and Labrador (NL), chief among them being a comprehensive framework and action plan for the production and distribution of hydrogen, which is publicly available; however, this is emphasized by Government of Newfoundland and Labrador (2022).

The lack of infrastructure in the province makes setting up the facilities required for hydrogen generation extremely difficult. The absence of current networks for hydrogen distribution is a significant factor contributing to this problem. The severe weather of Newfoundland and Labrador, which is marked by bitterly cold winters, also presents substantial obstacles to the effective and secure functioning of hydrogen systems. These circumstances may have an impact on hydrogen storage's effectiveness, raising questions about safety and decreasing operational effectiveness. Because hydrogen has low boiling and freezing points, it presents additional hurdles to the safety and viability of hydrogen systems in these environments. To effectively address these issues, specialized infrastructure and safety measures are required (Gao et al., 2022).

Significant financial obstacles, most notably expensive setup and operating expenses, surround the implementation of hydrogen systems. The high initial capital cost associated with setting up infrastructure for production, distribution, and storage is partly due to the complex and emerging nature of hydrogen technology. Additionally, potential investors and stakeholders need to consider the cost of importing various technologies, e.g., wind turbine components, considering the geographical position of the province (He et al., 2023).

The lack of specific knowledge about hydrogen technology and supply chain in the province is another challenge and necessitates the training and hiring of qualified individuals or partnering with outside organizations that have the necessary experience (Government of Newfoundland and Labrador, 2023*a*). To overcome the human resource constraints, intensive investment in training and educating local talents and strategic alliances on a national and worldwide level are required to augment NL's existing resources with knowledge, enabling the creation and application of hydrogen systems in the province.

6. Conclusions

Global warming, the uneven distribution of fossil fuels, along with Russia-Ukraine war, have accelerated policymakers to enhance energy security through renewable energy sources. Hydrogen from renewable sources is a promising option to address this challenge. In this vein, a green alliance between the European Union and Canada was formed. The Province of Newfoundland and Labrador (NL) demonstrates excellent potential to help Europe during their current energy crisis (due to its geopolitical situation), accelerating the movement towards creating a net zero emissions province, which is aligned with Canada's global environmental commitment.

This comprehensive systematic review paper includes all the papers related to hydrogen production, storage, and distribution in NL. A total of 16 papers were found, which were published between 2005 and 2023. In these papers, several keywords were most commonly observed, e.g., Canada, Newfoundland, economic analysis, energy storage, conventional methods, control systems, and carbon dioxide, which shows common research areas. We further analyzed the papers from the points of view of: (1) Production, (2) Storage, (3) Distribution, (4) Optimization, (5) Sustainability, and (6) Location; however, the limitation of this study is the lack of detailed focus on hydrogen production technologies and methods, which can be addressed by other researchers that may lead to new insights. Our findings are summarized in Table 5, and accordingly we recommended directions for academic communities, the Government of Newfoundland and Labrador, and industries interested in hydrogen production in the province and distribution.

Some of the directions are as follows: (1) there is an absence of assessment regarding the impact of hydrogen production on neighboring communities, including Leading Tickles, Botwood, Grand Falls-Windsor, St. George's, St. Alban's, Francois, Fortune, and St. Lawrence. (2) offshore sites in NL remain largely unexplored for hydrogen production, storage, and distribution, necessitating an evaluation of their potential to meet energy demands for offshore oil platforms or hydrogen export, (3) government insights emphasize diversifying energy sources, efficient transitions, equitable access, new revenue streams, impact assessments, and sustainability assessments for hydrogen projects, and (4) industries interested in the hydrogen sector are encouraged to prioritize sustainable practices, explore untapped onshore and offshore locations, and consider business partnerships and feasibility studies for various hydrogen sources and distribution methods. These research gaps and recommendations collectively contribute to advancing sustainable hydrogen solutions and facilitating NL's journey toward net-zero emissions.

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Authors contributions

Priya Sakthi contributed to investigation, methodology, conceptualization, and writing – original draft. Davoud Ghahremanlou performed investigation, conceptualization, writing – original draft, writing – review & editing, supervision, and project administration. Abdullah Bin Abdul Qavi Lardi participated in investigation and visualization. All authors have thoroughly read and given their approval for the final manuscript to be published.

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