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Assessing hydrogen supply and demand in the Liverpool City Region: a regional development review from stakeholders' perspective

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ABSTRACT

Under the UK's carbon neutrality goals for 2050, the Liverpool City Region's (LCR) strategic positioning, with its rich industrial heritage and infrastructure assets such as extensive port facilities and proximity to vast renewable energy resources, positions it as a potential leader in the UK's shift towards a hydrogen economy. Given this, the regional hydrogen industry and stakeholders in decarbonisation initiatives intend to undertake a critical review of the opportunities, challenges and uncertainties to local hydrogen supply and demand systems to assist in their decision-making. To achieve this goal, this study reviews the readiness of the hydrogen supply chain infrastructure within the LCR, which highlights four sectors in the hydrogen economy, i.e., production, storage, transportation, and utilisation. Subsequently, to offer the first-hand data in practice, a multi-faceted approach that incorporates a broad array of stakeholders through the Triple Helix (TH) model is adopted. Special attention is given to hydrogen's role in transforming heavy industry, transportation, and heating sectors, supported by significant local projects like HyNet North West. During a roundtable discussion, industry-academia-government stakeholders identify challenges in scaling up infrastructure and assess the economic and technological landscape for hydrogen adoption. To the best of our knowledge, this will be the first regional academic endeavour to comprehensively examine the alignment between hydrogen supply and demand, theory and practice. Based on a detailed SWOT analysis, this study outlines the region's strengths, including established industrial clusters and technological capabilities in manufacturing. It also highlights weaknesses such as the high costs associated with emerging hydrogen technologies, technological immaturity, and gaps in necessary infrastructure. The opportunities presented by national policy incentives and growing global demand for sustainable energy solutions are considered alongside threats, including regulatory complexities and the slow pace of public acceptance. This comprehensive examination not only maps the current landscape but also sets the stage for strategic interventions needed to realise hydrogen's full potential within the LCR, aiming to guide policymakers, industry leaders, and researchers in their efforts to foster a viable hydrogen economy. Moreover, the findings offer valuable insights that can inform the development of hydrogen strategies in other regions and cities.

1. Introduction

In 2019, an ambitious environmental programme set out by the UK government saw the UK eliminating or offsetting all of the country's greenhouse gas emissions by 2050 (Chaudry et al., 2022). This target is part of the global effort to combat climate change and is a concrete action required by the Paris Agreement for countries (Chen and Ghosh, 2024). To achieve this, the UK is taking a range of measures such as the energy transition, industrial reform and sustainable manufacturing (Helm, 2023). Of these, hydrogen is seen as a key component of a future low-carbon economy, particularly in sectors that are difficult to electrify, such as heavy industry, transport and heating (Gordon et al., 2023; Jahanbakhsh et al., 2024). Therefore, the UK government is working to expand hydrogen production capacity and build the associated infrastructure (Kuzemko, 2022). In this context, two significant hydrogen projects have progressed in the UK, namely HyNet North West and East

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Coast Cluster (HyNet North West, 2023).

HyNet North West is a flagship low-carbon project in the North West of England, covering the LCR, Cheshire and Greater Manchester. The heart of this project is the production of low-carbon hydrogen and the reduction of CO_2 emissions through carbon capture and storage (CCS) technology, to produce around 5 GW of low-carbon hydrogen by 2030 (HyNet North West, 2023). Particularly, the LCR, a significant industrial and port city in the North West, historically noted for high carbon emissions, now serves as a primary site for the HyNet project. This initiative is poised to have a profound impact on the Liverpool area, not only improving the carbon footprint of the region but also positioning the LCR as a leader in hydrogen development (Sovacool et al., 2023). With its substantial industrial base, port facilities, and critical infrastructure, the LCR is well-placed to develop a strong hydrogen supply chain. For instance, the region's proximity to renewable energy sources, such as offshore wind farms in the Irish Sea, and existing industrial clusters, makes it ideally suited for hydrogen application in manufacturing, transport, and logistics (Chedburn et al., 2022; Sovacool et al., 2023). Furthermore, regional endeavours like the LOOP project, the maritime innovation flagship project by Connected Places Catapult (CPC), etc., which focuses on delivering and utilising low-carbon hydrogen at scale, underscore the LCR's readiness to embrace hydrogen-based energy solutions.

While these developments represent important progress, a more systematic understanding is required to determine how individual initiatives converge into coherent, place-based strategies that align the hydrogen supply chain with emerging cross-sectoral demand. Within the LCR, the current evidence base remains fragmented by theme, leaving decision-makers without an integrated view of how supply-side readiness across production, storage, and transport correlates with near-term demand from critical regional users such as the Port of Liverpool's maritime cluster, heavy road freight and selected industrial sites. Moreover, a further limitation also lies in the absence of a transparent, LCR-specific framework for assessing supply chain maturity. Without such a framework, stakeholder judgements remain inconsistent and difficult to benchmark, limiting the ability to reconcile empirical findings with practical experience. In addition, existing mapping efforts often fail to inform time-sequenced decision-making or identify the appropriate policies needed to support implementation. As a result, strategic choices related to offtake prioritisation, infrastructure sequencing, and governance arrangements remain unclear and underspecified, limiting the region's capacity to coordinate hydrogen deployment effectively. To address these gaps and establish a robust foundation for regional hydrogen planning, this study formulates three core research questions. Firstly, what is the current and near-term readiness of hydrogen supply chains in the LCR across production, storage, transport and utilisation, and where do the key bottlenecks lie? Secondly, how does potential local supply capacity compare with the near-term demand from users in the LCR? This demand encompasses energy-intensive manufacturing, maritime shipping, heavy-duty road transport, public transport fleets, and emerging aviation applications. Thirdly, for different functional departments (such as government, industry, and academia), which policies are most likely to effectively advance project implementation sequencing, mitigate procurement risks, and accelerate the realisation of credible regional net-zero pathways?

To answer these questions, this study aims to map the current and future landscape of hydrogen supply and demand in the LCR, addressing both the technological readiness and the economic viability of hydrogen projects. Methodologically, the study adopts a comprehensive approach by conducting a regional review of hydrogen development for both supply and demand in the LCR. It then involves 31 key stakeholders from government, industry, and academia, utilising the Triple Helix (TH) model to enhance collaboration and knowledge exchange between different sectors (Kontovas et al., 2022). Specifically, the review explores several key dimensions of hydrogen development in the LCR, including hydrogen production methods, storage technologies, transportation infrastructure, and end-use applications. Through this process, the study identifies the regional strengths, weaknesses, opportunities, and threats (SWOT) in advancing its hydrogen economy. Practically, by providing a detailed understanding of hydrogen supply chains, this study contributes valuable insights to the ongoing discussions on decarbonisation and energy transition in the LCR as a strong case to promote the hydrogen energy development in cities. It offers practical and state-of-the-art guidance for policymakers, industry leaders, and researchers seeking to harness the region's potential in building a sustainable and competitive hydrogen economy.

This study is organised as follows: Section 2 introduces an overview of the study's methodology, including the design of the review and the structure of the roundtable discussions. Section 3 delves into specific aspects of the hydrogen supply chain, including production, storage, transportation, and utilisation. A comprehensive SWOT analysis is conducted in Section 4 to summarise the key findings and offer strategic insights for future development. Finally, Section 5 concludes this study.

2. Methodology

To comprehensively assess the readiness of hydrogen infrastructure in the LCR, this study adopts a mixed-method research design that combines a regional literature review, a facilitator-led roundtable discussion, and a structured SWOT analysis. Each component plays a distinct yet complementary role in addressing the multifaceted challenges of hydrogen development. Specifically, the literature review establishes a foundational understanding by synthesising theoretical advancements and practical insights, which sets the stage for informed stakeholder engagement. Building upon the literature findings, the roundtable discussion is designed to bring together key representatives to capture first-hand expert perspectives, validate regional insights, and facilitate cross-sectoral dialogue. This participatory method enables the collection of up-to-date information on technological progress, institutional readiness, and policy dynamics within the LCR (Kontovas et al., 2022). To systematically synthesise these insights and guide strategic reflection, a SWOT analysis is then conducted. This structured approach helps identify internal strengths and weaknesses, as well as external opportunities and threats, thereby supporting a comprehensive assessment of the LCR's hydrogen development landscape.

In this study, multiple data sources are gathered to review the readiness of hydrogen infrastructure in the LCR, including academic papers and project reports (which dominate the data sample, given the local topic and availability). This review provides a dual-faceted summary. One aspect focuses on the theoretical advancements and challenges in hydrogen production, storage, transport and utilisation technologies, while the other examines the current state and practical applicability of such infrastructure in Liverpool.

Following this, the roundtable discussion took place during a regional hydrogen stakeholder workshop, which was convened to understand and improve the potential for hydrogen supply and application within the LCR. Given the TH model, a total of 31 representatives from the government (7 people, including managers and officers from Liverpool City Region Combined Authority (LCRCA) for low carbon, port and energy), industry (11 people, including engineers and directors from energy companies, technology companies, water companies, consultancies and associations) and academia (13 people, including researchers from several regional research institutions with expertise in hydrogen, decarbonisation and supply chain) were invited to join the workshop, which provided a varied and enriched discussion for up-to-date information on the academic development, project progress and obstacles, and political factors. Notably, given the aim of generating a practical and actionable study of supply chain readiness and investment priorities, the TH model provides a fit-for-purpose framework for the workshop, while broader Quadruple or Penta Helix models incorporating civil society and additional societal actors require a broader scope and additional stages of public engagement that go beyond the remit of this study. Through a prior count, 9 of the representatives had less than 10 years of working experience, 13 had between 10 and 20 years of experience, and 9 had more than 20 years of experience, where such a "rugby ball" structure ensures a reasonable distribution of experience among participant stakeholders.

During this event, the following tasks were given to participants. To ensure a consistent scaling standard during the roundtable, all closed questions were administered on a seven-point Likert scale with the criteria for different scores being defined and reproduced in Appendix A. Participants received a brief, standardised instruction immediately before each task, were asked to select a single category per item, and were offered a "Skip/No idea" option where they lacked sufficient knowledge. Scores were coded from 1 to 7, with 4 as the neutral category, where "Skip/No idea" entries were treated as missing and excluded on an item-by-item basis. Aggregation was performed at the item level across all respondents, and the "weighted average" reported in Section 4 denotes the arithmetic mean with equal weight per respondent. For transparency, this study also examines medians and the dispersion of responses to check that conclusions were not driven by outliers. This procedure applies to production, storage and transport, and utilisation tasks alike, and it is aligned with the detailed scale descriptors provided for each question block in Appendix A.

