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Drivers, barriers and interventions for green hydrogen supply chains: A multi-actor framework

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ABSTRACT

Green hydrogen is seen as a critical enabler for global decarbonization. Nevertheless, the development of viable green hydrogen supply chains (GHSCs) remains limited. This study applies transition theory through the Multi-Level Perspective (MLP) to rigorously examine the complex dynamics shaping GHSC development from a multi-actor viewpoint. Based on an abductive multiple case study of twelve companies actively investing or planning to invest in GHSCs in Finland, we develop a conceptual framework that identifies the key drivers, barriers, and interventions influencing GHSC emergence and introduction into the socio-technical regime. The core systemic drivers and barriers are categorized across five dimensions: demand, economic aspects, technology and infrastructure, actor dynamics, and regulation and policies. The empirical findings emphasize that effective scale-up is hindered primarily by economic and institutional factors, instead of purely technological ones. This study also demonstrates that interventions must fit the distinct motivations and constraints faced by heterogeneous actors operating across the GHSC. Therefore, we provide actionable policy insights, specifying the demand for clear mechanisms, such as harmonized certification systems or industrial standards, to create the ground for collaborative long-term off-taker agreements with the ultimate effect of mitigating investment risks and fostering institutional alignment. These insights are particularly applicable in hard-to-abate sectors.

1. Introduction

As climate change accelerates, humanity is under pressure to reduce greenhouse gas emissions in the atmosphere significantly. At the same time, the global energy demand grows (International Energy Agency IEA, 2022). 73% of global greenhouse gases are energy-related (ClimateWatch, 2020). Achieving the global decarbonization goals (e.g., Paris Agreement, 2019) requires not only large-scale electrification based on renewable energy but also complementary solutions, e.g., for hard-to-abate sectors. Green hydrogen, produced via water electrolysis, has emerged as a critical enabler in this energy transition (Breyer et al. 2023). Hydrogen can be used directly in various applications (e.g., transportation, industrial processes) or, more importantly, as a feedstock for Power-to-X (PtX) products such as e-methanol, e-methane, and e-ammonia (Breyer et al. 2023). PtX economy refers to a future energy-industrial paradigm that uses abundant renewable electricity to produce hydrogen and, furthermore, a suite of products such as liquid fuels, chemicals, and materials (e.g., steel, carbon fibers), supporting the decarbonization of hard-to-abate sectors and enabling energy storage, sector coupling, and integration of various renewables (Breyer et al., 2024).

To facilitate this massive energy transition, new green hydrogen supply chains (GHSCs) must be rapidly developed and scaled (Vogl et al., 2021). GHSCs are complex and systemic entities, involving intricate interactions between multiple actors, technologies, and organizations (Sgarbossa et al., 2023). Thus, approaching GHSCs as a socio-technical system in transition is highly relevant. In line with transition theory (Geels, 2002; Geels and Kemp, 2007), and particularly the Multi-Level Perspective (MLP), socio-technical transitions, such as introducing GHSCs, progress through the dynamic interplay between niche innovations at the micro-level (radical, protected innovations developed typically by new entrants), the prevailing socio-technical regime at the meso-level (established rules, technologies, and actors like incumbents), and the broader socio-technical landscape at the macro-level (slow-changing external factors like climate change and resource availability). Moreover, a transition refers to a shift from one

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socio-technical system to another during which innovations replace the existing system and some incumbent actors collapse (Geels, 2002; Geels and Kemp, 2007).

International attention has increasingly emphasized the urgency to decarbonize hard-to-abate sectors. In response, many regions have published dedicated hydrogen strategies to capitalize on the potential PtX economy, which is projected to represent a USD 2.5 trillion global market by 2050 (Canadian Government, 2020; European Commission, 2020; Japanese Government, 2017; International Energy Agency IEA, 2020; Norwegian Government, 2020; UK Government, 2021; U.S Department of Energy, 2020). However, the development of GHSCs has progressed more slowly than expected. By 2024, only 434 of the 1572 announced hydrogen projects had reached final investment decision (FID), with committed capital totaling about USD 75 billion and significantly less than what would be required to stay on track with decarbonization goals (Hydrogen CouncilMcKinsey & Company, 2024). The slow progress highlights the challenges of moving from ambition to implementation.

Despite the growing relevance of green hydrogen, much of the current literature on GHSCs remains rooted in technological (e.g., Koulaki et al., 2021; Yu and Wang, 2021) and techno-economic considerations (Kim and Lee, 2008; Reuβ et al., 2019), typically driven by environmental sustainability goals (Almansoori and Betancourt-Torcat, 2016), while overlooking the roles, perspectives, and interactions of actors shaping the GHSCs (Sillman et al., 2025). Existing models rarely recognize the actor heterogeneity, coordination failures, and short/mid-term decision-making constraints. There is also a lack of empirical research based on real-world GHSC projects. These research gaps suggest a clear need for a multi-actor perspective; this is coupled with MLP to effectively align actor goals with overall system objectives and finally enable the realization of sustainable GHSCs.

This paper in fact, addresses the gaps by adopting a MLP, grounded in transition theory, with the ultimate goal to explore how actor-specific drivers, barriers, and interventions shape the emergence of GHSCs and their introduction into the socio-technical regime. Drawing on rich qualitative data collected mainly from interviews with decision-makers within twelve companies actively investing or planning to invest in GHSCs in Finland, we investigate the drivers and barriers experienced by the GHSC actors, and the interventions for addressing the identified drivers and barriers. Finland provides a particularly relevant empirical setting for examining the emergence of GHSCs due to its low-carbon electricity system, energy-intensive industrial base, active hydrogen projects, a national hydrogen resolution (Ministry of Economic Affairs and Employment of Finland, 2023), and opportunities for integrated Power-to-X value chains. We systematically analyze the resulting drivers, barriers, and interventions via five dimensions: demand, economic aspects, technology and infrastructure, actor dynamics, and regulation and policies, and recognize the heterogeneity of actors.

The paper contributes to transition literature by linking core MLP concepts with empirical insights on actor alignment and value chain coordination, specifically advancing understanding of how GHSCs transition into the energy regime. Furthermore, we apply MLP by explicitly incorporating actor heterogeneity, demonstrating that the success of complex transitions relies heavily on coordinating the differentiated actions and motivations of heterogeneous actors across the niche and regime levels.

The remainder of this paper is structured as follows: Section 2 presents a literature review that focuses on GHSCs and introduces the initial research framework; Section 3 describes the methodology used for this study; Sections 4 and 5, respectively, present and discuss the results and their implications, and Section 6 concludes.

2. Literature review

2.1. Hydrogen technology

Green hydrogen is considered one of the key pillars for the green energy transition. Hydrogen can be produced in many ways from both renewable and non-renewable energy sources. Given the decarbonization goals and the maturity of available technologies, this paper explicitly focuses on green hydrogen. It follows the definitions given by Incer-Valverde et al. (2023), stating that “green hydrogen is hydrogen produced from water electrolysis powered by renewable energy sources (RES)”. In water electrolysis, water is split into hydrogen and oxygen through electrochemical processing (Ince et al., 2021). Green hydrogen is furthermore referred to simply as hydrogen unless specified otherwise. Hydrogen can be used as such (e.g., in Fuel Cell Electric Vehicles, electricity generation, feedstock for industrial processes such as steel, cement, chemical, and glass production) or refined further into products such as e-methanol, e-methane, and e-ammonia (Breyer et al. 2023). These upgrading processes involve additional inputs such as carbon dioxide or nitrogen as well as energy losses (Pfennig et al., 2023; Ueckerdt et al., 2021). The production can be centralized or decentralized (Kiemel et al., 2024; Bhandari and Shah, 2021), and the technical end-to-end process for making hydrogen and its configuration depends, e.g., on the targeted product, preferred technologies, land use and infrastructure requirements, policies, demand, and environmental goals (Ince et al., 2021). The interdependence between the stages of GHSCs is evident; each stage both influences and is influenced by the other stages.

