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Limited scientific evidence for decarbonization of energy end-uses and the challenges to learning and empowerment of green hydrogen niches - insights from Canada

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ABSTRACT

Supporting inappropriate uses for hydrogen can delay climate action and decarbonization efforts should limit hydrogen to difficult-to-electrify end-uses. The introduction of novel green hydrogen niches to markets requires learning about which end-uses are appropriate for hydrogen and the empowerment of these niches. This work identifies and collates scientific evidence of when to use hydrogen over electrification of end-uses. The hydrogen end-uses being empowered by legitimization through discourse and resource mobilization are assessed in investment advice, 11 government plans, and 47 policies in Canada. The findings confirm the inattention to when to electrify and when to use hydrogen, observed in the very limited scientific evidence of only two approaches to prioritization, the lack of harmonization between the approaches, and the lack of legitimization of this information. Although some hydrogen end-uses being empowered align with scientific evidence, the most appropriate set of hydrogen end-uses that could contribute to decarbonization are not being legitimized and empowered in Canada. More attention should be paid and resources allocated to developing and legitimizing robust and scientifically based evidence of when to electrify and when to use hydrogen for energy end-uses. This novel method is globally applicable to other emerging technologies and policy analysis.

1. Introduction

Identifying decarbonization options that deliver rapid, substantial, and socially just reductions of greenhouse gas (GHG) emissions is crucial to mitigate climate change (IPCC, 2023). The energy sector is a focus for decarbonization since three quarters of global GHG emissions are associated with energy-related activities (IEA, 2024a). Hydrogen has gained attention globally as a possible pathway to decarbonize energy use (IEA, 2023a; IRENA, 2022a). For example, the public budget for research, development, and demonstration for hydrogen and fuel cells reported by International Energy Agency (IEA, 2024b) member countries has increased from 448 million EUR in 2016, to 2.23 billion EUR in 2023. Low-carbon hydrogen so far plays an insubstantial role in global production,[1] as 0.6 % of produced hydrogen is blue (produced from fossil fuels with carbon capture and storage), and only 0.1 % is green (produced from renewable energy) (IEA, 2023b).

There are negative consequences associated with all forms of low-carbon hydrogen (Aba et al., 2024; Schreyer et al., 2024). Blue hydrogen is criticized for making insubstantial contributions to decarbonization (Howarth and Jacobson, 2021; Plehwe et al., 2024), and green hydrogen is associated with higher material consumption, higher toxicity to humans and the environment, greater land and mineral use, and water depletion than electrification (Shen et al., 2024). Both are criticized for delaying reductions in carbon emissions (Rosenow and Lowes, 2021), the entrenchment of fossil fuel industry business models (Plehwe et al., 2024), and posing risks of increasing the costs of

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[1] 99 % of hydrogen use is gray (produced using fossil fuels without abatement technology), 0.6 % is blue hydrogen (produced from fossil fuels with carbon capture and storage), Global hydrogen production reached 95 Mt in 2022 (IEA, 2023b). From this total, the share of gray hydrogen production accounts for 99 % – of which 62 % is produced from natural gas, 21 % from coal, 16 % from refinery and petrochemical conversion processes, and 0.5 % from oil (IEA, 2023b). The share of blue hydrogen is 0.6 %, produced from fossil fuels with carbon capture utilization and storage, while the share of green hydrogen is only 0.1 %, produced through water electrolysis (IEA, 2023b).

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decarbonizing energy use (Droessler and Leach, 2024).

Many argue that electrification should be prioritized over hydrogen use in end-uses where electrification is considerably cheaper and more energy efficient (IRENA, 2020; Rosenow and Lowes, 2021), whereas hydrogen can play an important role in difficult-to-electrify end-uses (Schreyer et al., 2024). However, there is a lack of transparent information about how to prioritize one over the other when choosing between hydrogen and electrification or other alternatives (Carlson and Trencher, 2024; Kern et al., 2023; Rosenow and Lowes, 2021).

Research into green hydrogen production has made advancements in addressing the resource use of green hydrogen. Some studies point at the need for improving the cost-efficiency of water electrolysis (Li et al., 2023a) and developing smart grid technology for better aligning the supply and demand of green hydrogen (SaberiKamarposhti et al., 2024). Other works have highlighted the relevance of enhancing biomass-based green hydrogen production, focusing particularly on thermochemical and biological conversion processes (Qureshi et al., 2023). A novel research approach is proofing the efficiency of deriving green hydrogen from biomass through electrocatalysis. Studies are demonstrating higher hydrogen production yield with lower resource use than conventional production methods when experimenting with biomass materials. Early studies have identified the potential to double the hydrogen production rate compared to electrically produced green hydrogen, with efficiency of energy use improved by up to a third (Li et al., 2023b; Liu et al., 2022; Yu et al., 2023). This is an advancement in green hydrogen production that may have fewer negative social and environmental consequences than other forms of green hydrogen production.

Low-carbon innovations, such as novel green hydrogen production, are often inhibited from embedding and diffusing into socio-technical systems and markets (Hoicka et al., 2022). One key need to scale and diffuse a novel supply of green hydrogen is the identification of appropriate end-uses for hydrogen to establish within a supply chain. That is, to facilitate the adoption of the technology, knowledge is required on the technology being promoted about the underlying infrastructure, user and market needs, social and environmental impacts, regulatory frameworks, institutional structures, policies, and government incentives (Hoogma et al., 2002; Raven et al., 2016).

In socio-technical transitions theory, the introduction of a new technology or innovation that challenges the path dependency of a socio-technical system often has difficulty diffusing into markets. These new technologies or innovations require “protected spaces” (Köhler et al., 2019), referred to as niches, to develop and embed within supply chains. Niches support the diffusion of technology into markets by allowing new technologies to develop in a space that is protected from pressures and biases of the supply chains and institutional structures that favor unsustainable pathways (Kemp et al., 1998; Lopolito et al., 2022; Smith and Raven, 2012). Within the theory, “learning” is a critical dimension of protective spaces that nurtures a niche supported by the accumulation of relevant facts and data that continuously advance new understandings and ways to support the functions of the niche, such as experimentation for market development (Raven et al., 2016).

These novel methods of green hydrogen production can be articulated as innovation “niches” that require learning through information about specific markets and end-uses where it can be deployed. One critical area of learning is about which end-uses are best electrified and which end-uses are best supplied by hydrogen. Learning that supports the matching of green hydrogen production to end-use markets is necessary for protecting green hydrogen from market pressures of low cost-competitiveness and high investment costs. If there are hard to electrify energy uses that green hydrogen can fuel, then green hydrogen niches require protected spaces that identify those end-uses (Schwabe, 2024).

However, end-uses of hydrogen are found to be legitimized and promoted across sectors where electrification would be more appropriate (Korberg et al., 2023; Rosenow and Lowes, 2021; Schreyer et al., 2024). Over 20 national governments and the European Union have developed and released hydrogen strategies as a response to demands from the fossil fuel industry for policy support (Rosenow and Lowes, 2021). These strategies promote blue hydrogen as a replacement for oil and gas in different end-uses in industry, buildings, and transport (Rosenow and Lowes, 2021). Many of these promoted hydrogen applications are misleading, and unlikely to be decarbonized through the use of hydrogen (Carlson and Trencher, 2024; Kern et al., 2023; Rosenow and Lowes, 2021).

The motivation of the research is to introduce a novel green hydrogen niche to markets targeted at difficult-to-electrify end-uses. This requires the identification of appropriate initial end-uses that are best matched to be supplied by the green hydrogen (Schwabe, 2024). The objective of this study is to determine what learning about appropriate hydrogen end-uses for green hydrogen niches is available in Canada. This objective includes the assessment of the available knowledge about whether appropriate end-uses for hydrogen over electrification are being supported through legitimacy of discourse and resource mobilization.

This study progresses in three stages. First, we identify and collate evidence of transparent and scientific prioritizations of hydrogen end-uses compared to electrification. Second, we identify and collate which hydrogen end-uses are legitimized through discourse, in plans and policies, and which are being legitimized through resources, by analysing investment advice. This provides an indication of whether end-uses that are best electrified or best as hydrogen applications are being legitimized and supported in the Canadian market. This can provide an indicator of the quality of information for learning that a green hydrogen niche can draw on. The contribution of this study is the identification and collation of globally applicable evidence of hydrogen end-use prioritization that clarifies which end-uses are most appropriate to nurture green hydrogen niches, and an assessment of the state of this evidence.

2. Theory

To understand the environment into which green hydrogen niches are emerging, we start by understanding the theory of niches as protected spaces within the multi-level perspective, and the role of legitimacy in promoting niche innovations. Emerging innovations often struggle to diffuse into markets because of the complex interactions within and among socio-technical systems (Geels et al., 2018). The multi-level perspective outlines how innovations can emerge through interactions across three socio-technical system levels (Schot and Geels, 2008):

- Niches – are protected spaces that protect new innovations from competing with pressures and biases of incumbent regimes, while offering a safe space for experimentation with the co-evolution of technology, user practices and regulatory structures.
- Regimes – are the institutional structures that establish and reinforce dominant technological trajectories in a system.
- Landscapes – are developments external to socio-technical regimes that can influence the innovation process.

Niches allow new technologies to develop in a space that is protected from pressures and biases of dominant regimes in the socio-technical system (Schot and Geels, 2008), and can help promising low-carbon innovations to develop and embed within supply chains (Köhler et al., 2019). The contextualization of the niche-internal dimensions needs to be complemented with attention to niche external processes (Schot and Geels, 2008). Opportunities for diffusing a new technology appear when disruptions in dominant regimes caused by external landscape developments create appropriate conditions and the technology in the protected space is sufficiently mature (Köhler et al., 2019).

2.1. Legitimacy in the diffusion of low-carbon innovations

Legitimacy is a series of institutional actions oriented to create and strengthen a positive perception of emerging innovations and technologies proposed within a technology innovation system (Kivimaa and Kern, 2016; van Oorschot, 2018). Legitimacy can be employed by actors, networks, and institutions to favor or hinder the diffusion and scaling up of low-carbon innovations (Duygan et al., 2019). The effects of legitimization can be as impactful as techno-economic and efficiency considerations in the selection and diffusion of low-carbon innovations (van Oorschot, 2018; Rosenbloom et al., 2016). Duygan and colleagues (2019) highlight two ways of legitimizing an innovation: legitimacy can be built up through discourse about an innovation, and through the influence of actors and networks who can mobilize resources and other influential support. Positive discourses can create desirable perceptions of innovations, and the support of influential actors and networks can promote actions at different scales to push innovations towards diffusion (Duygan et al., 2019). Low-carbon energy use is supported when actors and networks mobilize across regimes to strengthen the legitimization of new low-carbon options while weakening supports to fossil fuel-based options in the innovation process (Hoicka et al., 2022).