1. Task 1: Identification of the state-of-the-art and influential factors for hydrogen production
2. Task 2: Identification of the state-of-the-art and influential factors for hydrogen storage and distribution
3. Task 3: Identification of the state-of-the-art and influential factors for hydrogen utilisation
4. Task 4: Collaborative opportunities across the hydrogen supply chain
5. Task 5: A comprehensive SWOT analysis for hydrogen development in LCR

Furthermore, to systematically synthesise these diverse inputs, the SWOT framework is chosen as the primary tool since it offers a transparent method for linking internal, locally controllable factors (strengths and weaknesses) to external drivers (opportunities and threats) in markets, policy, and technology. Compared with other multi-criteria decision analysis tools, such as the Analytic Hierarchy Process (AHP) or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), although these methods support formal ranking of options, they require pre-determination of empirical information that is not met during this early-stage scoping (Cao et al., 2025; Chen, 2019). By contrast, the SWOT enables rapid and structured consolidation of insights from both the literature and the roundtable, and crucially, is carried forward into the formulation of time-sequenced policy priorities for the LCR, making the synthesis both strategic and operational rather than merely descriptive.

3. Review of the hydrogen supply chain infrastructure readiness in the LCR

3.1. An overview of the LCR

The LCR, situated in the North West of England within Merseyside, is a critical area in addressing the UK's climate challenges. This region encompasses Liverpool and the boroughs of Knowsley, St Helens, Sefton, Wirral, and Halton, covering an area of about 722 square kilometres with a population of approximately 1.5 million. Research by Sovacool et al. (2024) highlights the Merseyside industrial cluster as a significant emitter, contributing 5.04 Mt of CO_2 annually, ranking it among the top five UK industrial clusters for emissions. In response to these environmental challenges and aligning with the UK Government's goal of achieving net zero carbon emissions by 2050, the LCRCA declared a "climate emergency" in May 2019. It is committed to taking decisive action to mitigate the impacts of climate change (Boyle et al., 2020). A pivotal element of this commitment is the HyNet project, which focuses on producing low-carbon hydrogen through natural gas reforming coupled with carbon capture technology (HyNet North West, 2023). Moreover, the project also includes developing a network for capturing and storing CO_2 in geological formations under Liverpool Bay, alongside a hydrogen distribution network that will serve various sectors across the North West of England and North Wales.

The North West industrial cluster, which HyNet will serve, extends from Flintshire and Wrexham through Cheshire to Greater Manchester and Lancashire. This region benefits from excellent connectivity via road, rail, and the Manchester Ship Canal, supported by international airports in Manchester and Liverpool and maritime access through the Dee and Mersey (served by the Port of Liverpool) estuaries (Clery and Gough, 2022). Furthermore, the North West industrial cluster region is also strategically vital to the UK's economy, integrating three Enterprise Partnerships (LEPs), i.e., Manchester, Liverpool, and Cheshire, which consist of the largest concentration of advanced manufacturing and chemical production sites in the UK (Clery and Gough, 2022; HyNet North West, 2021). For example, as one of the largest oil refineries in the UK, the Stanlow refinery is located at Ellesmere Port. Approximately 341,000 people are currently employed in the North West's manufacturing sector. According to estimates from Net Zero North West, such industrial decarbonisation projects could generate 6,000 employment positions in the cluster, generating £17 billion in gross value by 2040 (Clery and Gough, 2022).

In light of these developments, this section aims to provide a detailed review of the current hydrogen supply and demand in the LCR. It synthesises academic research and industry reports to offer a nuanced understanding of the infrastructure's readiness to support hydrogen distribution and showcase utilisation opportunities. These findings offer the first-hand data in guiding further development of hydrogen infrastructure in the LCR, pinpointing critical areas for intervention, and fostering a sustainable low-carbon future for the region. Such data will also serve to design the questions used in the roundtable discussion for SWOT analysis.

3.2. Supply infrastructure readiness in the LCR

3.2.1. Hydrogen production plant

According to Williams et al. (2022), small-scale and limited geography highly affects the production and utilisation of hydrogen. In fact, a key reason for such challenges is that infrastructure and industrial sites are highly interdependent, which affects the hydrogen supply chain's agility. To facilitate the energy transition, HyNet has launched a supply chain proposal to allow interested organisations to register interest in the project. This proposal will consist of two separate plants, Hydrogen Production Plant 1 (HPP1) and Hydrogen Production Plant 2 (HPP2). HPP1 will have an infrastructure that is capable of delivering a projected hydrogen supply of 350 MW of low-carbon hydrogen by 2025, which is expected to adopt the hydrogen production technologies of Gas Heated Reformer and Auto Thermal Reformer from Johnson Matthey and the post-combustion amine plant for carbon capture from Topsoe. For HPP2, it will increase HyNet's hydrogen production capacity to over 1000 MW by 2026 (McDonough, 2024a). At present, HPP2 has been awarded outline planning consent by Cheshire West and Chester Council and will enable green hydrogen projects to supply into the network.

Together, HPP1 and HPP2 will function as an early "anchor supply"

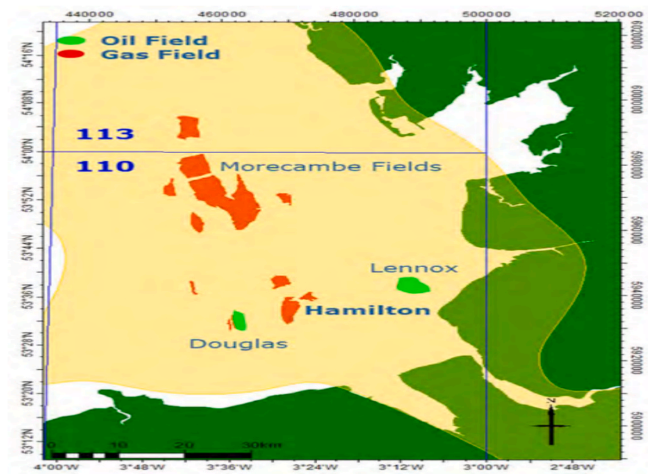

Fig. 1. Location of Hamilton and Lennox depleted oil fields (Green and Gammer, 2016).

for the region. They de-risk initial demand by offering scale, predictable specification and integration with capture and storage, while creating time and learning space for electrolytic projects to progress from concept toward operation. In strategic terms, this allows the LCR to prioritise offtake among heavy transport, port operations and selected industrial sites, diversify beyond a small number of bilateral buyers by using the network to widen offtaker access, and exploit brownfield co-location and skills at Stanlow to localise value capture. Although the practical risk includes over-reliance on a narrow offtake base, future solutions, e.g., diversification via the hydrogen network and visible, staged deployments in logistics and port equipment that convert perceived strength in transport into contracted demand, can be developed for mitigation. This sequencing supports a gradual pivot toward green hydrogen as additional renewable supply and electrolysers come online, without stranding near-term utilisation assets.

3.2.2. Wind turbine

The Frodsham Wind Farm is situated close to the Mersey Estuary, and it is proposed that it will generate green hydrogen (produced by the electrolysis of water, using renewable electricity with zero emissions) with a capacity of 50 MW. However, it has been concluded that there is simply not enough capacity to produce green hydrogen viably and at scale. Consequently, HyNet has opted to prioritise blue hydrogen (produced from natural gas and combined with CCS) over green hydrogen. This decision is attributed to two primary factors: the cost and the scale and availability of renewable electricity required for green hydrogen production. The HyNet region has an identified demand for 4 GW of hydrogen. To meet this demand with green hydrogen, approximately 6 GW of electricity would be needed. If this electricity is sourced from offshore wind, which operates at an average load factor of 50 %, a 12 GW wind farm would be required. However, the UK's total offshore wind capacity as of today is just 12 GW (McDonough, 2022).

3.3. Storage infrastructure readiness in the LCR

The Cadent Gas, the Liverpool – Manchester Hydrogen Cluster, the Northern Gas Networks, and H21 Leeds City Gate have previously assessed suitable locations around the UK for hydrogen production hubs (Aquaconsultants, 2017). Two of the key predetermined components for locating hydrogen hubs are: 1) close proximity to CCS infrastructure, with sufficient capacity to meet project CO_2 sequestration quantities; and 2) sufficient hydrogen storage capacity to meet demand profiles. The LCR and its surrounding area fulfil all the above conditions for a large-scale hydrogen supply chain.

3.3.1. Carbon capture and storage infrastructure readiness

Initially, the CO_2 storage in the LCR is confined to a depleted gas field in Liverpool Bay, i.e., the Hamilton & Lennox gas field, due to the prior research that determined its suitability in terms of geological, geographical and oceanographic factors and integration with the existing pipeline infrastructure. The Hamilton field was discovered in 1990, and gas was first produced in February 1997 (Green and Gammer, 2016). Preliminary geological and reservoir studies have determined that the Hamilton reservoir is very well connected hydraulically, and storage capacity is relatively insensitive to well placement. Therefore, injection wells will be strategically placed near existing gas production wells to minimise geological risk. Only part of the reservoir will need to be open to the wellbores to achieve the target injection rates of 5 Mt/year (Green and Gammer, 2016). According to the plan, this low reservoir pressure would initially require that CO_2 be injected in the gas phase until the pressure has increased sufficiently for liquid-phase injection (Green and Gammer, 2016) which is expected that the gas injection period will last for 13.6 years. Furthermore, as depicted in Fig. 1, the Hamilton & Lennox gas field is relatively close to the coastline (approximately 23 km from the Lancashire coast). The shallow part is identified with a depth of 694 m, and this site has significant pressure depletion, enabling the repurposing of existing on and offshore infrastructure in terms of cost-effectiveness (Clery and Gough, 2022; Green and Gammer, 2016; Liverpool Bay CCS Ltd, 2024).