2.2. Actors in green hydrogen supply chains

No matter their exact configurations, GHSCs consist of several interconnected stages, including electricity production, hydrogen generation, storage, distribution, and application. In addition to the material flow from production to application, the supply chain includes the full asset lifecycle of required infrastructure, such as electrolyzers (BS ISO 55000). Choices regarding production scale, hydrogen form, and mode of transportation (e.g., pipeline, truck, ship) influence cost structures, infrastructure requirements, and systemic integration (Brändle et al., 2021). The interconnected processes cannot thrive in isolation; they must be integrated into both the overall supply chain and the surrounding energy system. This makes the multi-actor approach especially central. The development and operation of GHSCs involve a wide range of actors (e.g., hydrogen producers, technology developers, infrastructure operators, end-users), each with different goals, motivations, resources, and constraints (Sgarbossa et al., 2023). An exemplary GHSC is visualized in Fig. 1.

2.3. Transition theory & Multi-Level Perspective (MLP) in GHSCs

This paper draws on the MLP to conceptualize the emergence of GHSCs as part of a broader socio-technical transition.

Transitions are considered long-term, multi-dimensional processes shaped by interactions between three layers: niche innovations (micro), socio-technical regimes (meso) and landscape (macro). Stabilizing and destabilizing factors influence the evolution of socio-technical systems by either reinforcing the existing regime or enabling the emergence of alternative configurations. Stabilizing forces are those that maintain the prevailing socio-technical regime and resist change. In contrast, destabilizing factors create pressure on the regime level to change. Transitions are not linear, but they unfold when exogenous pressures at the landscape level destabilize the existing regimes and open windows of opportunity for niche innovations to scale and break through into the existing systems (Geels, 2002; Geels and Kemp, 2007).

Furthermore, as highlighted by transition theory, actors are not passive recipients of change but active contributors shaping the direction and pace of transitions. System changes emerge from interactions

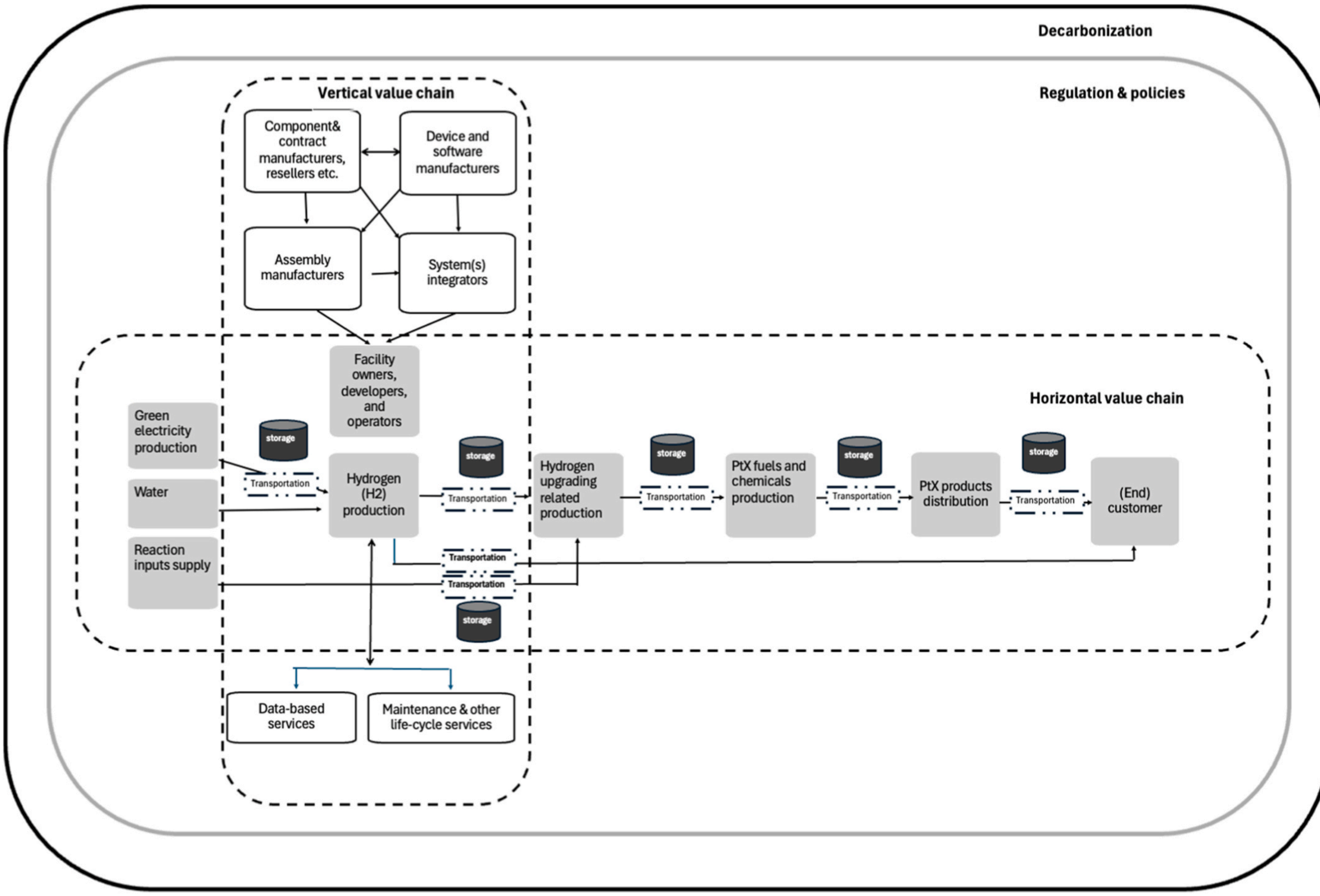

Fig. 1. Exemplary hydrogen supply chain (created by the authors).

between social groups with myopic perspectives and varying motivations (Geels and Kemp, 2007; Geels, 2012). Accordingly, no single actor introduces GHSCs at the regime level alone, but their implementation requires inter-organizational approaches (Seuring, 2004; Jesse et al., 2024; Sgarbossa et al., 2023).

Coherent with the transition theory and the need for a multi-actor perspective, the cooperation between actors is critical in creating, actualizing, and operating competitive GHSCs and moving them from niche innovations to the socio-technical regime (Al-Breiki and Bicer, 2021; De-Leon Almaraz et al., 2015). Different stakeholders and decision-makers influence various stages along the GHSC, resulting in various cooperation mechanisms (Cantú et al., 2021). Moreover, GHSCs operate under competitive pressures, and cooperation mechanisms depend on the level of hydrogen adoption and market growth (Sgarbossa et al., 2023).

Despite the strong policy narratives, GHSCs struggle to take off. Uncertain demand, high capital cost, and fragmented regulatory frameworks hinder investor confidence (Hydrogen CouncilMcKinsey & Company, 2024; Odenweller et al., 2022). Early GHSCs tend to be supply-driven due to the weather-dependent nature of green hydrogen production and the difficulty of reconfiguring the asset-intensive processes used to produce the selected end-products. Then, again, the level of hydrogen adoption is one of the main factors influencing optimal GHSC configurations and defining attractivity of an investment (e.g., high investment cost of hydrogen infrastructure) (Griffiths et al., 2021; Agnolucci and McDowall, 2013; Almansoori and Shah, 2009). These characteristics complicate the alignment of supply and demand (Reuβ et al., 2021) and give rise to a chicken-and-egg problem where the industry is struggling to stimulate both sides of the GHSCs simultaneously (European Commission, 2020; Department for Energy Security and Net Zero, 2021). Instead of the simultaneous growth of supply and demand, Leibowicz (2018) and Nicolle and Massol (2023) suggest that infrastructure comes first, and a push in the supply side would solve the chicken-and-egg problem and support the large-scale adoption of hydrogen technologies.

Governmental incentives and penalties are tools to address the mismatch between supply and demand and to balance the current price difference between renewable and fossil-based products (Azadnia et al., 2023; Peng et al., 2023; Quarton and Samsatli, 2021). Drawing learnings from other sustainability-driven transitions, the adoption of wind and solar energy has faced challenges similar to hydrogen: high costs and perceived risks compared to the fossil alternatives, low demand, technological immaturity, lack of infrastructure and standards, opposition by the public, etc. (Louwen et al., 2022). However, the technological development, learning curves, economies of scale, and policy supports have driven significant cost reductions and encouraged both supply and demand for wind and solar energy (Bin Abu Sofian et al., 2024). Additionally, collaboration among stakeholders has contributed to social acceptance, standardization, and the de-risking of wind and solar energy deployment (Kim et al., 2017). In 2022, wind and solar accounted for 11,7% of the global electricity mix with a growth of 18,2% from 2021, and the trend is expected to continue (International Renewable Energy Agency IRENA, 2024).