Action plans, roadmaps, strategies and policies legitimize the diffusion of low-carbon innovations by strengthening a positive vision of the proposed innovations (Bento and Fontes, 2019; Haque, 2022; Hoicka et al., 2022). Bento and Fontes' (2019) analysis of 10 technological plans and roadmaps published by six countries from 2009 to 2014 emphasized that roadmaps have a direct influence in strengthening legitimacy of innovations. These government-released roadmaps often depict the actors, networks and institutions, and the technology specific policy landscape that legitimize proposed technologies. Haque's (2022) analysis of national Technology Action Plans in 31 countries recognized that the plans can be considered as tools for creating legitimacy and often propose policy instruments that support the creation of legitimacy. Hoicka and colleagues (2022) analyzed energy and climate change action plans relevant to the Province of Ontario as indicators of presence of legitimacy on demand-side low-carbon innovations. Using quantitative analysis across 131 innovations, it was found that legitimacy support through discourse is positively correlated with the diffusion of low-carbon innovations (Hoicka et al., 2022).

2.2. Protected spaces for innovation niches

Protected spaces are needed to support innovation niches that are at a disadvantage compared with technologies that are established in the market and reinforced by the dominant socio-technical regimes (Smith and Raven, 2012). Niche-innovations require the support of actors, networks, and institutions to facilitate their emergence (Schot and Geels, 2008).

Three key features of protective spaces are shielding, nurturing, and empowering (Raven et al., 2016).

- Shielding refers to the niche characteristics that protect the space from external regime pressures. Examples of shielding include selecting favorable geographic locations and cultural contexts, as well as policy, innovation research, subsidies, and political support that are technology-specific (Raven et al., 2016).
- Nurturing refers to the elements in the socio-technical system that facilitate the development of the innovation (Raven et al., 2016). Examples include technology-specific public policies, strategic industrial research, market subsidies, and political support (Raven et al., 2016).
- Empowerment is supported by legitimacy through discourse and resources that help to structure or form the market for the innovation to diffuse into. Sometimes empowerment is supported by existing policies and supply chains (fit and conform) and sometimes new policies are needed for market transformation (stretch and transform) (Raven et al., 2016).

While the three are mutually reinforcing, nurturing is the most theoretically developed feature of niches that focuses on the needs of the protected space for the successful emergence of innovations (Raven et al., 2016).

Niches are nurtured through expectations, social networks, and learning processes (Schot and Geels, 2008).

- Expectations nurture innovations when they are shared by many actors and are supported by detailed and high-quality information on ongoing innovation development (Hoogma et al., 2002; Raven et al., 2016).
- Social networks nurture innovations when they include multiple and diverse stakeholders that can share relevant knowledge and mobilize resources to facilitate learning at multiple levels (Hoogma et al., 2002; Raven et al., 2016).
- Learning processes contribute to niche development by accumulating relevant facts and data that are helpful to continuously advancing new understandings and ways to support the protected space. The types of information that facilitates learning include specific aspects about infrastructure and technical development of design specifications, required complementary technology and infrastructure; understanding user characteristics and their requirements; the safety, energy and environmental aspects; the production and maintenance network needed to support the niche; and understanding regulatory frameworks and government policy, and the government's role in the introduction process and institutional structures and supportive policies (Hoogma et al., 2002; Raven et al., 2016).

2.3. Legitimizing and nurturing green hydrogen niches

Legitimization through discourse and the mobilization of resources support the empowerment of green hydrogen niches. Although studies of green hydrogen niches are relatively new and emerging, the evidence so far points to the critical importance of planning and support policies and financing to support the matching of green hydrogen niche supply to hydrogen end-use infrastructure and demand-side markets (Nurdiawati and Urban, 2022; Schwabe, 2024; Westrom, 2020). For example, the incorporation of green hydrogen into supply chains in Sweden was found to require effective planning and supporting policies (Nurdiawati and Urban, 2022). Insufficiently developed policy instruments for building and maintaining niche markets of hydrogen end-uses in Sweden was found to undermine the diffusion of green hydrogen niche innovations (Nurdiawati and Urban, 2022). In South Africa, O'Connell (2024) found that financing rules for green hydrogen are needed to better specify how financial resources from governments, private actors, and non-governmental institutions should be allocated to support the diffusion of green hydrogen into the national energy market. Embedding green hydrogen into the market requires learning on how to better develop clear and effective rules that guide financing decisions and on the energy regime dimensions where financing can impact the development of green hydrogen niches (e.g., policy, industry, market, technology, science, culture) (O'Connell, 2024). Schwabe (2024) found that the matching of green hydrogen supply to hydrogen end-uses empowers the diffusion of green hydrogen niches in Germany's supply chain. Meeting the technology and infrastructure needs of potential hydrogen end-use sectors requires aligning the activities of policymakers, private sector actors, end-users, civic organizations, and academic researchers who are involved in green hydrogen production and distribution to facilitate access to funding, knowledge development for land use management, and the creation of networks (Schwabe, 2024). A community-led wind and green hydrogen energy facility in Orkney, Scotland was legitimized through the mobilization of networks of private and public actors (Westrom, 2020). The community supported the diffusion of green hydrogen into the energy market through the creation of networks of hydrogen producers and end-users to match supply and demand capacity and by attracting capital and technology development (Westrom, 2020). Chile sought to produce green hydrogen to produce ammonia locally and for industrial use in refineries (Cruz et al., 2023). Legitimacy for green hydrogen was grown in Chile through resource mobilization. Chile attracted financial support and built international collaboration to boost private investments and technical capacity in national solar-wind based green hydrogen projects by involving national and international actors, such as the World Bank, national governments, and private investors (Cruz et al., 2023). Cruz et al. (2023) found that the major barriers for the development of green hydrogen markets in Chile were a lack of shared information on technology development to coordinate the matching of supply and demand markets to avoid high cost risks and social and environmental impacts.

Although the study of the implementation of green hydrogen is still nascent, these five international case studies point at the importance of learning that facilitates the matching of green hydrogen supply with end-use markets to embed green hydrogen niches into end-use markets. These studies suggest that there is a lack of information on technology and infrastructure needs, social and ecological impacts, policy instruments, and financing rules that inhibits the diffusion of green hydrogen niches. The empowerment of green hydrogen niches requires more accurate information on what uses for hydrogen should be legitimized by policy-making and planning and where financial resources should be allocated to avoid social, environmental, and economic risks. Sharing information among the different actors involved in the supply and demand sides of green hydrogen production is identified as crucial in the creation of networks and attracting financial support. The theory suggests that this also improves the quality of information needed for learning by aligning the knowledge development and legitimization efforts among actors and networks in the niche (Raven et al., 2016). Identifying what are appropriate end-use markets to be supplied by hydrogen use is a key step in advancing knowledge that point to where legitimization efforts should be directed.

2.4. Study focus

The motivation of the research is to introduce a novel green hydrogen niche to markets. One important step is to identify appropriate initial end-uses of hydrogen that are best supplied by the green hydrogen.

However, many scholars observe that hydrogen end-uses that do not effectively contribute to decarbonization are being empowered, leading to the legitimization of hydrogen end-uses that are more costly and inefficient compared with electrification (Kern et al., 2023). Kern et al. (2023) point out that hydrogen strategies have promoted hydrogen as a "panacea" solution, capable of decarbonizing different sectors, for economic and political interests. The uncertainty by actors and networks on what end-uses to support slows down the diffusion of hydrogen end-uses that can contribute to decarbonization (Kern et al., 2023). Cheng and Lee (2022) have stressed that national strategies supporting green and blue hydrogen often avoid delegitimizing the continued use of fossil fuels purposefully.

The legitimization of hydrogen end-uses that undermine decarbonization through their inclusion in plans and policies points at the need for information that better supports learning on hydrogen. According to Rosenow and Lowes (2021), distinguishing between "sensible and inappropriate use cases for hydrogen" (p. 1529) based on supporting evidence is critical to develop effective policies and supports for hydrogen uses for decarbonization. Focusing on prioritizing promising end-uses for hydrogen, instead of supporting a widespread use of hydrogen for all sectors in national strategies, is needed to focus on where hydrogen uses can be supported by policy-making to promote decarbonization that minimizes risks to safety, infrastructure capacity, social inequities, and financial losses (Carlson and Trencher, 2024; Scholvin et al., 2025). Transparent and evidence based information about when to prioritize hydrogen end-uses and when to prioritize electrification can also help to push back attempts by fossil fuel sectors to legitimize end-uses for vested political and economic interests (Kern et al., 2023).

Canada, the study context, is a major fossil fuel exporter and accounted for 7,546,979 TJ in net crude oil exports, and 2,021,003 TJ in gas exports in 2023 (IEA, n.d.). 80 % of GHG emissions in Canada are from energy use (Environment and Climate Change Canada, 2022). The public budget across the lifecycle of research, development and demonstration for hydrogen and fuel cells has risen rapidly from 39.2 million EUR in 2021, to 100.6 million in 2023 (IEA, 2024b).

Learning about which energy end-uses are better served by hydrogen is needed for protected spaces for green hydrogen niches, depicted in Fig. 1 as one focus of this study. Another focus of this study is to identify whether the hydrogen end-uses that are being legitimized and empowered within the Canadian context through discourse and resource support match with the evidence on which end-uses should be served by hydrogen. That is, whether appropriate end-uses of green hydrogen that could provide a protective niche space are empowered by legitimacy through discourse and resources.

3. Methods

The research proceeded in several steps. The first was to identify evidence on when to prioritize hydrogen for end-uses instead of electrification. The second step was to gather hydrogen plans, policies, and investment advice to understand which hydrogen end-uses are legitimized in Canada through discourse and resource support. The third step was to assess the legitimized hydrogen end-uses against the evidence supporting their prioritization to identify whether appropriate uses of hydrogen are being supported in Canada and the landscape of support for hydrogen end-uses. Fig. 2 illustrates the methodological process of the study.

3.1. Identifying scientific evidence for hydrogen end-use/application prioritization

Different approaches have attempted to clarify when to prioritize hydrogen end-uses over electrification to support policy- and decision-making. The first stage of analysis focused on finding transparent and reliable scientific evidence of prioritization of hydrogen end-uses compared to electrification. These literatures were found by conducting searches from April 2024 to June 2024 on the "hydrogen ladder", and through a process of snowballing references. Additional sources were identified by attending the workshop entitled "Green hydrogen: avoiding pitfalls to unlock its industrial potential in Canada" held at McGill University on April 11, 2024 (Otis-Laperrière et al., 2025). The identified sources were assessed for a transparent and peer-reviewed description of how the prioritization was developed, in one case an author was contacted for the methodology.

3.2. Identifying legitimized hydrogen end-uses and applications

Government-developed hydrogen plans and policies, and materials provided by influential clean technology actors and networks were analyzed to identify which hydrogen end-uses and applications were legitimized.