It has been reported that the repurposed field will have an estimated CO_2 storage capacity of 170 million tonnes (Liverpool Bay CCS Ltd, 2024). The temperature at the Hamilton site is above the critical temperature for CO_2, with the injected inventory being able to remain in a dense phase at that depth. However, heating will still be required to mitigate low-temperature risks and ensure single-phase conditions in the wells (Green and Gammer, 2016). Meanwhile, a secure containment is provided by the extensive mudstones and halite (rock salt), which are a proven seal for multiple hydrocarbon fields and facilitate an excellent caprock for the storage complex. It is expected that two replacement wells will be required when the operation shifts from gas-phase to liquid-phase injection (Green and Gammer, 2016). Moreover, the probability of repurposing assets like wells (side track existing wells), an onshore pipeline between Connah's Quay and the Point of Ayr, and an offshore pipeline between Point of Ayr and Douglas Platform, helps the CCS plan based on the Hamilton field remain attractive (Clery and Gough, 2022).

So far, the Hamilton field is regarded as one of the UK's lowest-cost CCS options. It has a levelised unit cost of £11/tonne, which is the second lowest for all UK fields (after Endurance in the North Sea), but it has a projected lower lifecycle cost (Aquaconsultants, 2017). The associated costs are shown in Table 1 and represented by capital (CAPEX), operating (OPEX), and abandonment (ABEX) (Green and Gammer, 2016). This appeals to all interested stakeholders in reducing costs, risk, and the complexity associated with decarbonisation projects (Clery and Gough, 2022). The shipping of CO_2 to Liverpool Bay could attract additional customers from the proposed South Wales cluster for integration into the HyNet North West combined hydrogen/CCS pipeline network (Hammond, 2022). Furthermore, approximately 40 km to the North of Hamilton is the Morecambe Gas Fields (see Fig. 1), which have a combined capacity of 1030 Mt CO_2 (Liverpool Bay CCS Ltd, 2024).

Table 1
Hamilton & Lennox repurposing cost estimate (Green and Gammer, 2016).

Category of Cost	Cost Estimate (£ millions)
CAPEX	281.5
OPEX	496.5
ABEX	95.7
Total Cost	873.4
Cost CO_2 Injected (£ per Tonne)	6.99

This site offers a build-out area once the Hamilton storage site is full, enhancing the sustained competitive advantage of CCS as a viable solution to the production of blue hydrogen.

Furthermore, another outstanding advantage of developing the CCS system is the creation of more employment opportunities, including direct employment like the installation of CCS equipment, the transportation of CO_2 and CCS consultancy and R&D, etc. Indirect employment would include 1) safeguarding and expanding employment in existing carbon-intensive industrial plants that would otherwise not be viable because of carbon legislation, 2) supporting the development of existing or new carbon-intensive industrial facilities that rely on CCS technology, etc.

To date, a Carbon Dioxide Appraisal and Storage Licence has been awarded to a company, namely Eni, by the UK Oil & Gas Authority (OGA) in October 2020. This licence contains a six-year appraisal term that permits planning and assessment that may result in a future application to the OGA for a storage permit. Following on from this, in October 2022, Eni submitted a Development Consent Order (DCO) application for the HyNet North West CO_2 pipeline. In March 2024, the Secretary of State for the UK Government's Department for Energy Security and Net Zero (DESNZ) granted this DCO, which brings the HyNet CCS cluster closer to the execution phase, with Final Investment Decision (FID) expected by September 2024. The UK Government's decision to grant a DCO to the HyNet CO_2 pipeline is an important milestone to allow for the world's first asset-based regulated CCS business.

As the enabling backbone for early blue hydrogen supply, the CCS system is a key factor for the region's initial hydrogen market. With this DCO and the emergence of more regulated business models, the region can progress from appraisal to execution, turning capture and storage from an uncertainty into an actionable service. Strategically, this underwrites early production volumes and gives the industry the confidence to sign multi-year offtake, while the public-facing implication is that performance must be transparent, e.g., capture rates, injection safety and monitoring should be reported against clear benchmarks to secure social licence. To avoid technological lock-in, CCS deployment should be accompanied by a published schedule for integrating electrolytic capacity and by siting and dispatch practices that reduce exposure to long-run fossil dependence. In short, CCS enables the first wave of hydrogen while signalling a credible pathway to higher shares of green hydrogen over time.

3.3.2. *Hydrogen storage infrastructure readiness*

A key obstacle to the implementation of hydrogen energy as an alternative to fossil fuels is its large-scale and long-term storage due to its low volumetric energy density in gaseous form (Harati et al., 2024). Considering the operational feasibility in the LCR, the salt cavern is identified as an ideal storage method compared with the other three, i.e., High Pressure (HP) Vessel, Hydrogen Transmission System (HTS) linepack and Ammonia.

Specifically, Cheshire is near the LCR and is one of the few locations where underground gas storage in salt caverns already exists on a large scale. Salt caverns are voids that are created by washing rock salt out in

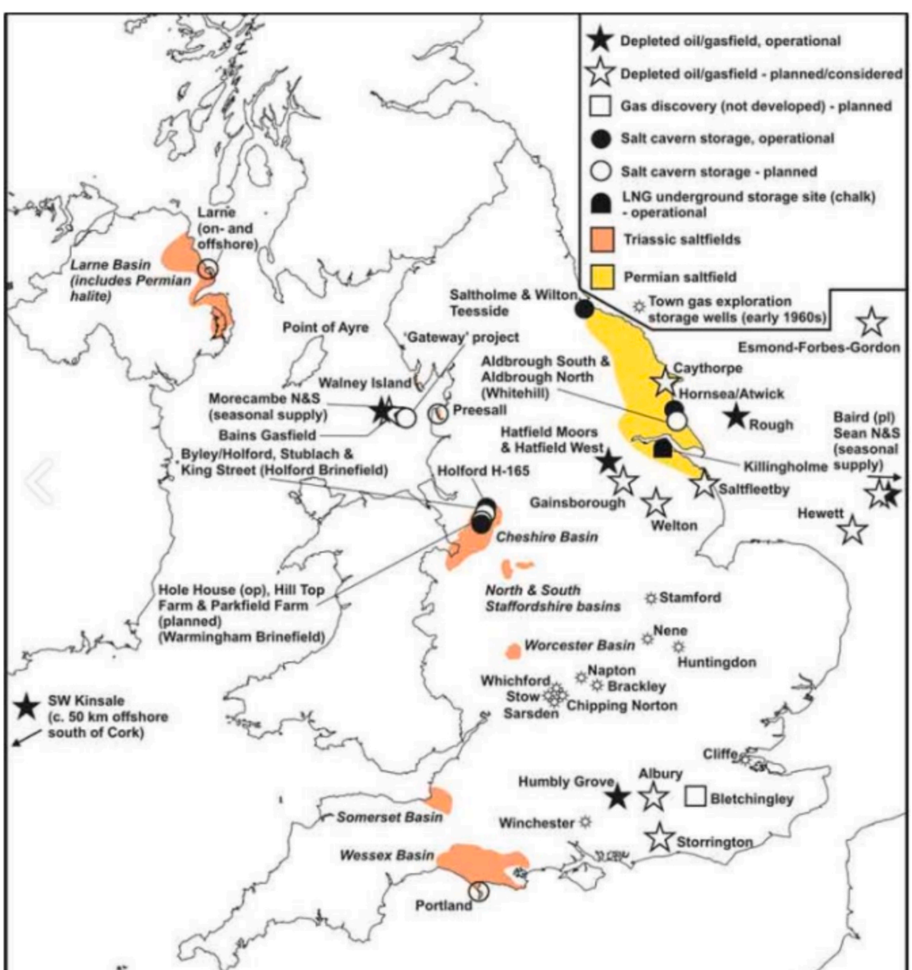

Fig. 2. The distribution of UK salt caverns (Aquaconsultants, 2017).

the form of brine, with advantages of relatively low storage costs, low leakage rates, and fast withdrawal and injection rates (Aquaconsultants, 2017; Edwards et al., 2021). Studies have shown that the integration of large-scale storage can considerably reduce the cost of hydrogen supply by providing flexibility and supply chain (Williams et al., 2022). To date, such an Underground Gas Storage (UGS) approach is a robust storage option that has been in operation for over 90 years, and there are approximately 630 facilities of various forms in operation (Aquaconsultants, 2017). Currently, some depleted oil/gas fields and salt caverns in operation are located at Rough (offshore Southern North Sea), Aldborough and Hornsea (East Yorkshire), Hatfield Moors (Yorkshire), Humbly Grove (Weald), and Holford and Hole House Farm (Cheshire), as shown in Fig. 2. The British Geological Society also reports that the UK has significant rock salt formations with a potential capacity of thousands TWh of future storage (Williams et al., 2022).

However, the storage of pure hydrogen in porous reservoir rocks is currently considered to be a low-maturity technology, with no operating precedent (Williams et al., 2022). Overall, the theoretical potential for cost-effective subsurface hydrogen storage that accounts for regional variations is poorly understood. In Table 2, the total theoretical storage capacity of onshore hydrogen storage caverns is calculated as 2150 TWh (Williams et al., 2022). The H21 North of England project has estimated that 8 TWh of inter-seasonal hydrogen storage would be required to support an 85 TWh HTS that encompasses the major conurbations of Leeds, Bradford, Wakefield, Huddersfield, Hull, Liverpool, Manchester, Teesside, Tyneside, and York (Williams et al., 2022). Furthermore, another 20 sites are at various stages in the protracted planning process, indicating that storage infrastructure is geographically limited (Aquaconsultants, 2017).

3.4. Transport infrastructure readiness in the LCR

3.4.1. Maritime

The Peel Ports Group is now a member of the North West Hydrogen Alliance (NWHA). Peel Ports is the second-largest seaport group in the UK, which operates the Manchester Ship Canal and the Port of Liverpool, which are considered key nodes within hydrogen supply chains. Meanwhile, it is investigating the potential utilisation of hydrogen as an alternative fuel source for its heavy plant equipment, mitigating its environmental impact and net zero strategy by 2040. Peel Ports has invested over £1.2 billion over the last decade to implement sustainable infrastructure and technologies (HyNet North West, 2021).

Furthermore, industrial partnerships have been sought with Stanlow Terminals Ltd, which has announced that it intends to develop a major import and storage terminal for green ammonia in the Port of Liverpool (HyNet North West, 2021). In fact, ammonia can be used as a carrier to transport and store hydrogen, as ‘ammonia cracking’ or ‘ammonia decomposition’ can produce hydrogen. This approach overcomes some of the technical challenges of direct hydrogen transport and storage, such as the low energy density of hydrogen and the requirement for HP storage. In this context, the Port of Liverpool provides deepwater access and an established maritime infrastructure, which is capable of handling the largest gas carrier vessels (Čučuk, 2023). The new terminal will enable the import and storage of more than one million tonnes of green ammonia (Stanlow Terminals, 2023). It is also envisioned that a fleet of zero-emission hydrogen-powered heavy goods vehicles (HGVs) will carry freight between sites in the LCR Freeport zone (Invest Liverpool, 2022).