2.4. Research gap and the initial research framework

While previous research has considered the technical, environmental, and economic aspects of hydrogen, less attention has been drawn to the actor-level dynamics that shape the GHSCs and their transition pathway. There is a significant gap in the literature to understand GHSCs from various actors' perspectives as a part of the energy transition. This study addresses the gap by answering the following research questions:

1. What are the drivers and barriers influencing the transition of GHSCs into the socio-technical regime?
2. How can actors intervene to advance the introduction of GHSC solutions into the socio-technical regime?

Guided by the two research questions, we develop a literature-informed framework to understand the transition of GHSCs from MLP. In the framework, drivers are defined as enabling conditions that motivate actor participation in GHSCs and challenge regime stability. Barriers refer to frictions, market failures, coordination problems, etc. that maintain the current dynamic stability and prohibit change in the regime level. Interventions are defined as strategic actions taken by GHSC actors to support the scale-up of GHSCs at the regime level. These components are analyzed across five literature-informed dimensions: demand, economic aspects, technology and infrastructure, actor dynamics, and regulation and policies (Table 1). The initial research framework, presented in Fig. 2, provides the basis for investigating how actors and system conditions interact to shape transition trajectories in the context of GHSCs.

3. Methodology

Aligned with the abductive nature of this research, a case study methodology was chosen to explore emerging concepts and phenomena, and to enable theory-building (Eisenhardt, 1989; Voss et al., 2002). Furthermore, multiple case studies were chosen to gather in-depth qualitative insights, enabling a comprehensive and robust analysis from diverse actor perspectives. We applied a purposive sampling approach in selecting case firms (Yin, 2013a).

Primary data collection was done via a semi-structured interview approach since it balances focus and flexibility in interview discussions (Eisenhardt, 1989). We interviewed decision-makers from 12 companies that are actively investing in GHSCs in Finland. These companies cover all the key stages of a GHSC, from production to application and from engineering to hardware sellers and consultants, thereby providing a comprehensive view of actors involved in the supply chains. We mainly interviewed one person per case company, but in one case, two company representatives were interviewed due to their highly different areas of expertise.

The Finnish context was chosen since it provides a particularly relevant empirical setting for examining the emergence of GHSCs. Finland combines a low-carbon electricity system, driven by a reliable electricity grid and rapidly expanding wind power (Statistics Finland, 2025a), with a strong base of energy-intensive process industries, such as steel, chemicals, pulp and paper, and maritime activities. Also, there are many GHSC projects in the development (H_2 Cluster Finland, 2025). Geographically, Finland is characterized by long distances, a scattered industrial structure, and limited existing hydrogen infrastructure, which increases the importance of infrastructure planning, coordination, and collaboration among actors. In addition, Finland has articulated a national hydrogen resolution (Ministry of Economic Affairs and Employment of Finland, 2023) that emphasizes energy security, domestic value creation, and integration into emerging European hydrogen markets. Furthermore, the availability of biogenic CO_2 streams from bio-based industries creates opportunities for integrated power-to-X value chains that couple green hydrogen with circular carbon flows (Statistics Finland, 2025b). These contextual factors make Finland an ideal case for examining the emerging GHSCs.

To ensure data triangulation and a rich understanding of each case, we systematically combined primary interview data with multiple secondary data sources, following Tracy (2010). This included pre-interview review of publicly available materials and post-interview follow-up investigation using company websites, news articles, press releases, and public reports. This multi-source approach enhanced the contextual interpretation of primary data and enabled validation and refinement of insights. The interviews focused on capturing decision-makers' perspectives regarding the future outlooks, the implementation of hydrogen supply chains, their key drivers and barriers, and interventions taken by actors to enhance GHSCs' role at the regime level. The interview questions are provided in Appendix 1, and the cases are summarized in Table 2. The interviews were conducted online via video call in May–August 2024.

The interviews lasted from 45 to 90 min. Every interview was recorded and transcribed. The initial transcription was done by MS Teams and was then checked by a researcher supported by the video recording. The transcription was then read multiple times and coded separately by two researchers. The involvement of two researchers enabled the comparison and synthesis of differing coding results. When needed, the interviewees were consulted for further clarification. The coding process is presented in Appendix 2. The coding was done according to the variables of the initial research framework. If an interviewee referred to a new variable that had not emerged from the literature review, it was added as a new code.

The most relevant information from the interview data was extracted to answer the research questions. The research framework was enriched via the within-case and cross-case analyses (Appendix 2) as variables emerged during the interviews. The validity and reliability of the research design were ensured according to the four tests suggested by Yin (2008).

Table 1
Regime-level core dimensions of GHSC transition identified from the literature.

Dimension	Definition	Reference
Demand	Demand by paying customers for GHSC related products and services	Almansoori and Shah (2009) Agnolucci and Mcdowall (2013) Kim and Lee (2008); Kiemel et al., 2024;
Economic aspects	Economic aspects affecting the profitability and financial feasibility of a GHSC or its part	Almansoori and Shah (2009) Kim and Lee (2008); Reuβ et al., (2019)
Technology and infrastructure	Any technology needed during the lifecycle of a GHSC	Koulaki et al., (2021); Yu and Wang (2021) Reuβ et al., (2019)
Actor dynamics	Interactions between actors participating in a GHSC	Seuring (2004); Jesse et al., (2024) Sgarbossa et al., (2023)
Regulation and policies	Regulations and policies affecting GHSCs	Azadnia et al., 2023; Quarton and Samsatli (2021); Peng et al., (2023)

4. Results

The interview data collected from 12 Finnish companies confirmed the suitability of the initial research framework, structured around five key dimensions, for understanding and classifying the complex socio-technical dynamics influencing GHSC emergence.

Fig. 3 visualizes the revised research framework that brings together the drivers and barriers that influence GHSC stabilization within the socio-technical regime. In particular, globally communicated decarbonization goals and corresponding regulatory frameworks were consistently identified as the primary drivers compelling the socio-technical regime to change, thus creating momentum for GHSCs. In addition, while stabilizing and destabilizing factors manifest differently across diverse actors, common systemic phenomena were observed: the actors' interventions for advancing the introduction of GHSC solutions in the socio-technical regime emerge from these observations.