3.2.1. Plan identification and analysis

Government-released federal and provincial hydrogen plans in Canada were reviewed to identify which hydrogen end-uses were being legitimized in discourse. The plans were gathered through a search of gray literature reports, policy literature, working papers, newsletters and government documents. The keywords used for the search included

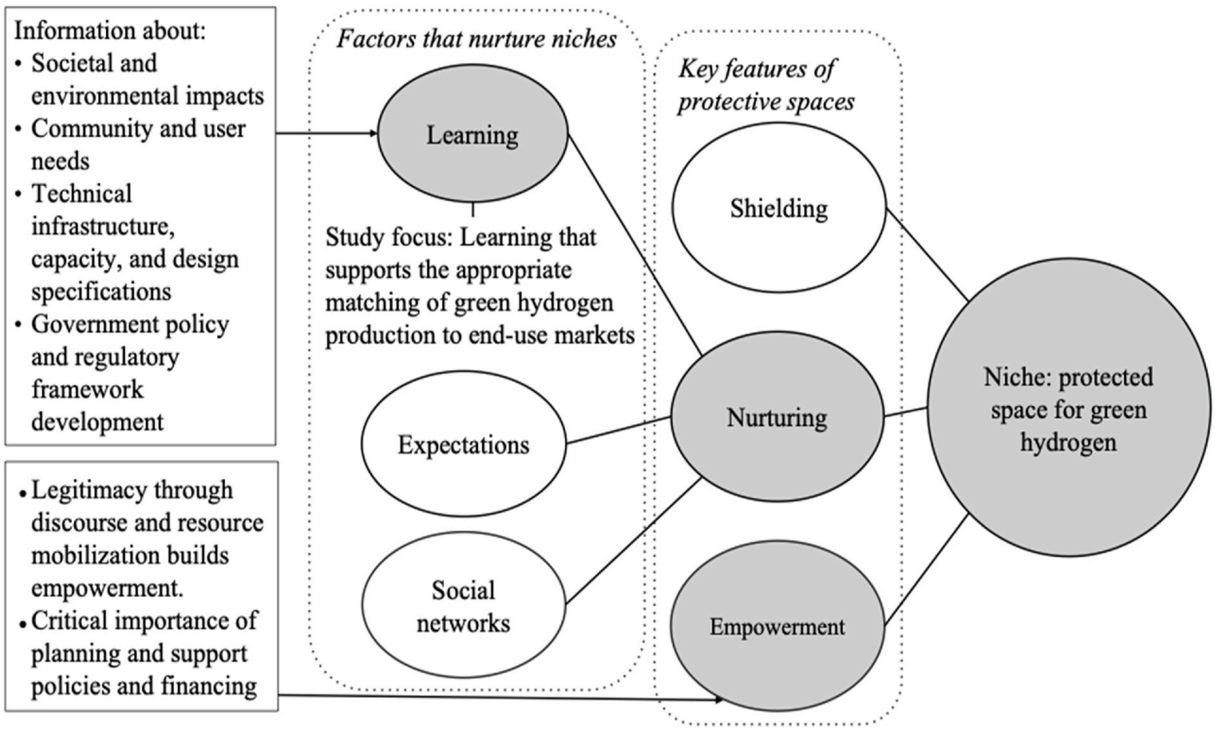

Fig. 1. Study focus: learning and empowerment for green hydrogen niches (based on Duygan et al., 2019; Hoogma et al., 2002; Nurdiawati and Urban, 2022; Raven et al., 2016; Schot and Geels, 2008; Schwabe, 2024).

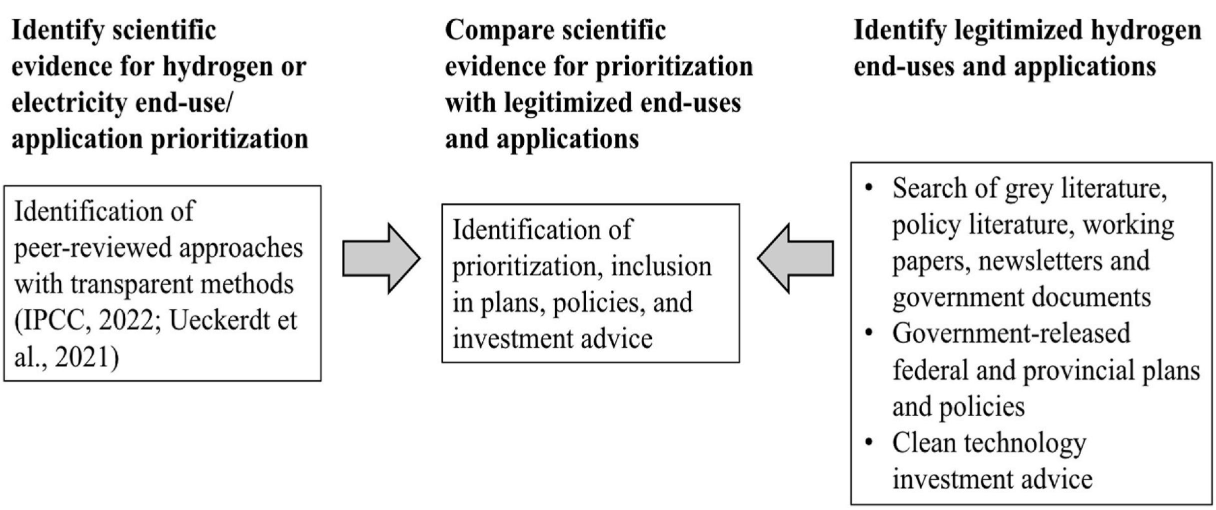

Fig. 2. Methodological process of the study.

the name of the province and the words "hydrogen plan" or "hydrogen strategy" (e.g., Québec + "hydrogen plan"). The federal hydrogen plan was retrieved from the Government of Canada website. The list of identified plans was reviewed by a hydrogen policy expert who added two sources and corroborated that the list was complete. The plans were identified between November 17, 2023, and July 22, 2024.

3.2.2. Policy identification and analysis

Hydrogen-related policies that are implemented in Canada were identified in the Canadian Climate Policy Partnership (C2P2) inventory of policies for climate change mitigation. The C2P2 inventory compiles 327 implemented and soon-to-be-implemented federal and provincial climate policies (Scott et al., 2024). Policies are classified as implemented when "compliance with the policy is currently required or support from the policy is currently available" (Scott et al., 2024, p. 8). The C2P2 inventory is the most comprehensive dataset from which to select climate policies in Canada, and its reliability is supported by a validation process. The inventory was developed by reviewing Canada's biennial reporting to the United Nations Framework Convention on Climate Change, climate plans, a pre-existing policy inventory, academic and government reviews of the database, government websites, press releases, jurisdictional policy documents, and annual reports from Crown corporations (Scott et al., 2024). The validation process consisted of two stages, first for interrater reliability by academics and non-government organization representatives, and second by governments of each jurisdiction covered by the dataset. 11 policies that support hydrogen use were found in the published inventory. A second stage of research identified 36 additional implemented technology specific policies supporting hydrogen use. The compilation of the hydrogen-related policies followed the same methodology as the published inventory and was validated by members of the C2P2 research team. Overall, 47 implemented policies that support hydrogen end-uses and applications were used for the analysis. The search was carried out in the period of June 2024 to August 2024.

3.2.3. Legitimacy through networks of clean technology investors

Investment perspectives on hydrogen end-uses were identified in Foresight 50 Canada's Most Investible Cleantech Ventures pitchbooks, developed by Foresight Canada (2021, 2022, 2023). Foresight Canada is a non-profit organization that aims to accelerate public and private adoption of clean technologies that can contribute to Canada's net-zero goals. Foresight 50 is an initiative that started in 2021 with the objective of publishing yearly pitch books that highlight the 50 most investable cleantech ventures based in Canada (Foresight Canada, 2021, 2022, 2023). The motivation of the initiative is to provide cleantech investors with information on promising low-carbon technologies in Canada, with the purpose of attracting investments to scale up these proposed technologies (Foresight Canada, 2023). Each year, a call for applications is released for private companies that have legal standing in Canada and demonstrate clear methods or mechanisms for minimizing environmental impacts (Foresight Canada, 2024). The applications are reviewed by an independent judging expert panel of investors and cleantech community partners from academia, public, private, and government sectors – spans different areas of expertise, including water, energy, low-carbon fuels, agriculture and food, urban areas, pharmaceuticals and biotech, software development, organic waste, and real estate, with 16 judges in 2021, 29 judges in 2022, and 41 judges in 2023. Finalist ventures are selected based on evaluation criteria that includes investability, potential environmental and employment impact, leadership and team, and probability of success (Foresight Canada, 2024).

The three existing Foresight 50 pitch books were analyzed to identify the promoted cleantech ventures that involve hydrogen end-uses. Table 1 found in the Supplementary Material – Table 1" lists the cleantech ventures included in the analysis and identifies hydrogen applications that they support or provide with their technologies, as well as the current and stated markets by the companies.

3.3. Assessing whether hydrogen end-uses and applications prioritized by evidence are supported by plans, policies and investment advice

The hydrogen end-uses and applications identified in the plans, policies and pitch books were compared to the scientific prioritization of hydrogen end-uses. Due to the variation in terminologies among end-uses and applications, an explanation of how the terminologies used by the evidence were used for the comparison can be found in the Supplementary Material in Table 2.

4. Results and discussion

4.1. Scientific prioritization of hydrogen end-uses and applications

Table 1 describes the six approaches to prioritization of hydrogen end-uses that were found, and includes an assessment of their description of the methodological approach and evidence used. Few of the approaches found provided transparent methodologies for hydrogen prioritization and the scientific evidence used. Two peer-reviewed publications with transparent methods and sources of evidence were identified: Ueckerdt and colleagues' (2021) merit order of end-uses for hydrogen prioritization published in Nature Climate Change Journal and the Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change entitled Climate Change 2022 – Mitigation of Climate Change (IPCC, 2022). Table 2 provides a description of how these two peer-reviewed approaches assessed whether to prioritize hydrogen end-uses and the evidence used

Table 1
Hydrogen end-use prioritization approaches found.

Publishing organization	Prioritization approach	Data and methods
Liebreich Associates (2023)	The hydrogen ladder	Aims to illustrate how likely it is that different types of end-uses will be significant users of hydrogen, based on projections of possible market share size. A methodology for the approach was not available.
International Renewable Energy Agency (2022)	Green hydrogen policy priority	Ranks hydrogen end-uses from high to low priority. This work emphasizes two main factors for priority setting for green hydrogen strategy: "technological readiness of the decarbonization solutions and the potential size of local hydrogen demand" (IRENA, 2022, p. 12). The analysis is based on data retrieved from previous works focused on hydrogen applications. The approach is based on other prioritization approaches but does not provide its own methodology for hydrogen prioritization.
Agora Energiewende and Agora Industry (2021)	No-regret hydrogen applications	Presents a prioritization ranking based on a range of reports of European Union scenarios "consistent with 1.5° pathways that include hydrogen modeling" (Agora Energiewende and Agora Industry, 2021, p. 11). The approach does not provide its own methodology for hydrogen prioritization.
Waddell et al. (2022)	Hydrogen decision tree	Developed a hydrogen decision tree as "a decision-making framework to support the conceptual understanding of where hydrogen should be utilized in a decarbonized economy" (Waddell et al., 2022, p. 11). Broadly, the hydrogen decision tree aims to determine whether adopting hydrogen end-uses makes sense, compared to the technical and economic readiness of electrification and other alternative fuels. The approach does not provide its own methodology for hydrogen prioritization.
Ueckerdt et al. in Nature Climate Change (2021)	Merit order of end-uses	Prioritizes end-uses for hydrogen by comparing the marginal abatement costs of replacing fossil fuels with hydrogen, e-fuels, and direct electrification using data and analysis generated by the International Energy Agency (IEA, 2017). The approach was mentioned by Rosenow and Lowes' (2021) as a salient attempt to identify sensible and inappropriate use cases for hydrogen. The document provides a scientific methodology for

(continued on next page)

Table 1 (*continued*)

Publishing organization	Prioritization approach	Data and methods
		prioritization that is peer-reviewed and published in the Nature Climate Change journal.
Intergovernmental Panel on Climate Change (IPCC, 2022)	Assessment on climate change mitigation technologies and actions	Conducted an evidence-based assessment of current and projected greenhouse gas emissions in different sectors along with promising options for decarbonization. This report highlights hydrogen as one key component for making progress towards global decarbonization goals, particularly in the transport and industry sectors. The assessment is peer-reviewed, based on a systematic assessment of the available scientific evidence and provides a detailed methodology.

to develop the assessment.