3.4.2. Pipeline

Pipelines have been extensively utilised to transport hydrogen for more than 50 years, and there are approximately 16,000 km in length, supplying hydrogen to refineries and chemical plants globally (Ball and Wietschel, 2009). In the LCR and its surrounding areas, the HyNet project is developing 125 km (77 miles) of pipeline to safely distribute hydrogen produced by Vertex Hydrogen at the Stanlow Manufacturing Complex, or the Inovyn (Cheshire) storage site (HyNet North West, 2023).

Preliminary order limits represent the boundary of the maximum development area needed for the project. This includes temporary works, like construction access and storage, and permanent works, such as the pipeline and associated facilities, which are depicted below in Fig. 3. Operational maintenance will take place from the current Cadent depots. The onshore pipelines to deliver hydrogen to the end user still need to be built (HyNet North West, 2023). The details of this proposal (blue solid line) are as follows:

(1) West corridor: Stanlow to the Central Hub, and the Runcorn spur

The preliminary order limits in the western corridor start at Vertex Hydrogen’s HPP at the Stanlow Manufacturing Complex. From there, the pipeline route runs approximately 9.7 km (6 miles) east to the Rocksavage Hydrogen Above Ground Installation (HAGI) and then approximately 9.7 km (6 miles) southeast to the Central Hub HAGI, primarily through open fields. The route avoids the Mersey Estuary Special Protection Area (SPA).

(2) North corridor: St Helens to the Central Hub and the St Helens and Warrington spurs

The preliminary order limits in the northern corridor start at the Central Hub HAGI. From there, they cover approximately 12 km (7.4 miles) north to the Higher Walton HAGI and then approximately 9 km (5.5 miles) northwest to the Clock Face HAGI. They then continue broadly north for around 8 km (5 miles) before finishing at the St Helens HAGI. Between the Central Hub HAGI and Sutton Heath, the corridor typically runs through open fields before getting closer to residential areas and the industrial setting of Ravenhead.

(3) East corridor: Central Hub to Partington, and the Warburton and Partington spurs

The preliminary order limits in the eastern corridor start at the Central Hub HAGI. From there, they travel approximately 20.4 km (12.6 miles) northeast to the Warburton HAGI. They then continue northeast for approximately 4.7 km (2.9 miles) before continuing northeast to the Partington HAGI. The route for this corridor is typically through open fields.

Table 2
Salt caverns in the UK (Williams et al., 2022).

Region	Number of Available Caverns	Combined Cushion Gas Requirement of all Caverns (Kilotonnes)	Combined Working Hydrogen Mass of all Caverns (Kilotonnes)	Combined Theoretical Energy Storage Capacity of Gas Caverns (TWh)
Cheshire Basin	1297	2,536	3,867	129
East Yorkshire	8425	30,860	43,963	1,465
Wessex	3378	11,442	16,703	557

Fig. 3. The proposed pipeline network (HyNet North West, 2023).

(4) South corridor: Central Hub to Hydrogen Storage Facility and the Northwich spur

The preliminary order limits in the south corridor start at the Central Hub HAGI. From there, the south corridor runs approximately 20.5 km south to the hydrogen storage facility. This will store hydrogen in Inovyn's underground caverns to the south of Northwich. Hydrogen stored in these caverns will be transported to industrial customers.

However, a consultancy report for the HyNet North West project indicated a measure of opposition towards pipelines that would transit from Stanlow and Ince to Liverpool Bay, with only 26 % of respondents being in favour of the pipeline and acknowledging that safety and storage were of prime concern (Clery and Gough, 2022). Comments raised during the HPP consultation related to the perceived environmental impacts, health and safety, traffic volume, and economic benefits. Specific concerns were also lodged in relation to the impact on the village of Elton and included CO_2 leakage (with comparisons to fracking) and the continuing use of fossil fuels, including a comment citing academic research that blue hydrogen does not support the transition to a net zero economy (Clery and Gough, 2022).

3.5. Demand for consumption of hydrogen in the LCR

3.5.1. Industrial consumption

The LCR has another significant competitive economic advantage in the low-carbon sector, some of which are world-leading in offshore, hydrogen, and biomass technologies. For example, ULEMCo, based in Sefton, is a global pioneer of technology to convert commercial vehicles to be fuelled by hydrogen. They have recently been awarded £7.9 million of Government funding to develop hydrogen fuel technologies for emergency vehicles (Invest Liverpool, 2023). Furthermore, this study identifies potential hydrogen off-takers in the LCR, as shown in Table 3.

Various trials have been conducted in the LCR and surrounding areas to determine how hydrogen can replace fossil fuels in the manufacturing sector (Renewable Energy Installer & Specifier, 2021). For example, the UK glass manufacturing sector includes 13 large manufacturers that are geographically concentrated along the M62 corridor, which transits from Hull in the Humber Estuary in the east, past Leeds, Manchester, to Liverpool and Cheshire in the west (Balderson et al., 2022). Pilkington Glass, based in St Helens, Merseyside, has committed to an overall 30 % reduction in carbon emissions by 2030 (McDonough, 2024c). However, decarbonisation of the glass sector will instigate sequential periods of technological change, increasing demand for engineers who possess strong project management skills. There is also an anticipated initial demand for electricians, welders, and machine fitters who will be tasked with installing the new technologies. Once the new technologies have been successfully installed, the demand will shift towards apprentices who specialise in mechanical, electrical or control, robotics, and instrumentation (Renewable Energy Installer & Specifier, 2021). The failure to attract talent into the industry will exacerbate the already prevalent skills shortage and pose a substantial risk to industrial decarbonisation implementation (Lewis et al., 2023). As a result, it has been argued that there appears to be a degree of disconnect between the glass sector decarbonisation strategies and the shop floor. It seems that the glass manufacturing sector is taking the net-zero targets seriously; however, its impact on the shop workers has not yet been fully considered (Renewable Energy Installer & Specifier, 2021). Therefore, commercialisation of hydrogen for the traditional manufacturing sector and heavy industry is considered to be a relatively slow process that may take up to 20 years to develop (Balderson et al., 2022).

3.5.2. Domestic consumption

Cadent, a gas distribution company, is responsible for half of the natural gas distribution networks in the UK. This company is embarking

Table 3
Industrial consumption of hydrogen in LCR.

Industry	Current state	Example	Hydrogen key
Glass / Ceramics	• Hydrogen is a promising option for high-temperature processes, but it faces competition from electrification in glass heating due to the efficiency of electric furnaces. Consumer willingness to pay varies significantly based on the product type and the desire for a sustainable supply chain, as seen with brands like those in the perfume industry. • The UK industry is mandated to reduce emissions by two-thirds by 2035 and achieve full reduction by 2050. However, the glass sector is hampered by a lack of policy and funding, with targets often being set internally by companies (British Glass, 2020).	Pilkington Nippon Glass Saint Gobain	Blue hydrogen
Food / Consumer Goods	• The food processing industry relies heavily on heat, which is currently predominantly provided by natural gas. The proposed pathway involves initially converting existing boilers to use a hydrogen blend, to eventually transition to 100 % hydrogen use. • The high cost of hydrogen is expected to be a significant challenge. Early adopters will likely be brands that can effectively market the sustainability of their products and pass the additional costs onto consumers. Distilleries and breweries appear to be leading the way in this area (Department for Business, Energy & Industrial Strategy, 2021).	G&J Distillers Heinz Factory Coors Brewery Greencore	Blue hydrogen Green hydrogen
Refining	• Blue hydrogen has been identified as a key alternative to grey hydrogen, particularly for its use in oil hydrocracking. • Funding is expected to be available for end-to-end projects through the Net Zero Innovation Portfolio's Industrial Hydrogen Accelerator, which aims to demonstrate the transition to hydrogen as a fuel source (Department for Energy Security and Net Zero, Department for Business Energy Industrial Strategy, 2021). • Hydrogen production will typically occur on-site, with decarbonisation efforts expected to be managed by major oil and gas companies.	Stanlow refinery	Blue hydrogen
Fertiliser Production	• Hydrogen is a viable pathway, particularly for producing ammonia as a byproduct, though this relies heavily on advancements in CCS and the expansion of renewable energy capacity. • The fertiliser industry has significant experience in complying with ATEX (short for Atmospheres Explosibles Regulation) and other related regulatory requirements, such as the Pressure Equipment Directive, making the transition to hydrogen as a fuel source quite feasible (Proba, 2024). • Currently, there is no specific policy or funding in place.	Ince	Blue hydrogen
Chemicals	• The transition to low-carbon hydrogen to replace existing grey hydrogen is possible, but it relies on renewable energy becoming competitively priced and widely available (Energy Live News Ltd, 2021). • There are no specific policies or targets to support particular sub-sectors, such as methanol production; however, the net-zero hydrogen fund may be an option, as hydrogen availability is crucial (Global Energy Group, 2021). • The use of grey hydrogen does not require any changes to infrastructure or assets.	Tata Chemicals Saria UK Palace Chemicals	Blue hydrogen
Aggregates	• CCS is the primary solution for addressing unavoidable emissions from the production process, particularly calcination (Mineral Products Association et al., 2019). • The BEIS fuel switching program is funding zero-carbon fuel mix tests, with additional research supported by the BEIS Industrial Energy Efficiency Accelerator to facilitate the development of low-carbon cement (Heidelberg Materials, 2021). • These sites are spread across various industrial locations, presenting infrastructure challenges.	Cemex	Blue hydrogen

on a project that involves blending hydrogen with natural gas to supply households in Liverpool and Manchester (Samsatli and Samsatli, 2019). HyNet, in partnership with Cadent, is set to participate in a two-year pilot study to heat residential premises in Whitby, a village in Ellesmere Port, utilising hydrogen power. Under the pilot study, 2,000 homes would be compelled to fit a hydrogen boiler, enabling a test of its suitability. However, the plans for a pilot test met with strong opposition from residents over safety concerns, who said that they "felt like lab rats". Justin Madders, Labour MP for Ellesmere Port and Neston, also remarked, "it is clear that asking people to try experimental new forms of energy consumption for their homes will not work unless basic questions about safety, efficacy, and cost can be answered from the start. It is also clear that leaving people with the impression that this was happening without their consent sent entirely the wrong message out about how we need to tackle climate change" (BBC, 2023). Furthermore, the HyNet project also needs to change the narrative of local communities in Liverpool, who question whether the project will provide benefits to the city centre region, given that its production sites are in the Wirral and West Cheshire areas (Department for Business Energy & Industrial Strategy, 2022).