The refined research framework is elaborated next via the five core

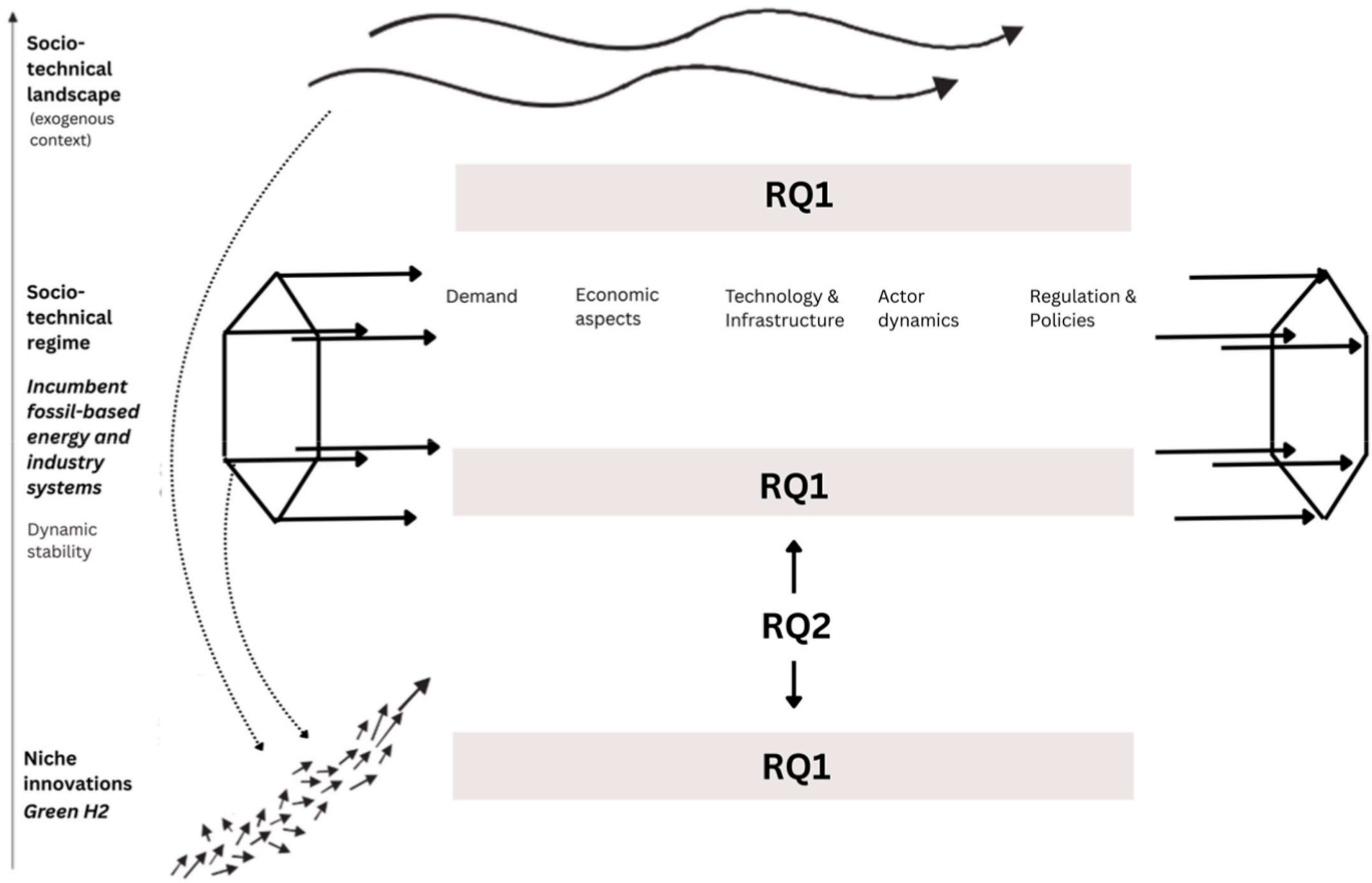

Fig. 2. Initial research framework adapted from Geels and Kemp (2007) and created by the authors.

Table 2
Summary of the cases.

Case Firm	Country	Actor	Actor type	No. Employees	No. Interviews	Interviewee(s') title(s)	Interviewee ID
A	Austria, Finland	Engineering & supplier	Incumbent	30 000	1	Business development manager, PtX and e-Fuels	PA
B	Finland	Consultancy	External expert	450	2	Director of Energy Consulting; Senior Consultant	PB1 PB2
C	Finland	Energy & H2 producer	Incumbent	5200	1	Technical director, PtX	PC
D	Finland	Energy & H2 producer	Incumbent	1000	1	Vice President, Hydrogen & PtX	PD
E	Finland	O&G, H2 producer & user	Incumbent	6000	1	Technology Director, renewable hydrogen &PtX	PE
F	Finland	O&G, synthetic fuel production	Incumbent	900	1	Process technology specialist, Renewables and PtX	PF
G	Finland	Producer of H2 and synthetic fuels	Niche	20	1	Business Development Director	PG
H	Sweden, Finland	User of H2	Incumbent	14 000	1	HSE Director	PH
I	Finland	H2 Distributor	Niche	20	1	Project Director	PI
J	Finland	Energy & CO2 producer	Incumbent	16 600	1	Business Development Manager	PJ
K	Finland	H2 Distributor	Incumbent	150	1	Director of Hydrogen unit, R&D&I	PK
L	Germany	Investor, project developer	Incumbent	150	1	Director, Infrastructure Engineering	PL

dimensions and the related interventions in general and on an actor-level.

4.1. Drivers, barriers, and interventions

4.1.1. Demand

4.1.1.1. Demand-related drivers. Demand and market development play a crucial role in defining GHSCs. The growing demand for hydrogen in fact, drives actors to participate in GHSCs and develop offerings for the market's needs.

By large, the use cases for hydrogen and its derivatives are already operational, but they currently rely on non-renewable inputs. These non-renewable products could technically be replaced with their green alternatives. Decarbonization is a significant factor behind the growing demand as customers of GHSCs are launching net-zero strategies, and regulatory pressure is forcing sectors, such as maritime, to reach carbon neutrality. Several interviewees discussed business opportunities

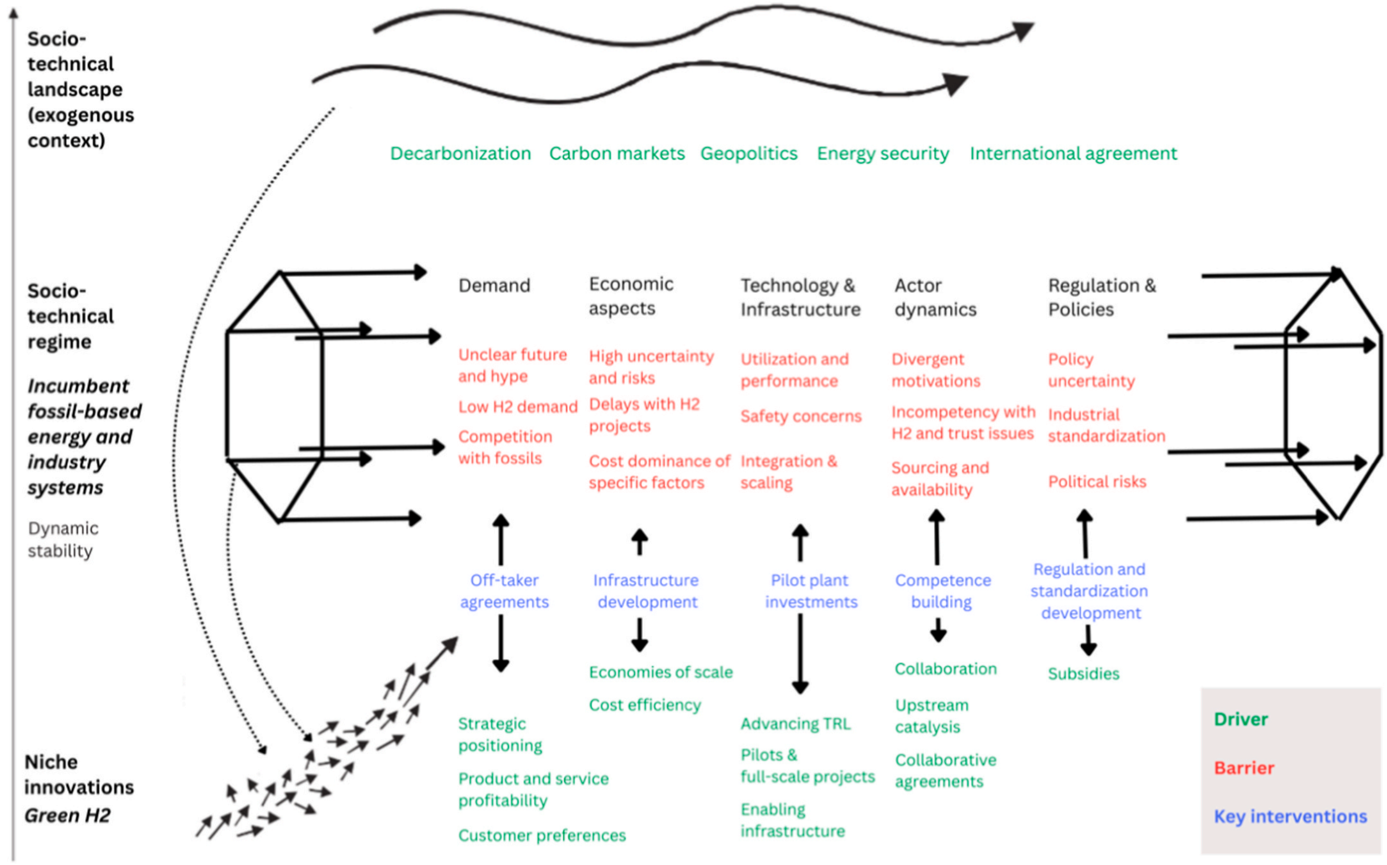

Fig. 3. Refined research framework: Drivers, Barriers, and Interventions by GHSC actors.

emerging from specific niche markets, emphasizing the importance of identifying sectors under the greatest regulatory pressure.

Niche level innovations play a critical role in driving regime-level change. GHSC actors are actively experimenting with different applications and processes to find viable product-market fits. Diversification into high-value products such as hydrogen-based chemicals, fuel cells, or storage systems, opens opportunities for enhancing product profitability. Additionally, product and service development can create new revenue streams via, e.g., utilization of side streams, data analysis, and system integration. Protective spaces – facilitated by pilot plant investments and related experimentation – eventually enable actors to develop and iterate their solutions before scaling up.