4.2. Legitimization of hydrogen end-uses through plans

Of ten provinces and three territories, hydrogen plans have been released by the federal Government of Canada, and seven provinces (Alberta, British Columbia, New Brunswick, Newfoundland and Labrador, Nova Scotia, Ontario, and Québec). These include hydrogen action plans, strategies, or roadmap preliminary hydrogen opportunities report (Manitoba), a hydrogen exploratory workshop (Northwest Territories), and a report on hydrogen decarbonization opportunities (Yukon). Most plans were developed via consultation processes with stakeholders from government, academia, industry, Indigenous communities, and non-government organizations.[2] Only the hydrogen plans released by Newfoundland and Labrador, Nova Scotia, and Québec stated a clear focus on supporting green hydrogen.[3] The goals, motivations or ambitions stated by the plans (shown in Table 3) position hydrogen use and technology development as means to replace fossil fuel end-uses, pursue climate change or net-zero goals, and establish a hydrogen economy that creates jobs, attracts investments, develops supply chains, and boosts export markets.

4.3. Are hydrogen end-uses and applications prioritized by evidence also supported by plans, policies and investment advice?

The hydrogen end-uses that are mentioned in plans, policies and pitch books are listed in Figs. 3–6 (with legend for all Figures in Table 4), and categorized by the end-uses or applications, using the terminology defined by the IPCC and Ueckerdt et al. The results are organized by whether there is consistency or inconsistency between evidence and legitimacy for end-use applications.

4.3.1. Findings of consistency between scientific evidence and legitimized end-uses and applications

There are 11 hydrogen end-use applications for which there is consistency between evidence for their prioritization over electrification and legitimacy (Figs. 3 and 4).

- In four cases (commercial and residential water heating as supplied through hydrogen in natural gas pipelines, and chemicals used as energy for both < and >400 °C industrial heat), hydrogen use is unlikely to compete with the costs of electrification, and no support is found in policies, plans or recommended ventures for these end-uses using hydrogen.
- In seven cases, there is strong confidence or evidence that hydrogen is an important option for decarbonization. These are chemical feedstocks (supported by 10 plans, 10 policies, and five recommended ventures), direct reduction for primary steelmaking (supported by five plans, seven policies, and three recommended ventures), fuel for industry and manufacturing processes (supported by six plans, six policies, and two recommended ventures), fuel for

Table 2
Description of hydrogen end-use assessments and evidence used by Ueckerdt et al. (2021) and IPCC (2022) approaches.

Authors	Assessment description	Evidence used
Ueckerdt et al. (2021)	This approach divides end-use sectors into three prioritization categories. Category 1 includes sectors where direct electrification is significantly cheaper and more efficient than using hydrogen. Category 2 includes sectors where the marginal abatement costs of replacing fuels with electrification are similar to the costs of using hydrogen as replacement. Category 3 includes sectors where electrification is very difficult due to reliance on hydrocarbons for production processes, technical maturity, and costs.	The decision of whether end-uses are hard to decarbonize by electrification is based on the Energy Technology Perspectives 2017 report by the IEA (2017). The report develops projections on energy technology based on past trends, and highlights opportunities and challenges for decarbonization in the industry, transport, and buildings sectors. The analysis identifies sectors that are difficult to decarbonize by electrification due to reliance on fossil fuels for production processes, technical immaturity, and costs. To develop the prioritization ranking, Ueckerdt and colleagues paired the identified hard-to-decarbonize end-uses with the costs of replacing natural gas and liquid fossil fuels with e-methane and liquid e-fuels.
Intergovernmental Panel on Climate Change (IPCC, 2022)	The IPCC assessed hydrogen applications by their associated levels of confidence. The IPCC qualifies levels of confidence across 5 categories of “very low,” “low,” “medium,” “high,” and “very high.” the level of confidence increases with increasing levels of evidence and degrees of agreement (Mastrandrea et al., 2010). The level of confidence is assigned to hydrogen applications based on the type, amount, consistency, and quality of the evidence, along with the degree of agreement found in the evidence.	The evidence used for this report was retrieved through a review of literature accepted for publication by October 2021, including peer-reviewed articles published in scientific journals, reports, and government publications. The data gathered from the literature review was used to determine the existing level of confidence on the potential impact of hydrogen applications in decarbonizing key sectors compared to other available options.

[2] Two provinces did not specify the methodology used for the elaboration of the hydrogen plan (British Columbia and Nova Scotia).

[3] One goal stated by the Alberta hydrogen roadmap is to revitalize the natural gas sector.

Table 3
Methodologies and goals, motivations or ambitions of hydrogen plan development.

Jurisdiction	Plan	Stakeholder engagement and methods	Stated goals, motivations or ambitions
Canada	Hydrogen strategy for Canada – seizing the opportunities for hydrogen (Government of Canada, 2020)	Consultations with stakeholders from the private sector, associations and NGOs, academia and research groups, Federal and Provincial governments, and Indigenous organizations, communities, and businesses, linkages with working groups, demand modeling	The Hydrogen Strategy for Canada lays out an ambitious framework for actions that will cement hydrogen as a tool to achieve our goal of net-zero emissions by 2050 and position Canada as a global, industrial leader of clean renewable fuels. This Strategy is a call to action. It will spur investments and strategic partnerships across the country and beyond our borders. It will position Canada to seize economic and environmental opportunities that exist coast to coast. Expanding our exports. Creating as many as 350,000 good, green jobs over the next three decades. All while dramatically reducing our greenhouse gas emissions. And putting a net-zero future within our reach.
Alberta	Alberta hydrogen roadmap (Government of Alberta, 2021)	Consultation with stakeholders from industry, academia, municipalities, Indigenous organizations and non-governmental organizations, and third party research. Stakeholders advised of key requirements needed to enable a hydrogen economy in Alberta	The Hydrogen Roadmap represents the next step on our path to revitalizing Alberta's natural gas sector – and to integrating clean hydrogen into our existing energy systems. Alberta's Hydrogen Roadmap connects ambition to action to outcome. It is an action plan that integrates hydrogen with the province's existing energy system and propels Alberta into the global hydrogen economy.
British Columbia (BC)	BC hydrogen strategy – a sustainable pathway for B.C.'s energy transition (Government of British Columbia, 2021)	Not provided	BC can be a world leader in the growing hydrogen economy creating new clean technology jobs and opportunities for people across the province. Objectives: ●Promote innovation and investment in the production and deployment of hydrogen to achieve the energy system transformation required to meet CleanBC greenhouse gas (GHG) reduction targets ●Create economic development opportunities across BC through increased and equitable employment in trades, cleantech and energy services ●Improve air quality and reduce contamination and noise pollution in urban and remote communities ●Make clean energy solutions more diverse, convenient, available and affordable for British Columbians ●Fulfill BC's commitments under the Declaration on the Rights of Indigenous Peoples Act
Manitoba	Preliminary opportunities report – setting the direction for hydrogen development in Manitoba (Manitoba Energy Development Initiative, 2003)	Preliminary assessments conducted by five working groups. Participating organizations include government, utility, university, and industry representatives.	The progressive movement toward a cleaner energy economy, based on hydrogen, will result in new technologies, as well as increased use of renewable energy sources, creating new economic opportunities. In anticipation of this future, Manitoba has begun the process to develop a Hydrogen Economic Development Strategy that will allow the province to best position itself for the anticipated transition, in the near-term, medium-term and long-term. The objective of the preliminary assessments was to identify opportunities that could form the basis of a Hydrogen Economic

(continued on next page)

Table 3 (*continued*)

Jurisdiction	Plan	Stakeholder engagement and methods	Stated goals, motivations or ambitions
			Development Strategy, with a focus on identifying opportunities that would make sense for Manitoba, by creating manufacturing or service value-add, export potential, long-term high value employment, or knowledge and skills. The intent was for Working Groups to focus primarily on "generic" opportunities within the near-term, medium-term and long-term, given that there might be differing commercial interests. At the same time, it was also desired for Working Groups to identify tangible first steps and demonstration projects as part of the overall assessment process that would lead to a better ultimate understanding of how to exploit opportunities.
New Brunswick	New Brunswick hydrogen roadmap (Province of New Brunswick, 2024)	Engagement with New Brunswick based energy interests and environmental groups, public and community representatives, First Nation communities, industry proponents, and technology providers. Based on the feedback received through this preliminary engagement process, five key principles were determined as being critical in the development of the New Brunswick Hydrogen Roadmap.	Our province's location, vast natural resources including wind and our leading-edge work on Small Modular Reactors (SMRs) positions our province to be a clean hydrogen leader and innovator. We intend to seize on that opportunity. The goal of the Hydrogen Roadmap is to establish hydrogen as a source of clean energy for New Brunswick. Development of a hydrogen sector in the province will bring new business investment, helping to grow the economy of New Brunswick, while providing our province with an opportunity for significant decarbonization and energy security for the future. This goal is fully aligned with our net-zero objectives and the New Brunswick Climate Change Action Plan and will enable New Brunswick to power our economy and the world with clean energy.
Newfound-land and Labrador	Hydrogen development action plan (Government of Newfoundland and Labrador, 2024)	Input received from the public, industry, and stakeholders, including government, research institutions, industry associations	Newfoundland and Labrador has the natural resources critical to Canada achieving its net-zero target by 2050, and supporting the global effort to decarbonize. Further developing the province's clean energy industry will increase jobs, develop supply chains, support innovation, and increase revenues, creating an unprecedented opportunity for economic growth in the province. The release of the province's Hydrogen Development Action Plan is the next step in enabling the development of a green hydrogen and ammonia production industry in Newfoundland and Labrador. With 31 action items over a three-year period in areas such as markets, regulation, industry, and training and jobs, this plan will advance the province's status as a global supplier of clean energy. Given the evolving nature of this industry, this plan will be nimble to maximize Newfoundland and Labrador's global competitiveness and ability to produce green hydrogen and ammonia for export markets.
Northwest Territories	Can hydrogen power the North? An exploratory workshop hosted by the GNWT (Government of	Hosted a workshop with stakeholders, including economic development organizations from Indigenous	Hydrogen may offer another opportunity to reduce fossil fuels for end-uses we don't currently have

(*continued on next page*)

Table 3 (*continued*)