From this, it is clear that consumers are important stakeholders in the conversion to hydrogen power, and it is very apparent that they should constitute an integral part of the conversion. Service providers must commit to communicating the benefits of hydrogen and how it will impact consumers, preparing them for the transition. It is recommended by the Hydrogen Taskforce that industry and government should jointly develop a public information programme for the hydrogen transition, catering for different end-users (Hydrogen Taskforce, 2021). As well, Quantitative Risk Assessments (QRAs) and Hazard and Operability (HAZOP) studies should be undertaken by individual projects to mitigate risks and public safety concerns.

3.5.3. Public transport consumption

The utilisation of hydrogen in the transportation sector is gaining traction due to its potential to reduce emissions significantly. As a clean energy source, hydrogen fuel cells produce only water vapour as a byproduct, offering an environmentally friendly alternative to traditional fossil fuels. This shift not only supports global efforts to combat climate change but also enhances energy efficiency and dependence on renewable energy sources. With advancements in technology and infrastructure, hydrogen is poised to play a crucial role in transforming transportation towards sustainability. Table 4 lists several potential hydrogen off-takers in the transportation area, and some representative examples will be introduced.

(1) Hydrogen-powered bus

Transiting to a low-carbon transport infrastructure represents both a challenge and an opportunity for the LCR. Hydrogen-powered buses are regarded as a trailblazer for the LCR in delivering sustainable public transport. However, they were withdrawn from service due to a global supply chain shortage of hydrogen, highlighting market uncertainty in light of the significant investment made by the LCRCA that totals £12.5 million (The Procurement Partnership Ltd, 2021). At present, the buses

Table 4
Transport consumption of hydrogen in LCR.

Industry	Current state	Example	Hydrogen key
Port Operation	• Decarbonisation strategies for port operations are divided between electrification and hydrogen. • Hydrogen is a promising alternative to diesel for onshore port equipment that is challenging to electrify, such as heavy-duty shunting equipment and large industrial mobile cranes. • Hydrogen may also be used to power support vessels, including tugboats, pilotage vessels, and wind farm support vessels (CTVs).	Port of Liverpool	Green hydrogen
Shipping	• Decarbonising the shipping sector is particularly challenging and will likely require hydrogen derivatives like methanol or ammonia, as pure hydrogen is not volumetrically feasible for long voyages (MAN Energy Solutions, 2022). • Currently, most ships entering European waters refuel at the Port of Rotterdam, but there are opportunities for UK ports to capture part of this market, especially given potential shortages of derivative fuels. • The industry has experience in managing these products, and the necessary infrastructure is largely in place; however, larger storage tanks will be needed due to the lower energy density of methanol and ammonia.	Stena Line	Hydrogen derivative
Aviation	• Electrification is not feasible for mid to long-haul aviation. • The focus is on gradually replacing traditional aviation fuel with Sustainable Aviation Fuel (SAF), alongside the development of electrification and hydrogen projects. The government has mandated a 10 % SAF blend by 2030 (Department for Transport and The Rt Hon Mark Harper, 2024). • Airlines are under significant pressure from customers to decarbonise, presenting an opportunity to gain a competitive edge.	Liverpool Airport EasyJet	Hydrogen derivative
Buses / Refuse Collection Vehicles	• Battery Electric Vehicles (BEVs) are expected to dominate in urban environments, particularly on shorter routes with less hilly terrain and easy access to charging stations. • Hydrogen vehicles offer a solution in areas with limited grid capacity, low electricity supply, hilly terrains, and where long duty cycles are necessary. Fuel Cell Electric (FCE) buses are well-suited for routes with significant elevation and longer distances. • There are currently 20 hydrogen buses in operation locally, with plans to double this number to 40 in the coming years (The Procurement Partnership Ltd, 2021).	LCRCA owns 20 Alexander Dennis Enviro400FCEV hydrogen fuel cell-electric double-decker buses.	Green hydrogen
HGVs	• All Internal Combustion Engine (ICE) powered HGVs will be banned by 2040, with some classes banned by 2035 (TankSafe, 2023). • Fuel Cell Electric Vehicles (FCEVs) are particularly well-suited for heavier loads (44 tonnes) and point-to-point duty cycles where opportunities for base charging are limited. • Off-takers face tight margins, and the high current costs of hydrogen, along with insufficient refuelling infrastructure, are causing logistics companies to delay decarbonisation efforts.	Hermes Depot B&M Depot FEDEX Depot	Green hydrogen

do not conform to being a net-zero mode of transport, due to the hydrogen being produced from fossil fuels. The long-term objective is to utilise green hydrogen when it is more commercially available.

(2) Hydrogen-fuelled aircraft

By the mid-2030s, the budget airline EasyJet is planning and accelerating its efforts to operate a hydrogen-fuelled aircraft. EasyJet expects to power 25 routes out of Liverpool John Lennon Airport with hydrogen. Given this, Rolls-Royce has conducted a series of tests at its facilities at Solihull, in the West Midlands. These tests are solving the engineering challenges of chilling low-pressure hydrogen below -250 °C, enabling its pumping into a jet engine (McDonough, 2024b). Furthermore, Manchester Airport has signed a Memorandum of Understanding (MoU) with HyNet, Progressive Energy, and Cadent to supply low-carbon hydrogen fuel (Manchester Airport, 2022). However, there is considerable work to be completed to ensure operators regarding hydrogen safety. The early introduction of hydrogen to airports for non-aircraft applications may assist in supporting familiarity of operation, focusing on backup generation, hydrogen bus fuelling, and ground vehicles (Catapult, 2023).

(3) Hydrogen-powered train

In 2020, Alstom Transport (UK) Ltd announced plans to build a new 'Breeze' 600 series of green hydrogen trains. When fully operational, it is anticipated that the project will generate 200 high-quality engineering positions at Alstom's Widnes Transport Technology Centre. However, the project will require a commitment from the UK Government to upgrade the railway network with hydrogen trains. The Breeze 600 series is a conversion project involving the engineering of the existing Class 321, considered as the UK's most reliable rolling stock. The Class 321 is a fit in terms of characteristics, fleet size and availability for conversion to a hydrogen multiple unit (HMU). At present, Alstom is planning to test hydrogen-powered trains in the Merseyside area. There have been high-level negotiations with the LCR regarding the development of a demonstrator (Fowler, 2017).

3.6. A concern of the supply chain costs

From the production perspective, one of the most important constraints of a regional hydrogen cluster is the localised costs of renewable energy production. The cost of hydrogen varies significantly across regions due to the availability of energy inputs (Caglayan et al., 2021). The scale-up of hydrogen from a supply and demand perspective is dependent on access to a cost-effective network infrastructure that provides security of supply to customers (Williams et al., 2022). However, it is argued that for oil refinery decarbonisation (CCS, hydrogen fuel switching and hydrogen production) (Essar Oil based in Merseyside), the cost will equate to £1.2 billion, which is very prohibitive (Wickham et al., 2022).

From the transport perspective, transport infrastructure in the LCR will need to be repurposed or purpose-built, incurring high up-front costs (Department for Business Energy & Industrial Strategy, 2022). As a result, HyNet plans to offset infrastructure construction costs through UK Government funding, totalling £72 million (HyNet North West, 2021). The funding comprises £33 million from the UK Research and Innovation (UKRI) through the Industrial Decarbonisation Challenge (IDC) Fund and £39 million of consortium partner contribution (HyNet North West, 2021). Once commissioned, market prices plus government payments will provide income to the operating companies over (typically) 15-year contracts, which include:

- Hydrogen production: Revenue support for producers using a contract for difference so that the off-taker sale price is equal to the natural gas price – Low Carbon Hydrogen Agreement.
- CO_2 transport and storage: Regulated asset base model with allowed revenue influencing network charges to users of the infrastructure, with additional income via Carbon Dioxide Transport and Storage Revenue Support Contract.
- Hydrogen transport: Regulated asset base model with allowed revenue influencing network charges to users of the infrastructure, with additional income via Hydrogen Transport Revenue Support Contract.

4. SWOT analysis through roundtable discussion

The roundtable discussions facilitate further understanding by probing the opinions of stakeholders, where discussion tasks are drafted by the information/data from Section 3. Specifically, the detailed descriptions of ongoing projects (e.g., HPP1, HPP2, and CCS infrastructure), technical bottlenecks (e.g., green hydrogen cost, safety concerns, and public acceptance), and sector-specific applications (e.g., industrial, domestic, and transport demand) enable the development of targeted and context-sensitive discussion tasks. These tasks (see Appendix A) are designed to probe stakeholder perceptions of technological maturity, infrastructure gaps, and strategic opportunities in line with the region's actual conditions. Furthermore, the insights from Section 3 ensure that the SWOT analysis is not conducted in abstraction, but is instead anchored in the practical realities of the LCR's hydrogen transition pathway.

In this study, the roundtable discussion is chaired by a facilitator who guides and structures the conversations around the tasks outlined in the following sections. All participants are asked to answer these tasks by quantitative scoring and open discussions, where their answers are recorded. The criteria for different scores are presented in Appendix A. The collected information is processed, integrated, and analysed, and the results are summarised and presented below.

4.1. Identification of the state-of-the-art and influential factors for hydrogen production

4.1.1. Hydrogen production technology development within the LCR

Fig. 4 demonstrates the responses from attendees regarding the current state of production technology development within the LCR. The comparison between steam methane reforming (SMR) and electrolysis shows that electrolysis is perceived as more developed within the LCR, with a higher weighted average score (4.5 vs. SMR's 4.0). While SMR has a wider spread of opinions, with several respondents rating it both low (1) and high (7), electrolysis is more consistently rated in the middle-to-high range, reflecting broader confidence in its development. This distinction likely highlights the growing preference for electrolysis as a cleaner, renewable hydrogen production method, aligned with decarbonisation efforts. Whereas SMR, though established, may face scepticism due to its reliance on natural gas and carbon emissions unless combined with carbon capture technologies. This perception could be due to the higher number of planned electrolytic projects around the LCR compared to reforming, as shown in Fig. 5. However, most of these projects are still around the concept and feasibility stages, apart from the one in St Helens, which has progressed into the Front-end Engineering Design (FEED), all of which would at least take another 4–9 years to be operational.