On another side, evolving societal expectations and shifting customer preferences that favor sustainability are putting pressure on incumbent regimes; while brand value is often associated with sustainability, which in turn reinforces the "windows of opportunity" for niche innovations.

Furthermore, regulatory and economic pressures drive demand towards GHSCs, especially in hard-to-abate sectors. These sectors are more willing to absorb green premiums, thus creating early market demand for GHSC solutions. As one interview stated, *"you need to serve a market where there is a regulatory price pain"* (PE). As a response, actors adopt a strategic approach to align their internal strategies with broader decarbonization goals. Indeed, successful strategic positioning can become a competitive advantage as the regime changes.

4.1.1.2. Demand-related barriers. The absence of stable demand and unclear market development are among the most critical barriers for actors to participate in GHSCs, commit capital, and define solid long-term strategies.

In many sectors, especially in cost-sensitive and high-volume industries, fossil-based alternatives remain economically dominant and make economic lock-ins evident as GHSCs involve major upfront capital expenditures (e.g., steelmaking with coal versus with hydrogen). Today, actors prioritize cost efficiency over environmental performance, which limits their willingness to pay a green premium unless externally mandated or incentivized.

Furthermore, the interviewees describe the pressing chicken-and-egg problem where producers hesitate to scale up without demand and potential off-takers delay commitments due to uncertain availability and pricing.

These dynamics project the rigors of the current socio-technical regime, whose dimensions are fine-tuned to incumbent fossil-based energy and industry systems.

Regulation aimed at advancing hydrogen adoption has not yet yielded a substantial market base or concrete market signals. The lack of harmonized and predictable regulation makes it challenging for actors to forecast market growth and identify high-potential market segments. Instead, hype and speculative guesses about future demand have created unrealistic expectations and investment hesitancy. As summarized by PH, *"we only try to make the best possible guess.*

4.1.1.3. Demand-related interventions. The pressure on the regime encourages new strategic positioning to exploit the "windows of opportunity". Product and service development can be part of the strategic positioning.

To counterbalance the regime-level uncertainties, collaborative contracts, including official contracts, such as off-taker agreements and joint ventures, have emerged as important niche-enabling interventions that support the development of GHSCs and ensure sufficient demand. E.g., off-taker agreements reduce demand risks by locking in demand in terms of volume, price, and duration, and offer legitimacy and stability for emerging projects.

Collaborative contracts not only de-risk investment decisions but also create shared innovation environments where actors can pool expertise and build trust across GHSCs. By default, the actors preferred commitments to well-established players over startups, primarily to secure the availability of agreed warranties, the solvency of their supply chain actors, and, in general, the existence of their key partners in the upcoming decades.

4.1.2. Economic aspects

4.1.2.1. Economic aspects-related drivers. Economic aspects drive the participation in GHSCs as actors aim at financial gains, returns on investments, and profitability.

Regardless of the challenges in building feasible business cases around GHSCs today, the interviewees recognized the economic opportunities in GHSCs, especially in the mid and long-term. The interviewed investor (PL) summarized the ingredients of an economically feasible project as *"1) you produce a product that has a relevant market, 2) you have green electricity compliant with regulations, and 3) the necessary infrastructure"* (PL). GHSCs are highly capital-intensive exercises, and the cost inefficiencies have blocked many projects from commercializing. Nowadays, technological advancements are projected to significantly decrease costs, both operational expenses (OPEX) and capital expenditures (CAPEX), leading to enhanced competitiveness and cost efficiency of GHSCs.

The introduction of carbon markets and pricing mechanisms further incentivizes the adoption of hydrogen by internalizing the environmental cost of carbon emissions. As said by a representative of an oil and gas firm, *"of course, lowering carbon intensity increases the value of our products"* (PE).

Moreover, economies of scale achieved through large-scale deployment reduce unit costs and further foster the competitiveness of GHSCs. Through real-life experiences and investments, the learning curve enhances the economic feasibility of hydrogen projects and mitigates associated risks.

4.1.2.2. Economic aspects-related barriers. Economic aspects of GHSCs also pose significant challenges.

GHSCs require capital-intensive investments upfront, and the current market environment, characterized by uncertainty over the growth of hydrogen utilization, makes their return on investment (ROI) speculative. High costs, including OPEX and CAPEX linked to specific activities, such as electricity costs, as the dominating factor, reduce the attractiveness of GHSC-related investments. Specifically, electrolysis, distribution, and storage costs for hydrogen are substantial, and they limit scalability. The volatility in renewable energy markets adds another layer of economic complexity.

Uncertainties and risks about market development, technological advancements (with no clear consensus on which solutions will dominate the market in the future), and regulatory development, among other factors, also encourage actors to derisk their GHSC investments by waiting. For instance, if the cost of hydrogen production is expected to drop to one-third of its current price within five years, committing to a fixed price for the next decade could prove economically detrimental. Once knowing the exact regulation and having *"the winning"* technology available, it is easier to estimate the attractiveness of a business case. Also, *"the biggest demotivating factor in our horizon, given that we have a well-established and highly profitable business, is that … I mean, this hydrogen competes with our existing business"* (PE) describes the innovator's dilemma linked to cannibalizing and changing current business. The solution to this dilemma links back to market dynamics and regulation. These are all reasons that motivate delaying hydrogen projects.

4.1.2.3. Economic aspects-related interventions. Investments in hydrogen-specific infrastructure, such as pipelines, storage facilities, and refueling stations, are necessary to scale up supply chain operations, lower logistical inefficiencies, reach economies of scale, and connect producers with end-users.

Several case companies are actively engaged in infrastructure development and planning. One of the case companies was actively preparing for hydrogen pipeline construction and was in constant dialogue with the public-sector decision-makers. Others contributed to the collaborative planning process to determine optimal pipeline locations and maximize its benefits for the emerging hydrogen ecosystem in Finland and Europe. These efforts demonstrate how infrastructure decisions play a critical role in scaling up GHSCs. Strategic coordination within GHSC is essential. Since a pipeline is designed to connect supply and demand, it is crucial to ensure its optimal location in relation to its users. This also helps in avoiding asset underutilization.

In the absence of ideal infrastructure, two actors implemented a suboptimal logistical workaround to sustain project momentum and foster organizational learning, showcasing niche actors' adaptive capabilities under transitional constraints. Also, subsidies were considered a valuable tool for enabling actors to invest in GHSCs already now.

4.1.3. Technology and infrastructure

4.1.3.1. Technology and infrastructure-related drivers. Technology and infrastructure advancements are essential enablers of GHSCs. Advancements in Technology Readiness Levels (TRL) of key technologies, such as electrolyzers, have improved efficiency, reliability, and safety, while also lowering the costs of hydrogen production, transportation, and storage technologies. Unlike the academic literature, the interviewees did not consider technical factors a major limitation for adopting hydrogen. It was more about finding *"the winning technology"* (PC). Hydrogen (gray) was discussed *"as part of the industry routines for a long time"* (PF), and the confidence in key technologies of water electrolysis was strong: *"Thinking about hydrogen production, I think electrolyzers are not the problem"* (PC).

Demonstration projects, which test, deploy, and improve new technologies, lower technological risks and enable GHSC actors to gain expertise and learn from others, thus facilitating the shift from pilots to full scale.

Additionally, the envisioned hydrogen infrastructure facilitates efficient connections between production and demand. Several interviewees described the upcoming hydrogen pipeline in Finland as a key driver they planned to connect to. There was a consensus about the need for hydrogen storage, but the visions vary. At the same time, some advocated for national hydrogen storage contributing to the national security of supply. Most considered the greatest potential in the storage used locally for a company's internal use. While waiting for the high-volume enabling pipeline, various storage and road transportation solutions were tested and applied to get started.

4.1.3.2. Technology and infrastructure-related barriers. In terms of technological and infrastructure-related barriers, they are deeply connected to the other barrier categories.

Many technologies critical to cost-efficient GHSCs remain at low TRL levels and thus increase the technological risks for large-scale adoption. Then, again, a lack of operational examples creates hesitation among investors and policymakers to invest in full-scale deployment. For now, the low efficiency and performance of electrolyzers and storage solutions limit the commercial viability of hydrogen.