Jurisdiction	Plan	Stakeholder engagement and methods	Stated goals, motivations or ambitions
	Northwest Territories, 2003)	governments, communities, utilities, industry, non-governmental organizations, as well as the Government of Northwest Territories	a solution for in the North. The objectives of this workshop were to share what we know about hydrogen-based technologies, initiate a conversation with our partners and stakeholders about the potential role for hydrogen in the NWT's energy system and economy, and identify the key questions that will need to be answered before next steps are taken.
Nova Scotia	Green hydrogen action plan (Government of Nova Scotia, 2023)	Not provided	Building on Nova Scotia's track record of leadership in sustainable prosperity, this Action Plan outlines a path for the Province to support the emergence of a sector that: ●makes best use of the province's natural resources to produce green hydrogen and hydrogen derivatives for export and domestic use; ●supports sustainable prosperity and the achievement of Nova Scotia's climate change goals; and ●produces local benefits that increase Nova Scotians' social and economic well-being.
Ontario	Ontario's low-carbon hydrogen strategy (Government of Ontario, 2022)	Targeted and public consultation with stakeholders in the clean energy sector, including hydrogen stakeholders, Indigenous communities, industry, academia, environmental groups and the public. The consultations were done through conducting clean technology sector engagement, posting a low-carbon hydrogen discussion paper, hosting stakeholder webinars, and a hydrogen strategy working group	Ontario's low-carbon hydrogen strategy sets out a vision for a low-carbon hydrogen economy in our province – one where we can leverage our many strengths to develop a self-sustaining sector in Ontario, evolve our energy system, create local jobs and attract investment while reducing greenhouse gas (GHG) emissions. Ontario's hydrogen strategy sets out a path where eight concrete and immediate actions are expected to lead to an eight-fold increase in the province's production capacity of low-carbon hydrogen and support the nascent market to meet its potential.
Québec	2030 Quebéc green hydrogen and bioenergy strategy (Gouvernement du Québec, 2022)	Consultation with actors in the academic, social and economic communities and Indigenous Nations	The Gouvernement du Québec is committed to a concrete approach toward the decarbonization of the economy. To do this, it intends to deploy a business environment that will favor green hydrogen and bioenergy production developed sustainably, with the ambition that these types of energy are consumed on a priority basis in Québec to generate direct impacts here.
Yukon	Potential of hydrogen to help decarbonize the Yukon (Government of Yukon, 2022)	Quantitative scenario modeling representing the Yukon's energy-economic system. Stakeholder outreach included representatives from local government, local utility, local business, local municipality, local research organization, and national hydrogen or remote community energy experts	In September 2020, the Government of Yukon released its Our Clean Future climate change strategy. This strategy will help reduce greenhouse gas emissions, though analysis suggests additional reductions will be required to achieve territorial targets in 2030. The Government of Yukon Department of Energy, Mines and Resources is interested to understand the potential for hydrogen to help close this gap and to further decarbonize the territory's energy system through 2050. The purpose of this analysis is to assess the potential for hydrogen to decarbonize the Yukon's energy system and help the territory meet its greenhouse gas emissions targets.

End-use/ Application terminology**: Ueckerdt et al. (2021);** IPCC (2022)	**Evidence for prioritization**		**Legitimacy**	
	Ueckerdt et al. categorization*	**IPCC decarbonization potential****	**Plans Mentioned In (n Implemented Policies Supporting End use/** Application)	**Recommended Ventures (n)**
Chemicals (feedstocks); Chemical feedstocks (e.g., ammonia, methane, methanol, synthetic hydrocarbons and alcohol)	Category 3	High confidence	**10 plans, 10 policies**: Alberta (5), British Columbia (1), Canada (2), Manitoba (0), New Brunswick (0), Newfoundland and Labrador (0), Northwest Territories (0), Nova Scotia (1), Ontario (1), Quebec (0)	5
Direct reduction for primary steelmaking	not specified, not comparable	High confidence	**5 plans, 7 policies**: British Columbia (1), Canada (2), Newfoundland and Labrador (0), Ontario (0), Québec (0), (4 in Alberta)	3
Fuel for light industry and manufacturing processes (other industry)	not specified, not comparable	High confidence	**6 plans, 6 policies**: Alberta (4), British Columbia (0), Canada (1), Nova Scotia (1), Ontario (0), Québec (0)	2
Fuel for mining	not specified, not comparable	High confidence	**5 plans, 7 policies**: Alberta (4), Canada (1), Manitoba (0) Newfoundland and Labrador (0), Northwest Territories (0), (1 in British Columbia), (1 in Nova Scotia)	0
Grid balancing services (hydrogen storage for chemical process use, demand response, incorporation of larger shares of variable solar PV and wind power)	not specified, not comparable	High confidence	**7 plans, 4 policies**: Alberta (2), Canada (0), Manitoba (0), Northwest Territories (0), Nova Scotia (1), Québec (0). Yukon (0), (1 in Ontario)	2
Marine fuels using ammonia produced with low-carbon hydrogen	not specified, not comparable	High confidence	**7 plans, 3 policies**: British Columbia (1), Canada (0), Manitoba (0), Newfoundland and Labrador (0), Nova Scotia (1). Québec (0). Yukon (0), (1 in Alberta)	1
Iron and steel (blast furnaces, coke ovens)	Category 3	not specified, not comparable	**5 plans, 7 policies:** British Columbia (1), Canada (2), Newfoundland and Labrador (0), Ontario (0), Québec (0), (4 in Alberta)	3

Fig. 3. Consistency between evidence and legitimacy for hydrogen applications/end-uses (with mentions in plans, policies and investment advice).

End-use/ Application terminology**: Ueckerdt et al. (2021);** IPCC (2022)	**Evidence for prioritization**		**Legitimacy**	
	Ueckerdt et al. categorization*	**IPCC decarbonization potential****	**Plans Mentioned In (n Implemented Policies Supporting End use/** Application)	**Recommended Ventures (n)**
Commercial/water heating	Category 1	Not assessed	Not supported by plans (0)	0
Residential/water heating	Category 1	Not assessed	Not supported by plans (0)	0
Chemicals (energy, <400 °C industrial heat)	Category 1	not specified, not comparable	Not supported by plans (0)	0
Chemicals (energy, >400 °C industrial heat)	Category 2	not specified, not comparable	Not supported by plans (0)	0
*, ** See Legend in Table 4				

Fig. 4. Consistency between evidence and legitimacy for hydrogen applications/end-uses (with no mentions in plans, policies, and investment advice).

mining (supported by five plans and seven policies, with no mentions by recommended ventures), grid balancing services (supported by seven plans, four policies, and two recommended ventures), marine fuels using ammonia produced with low-carbon hydrogen (supported by seven plans, three policies, and one recommended venture), and iron and steel (blast furnaces, coke ovens) (supported by five plans, seven policies, and three recommended ventures).

- Chemical feedstocks is the only end-use found that is difficult to electrify, has high confidence of decarbonization potential through hydrogen, and is not only mentioned in 10 plans, and 10 policies, but has the highest number of recommended ventures (five).

4.3.2. Findings of inconsistency between scientific evidence and legitimized end-uses and applications

There are seven hydrogen end-use applications (Fig. 5) that are considered by Ueckerdt et al. as better provided through electrification or associated by the IPCC with low confidence of decarbonization potential, but that were found to receive support from plans, policies, and recommended ventures.

- In two cases (commercial and residential heating), direct electrification is significantly cheaper and the decarbonization potential is considered very modest, but there is support from seven plans, seven

End-use/ Application terminology**: Ueckerdt et al. (2021);** IPCC (2022)	**Evidence for prioritization**		**Legitimacy**	
	Ueckerdt et al. categorization*	**IPCC decarbonization potential****	**Plans Mentioned In (n Implemented Policies Supporting End use/** Application)	**Recommended Ventures (n)**
Commercial/space heating	Category 1	Not assessed	**7 plans, 4 policies:** Alberta (3), British Columbia (0), Canada (0), Northwest Territories (0), Nova Scotia (1), Ontario (0), Yukon (0)	1
Residential/space heating	Category 1	Not assessed	**7 plans, 3 policies**: Alberta (2), British Columbia Canada, Northwest Territories, Nova Scotia (1), Ontario, Yukon	1
Freight/light road	Category 1	Not assessed	**6 plans, 16 policies**: Alberta (5), British Columbia (3), Canada (3), Manitoba (0), New Brunswick (0) Yukon (2), (1 in Nova Scotia), (1 in Ontario), (1 in Québec)	3
Passenger/light road	Category 1	Not assessed	**6 plans, 16 policies:** Alberta (5), British Columbia (3), Canada (3), Manitoba (0), New Brunswick (0), Yukon (2), (1 in Nova Scotia), (1 in Ontario), (1 in Québec)	3
Other industry (high temperature heat <400 °C)	Category 1	not specified, not comparable	**6 plans, 6 policies**: Alberta (4), British Columbia (0), Canada (1), Nova Scotia (1), Ontario (0), Québec (0)	2
Pulp and paper	Category 1	not specified, not comparable	**3 plans, 5 policies**: Alberta (3), British Columbia (1), Canada (1)	2
Jet and marine fuels with CO2 capture through direct air capture	not specified, not comparable	Low confidence	**8 plans, 4 policies**: Alberta (2), British Columbia (1), Canada (0), Manitoba (0), Newfoundland and Labrador (0), Nova Scotia (1), Québec (0), Yukon (0)	1
*, ** See Legend in Table 4				

Fig. 5. Inconsistencies between evidence and legitimacy for hydrogen applications/end-uses.

policies (four in commercial and three in residential heating), and one recommended venture to use hydrogen instead.

- In two other cases (freight/light road and passenger/light road), the evidence suggests that hydrogen end-use is unlikely to compete with the costs of electrification. There was support from 16 policies, and mentions in six plans and three recommended ventures for these end-uses to be fueled by hydrogen.
- The evidence identifies electrification for pulp and paper as a better option than hydrogen. There was support from three plans, five policies, and two ventures were recommended to use hydrogen instead.
- In the case of jet and marine fuels with CO2 capture through direct air capture, the evidence provided low confidence of decarbonization potential. There is support in eight plans, four policies and one recommended venture to use hydrogen instead.

4.3.3. Inconsistency in prioritization methods

The IPCC (2022) and Ueckerdt et al. (2021) approaches to prioritize electrification or hydrogen fueling end-uses sometimes had inconsistent terminologies, and or inconsistent prioritizations. For example, Ueckerdt et al. distinguish between specific temperature requirements in the chemical and industry sectors, type of light passenger and light freight vehicles, space heating (residential or commercial), and iron and steel production (with or without the use of blast furnaces and coke ovens). Whereas the IPCC assesses the chemical and light industry sectors without distinguishing temperatures, and excludes light vehicles and space heating from their assessment since hydrogen use in these sectors is considered as having unsubstantial decarbonization potential, and assesses steelmaking without distinguishing whether blast furnaces and coke ovens are required. Ueckerdt et al. provide a specific end-use categorization for pulp and paper, while the IPCC assesses pulp and paper within the broader typology of light industry uses. The IPCC assessment considers "Marine fuels" while Ueckerdt et al. assess the marine fuels within a typology of shipping. More details of the inconsistencies in terminologies between the two approaches are provided in Supplementary Materials – Specifications for Figs. 3–6.