On the contrary, there are three reforming and carbon capture-enabled projects around LCR, which are included within those two projects by HyNet, i.e., HPP1 and HPP2, both of which are based in Ellesmere Port. Spearheaded by Protos, the third project is based on recycling plastic waste to produce hydrogen. Despite its significantly smaller capacity of 1 MW, the proposed hub seeks to create a symbiosis where businesses can enable themselves and their neighbours to meet their sustainability objectives and reach net-zero emission goals. Hence, despite the higher number of planned electrolytic projects, when considering the most developed production technology around LCR, reforming with carbon capture technology is leading the way forward for the time being.

Therefore, based on the aforementioned points, reforming combined with carbon capture is still a dominant hydrogen production method for industrial use. Due to its reliability and continuous supply offered by blue hydrogen, it can operate at a constant rate, providing hydrogen 95 % of the time. Green hydrogen is subject to fluctuations based on the availability of renewable energy. Additionally, the cost of producing blue hydrogen is currently three times cheaper than green hydrogen, making it the preferred short-term option. However, it also highlights the fact that green hydrogen holds significant potential for cost reduction through economies of scale and is expected to grow over time. Despite the advantages of SMR, concerns have been raised by climate scientists regarding the reliance on reforming and carbon capture technologies, which are viewed by some as unproven and potentially harmful to the UK's net-zero goals, as these technologies could perpetuate dependence on fossil fuels, creating a contentious debate about the future of hydrogen production in the region.

4.1.2. Factors affecting local hydrogen production

This study identified seven factors affecting hydrogen production and further assessed their strengths and weaknesses according to attendees' scoring, the results can be seen in Fig. 6.

Specifically, geographic location is seen as a clear strength, with the highest weighted average of 5.8. A deeper rationale is that the strategic impact, such as proximity to ports, access to feedstock, in particular offshore windfarm developments in the Irish Sea, and existing industrial plants, provides a solid foundation for hydrogen development. The existence of microgrids at port facilities, reducing reliance on the national grid, presents an additional advantage, allowing for more localised energy management and boosting the region's capacity for hydrogen production.

Costs, however, remain a significant weakness with a weighted average of 3.3. In relation to green hydrogen through electrolytic projects, high grid connection costs and time-consuming processes discourage developers, especially when they must shoulder the full cost of grid upgrades. Government efforts to spread these costs more evenly among developers are a step in the right direction, but competitive funding opportunities with restrictive ceilings exacerbate the issue.

Safety is perceived as a weakness with a weighted average of 3.6, due to the limited industry experience with large-scale hydrogen projects, which may increase operational risks. Regulatory frameworks may also not be fully developed or aligned with emerging hydrogen technologies, creating potential safety gaps. Workforce preparedness is also a concern, as inadequate training may lead to accidents.

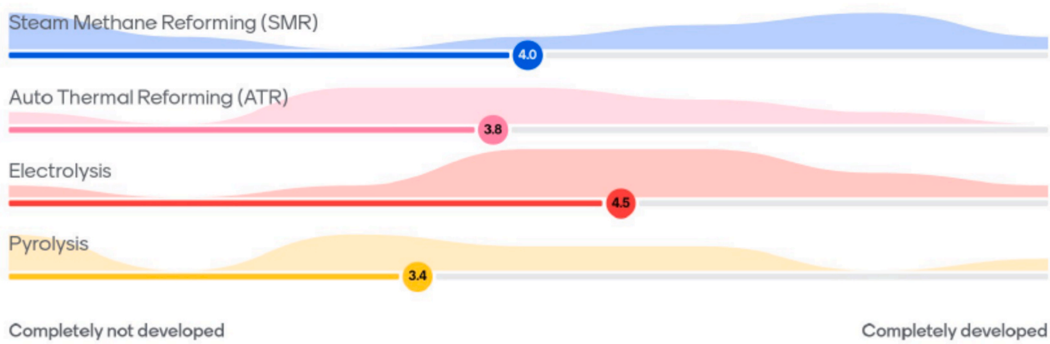

Fig. 4. Response to the current state of production technology within the LCR.

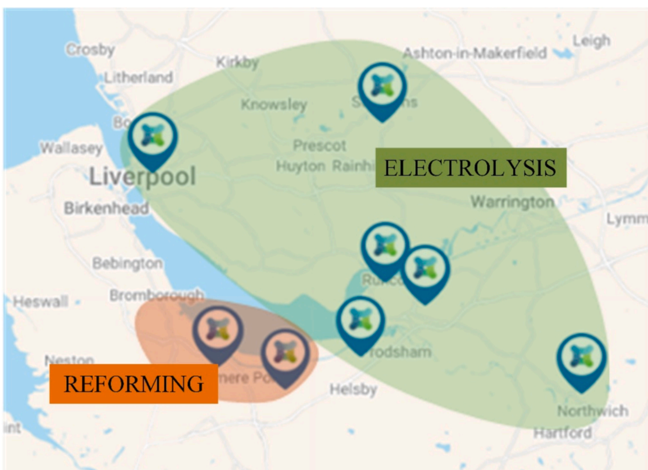

Fig. 5. Hydrogen projects around LCR (Hydrogen UK, 2024).

Policy/regulation and public acceptance present a mixed picture, being both a threat and an opportunity. Although the government is working to improve grid access and reduce financial burdens on developers, regulatory barriers still exist, such as delays in grid connection and high costs associated with upgrades. Given this, current policy frameworks need to be adapted to better support hydrogen deployment, which, if addressed, could significantly boost local production. Moreover, as reviewed in Section 3.5.2, while some public support exists, concerns about safety and practicality need to be addressed through community engagement and education. The government and industry should maintain transparency, communicate ongoing efforts to mitigate risks, and emphasise the potential public benefits of hydrogen adoption, helping to secure broader support.

Both skills and infrastructure readiness are viewed as strengths, with weighted averages of 4.8, but they also represent opportunities for further improvement. The region has access to the necessary expertise, but stronger collaboration with universities could enhance workforce training. Grid capacity, on the other hand, remains a bottleneck, and reliance on the national grid can lead to delays and costs. The idea of microgrids offers an opportunity to expedite infrastructure development, providing flexibility in hydrogen production.

4.2. Identification of the state-of-the-art and influential factors for hydrogen storage and distribution

4.2.1. Hydrogen storage within the LCR

Fig. 7 suggests that compressed gas in aboveground tanks is considered the most suitable and well-developed hydrogen storage option within the LCR, with a weighted average of 5.8. This preference likely stems from practical advantages such as scalability and integration with the current infrastructure (e.g., roads or pipelines), making it the most viable short-term solution. Meanwhile, the suitability of this method is reinforced by its ease of deployment without the need for significant new infrastructure, making it a logical choice currently.

Liquefied hydrogen in storage tanks follows closely with a weighted average of 4.9, indicating that while it is a viable option, it is viewed as less immediate compared to aboveground storage. Storing hydrogen as a liquid requires cryogenic conditions, which involve higher costs and technological requirements. This method, however, could serve niche applications where large volumes of hydrogen are needed, particularly for long-distance transport or industrial use, where the energy density of liquefied hydrogen becomes advantageous.

Liquid organic hydrogen carriers (LOHC), with a weighted average

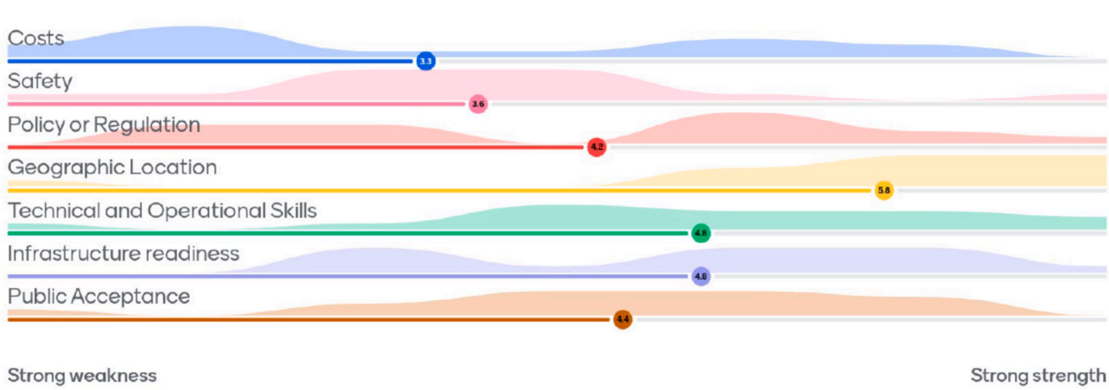

Fig. 6. Response to strengths and weaknesses for local hydrogen production.

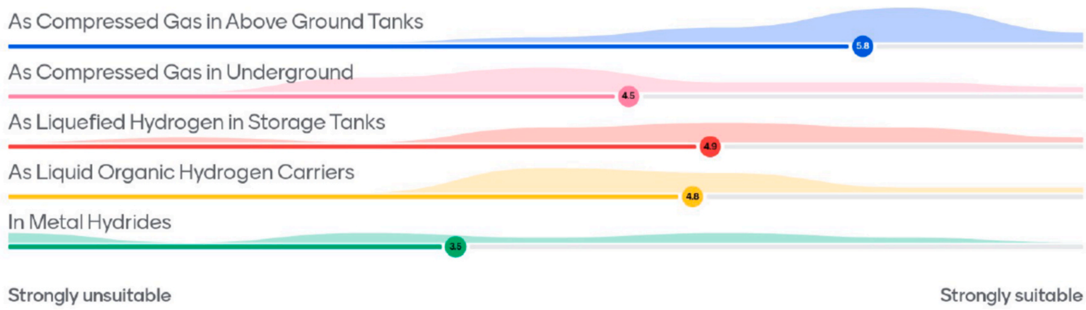

Fig. 7. Response to hydrogen storage methods for LCR.

of 4.8, also show promise as a storage method, especially for long-distance transport and safer handling of hydrogen. LOHC technology allows hydrogen to be stored and transported in a stable, non-flammable liquid form, making it a potentially safer option for specific applications. However, the technology is less mature than compressed gas storage, and further research is needed to refine its efficiency and cost-effectiveness.