Scalability challenges arise due to the integration challenges described e.g. by (PC): *"Operating the overall system is the problem; taking ammonia or methanol production with water electrolysis as an example, they do not match in scale. You need to have an insanely huge electrolysis plant for making a small ammonia production site to work. There is an integration* *problem."*

Furthermore, safety considerations for hydrogen production, storage, and transportation are significant hurdles, as these processes require specialized handling and infrastructure. Hydrogen is a highly explosive gas, and the bad historical experiences and accidents have left their mark on hydrogen's reputation. The lack of transportation infrastructure, such as pipelines and refueling stations, remains a bottleneck for downstream development. Also, unreliable component availability across the lifecycle of a GHSC was considered a risk.

4.1.3.3. Technology and infrastructure-related interventions. Pilot plant investments are a widely adopted approach for stabilizing niche trajectories and preparing the conditions for regime-level diffusion and scaling.

The pilots facilitate protected experimental spaces at the niche level where actors can test, validate, and refine GHSC solutions under real-world conditions. The primary goal is to demonstrate the techno-economic viability of GHSC solutions and, furthermore, derisk the future full-scale projects. Beyond technical validation, pilot plants help in gaining practical experiences, fostering cross-actor collaboration and supply chain integration. A few interviewees noted that pilot projects also help identify reliable partners and familiarize them with the capabilities, expectations, and processes of other GHSC actors. This collaborative dimension enhances pilots' value as an early-stage coordination mechanism. Furthermore, pilots were named as potential entry points for emerging actors, such as startups, as they provide them with visibility, credibility, and access to established networks.

4.1.4. Actor dynamics

4.1.4.1. Actor dynamics-related drivers. Actor dynamics have a major influence on GHSC success due to the inherent interdependence of GHSC stages and actors.

The interviews highlighted the importance of collaborative networks that invite actors to participate in globally competitive GHSCs, thereby promoting market development for hydrogen both generally and on a regional level. (PE) highlighted the importance of collaboration between actors operating in the same country and reminded that *"Finland is a tiny area, so don't you dare to fight in the same sandbox. There is space for everyone, and everyone is needed"*. Decarbonization and PtX initiatives in existing business environments make it relatively easy to get involved. Also, sometimes they emerge around the existing business ecosystems: *"Over the years, our entire value chain has been optimized to serve the surrounding car industry, so it is rather logical to continue focusing on that sector"* (PH).

In addition, upstream catalysts, such as an existing carbon dioxide side stream relevant to the production of some hydrogen derivatives, might drive an actor to look for monetization opportunities with the surrounding actors.

Multi-actor projects and consortia facilitate actors' exploration of opportunities in GHSCs, while collaboration between actors promotes knowledge sharing and risk mitigation. The need for energy and resource availability drives the development of partnerships in GHSCs as actors aim to secure them. Ultimately, the actor interactions come down to commercial contracts and formalized agreements.

4.1.4.2. Actor dynamics-related barriers. Actor dynamics also create barriers for participating in GHSCs.

Given the interdependencies of GHSC actors and their long-term commitments to infrastructure, trustworthy interactions between them are crucial. The interviewees felt that developing GHSCs is new to most actors, and capabilities and competencies among actors are uneven. The interviewees highlighted the lack of skills, talent, and experience, as well as the frustration in finding high-quality partners to collaborate with. While several actors had dreamed of "turn-key solution" deals and initiated collaboration with external professionals, the disappointing experiences led them to develop these important activities in-house. The disappointments stemmed from over-optimism, poor quality outcomes, and project delays, which in turn led to trust issues between actors. *"Our initial idea was to have a consultant-led approach but after the first exercise, I realized they have no clue about anything"* (PD). On the other hand, the consultants working as external professionals (PB1, PB2) did not recognize the issues related to poor skills. Still, they acknowledged that many of the GHSC considerations are new to the involved actors, and the expertise is continuously evolving.

Collaboration and building mutually attractive business cases are another significant barrier; mismatches in motivations and gained benefits among actors have resulted in inefficient decision-making, fragmented efforts, and failed investments. For example, one interviewee described an initiative between a hydrogen producer and a hydrogen user as *"we really tried but could not find a way to make a good business for both-at least for now"* (PC). The other party also confirmed this narrative. Additionally, integration challenges and coordination gaps raise unanswered questions. Integration problems were not only raised by technical challenges but also by a lack of a common vocabulary among specialized experts. This communication challenge was described as *"the aspiring collaborators are only talking about their own specialty without understanding the others. Thus, I think we are dealing with a basic communication issue"* (PF).

The chicken-and-egg problem remains pervasive: without demand, actors hesitate to commit to GHSCs, and infrastructure investments remain limited. Then. again, demand cannot grow without infrastructure, hydrogen availability, and all the actors needed to form a GHSC.

4.1.4.3. Actor dynamics-related interventions. Harnessing and developing competencies is critical for supporting the scaling of GHSC. Even if large-scale green hydrogen projects are novel, many of the relevant capabilities already exist in incumbent sectors. For example, hydrogen has been part of the oil companies' daily lives for decades, and engineering companies have a long heritage in engineering and ramping up large-scale industrial facilities. This expertise can be applied in GHSC deployment, as one interviewee described, *"thanks to our current business operations, we have a massive opportunity to take over several stages of the GHSC."*

Internal capability building was identified as essential to address skill shortages and accelerate learning. Concrete actions to strengthen hydrogen-specific knowledge and reduce risk are hiring, internal training, and materializing GHSC projects such as pilots.

In parallel, collaboration enables actors to benefit from the surrounding capabilities. Interviewees emphasized the importance of reliable partners and formalized procedures, methods, and standards, for example, in procurement and engineering, to ensure operational continuity. Intentional capability management was deemed important, with interviewees describing their decisions on which capabilities and assets to acquire and which to develop in-house. Collaborative actor dynamics support niche stabilization and facilitate alignment with future regime configurations.

4.1.5. Regulation and policies

4.1.5.1. Regulation and policies-related drivers. Regulation and policies landscape, accompanied by standardization, has a critical role in creating markets for hydrogen and PtX more broadly.

Regulation is the key tool for internalizing environmental impacts into monetary prices. International decarbonization agreements set ambitious emission reduction targets, communicate the envisioned direction for the development of GHSCs, and drive investments in hydrogen solutions. Distribution obligations support demand creation and ensure the supply of hydrogen for its users.

In Finland, concerns around energy security have driven prioritization of local and European GHSC actors, while the global export potential is recognized.

Additionally, government incentives are catalyzing the deployment of GHSCs by carrying risks and reducing the price gap between renewable and non-renewable options. These governmental incentives typically prioritize and even require the participation of local actors in the form of subsidies.

4.1.5.2. Regulation and policies-related barriers. Policy uncertainty, combined with missing regulations and standards, creates an environment of risk that deters profit-driven actors from investing without clear long-term guidelines. One interviewee verbalized the dominating sentiment by *"unfortunately, despite how noble, peace-loving, and world-improving we might strive to be as a people, humanity has not been very successful in saving nature voluntarily- and it is not doing so now either. Thus, regulation is needed"* (PJ). Inconsistent regulatory frameworks across regions further escalate the regulation and policies-related barriers by making it difficult to build and align business strategies and, for example, decide whether carbon dioxide should be "put to the ground" or to the production of hydrogen-based synthetic fuels.

The interviewed actors who are actively building GHSC-linked facilities were frustrated with the lack of industrial standards and safety instructions. In the absence of suitable standards, e.g., for industrial sites and hydrogen fueling stations, examples were searched from other countries, such as the U.S. Slow permitting processes not only delay project timelines and increase administrative costs but also kill projects entirely. The lack of cohesive international policies creates fragmentation, making the development of integrated hydrogen markets harder, even at the EU level.

Additionally, geography-related political risks were identified as a significant concern and barrier.

4.1.5.3. Regulation and policies-related interventions. Regulation plays a key role in shaping and defining market conditions, de-risking investments, and accelerating the GHSC breakthroughs.

By engaging in regulatory development, companies can influence the direction of regulatory frameworks and promote their alignment with emerging industry needs. From the analyzed cases, especially the larger companies were actively engaged in regulatory development and in direct contact with policymakers. Such engagement includes but is not limited to lobbying, advisory roles, and participation in policymaking forums. Collaboration between industry stakeholders and governments appeared essential for establishing effective mechanisms such as carbon pricing, production subsidies, and investment incentives that truly support GHSC niche technologies in establishing themselves at the regime level.