4.3.4. Lack of harmonization and consistency

There are ten hydrogen end-use applications that are supported by plans, policies and recommended ventures but where the evidence provided by Ueckerdt et al. (2021) and IPCC (2022) is inconsistent. In some cases, there is medium confidence in prioritization (meaning that there is medium or limited agreement and medium or robust evidence for the potential for decarbonization) (Fig. 6).

- Shipping and aviation are considered by Ueckerdt et al. (2021) as important end-uses for hydrogen use in sectors that are difficult to electrify, although there is medium confidence of decarbonization potential from the IPCC assessment for each of these applications. There is support from seven plans, four policies, and two recommended ventures for hydrogen use in shipping applications, and support from seven plans, six policies, and one recommended venture for hydrogen use in aviation applications.
- For heavy-duty vehicles, Ueckerdt et al.'s (2021) analysis shows that direct electrification and hydrogen use have similar costs. There is medium confidence on decarbonization potential in the IPCC report. Heavy duty vehicles are receiving support from 11 plans, 12 policies, and four recommended ventures for hydrogen use.
- In three cases (cement, iron and steel without blast furnaces or coke ovens, and other industries for high temperature heat >400 °C uses), Ueckerdt et al.'s analysis shows that the costs of direct electrification and hydrogen use are similar. These applications were not mentioned in the IPCC assessment. Cement is supported by three plans, six policies, and three recommended ventures. Iron and steel without blast furnaces or coke ovens is supported by five plans, seven policies, and three recommended ventures. Other industries for high temperature heat (>400 °C) is supported by six plans, six policies, and two recommended ventures.
- The applications of rail and exports were not assessed for hydrogen use by Ueckerdt et al. There is medium confidence of relevant

End-use/ Application terminology: Ueckerdt et al. (2021); IPCC (2022)	Evidence for prioritization		Legitimacy	
	Ueckerdt et al. categorization*	IPCC decarbonization potential**	Plans Mentioned In (n Implemented Policies Supporting End use/ Application)	Recommended Ventures (n)
Freight/shipping; Long-haul shipping (hydrogen-based fuels like ammonia, synthetic fuels)	Category 3	Medium confidence	**7 plans, 4 policies:** Alberta (2), British Columbia (1), Canada (0), Manitoba (0), New Brunswick (0), Newfoundland and Labrador (0), Nova Scotia (1)	2
Passenger/air; Aviation (hydrogen-based fuels like ammonia, synthetic fuels)	Category 3	Medium confidence	**7 plans, 6 policies:** Alberta (3), British Columbia (2), Canada (0), Manitoba (0), Nova Scotia (1), Québec (0), Yukon (0)	1
Freight/heavy road; Land-based, long-range, heavy-duty trucks (as complement to electrification)	Category 2	Medium confidence	**11 plans, 12 policies**: Alberta (5), British Columbia (2), Canada (3), Manitoba (0), New Brunswick (0), Newfoundland and Labrador (0), Northwest Territories (0), Nova Scotia (1), Ontario (1), Québec (0), Yukon (0)	4
Cement	Category 2	not specified, not comparable	**3 plans, 6 policies**: British Columbia (1), Canada (2), Nova Scotia (1), (2 in Alberta)	3
Iron and steel (without blast furnaces, coke ovens)	Category 2	not specified, not comparable	**5 plans, 7 policies**: British Columbia (1), Canada (2), Newfoundland and Labrador (0), Ontario (0), Québec (0), (4 in Alberta)	3
Other industry (high temperature heat >400 °C)	Category 2	not specified, not comparable	**6 plans, 6 policies:** Alberta (4), British Columbia (0), Canada (1), Nova Scotia (1), Ontario (0), Québec (0)	2
Rail	not specified, not comparable	Medium confidence	**4 plans, 4 policies:** Alberta (2), British Columbia (1), Canada (0), Manitoba (0), (1 in Nova Scotia)	0
Exports – hydrogen-based chemicals and materials (e.g., methanol, ammonia)	not specified, not comparable	Medium confidence	**9 plans, 3 policies:** Alberta (3), British Columbia (0), Canada (0), Manitoba (0), New Brunswick (0), Newfoundland and Labrador (0), Nova Scotia (0), Ontario (0), Québec (0)	0
Commercial space heating (not easily accessible for heat pumps, district or electric central heating)	Category 2	Not assessed	**7 plans, 4 policies**: Alberta (3), British Columbia (0), Canada (0), Northwest Territories (0), Nova Scotia (1), Ontario (0), Yukon (0)	1
Residential space heating (not easily accessible for heat pumps, district or electric central heating)	Category 2	Not assessed	**7 plans, 3 policies:** Alberta (2), British Columbia, Canada, Northwest Territories, Nova Scotia (1 policy), Ontario, Yukon	1
*, ** See Legend Table 4				

Fig. 6. Inconsistent or medium confidence in evidence compared to legitimacy.

Table 4
Legend for Figs. 3–6.

*The categorization of end-use sectors by Ueckerdt et al. (2021) is described as follows: Category 1: sectors in which direct electrification is significantly cheaper than using e-fuels, including hydrogen – light duty vehicles, low/mid temperature industrial heat (<400 °C, e.g., steam generation), space heating. Category 2: sectors in which direct electrification and e-fuels and hydrogen have similar costs – high temperature heat (>400 °C), heavy-duty transport. Category 3: impossible-to-electrify sectors in which e-fuels and hydrogen go beyond the barriers of direct electrification – aviation, shipping, feedstocks, primary steel Not categorized: no evidence of the hydrogen end-use being able to compete with direct electrification costs

**Based on Mastrandrea et al. (2010) a level of confidence depends on how robust the evidence is (evidence is robust when there are multiple, consistent independent lines of high-quality evidence) and how much agreement there is across the evidence for the potential for decarbonization. High confidence means there is robust evidence with high agreement for the potential for decarbonization. Low-confidence means that there is low agreement and/or limited evidence for the potential for decarbonization. Medium confidence means that there is medium or limited agreement and medium or robust evidence for the potential for decarbonization. Not assessed: when there was no evidence of the hydrogen end-use playing a key role in decarbonization the IPCC report did not provide an assessment.

decarbonization potential in the IPCC assessment. Rail is receiving support from four plans and four policies for hydrogen use, and exports is receiving support from nine plans and three policies. The end-uses are not mentioned by recommended ventures for hydrogen use.

- Hydrogen use for commercial and residential space heating that is not easily accessible for heat pumps, district or electric central heating, is considered by Ueckerdt et al. as having similar costs to direct electrification but considered by the IPCC as having unsubstantial decarbonization potential. These end-uses are supported in mentions from seven plans, seven policies (four for commercial and three for residential heating), and one recommended venture.

4.4. Discussion summary

Plans, policies and financial investment are all found to be important sources of legitimization through discourse and resource mobilization for the empowerment of hydrogen niches (Nurdiawati and Urban, 2022; Schwabe, 2024; Westrom, 2020). There are concerns raised in the literature that many hydrogen end-uses that are being promoted globally by plans and policies are inappropriate and better served by electricity in order to decarbonize (Carlson and Trencher, 2024; Kern et al., 2023; Rosenow and Lowes, 2021).

Our findings show that there are seven end-uses that are better electrified that are being legitimized through discourse and resource mobilization to use hydrogen instead. For example, commercial and residential space heating, light road freight and passenger vehicles, other industry uses (high temperature heat <400 °C), pulp and paper, and jet and marine fuels with carbon capture are considered best electrified by the evidence (IPCC, 2022; Ueckerdt et al., 2021). Empowering hydrogen end-uses that are better decarbonized through electrification poses severe social and environmental risks by reinforcing carbon lock-in and delaying climate action (Carter and Dordi, 2021; Levin, 2022).

Our findings also show that for ten end-uses, there is a lack of harmonization between the two prioritization methods.[4] In two of these cases, commercial and residential heating that are not easily accessible for heat pumps, district or electric central heating, Ueckerdt et al. (2021) show similar costs between electrification and hydrogen use, while the IPCC report does not assess these end-uses because there was no evidence of the hydrogen end-use playing a key role in decarbonization. There are three end-uses that Ueckerdt et al. find to be comparable costs for electricity and hydrogen (cement, iron and steel without using blast furnaces or coke ovens, and industrial uses for temperature heat >400 °C), however, the IPCC report does not mention these technologies. Two end-uses, shipping and aviation, are found by Ueckerdt et al. to be cheaper to use hydrogen than electrification although the IPCC has medium confidence. Our findings show that all of these end-uses are legitimized in plans, policies and investment advice to use hydrogen. In two cases, rail and exports, the IPCC finds medium confidence, while Ueckerdt et al. do not mention these technologies. These end-uses are included in plans and policies but not investment advice.

However, there are four end-uses, commercial and residential water heating (as supplied by hydrogen in natural gas pipelines), and chemicals used as energy for both < and >400 °C industrial heat, that the evidence shows are better electrified (IPCC, 2022; Ueckerdt et al., 2021). These are not found to be legitimized by any plans, policies, or investment advice.

Matching the production of green hydrogen to end-use markets is crucial in protecting green hydrogen niches from dominant socio-technical regime pressures and facilitating the embedding of green hydrogen into supply chains (Nurdiawati and Urban, 2022; Schwabe, 2024; Westrom, 2020). Our findings show that there are seven end-uses that are better served through using hydrogen instead of electrification. Chemical feedstocks, direct reduction for primary steelmaking, fuel for industry and manufacturing processes, fuel for mining, grid balancing services, marine fuels using ammonia produced with low-carbon hydrogen, and iron and steel (using blast furnaces, coke ovens) are found to be cheaper than electrification and appropriate hydrogen uses that have promising decarbonization potential (IPCC, 2022; Ueckerdt et al., 2021). These end-uses are legitimized by plans, policies, and investment advice. This alignment between the evidence and legitimization indicates a positive context for the empowerment of green hydrogen niches that match with these seven end-uses.

The two transparent and peer-reviewed methods of prioritizing hydrogen end-uses that were found contain inconsistent lists of technologies and terminologies (see Supplementary Materials for additional details). These inconsistencies in terminology result in deficits in the information required for learning to nurture protective spaces for green hydrogen niches. The implications of our findings are that green hydrogen niches are not being empowered to match with end-uses for which hydrogen is more appropriate than electrification. This is a critically important consideration, given that a lack of reliable information often undermines investment in low-carbon technologies needed to support their diffusion into markets (Jordaan et al., 2017).

One limitation of this work is that we did not measure the extent to which strategies, policies, plans and investment advice across Canada are providing legitimacy to the electrification of end-uses for which hydrogen is considered less-suitable than electrification or has medium or low confidence in assessments. The legitimization could be tested with a study similar to Jordaan et al. (2017) to examine investment in the range of hydrogen end-uses. These limitations should be elaborated on in future research.

5. Conclusion and policy implications

The role of hydrogen in global decarbonization pathways by 2050 remains uncertain due to challenges related to production methods, more knowledge required on end-use and market needs, and infrastructure capacity (IEA, 2023a). The findings of this study are relevant to improving efforts to build decarbonization pathways to use green hydrogen to reduce carbon emissions in energy use. It is important to provide transparent evidence that outlines when to prioritize electricity and when to prioritize hydrogen for energy end-uses. This information supports the learning required for a protected space for green hydrogen niches that can contribute to decarbonization. It is also important to empower appropriate end-uses of green hydrogen that could contribute to decarbonization by legitimizing the end-uses that are supported by scientific evidence through discourse and resources.