On the other hand, compressed gas in underground storage receives a weighted average of 4.5, reflecting moderate interest but highlighting the barriers to its adoption, such as higher costs, lower technical readiness, and the need for additional research in the region. Although Section 3.3.2 has acknowledged the strategic geographical position of the LCR with its neighbouring salt caverns in Cheshire and the success of the well-established salt cavity hydrogen storage in Teesside, it is facing significant investment and infrastructure development, which the LCR may not yet be prepared for. Nonetheless, as hydrogen demand grows, underground storage could become a more attractive option for its long-term capacity and ability to store large quantities securely.

Metal hydrides are scored the lowest, with a weighted average of 3.5, indicating that this method is not currently viewed as a priority in the LCR. While metal hydrides offer safe and compact hydrogen storage, their relatively low capacity and high cost, along with technical limitations, make them less suitable for large-scale deployment at present.

4.2.2. Hydrogen transport method for LCR

Fig. 8 shows that all three methods are somewhat equally effective; this is due to the strategic location of the LCR. Specifically, pipeline networks are rated the most effective method for hydrogen transport within the LCR, with a weighted average of 5.6. Pipeline networks are ideal for continuous, large-volume transport over shorter distances, especially for supplying hydrogen to regional clusters with consistent demand. Though they require significant initial infrastructure investment, they offer cost efficiency over time.

This perception is substantiated by numerous industrial and government initiatives, the most prominent being the HyNet North West hydrogen pipeline plan, as shown in Fig. 9, which is also a partially enlarged view of the solid blue portion of Fig. 3. Currently, National Gas is paving the way to demonstrate that the National Transmission System and existing gas pipelines and assets can operate safely with hydrogen through their FutureGrid HP test facility at DNV Spadeadam (National Gas, 2024), while the UK government is also working towards a strategic policy decision to support blending of up to 20 % hydrogen by volume into GB gas distribution networks. These collective initiatives will position pipelines as a dominant transport method within the LCR.

With regards to inland hydrogen transportation, tankers/tube trailers, with a weighted average of 5.4, are suited for flexible, smaller-scale distribution, particularly where hydrogen demand is decentralised or pipeline infrastructure is unfeasible. This method allows for scaling up or down depending on immediate needs, making it useful in areas with fluctuating or emerging hydrogen demand. Marine vessels, with a weighted average of 5.5, are particularly effective for international transport or moving hydrogen across large bodies of water, especially in liquefied form. This option is vital for export scenarios or transporting hydrogen from coastal production sites to global markets. Together, these transport methods provide complementary options depending on the distance, scale, and purpose of hydrogen movement within the LCR.

4.2.3. Factors affecting local transport of hydrogen

Fig. 10 highlights key strengths and weaknesses in developing an effective hydrogen distribution network within the LCR. Geographic location still emerges as the strongest factor, with a weighted average of 5.3.

However, the costs scored a low weighted average of 3.5, indicating that financial barriers remain significant. The high cost of building and maintaining infrastructure, such as pipelines, is seen as a considerable obstacle. There are mechanisms like the regulated asset base, which distribute costs among gas consumers, but concerns about cost burdens on natural gas consumers persist. Furthermore, the gradual replacement of natural gas with hydrogen may result in increased energy costs, affecting the pace of infrastructure development.

Infrastructure readiness, with a weighted average of 3.9, shows mixed perceptions. Despite promising projects like HyNet, challenges remain in repurposing existing pipelines for hydrogen use. The uncertainty about hydrogen tolerance in existing plastic pipelines raises concerns about the infrastructure's preparedness. This indicates a need for further reinforcement to ensure hydrogen compatibility, as well as additional research into repurposing.

Skill availability receives a more favourable score of 4.7, suggesting that the region has a growing talent pool in technical and operational skills. However, more investment in training and education is likely needed to sustain this strength as hydrogen distribution expands.

Policy and regulation scored 4.3, reflecting moderate confidence in the regulatory landscape. While some legislation exists, the lack of standardised protocols for hydrogen transport poses a barrier. Creating and enforcing consistent safety legislation across the sector is essential to gaining public trust and ensuring the safe operation of hydrogen infrastructure.

The absence of clear safety standards complicates the development of hydrogen transport and is closely tied to concerns about safety and poor public acceptance, which scored 3.6 and 3.4, respectively. Academic and professional literature also emphasises this, as demonstrated by the following passage from (Aria, 2019).

"The general public remains sceptical; in the minds of people, hydrogen is often synonymous with danger, especially since the

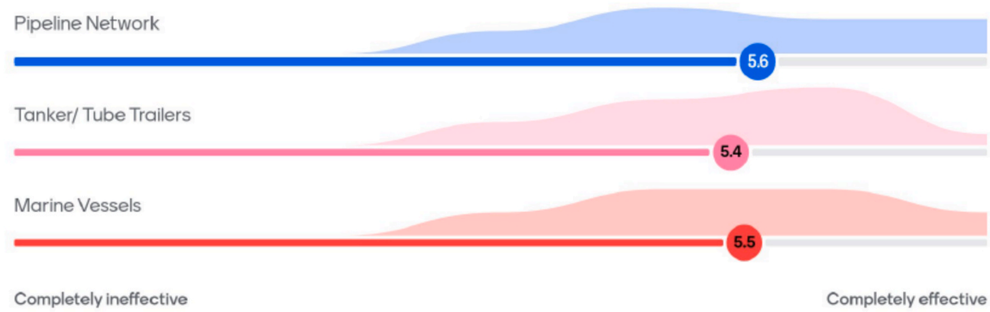

Fig. 8. Response to effectiveness of hydrogen transport methods.

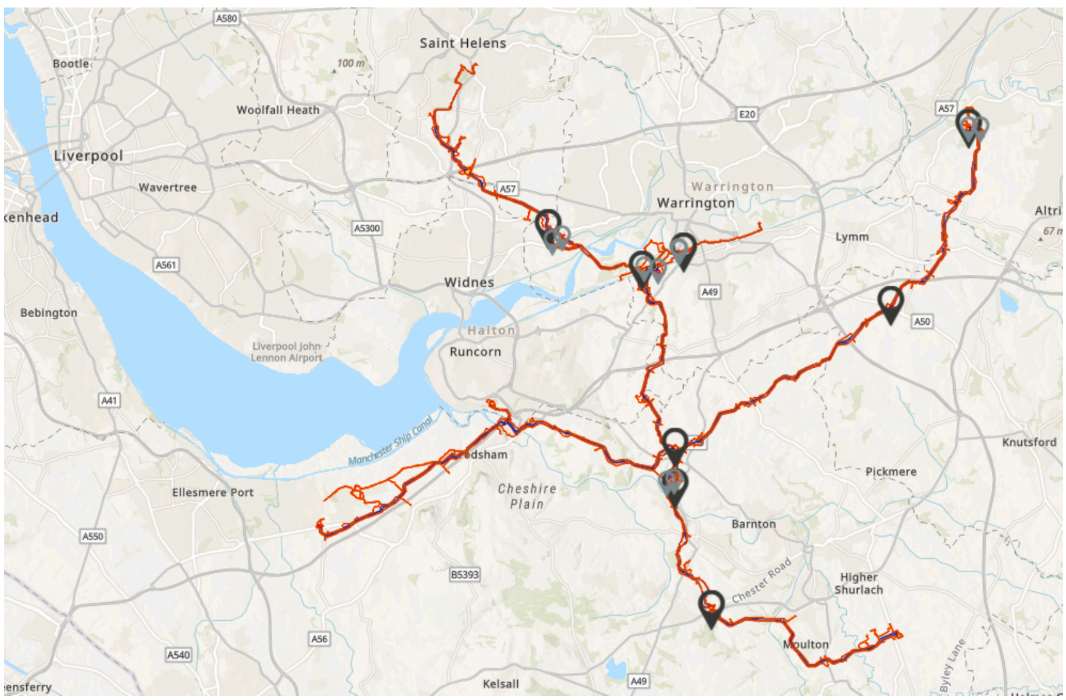

Fig. 9. HyNet hydrogen pipeline plan (Cadent, 2024).

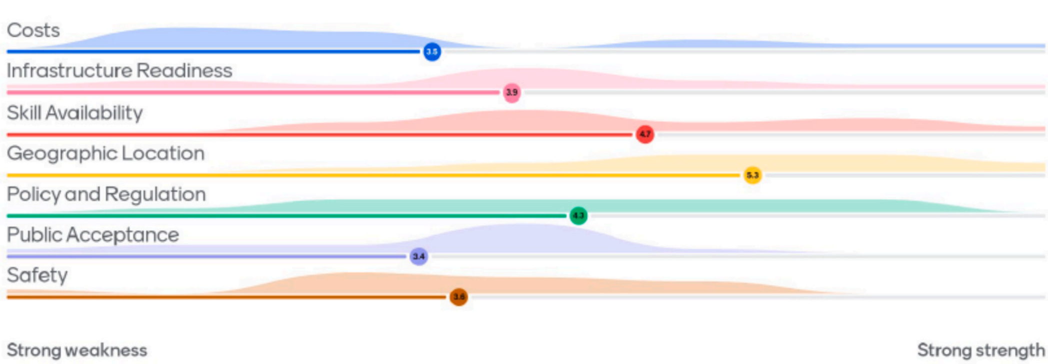

Fig. 10. Response to strengths and weaknesses for local transport of hydrogen.

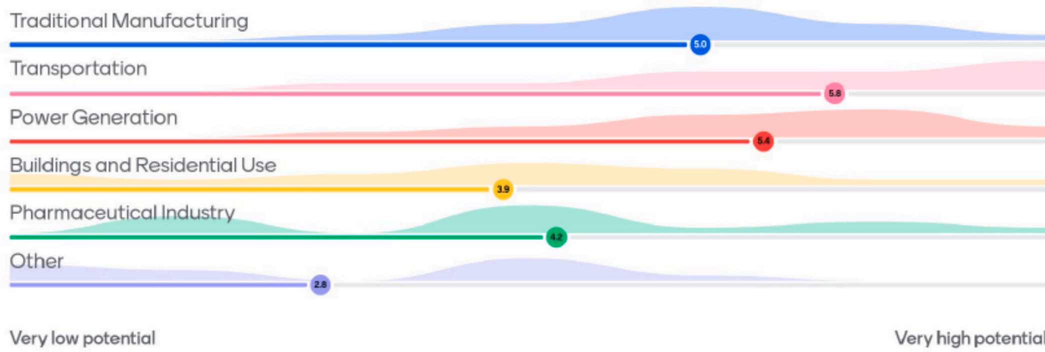

Fig. 11. Response to the potential for local utilisation of hydrogen.