Standardization is an effective mechanism for ensuring the quality, safety, and interoperability of GHSC technologies across production, storage, distribution, and end-use. As for regulatory development, participation in standard-setting processes was considered a way to harmonize practices across geographies and, even more importantly, a strategic opportunity to shape the future technical norms so that they align with actors' offerings and commercial interests.

4.2. Heterogeneity in the actor pool

A deeper analysis shows that GHSC actors are not homogeneous, but their position in the value chain dictates their primary concerns and strategic interventions. Table 3 breaks down the interventions by actors addressing different MLP levels, and Table 4 compares the primary drivers, critical barriers, and key interventions of three actor types derived from case data. The heterogeneity of different actors emerges.

This differentiated view demonstrates that, while all actors face systemic challenges, like policy uncertainty, they approach GHSCs in different ways. Incumbent actors prioritize financial security and long-term supply chain resilience, leveraging their scale to mitigate risk by performing selective supplier vetting and engaging in regime-level lobbying. Niche actors focus on local deployment and institutional workarounds to advance development, even in the absence of industry-wide references and supportive regulation. External experts are positioned to bridge the current capability gaps, providing the foundational engineering and financial modeling required for projects to reach investment readiness, and supporting the execution across various projects.

Given the divergence between the actors, the success of complex GHSC transition relies heavily on coordinating the differentiated actions of heterogeneous actors between the niche and regime levels, with the end purpose to ensure actor alignment and to mitigate economic and institutional uncertainties.

5. Theoretical contribution and policy implications

"The best way to predict the future is to create it" (P. Drucker). This sentiment holds relevance in the current transition of GHSCs, in which their role in decarbonization is widely acknowledged. Still, their realization depends largely on international alignment across multiple socio-technical dimensions. If the ambitions around decarbonization goals are real, the current phase of development is insufficient. If the climate goals and agreements, such as the Paris Agreement, are not genuine, it becomes even more vital to find ways to build green energy systems that are not only regenerative from the environmental point of

Table 3
Interventions by actors and the addressed MLP level.

MLP Level	Interventions (actions by actors)	Purpose	Actors
Socio-technical landscape (macro)	Regulatory pressure in hard-to-abate sectors act as a landscape-level force that reinforces regime destabilization.	The landscape level, such as the global climate goals and energy security strategies, serves as the primary driver and justification for engaging in GHSCs.	None directly
Socio-technical regime (meso)	Policy shaping (public relations, dialogue with policymakers, active lobbying) and standardization (active participation in standard-setting). Strategic positioning to exploit the "windows of opportunity" created by the pressure on the regime. Harnessing competences and internal capability building. Transportation and infrastructure development.	Several structural changes at the regime level are addressed, such as implementing pricing mechanisms reflecting environmental externalities, or systematically removing institutional lock-ins favoring incumbent actors.	Primary the incumbents, the niche actors with limited capacity and influence
Niche innovations (micro)	Pilot plant investments including co-investments. Product and service development. Implementing sub-optimal logistical workarounds for keeping project momentum and making progress (e.g., containerized road transport of hydrogen). Collaborative contracts, e.g. long-term off-taker agreements and joint ventures.	Smaller scale trials foster experimentation and derisk early-stage activities. Pilots create protected spaces to test and validate GHSC solutions. Collaborative contracts mitigate risks and guarantee stable revenue streams, solving the chicken-and-egg problem.	All case actors

view but also no-brainers from the economic and social point of view. The global electricity demand is estimated to more than double by 2050 (International Energy Agency IEA, 2022), and at least this electricity addition must come from renewable sources. Our study contributes to the growing body of transition literature by providing empirical insights into the interplay of drivers, barriers, and interventions that shape the emergence of GHSCs.

Our analysis of drivers, barriers, and interventions in GHSCs aligns broadly with the existing literature on hydrogen adoption barriers, which consistently identifies the primary constraints as systemic rather than purely technological (Wu et al., 2021; Anderhofstadt and Spinler, 2019; Bolz et al., 2024; Sahebi et al., 2025). Our findings reinforce prior evidence that demand and financial factors constitute central barriers to green hydrogen adoption (Zahler et al., 2022).

Consistent with Bolz et al. (2024) that analyzes short-term hydrogen adoption barriers across decision levels in the transportation sector, our results highlight the critical role of regulation and policy frameworks in shaping hydrogen deployment. However, while Bolz et al. (2024) focus on categorizing and ranking barriers across decision-making levels, our study extends this perspective by explicitly accounting for actor heterogeneity across the GHSC. We show that different actor types experience and prioritize barriers and drivers differently and accordingly adopt distinct strategic interventions to navigate systemic constraints and opportunities.

5.1. Theoretical contribution

Building on the transition theory and MLP (Geels, 2002; Geels and Kemp, 2007), this paper demonstrates specific mechanisms through which actors orchestrate the integration of GHSCs into the prevailing energy regime and explicitly incorporates actor heterogeneity into the analysis. Three major facets emerge from the multi-actor perspective.

5.1.1. Landscape pressure for regime destabilization

Our findings underline the centrality of regulatory pressure in hard-to-abate sectors as the most substantial driver. This pressure, such as the mandated requirements for utilizing "green premiums" or achieving stringent decarbonization goals, operates as a powerful landscape-level force that reinforces the destabilization of the existing fossil-based regime.

Crucially, our empirical evidence adds granularity to the MLP by revealing how actors actively respond to and strategically leverage these landscape signals at the regime level. Actors consciously position themselves in specific niche markets, such as heavy transport or industrial usage (e.g., steel, shipping), where regulatory burdens translate into concrete business opportunities, thereby accelerating the transition process and increasing the perceived value of green products. This strategic positioning is not a passive reaction, but an intentional intervention designed to exploit the "windows of opportunity" created by the pressure on the regime.

5.1.2. Niche stabilization through collaborative interventions

The persistence of economic and institutional barriers, particularly the "chicken-and-egg problem" related to guaranteed demand and supply, underscores the socio-technical regime's resistance to change. While previous literature (e.g., Seuring, 2004; Jesse et al., 2024) shows that implementation of a transition requires inter-organizational approaches, our results specify how actors intervene to break through into the socio-technical regime, looking for collaboration from the niche level.

Key collaborative mechanisms identified include pilot projects and, fundamentally, the establishment of long-term off-taker agreements. These interventions are critical because they mitigate techno-economic uncertainty and guarantee stable revenue streams, which are essential for securing project bankability, a primary concern for major investors. By establishing these formalized contracts and collaborative networks, actors foster necessary institutional learning and build the trust required to advance GHSCs.

5.1.3. The role of heterogeneity in shaping the transition

A significant theoretical contribution is derived from analyzing the heterogeneity of the actors involved. While literature already acknowledges the differing actor motivations in GHSCs (Sgarbossa et al., 2023), we demonstrate that the motivations, barriers, and strategic interventions are highly dependent on an actor's position within the emerging supply chain, and they cannot be treated as a homogeneous group.

Incumbent actors: These actors operate primarily at the regime level. Their focus is on risk-aversion and ensuring attractive profitability, requiring investments to be technically secured for lifetimes up to 20 years. Their interventions are geared toward regime shaping, involving large-scale investments treated initially as "development projects", strict supplier vetting (checking, e.g., financial solvency), and high-level policy engagement to align technical norms and standards with commercial interests.

Niche actors: These actors concentrate on short-to mid-term operational reality and local implementation. Their core challenges relate to the lack of standardized physical infrastructure and regulatory fragmentation. Their interventions often involve adaptive logistical workarounds (e.g., utilizing containerized road transport) to maintain project momentum. They also grapple with the high cost of institutional compliance, including mandatory, expensive site-specific risk management procedures, which are necessitated by the absence of industry safety standards.

External experts: This intermediary group primarily addresses the market's current capability gap. Their intervention strategy focuses on ensuring project investment readiness by modeling viable techno-economic outcomes, standardizing complex procurement processes and promoting more GHSC investments in their market area. Their operational barrier often lies in performing well when doing things for the first time.

By detailing these divergent strategic responses, this study refines MLP theory, underscoring that the success of complex transitions like GHSCs relies heavily on coordinating the differentiated actions of heterogeneous actors across and between the niche and regime levels.