This study makes several novel contributions. First, we identify and collate evidence of hydrogen end-use prioritization that clarifies which end-uses are most appropriate to nurture and empower green hydrogen niches. This evidence is compared to relevant sources of legitimacy through discourse and resource mobilization. The policy implications of this contribution are that this method is globally applicable to other emerging technologies and policy analysis.

We find that there is inattention to when to electrify and when to use hydrogen, observed in the very limited scientific evidence for prioritization, the lack of harmonization between the evidence for prioritization decisions, and the lack of diffusing this information to legitimize it through discourse and resource mobilization. In order to support learning and empowerment that supports the matching of green hydrogen production to appropriate end-use markets, our findings show that more attention should be paid and resources allocated to developing and legitimizing robust and scientifically based evidence of when to electrify and when to use hydrogen for energy end-uses. This future work should find ways to harmonize and clarify differences in terminologies, standards of prioritization, and under which circumstances these prioritizations should be applied. For example, differences on how end-uses are categorized in the selected approaches, such as temperature requirements and specific sector applications, prevented more direct comparisons between the evidence and forms of legitimization. Further evidence about hydrogen end-uses for which there exists medium confidence assessments by the IPCC should be collated and enhanced.

Public debates in Canada have linked hydrogen with carbon lock-in, the reinforcement of fossil fuel-based energy systems, and delaying climate action (Carter and Dordi, 2021; Levin, 2022). This study finds that government-released federal, provincial, and territorial plans, hydrogen-related policies, and investment advice in Canada are not legitimizing the most appropriate set of hydrogen end-uses. The findings show that many uses for hydrogen that are unlikely to compete with electrification costs or provide a substantial decarbonization potential are being legitimized through discourse and mobilization of resources, through these plans, policies and investment advice. Transparent scientific information should be applied to the development of policies, plans, and investment information to guide the development of hydrogen niches that are likely to contribute to decarbonization.

These findings are significant to climate change mitigation policies because supporting inappropriate uses for hydrogen can lock-in fossil fuels and delay climate action by creating uncertainty about which end-uses to support and allowing the continued use of fossil fuel infrastructure (Kern et al., 2023; Plehwe et al., 2024; Rosenow and Lowes, 2021). Our study proposes specific approaches to support distinguishing between appropriate and inappropriate uses of hydrogen to support policy makers and decision making that advances decarbonization.

[4] Where in some cases the IPCC evidence is medium confidence (there is a medium or limited agreement and medium or robust evidence for substantial decarbonization potential).

CRediT authorship contribution statement

F. Ignacio Aguilar: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization, Writing – review & editing. **Christina E. Hoicka:** Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Writing – review & editing. **Ali Seifitokaldani:** Writing – original draft, Supervision, Resources, Funding acquisition.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2025.114763.

Data availability

The Canadian Climate Policy Inventory used to support the findings of this study is openly available at: https://doi.org/10.5683/SP3/SFYABX. All other sources of data are provided in text and supplementary materials.

References

Aba, M.M., Sauer, I.L., Amado, N.B., 2024. Comparative review of hydrogen and electricity as energy carriers for the energy transition. Int. J. Hydrogen Energy 57, 660–678. https://doi.org/10.1016/j.ijhydene.2024.01.034.

Bento, N., Fontes, M., 2019. Emergence of floating offshore wind energy: technology and industry. Renew. Sustain. Energy Rev. 99, 66–82. https://doi.org/10.1016/j.rser.2018.09.035.

Carlson, J.T., Trencher, G., 2024. A framework for considering decarbonisation risks emerging from low-carbon hydrogen supply chains. Energy Res. Social Sci. 116, 103685. https://doi.org/10.1016/j.erss.2024.103685.

Carter, A.V., Dordi, T., 2021. Correcting Canada's "one eye shut" climate policy. https://cascadeinstitute.org/wp-content/uploads/2021/04/Carter-Dordi-Canadas-one-eye-shut-climate-policy-1.1-April-16.pdf. (Accessed 20 September 2024).

Cheng, W., Lee, S., 2022. How green are the national hydrogen strategies? Sustainability 14 (3), 1930. https://doi.org/10.3390/su14031930.

Cruz, O., Konstantinou, E., McArthur, J., 2023. Legitimising the emerging green hydrogen industry: the case of Chile. In: Cantoni, F., Corazza, L., De Nito, E., Di Nauta, P., Favari, E. (Eds.), Complexity and Sustainability in Megaprojects - Merit Workshop 2023. Springer Nature Switzerland, Cham, Switzerland, pp. 203–213. https://doi.org/10.1007/978-3-031-59703-9.

Droessler, M., Leach, A., 2024. Green with envy? Hydrogen production in a carbon-constrained world. Energy Policy 186, 113982. https://doi.org/10.1016/j.enpol.2024.113982.

Duygan, M., Stauffacher, M., Meylan, G., 2019. A heuristic for conceptualizing and uncovering the determinants of agency in socio-technical transitions. Environ. Innov. Soc. Transit. 33, 1329. https://doi.org/10.1016/j.eist.2019.02.002.

Energiewende, Agora, Industry, Agora, 2021. 12 insights on hydrogen. https://www.agora-industry.org/fileadmin/Projekte/2021/2021_11_H2_Insights/A-EW_245_H2_Insights_WEB.pdf. (Accessed 21 July 2024).

Environment and Climate Change Canada, 2022. National inventory report 1990-2020: greenhouse gas sources and sinks. Canada – Canada's submission to the United Nations framework convention on climate change. https://unfccc.int/documents/461919. (Accessed 3 December 2023).

Foresight Canada, 2021. Foresight 50 pitchbook 2021. https://foresightcac.com/report/2021-foresight-50-pitchbook. (Accessed 11 September 2024).

Foresight Canada, 2022. Foresight 50 pitchbook 2022. https://foresightcac.com/announcement/meet-canadas-most-investable-cleantech-ventures-the-2022-foresight-50. (Accessed 11 September 2024).

Foresight Canada, 2023. Foresight 50 pitchbook 2023. https://foresightcac.com/foresight-50-2023-honourees. (Accessed 11 September 2024).

Foresight Canada, 2024. Are you one of Canada's Most investible ventures? https://foresightcac.com/foresight-50-application. (Accessed 12 September 2024).

Geels, F.W., Schwanen, T., Sorrell, S., Jenkins, K., Sovacool, B.K., 2018. Reducing energy demand through low carbon innovation: a sociotechnical transitions perspective and thirteen research debates. Energy Res. Social Sci. 40, 23–35. https://doi.org/10.1016/j.erss.2017.11.003.

Gouvernement du Québec, 2022. 2030 Québec green hydrogen and bioenergy strategy. https://cdn-contenu.quebec.ca/cdn-contenu/adm/min/economie/publications-adm/politique/PO_strategy_green-hydrogen-bioenergies_screen-version_MEIE.pdf. (Accessed 2 December 2023).

Government of Alberta, 2021. Alberta hydrogen roadmap. https://open.alberta.ca/dataset/d7749512-25dc-43a5-86f1-e8b5aaec7db4/resource/538a7827-9d13-4b06-9d1d-d52b851c8a2a/download/energy-alberta-hydrogen-roadmap-2021.pdf. (Accessed 2 December 2023).

Government of British Columbia, 2021. B.C. hydrogen strategy – a sustainable pathway for b.C.'s energy transition. https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/electricity-alternative-energy/electricity/bc-hydro-review/bc_hydrogen_strategy_final.pdf. (Accessed 3 December 2023).

Government of Canada, 2020. Hydrogen strategy for Canada – seizing the opportunities for hydrogen. https://natural-resources.canada.ca/sites/nrcan/files/environment/hydrogen/NRCan_Hydrogen-Strategy-Canada-na-en-v3.pdf. (Accessed 3 December 2023).

Government of Newfoundland and Labrador, 2024. Hydrogen development action plan. https://www.gov.nl.ca/iet/files/Hydrogen-Development-Action-Plan.pdf. (Accessed 22 May 2024).

Government of Northwest Territories, 2023. Can hydrogen power the north? An exploratory workshop hosted by the GNWT. https://www.inf.gov.nt.ca/sites/inf/files/resources/hydrogen_workshop_report_2023.pdf. (Accessed 22 May 2024).

Government of Nova Scotia, 2023. Green hydrogen action plan. https://novascotia.ca/green-hydrogen/docs/green-hydrogen-action-plan.pdf. (Accessed 22 May 2024).

Government of Ontario, 2022. Ontario's low-carbon hydrogen strategy – a path forward. https://www.ontario.ca/files/2022-04/energy-ontarios-low-carbon-hydrogen-strategy-en-2022-04-11.pdf. (Accessed 28 November 2023).

Government of Yukon, 2022. Potential of hydrogen to help decarbonize the Yukon. https://yukon.ca/sites/yukon.ca/files/emr/emr-potential-hydrogen-help-decarbonize-yukon.pdf. (Accessed 22 May 2024).

Haque, N., 2022. Planning for clean technology diffusion: identifying innovation system functions in country technology action plans. Energy Res. Social Sci. 90, 102595. https://doi.org/10.1016/j.erss.2022.102595.

Hoicka, C.E., Zhao, Y., McMaster, M.L., Das, R.R., 2022. Diffusion of demand-side low-carbon innovations and socio-technical energy system change. Renew. Sustain. Energy Transit. 2, 100034. https://doi.org/10.1016/j.rset.2022.100034.

Hoogma, R., Kemp, R., Schot, J., Truffer, B., 2002. Experimenting for Sustainable Transport: the Approach of Strategic Niche Management. Spon, London. https://doi.org/10.4324/9780203994061.

Howarth, R.W., Jacobson, M.Z., 2021. How green is blue hydrogen? Energy Sci. Eng. 9 (10), 1676–1687. https://doi.org/10.1002/ese3.956.

IEA, 2017. Energy technology perspectives 2017-Catalyzing energy technology transformations. https://iea.blob.core.windows.net/assets/a6587f9f-e56c-4b1d-96e4-5a4da78f12fa/Energy_Technology_Perspectives_2017-PDF.pdf. (Accessed 25 June 2024).

IEA, 2023a. Net zero roadmap: a global pathway to keep the 1.5 °C goal in reach - 2023 update. https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach. (Accessed 8 October 2024).

IEA, 2023b. Global hydrogen review 2023. https://iea.blob.core.windows.net/assets/ecdfc3bb-d212-4a4c-9ff7-6ce5b1e19cef/GlobalHydrogenReview2023.pdf. (Accessed 2 July 2024).

IEA, 2024a. Greenhouse gas emissions from energy data explorer. https://www.iea.org/data-and-statistics/data-tools/greenhouse-gas-emissions-from-energy-data-explorer. (Accessed 24 July 2024).

IEA, 2024b. Energy technology RD&D budgets data explorer – data tools – IEA. https://www.iea.org/data-and-statistics/data-tools/energy-technology-rdd-budgets-data-explorer. (Accessed 17 May 2024).

Intergovernmental Panel on Climate Change (IPCC), 2023. Climate change 2023: synthesis report. Contribution of working groups I. In: Lee, H., Romero, J. (Eds.), II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland. https://www.ipcc.ch/report/ar6/syr/. (Accessed 25 June 2024).

International Energy Agency (IEA), n.d. Canada – countries & regions. https://www.iea.org/countries/canada (accessed 24 July 2024).

International Renewable Energy Agency (IRENA), 2022. Geopolitics of the energy transformation: the hydrogen factor. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jan/IRENA_Geopolitics_Hydrogen_2022.pdf?rev=1cfe49eee979409686f101ce24ffd71a. (Accessed 4 October 2024).

IPCC, 2022. Climate change 2022: mitigation of climate change. Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/ar6/wg3/. (Accessed 1 July 2024).

IRENA, 2020. Green hydrogen: a guide to policy making. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_hydrogen_policy_2020.pdf. (Accessed 7 June 2020).

IRENA, 2022. Green hydrogen for industry: a guide to policy making. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Mar/IRENA_Green_Hydrogen_Industry_2022.pdf. (Accessed 25 June 2024).

Jordaan, S.M., Romo-Rabago, E., McLeary, R., Reidy, L., Nazari, J., Herremans, I.M., 2017. The role of energy technology innovation in reducing greenhouse gas emissions: a case study of Canada. Renew. Sustain. Energy Rev. 78, 1397–1409. https://doi.org/10.1016/j.rser.2017.05.162.

Kemp, R., Schot, J., Hoogma, R., 1998. Regime shifts to sustainability through processes of niche formation: the approach of strategic niche management. Technol. Anal. Strat. Manag. 10 (2), 175–198. https://doi.org/10.1080/09537329808524310.

Kern, F., Schmelzle, F., Hummel, M., 2023. Hydrogen as a panacea for decarbonising everything? Exploring contested hydrogen pathways in Germany. Environ. Res. Lett. 18 (11), 114017. https://doi.org/10.1088/1748-9326/acff0e.

Kivimaa, P., Kern, F., 2016. Creative destruction or mere niche support? Innovation policy mixes for sustainability transitions. Res. Pol. 45 (1), 205–217. https://doi.org/10.1016/j.respol.2015.09.008.

Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.

Korberg, A.D., Thellufsen, J.Z., Skov, I.R., Chang, M., Paardekooper, S., Lund, H., Mathiesen, B.V., 2023. On the feasibility of direct hydrogen utilisation in a fossil-free Europe. Int. J. Hydrogen Energy 48 (8), 2877–2891. https://doi.org/10.1016/j.ijhydene.2022.10.170.

Levin, J., 2022. Standing senate committee on energy, the environment and natural resources (44th parliament, 1st session). https://sencanada.ca/en/Content/Sen/Committee/441/ENEV/21EV-55677-E. (Accessed 17 July 2024).

Li, X., Raorane, C.J., Xia, C., Wu, Y., Tran, T.K.N., Khademi, T., 2023a. Latest approaches on green hydrogen as a potential source of renewable energy towards sustainable energy: spotlighting of recent innovations, challenges and future insights. Fuel 334, 126684. https://doi.org/10.1016/j.fuel.2022.126684.

Li, Z., Zhang, Y., Yang, Q., Wu, J., Ren, Z., Si, F., Zhao, J., Chen, J., 2023b. Hydrogen co-production via nickel-gold electrocatalysis of water and formaldehyde. iScience 26 (10), 107994. https://doi.org/10.1016/j.isci.2023.107994.

Liebreich Associates, 2023. Hydrogen ladder version 5.0. https://www.linkedin.com/pulse/hydrogen-ladder-version-50-michael-liebreich/. (Accessed 2 June 2024).

Liu, H., Agrawal, N., Ganguly, A., Chen, Y., Lee, J., Yu, J., Huang, W., Mba Wright, M., Janik, M.J., Li, W., 2022. Ultra-low voltage bipolar hydrogen production from biomass-derived aldehydes and water in membrane-less electrolyzers. Energy Environ. Sci. 15 (10), 4175–4189. https://doi.org/10.1039/D2EE01427K.

Lopolito, A., Falcone, P.M., Sica, E., 2022. The role of proximity in sustainability transitions: a technological niche evolution analysis. Res. Pol. 51 (3), 104464. https://doi.org/10.1016/j.respol.2021.104464, 2022.

Manitoba Energy Development Initiative, 2003. Preliminary hydrogen opportunities report. https://www.gov.mb.ca/sd/environment_and_biodiversity/energy/pubs/hydrogen.pdf. (Accessed 3 December 2023).

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., Zwiers, F.W., 2010. Guidance note for lead authors of the IPCC fifth assessment report on consistent treatment of uncertainties. https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf. (Accessed 12 July 2024).

Nurdiawati, A., Urban, F., 2022. Decarbonising the refinery sector: a socio-technical analysis of advanced biofuels, green hydrogen and carbon capture and storage developments in Sweden. Energy Res. Social Sci. 84, 102358. https://doi.org/10.1016/j.erss.2021.102358.

O'Connell, A.-L., 2024. The financing dynamics of niche innovation in energy transitions: a South African perspective. Energy Res. Social Sci. 111, 103478. https://doi.org/10.1016/j.erss.2024.103478.

Otis-Laperrière, J., Boudreau, P., Xu, T., Marshall, D., Jordaan, S.M., Bergthorson, J.M., 2025. Green Hydrogen: Avoiding Pitfalls to Unlock Its Industrial Potential in Canada. Trottier Family Foundation, McGill Faculty of Engineering, Trottier Institute for Sustainability in Engineering and Design (TISED). https://www.mcgill.ca/tised/research/research-workshop-program-rwp/past-rwps/rwp-2024-hydrogen-workshop. (Accessed 15 May 2025).

Plehwe, D., Neujeffski, M., Haas, T., 2024. Climate obstruction in the european union: business coalitions and the technocracy of delay. In: Brulle, R.J., Roberts, T.J., Spencer, M.C. (Eds.), Climate Obstruction Across Europe. Oxford University Press, pp. 320–346. https://doi.org/10.1093/oso/9780197762042.003.0013.

Province of New Brunswick, 2024. New Brunswick hydrogen roadmap. https://www2.gnb.ca/content/dam/gnb/Departments/en/pdf/Hydrogen-hydrogene/hydrogen-roadmap-e.pdf. (Accessed 22 July 2024).

Qureshi, F., Yusuf, M., Tahir, M., Haq, M., Mohamed, M.M.I., Kamyab, H., Nguyen, H.-H. T., Vo, D.-V.N., Ibrahim, H., 2023. Renewable hydrogen production via biological and thermochemical routes: nanomaterials, economic analysis and challenges. Process Saf. Environ. Prot. 179, 68–88. https://doi.org/10.1016/j.psep.2023.07.075.

Raven, R., Kern, F., Verhees, B., Smith, A., 2016. Niche construction and empowerment through socio-political work. A meta-analysis of six low-carbon technology cases. Environ. Innov. Soc. Transit. 18, 164–180. https://doi.org/10.1016/j.eist.2015.02.002.

Rosenbloom, D., Benton, H., Meadowcroft, J., 2016. Framing the sun: a discursive approach to understanding multi-dimensional interactions within socio-technical transitions through the case of solar electricity in Ontario, Canada. Res. Pol. 45 (6), 1275–1290. https://doi.org/10.1016/j.respol.2016.03.012.

Rosenow, J., Lowes, R., 2021. Will blue hydrogen lock us into fossil fuels forever? One Earth 4 (11), 1527–1529. https://doi.org/10.1016/j.oneear.2021.10.018.

SaberiKamarposhti, M., Kamyab, H., Krishnan, S., Yusuf, M., Rezania, S., Chelliapan, S., Khorami, M., 2024. A comprehensive review of AI-enhanced smart grid integration for hydrogen energy: advances, challenges, and future prospects. Int. J. Hydrogen Energy 67, 1009–1025. https://doi.org/10.1016/j.ijhydene.2024.01.129.

Scholvin, S., Black, A., Robbins, G., 2025. De-risking green hydrogen? Insights from Chile and South Africa. Energy Policy 198, 114485. https://doi.org/10.1016/j.enpol.2024.114485.

Schot, J., Geels, F.W., 2008. Strategic niche management and sustainable innovation journeys: theory, findings, research agenda, and policy. Technol. Anal. Strat. Manag. 20 (5), 537–554. https://doi.org/10.1080/09537320802292651.

Schreyer, F., Ueckerdt, F., Pietzcker, R., Rottoli, M., Madeddu, S., Pehl, M., Hasse, R., Luderer, G., 2024. Distinct roles of direct and indirect electrification in pathways to a renewables-dominated European energy system. One Earth 7 (2), 226–241. https://doi.org/10.1016/j.oneear.2024.01.015.

Schwabe, J., 2024. Regime-driven niches and institutional entrepreneurs: adding hydrogen to regional energy systems in Germany. Energy Res. Social Sci. 108, 103357. https://doi.org/10.1016/j.erss.2023.103357.

Scott, W., Winter, J., Munzur, A., Koch, K., 2024. Developing a climate change mitigation policy inventory for Canada. SSRN. https://doi.org/10.2139/ssrn.4920154.

Shen, H., Crespo Del Granado, P., Jorge, R.S., Löffler, J., 2024. Environmental and climate impacts of a large-scale deployment of green hydrogen in Europe. Energy and Climate Change 5, 100133. https://doi.org/10.1016/j.egycc.2024.100133.

Smith, A., Raven, R., 2012. What is protective space? Reconsidering niches in transitions to sustainability. Res. Pol. 41 (6), 1025–1036. https://doi.org/10.1016/j.respol.2011.12.012.

Ueckerdt, F., Bauer, C., Dirnaichner, A., Everall, J., Sacchi, R., Luderer, G., 2021. Potential and risks of hydrogen-based e-fuels in climate change mitigation. Nat. Clim. Change 11 (5), 384–393. https://doi.org/10.1038/s41558-021-01032-7.

van Oorschot, J.A.W.H., Hofman, E., Halman, J.I.M., 2018. A bibliometric review of the innovation adoption literature. Technol. Forecast. Soc. Change 134, 1–21. https://doi.org/10.1016/j.techfore.2018.04.032.

Waddell, A., Hayley, B., Jones, R., 2022. The clean hydrogen ladder and the annual decarbonization perspective - applications for hydrogen in a decarbonized economy. https://www.evolved.energy/post/adp2022-hydrogen. (Accessed 1 May 2024).

Westrom, M., 2020. Winds of change: legitimacy, withdrawal, and interdependency from a decentralized wind-to-hydrogen regime in orkney, Scotland. Energy Res. Social Sci. 60, 101332. https://doi.org/10.1016/j.erss.2019.101332.

Yu, H., Jiang, S., Zhan, W., Liang, Y., Deng, K., Wang, Z., Xu, Y., Wang, H., Wang, L., 2023. Formaldehyde oxidation boosts ultra-low cell voltage industrial current density water electrolysis for dual hydrogen production. Chem. Eng. J. 475, 146210. https://doi.org/10.1016/j.cej.2023.146210.