5.2. Policy implications

To accelerate the implementation and scale-up of GHSCs, policy interventions must be concrete, targeted, and directly address the specific institutional and economic barriers identified by actors. Each MLP level is involved.

5.2.1. Landscape level

At the highest level, GHSC-related policies must align with the global climate goals and energy security strategies, both of which were emphasized by interviewees as central justifications for engagement in GHSCs. Responding to shifting societal values and long-term decarbonization commitments requires policy coherence and fiscal strategies that embed GHSCs into broader visions of a low-carbon economy in a credible way. Such directionality at the macro level is essential for creating legitimacy and reducing uncertainty for long-term infrastructure and industrial investments.

5.2.2. Socio-technical regime level

Policy should promote structural changes that create a level playing field for GHSCs in relation to fossil-based incumbents. The technology for successful GHSCs is now available; policies must now support its scaling up in a financially attractive manner. To this end, it appears essential to introduce pricing mechanisms that reflect environmental externalities. This includes strengthening carbon pricing and systematically removing institutional lock-ins that favor incumbent actors. Furthermore, the industry demands the immediate implementation of

Table 4
Primary drivers, critical barriers and key interventions by actors.

Dimension	Incumbent actors	Niche actors	External experts
Primary Drivers	Product value enhancement: reducing carbon intensity increases product value in regulated markets.	First-mover advantage and market creation; securing strategic sites and opening infrastructure pathways.	Investment readiness: creating viable techno-economic models and investment cases for clients.
Critical Barriers	Capital and scaling risk: massive capital commitments (even multi-billion) require guaranteed long-term profitability and certainty in supply chains.	Regulatory fragmentation and initial investment; lack of general safety standards that lead into expensive site-specific redesigns; high cost of entering the markets.	Finding suitable collaborators; unrealistic customer expectations
Key interventions	Regime shaping and strategic sourcing: active engagement in policy and standardization (e.g. in Brussels), building internal expertise to manage complex supply chains, industrial pilot projects.	Local workarounds and partnerships: utilizing sub-optimal solutions for getting the operations going, maintaining the project momentum, and improving the offering.	Phase-specific support: promotion of GHSC investments in general, focus on early-stage feasibility studies and technical conceptualization, and later providing project management, expansion of the reference list.

harmonized certification systems for green hydrogen to create clear, non-speculative market signals and facilitate investment decisions. Additionally, policymakers should prioritize expediting the currently slow and unclear permitting processes. A key action involves harmonizing industrial standards and safety instructions across national borders. The absence of standardized safety guidelines compels niche actors to conduct costly, site-specific risk assessments, resulting in considerable friction and slow down.

5.2.3. Niche level

Policy should actively derisk early-stage GHSC activities and nurture the essential linkages between the niche and the regime levels. Policy support must be directed toward mechanisms that guarantee demand, thereby solving the "chicken-and-egg problem". This includes promoting and supporting long-term off-taker agreements, as well as implementing clear distribution obligations. These mechanisms directly address the high investment risk and uncertainty cited by developers and investors. Support mechanisms should recognize actor heterogeneity. For niche actors, policy should accelerate the provision of standardized, lower-cost compliance practices for local infrastructure. For incumbent actors, policy could reward investments that exceed baseline requirements (e.g., through carbon-intensity reduction mandates) to increase product value and drive higher rates of return. Public support should fund pilot projects and collaborative initiatives that build trust and advance capability building and institutional learning. Encouraging the formation of actor networks is vital, as reliable partnerships often constitute the core competence driving successful GHSC projects.

5.2.4. Concluding remarks

The policy implications above discussed call for policymaking instead of policy-taking, and active regime shaping instead of passive adaptation.

As our findings show, the success of GHSCs depends not only on technological advancement but also on the ability of policies to orchestrate economic feasibility, regulatory clarity, and actor alignment across multiple levels. By engaging in policy development, industry actors can help institutionalize GHSCs and co-create an investable, resilient, and scalable PtX economy.

Experiences from other energy transitions show that systemic green transitions are possible. Wind and solar electricity faced massive insecurities in their early phases of development (e.g., Louwen et al., 2022; Rasmussen et al., 2011) but are now representing about 12% of the global electricity mix and the cheapest form of electricity in most markets (International Energy Agency IEA, 2021). The scale and complexity of GHSCs go far beyond these precedents, but there is still a lot we can learn from the experiences with wind and solar. For example, before the commercial large-scale feasibility, wind and solar energy projects were heavily subsidized by governments.

6. Limitations and future developments

6.1. Limitations

This paper is subject to several limitations. First, the data for the analysis is collected from only 12 cases that focus on a specific geographic context, namely Finland. This limits the generalizability of the research but also provides opportunities for future research in the form of comparisons and expansions. Additionally, the reliability of interview data may be compromised by biases and the novelty of the topic. Secondly, the markets around GHSCs are developing rapidly, as, for example, the technology, regulations, policies, and market dynamics are changing. Thus, the findings might require updates relatively quickly. Thirdly, the research aims to build a comprehensive framework to describe a real-life phenomenon. Given the complexity of the phenomenon, the framework might not be complete and requires further elaboration. Lastly, building on the complexity, hydrogen, with all its production methods and “colors”, is only a small part of decarbonization, and it shall be looked holistically in the context of renewable energy-based systems more broadly and compared with the other advancing solutions and technologies.

6.2. Future developments

Our findings highlight the need for a better understanding of actor dynamics across GHSCs. The multi-actor nature of GHSCs in the context of energy transition requires further research to investigate the different collaboration, competition, and cooperation mechanisms within GHSCs and between the niche and regime level actors. The emerging business models and business ecosystems, including real case examples, deserve further investigation as GHSCs mature. Furthermore, practical tools for modeling and guiding GHSC development at an actor, value chain, and socio-technical regime level are needed to complement the existing techno-economic models. These tools should support decision-making related to asset lifecycle management, actor alignment, risk-sharing and acceptance, sustainable value chain optimization across different time horizons, and effective policy design. Sub-optimization is a good start, but we must move towards a system that unlocks the benefits of PtX in all aspects of sustainability.

Given the complexity of GHSCs, future research should delve deeper into the dynamics between the actors in the short-, mid and long-term to enable the development of competitive GHSCs. As mentioned in the beginning, there are many ways to produce hydrogen. Thus, the role of different hydrogen “colors,” such as blue hydrogen, produced from steam methane reforming, including CCUS and turquoise hydrogen, produced from pyrolysis of methane and solid CO2 storage (Incer-Valverde et al. (2023), in facilitating the transition toward clean hydrogen supply chains merit further investigation, as all low-carbon pathways may play complementary roles in advancing the shift toward truly clean hydrogen systems.

Finally, the policies impacting GHSCs offer multiple avenues for future research, and the role of GHSCs in the context of energy security requires further understanding.

7. Conclusion

This study applied Multi-Level Perspective (MLP) and a multi-actor lens to investigate the emergence and implementation of Green Hydrogen Supply Chains (GHSCs), finding that economic and institutional factors fundamentally constrain their scale-up.

Our primary theoretical contribution applies the MLP by detailing the mechanisms of transition through actor heterogeneity. We foresee how landscape-level regulatory pressures in hard-to-abate sectors strategically enable regime destabilization, which actors, furthermore, exploit via different strategic interventions. In particular: incumbent actors focus on regime shaping and risk-aversion, while niche actors employ local workarounds to sustain project momentum and, finally, external experts bridge the current capability gaps and support project planning and execution.

According to our findings, the success of GHSCs transitioning into the mainstream energy system relies on coordinating the differentiated actions of heterogeneous actors through collaborative mechanisms, particularly via long-term off-take agreements and pilot projects, necessary for securing project bankability and for building competence and trust. Policymaking has a key role: it must provide specific and credible solutions, including harmonized regulatory frameworks and industrial standards, with the ultimate goal to mitigate investment risks, speed up the permitting processes, and orchestrate the imperative institutional and financial alignment for sustainable and scalable GHSCs.

CRediT authorship contribution statement

Maija Luukka: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Project Management. **Antti Ylä-Kujala:** Conceptualization, Software, Validation, Formal analysis, Investigation, Writing – review & editing. **Federico Caniato:** Conceptualization, Methodology, Validation, Writing – review & editing, Funding acquisition. **Marco Macchi:** Conceptualization, Methodology, Validation, Writing – review & editing.

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Declaration of competing interest

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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.2026.115160.

Data availability

The data that has been used is confidential.

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