Hindenburg disaster on 6 May 1937. The best way to calm the fears is to carry out an objective analysis of risks related to hydrogen in order to define and implement preventive and protective measures to avoid such accidents from recurring or at least keep the consequences to a strict minimum".

Simultaneously, public education and outreach efforts are necessary to improve understanding and acceptance of hydrogen technologies.

4.3. *Identification of the state-of-the-art and influential factors for hydrogen utilisation*

4.3.1. *Hydrogen utilisation within the LCR*

Fig. 11 illustrates responses to strengths and weaknesses for local utilisation of hydrogen. With a weighted average of 5.8, the transportation sector is ranked highest in terms of utilisation potential. This aligns with the ongoing initiatives in LCR, where hydrogen is being considered for heavy-duty vehicles like buses, lorries, and ferries. Hydrogen's role in reducing emissions in long-haul and heavy-duty transport is a key focus, and several pilot projects are already underway, as shown in Table 4. The survey results reinforce this sector's strong potential for hydrogen, emphasising the need for dedicated refuelling infrastructure to support long-distance routes. Additionally, collaboration with other regions and international stakeholders will be essential for establishing a robust hydrogen transport network.

Power generation receives a weighted average of 5.4, highlighting its potential as a reserve energy source. Hydrogen is seen as a viable backup for times of low renewable energy output, particularly in scenarios where offshore wind energy may be insufficient. However, hydrogen is not perceived as a primary solution for power generation but rather as a complementary option during renewable energy shortages, such as in the winter months. The feasibility of hydrogen in power generation is contingent on the expansion of renewable energy infrastructure in the LCR.

Traditional manufacturing sectors, such as energy-intensive industries like Pilkington and Unilever, are scored a weighted average of 5. Hydrogen is considered essential in these industries, where high temperatures are required for production processes, and combustion gases like hydrogen could be the most viable alternative. The need for clean, high-temperature fuel in these sectors underscores the importance of hydrogen as a key enabler for industrial decarbonisation in the region.

Buildings and residential use are scored a weighted average of 3.9, reflecting a lower potential for hydrogen in this sector. The consensus is that other technologies, such as electric boilers and heat pumps, are more suitable for decarbonising residential heating. Hydrogen's production and distribution challenges, combined with the presence of more mature alternatives, contribute to its limited potential in this area. However, hydrogen may still play a role in specific large-scale residential projects or in regions where other energy solutions are less viable.

4.3.2. *Factors affecting local hydrogen utilisation*

From Fig. 12, the survey results provide valuable insights into the various factors influencing the transition to hydrogen within the LCR, highlighting both key strengths and challenges. One of the most significant weaknesses identified is still the cost of hydrogen. With a weighted average of 2.9, respondents perceive the cost of production, storage, and distribution as a major hurdle. While some sectors may absorb these higher costs, particularly energy-intensive industries, no clear strategies are proposed to mitigate the financial challenges. The region could explore avenues to capitalise on demand from sectors like heavy industry or specialised transport, where costs could potentially be passed on to end consumers.

In contrast, demand for hydrogen is identified as one of the region's major strengths, with a high weighted average of 5.5. The LCR's industrial profile, particularly its high-energy sectors, creates a strong foundation for predictable demand. The transportation sector, especially heavy-duty transport like buses and lorries, represents significant potential for hydrogen utilisation. Additionally, the region's strategic location with its port and well-established industrial infrastructure makes it ideally suited for both local and export demands, particularly in the maritime sector. This demand could help justify the initial high costs associated with hydrogen infrastructure, spurring further investment.

In terms of technical and operational skills, the region shows a moderate level of preparedness, with a weighted average of 4.7. While not considered a critical weakness, there is recognition that upskilling the workforce is essential for the hydrogen transition. Training is needed in areas such as hydrogen vehicle maintenance, fleet management, and retrofitting. Collaboration between academic institutions and industries will be crucial to ensuring that the workforce is adequately prepared to handle these new technologies and operational demands.

The policy and regulatory environment also presents a challenge, with a weighted average score of 4.3. The absence of standardised hydrogen policies and regulatory frameworks is a significant barrier to wider adoption. Respondents emphasise the need for government intervention in the form of subsidies, emission regulations, and other market incentives to foster investment in hydrogen technologies. Without a cohesive policy landscape, uncertainty will continue to hinder private-sector investment and infrastructure development in the region.

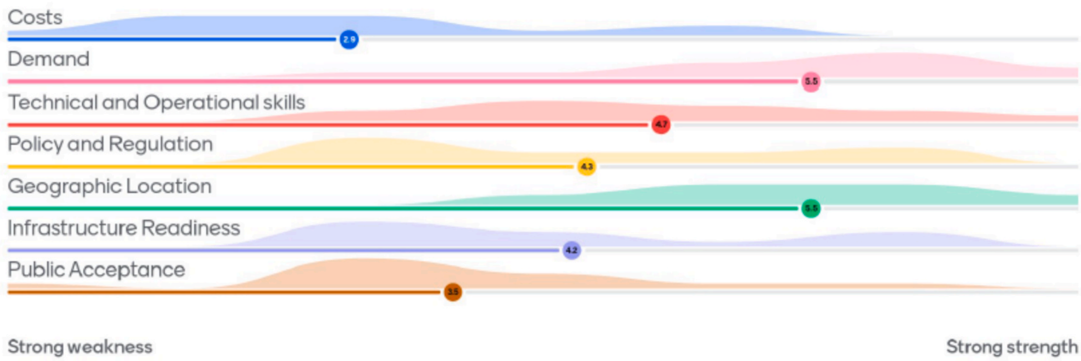

Fig. 12. Response to strengths and weaknesses for local utilisation of hydrogen.

4.4. Collaborative opportunities across the supply chain

The transition to a hydrogen economy presents numerous opportunities for the LCR, particularly through collaborative projects across the maritime, public transport, and automotive sectors. Coordinated efforts between industry, government, and academia will be critical in accelerating hydrogen production and adoption. Launching pilot projects and demonstrating hydrogen technology in practical applications will build confidence among stakeholders, create early demand, and facilitate widespread adoption. Some potential opportunities raised during the discussion are described below while more raw information can be found in Appendix B. In addition, several suggestions are provided below for the collaborative opportunities.

1. Maritime sector

The maritime sector offers significant potential for hydrogen adoption due to the high energy demands of large ships and river vessels. This scale of demand makes the sector well-suited for pilot hydrogen production projects, providing a commercial validation opportunity that smaller projects, such as hydrogen-powered buses, may lack. A focus on maritime hydrogen projects would create an ideal testing ground for scaling up hydrogen technologies while contributing to the region's decarbonisation goals.

2. Local fleets and public sector

Local fleets, including lorry and bus fleets, represent another important early market for hydrogen. The Port of Liverpool's HGV fleet, alongside public transportation, can play a key role in creating early demand for hydrogen in the region. Coordinating efforts between public sector fleets and the private sector will foster cooperation, stimulate demand, and promote practical demonstrations of hydrogen-powered vehicles, which can alleviate doubts about the technology's effectiveness.

3. Automotive and green energy integration

The integration of hydrogen infrastructure with key industrial sites, such as the automotive plants in South Liverpool, presents an opportunity to localise hydrogen supply chains. Connecting the Port of Liverpool with automotive production sites through hydrogen infrastructure would help establish a reliable, localised hydrogen network. This initiative could support both manufacturing operations and broader regional hydrogen use, linking energy demand with hydrogen supply.

4. Public acceptance through demonstration

Practical demonstrations of hydrogen-powered technologies, such as trucks, buses, and river vessels, are crucial to gaining public acceptance. Stakeholders and the public need to see hydrogen technology in operation to be convinced of its viability. Publicly visible pilot projects, involving trucks or lorries operating with hydrogen fuel, will help alleviate scepticism and build confidence in the region's hydrogen transition.

5. Collaborative industry-government-academia projects

Collaboration between industry, government, and academia is essential for advancing hydrogen production and utilisation. Academia can contribute through research, training, and skill-based education, while industry offers practical implementation expertise. The government, both national and local, plays a vital role in providing regulatory support, funding, and public awareness campaigns. These stakeholders must work together to align their efforts and create a clear strategy for hydrogen development in the region.

6. International funding and strategic planning

Collaborative efforts should focus on engaging with international funding programs such as the EU Horizon program, which can provide the necessary financial support for research, development, and pilot projects. Establishing a comprehensive strategy and project pipeline will improve access to funding sources and increase the likelihood of successful project implementation.

7. Holistic local area energy planning

Implementing a Local Area Energy Planning (LAEP) framework can help map hydrogen demand across the region and align it with the national energy architecture. This approach would enable the optimisation of resource allocation, ensuring that hydrogen production and distribution systems are integrated with broader regional and national energy networks.

4.5. A comprehensive SWOT analysis

This summary in Table 5 highlights the potential for hydrogen development through the analysis of the data collected from Sections 4.1 to 4.4, which provides a quick overview of strengths, weaknesses, opportunities and threats across the hydrogen supply chain. It also

Table 5
SWOT analysis for hydrogen development within the LCR.

Strength	Weakness
Production • Available and mature hydrogen production through reforming with carbon capture • Strategic location (proximity to ports, feedstock, renewable energy) • Available technical & operational skills Storage • Experiences in storing compressed gas in aboveground tanks Transport • Available and developing pipeline networks • Available tube trailers/ tankers Utilisation • Predominantly buses and HGVs in the transport sector	Production • Cost of producing green hydrogen • Lack of policy & regulatory framework to expedite hydrogen deployment Storage • Lack of demand clarity & new technologies Transport • Cost of building and maintaining pipeline infrastructure • Public perception Utilisation • Levelised cost of hydrogen • Lack of infrastructure readiness for utilising hydrogen
Opportunities Production • Scaling up of green hydrogen production projects • Development of more microgrids Storage • Potential to store compressed gas in underground storage (Salt Caverns) • Potential to develop hydrogen liquefaction Transport • Available port for transporting hydrogen by marine vessels • Repurpose pipelines • Create and enforce consistent safety legislation Utilisation • Utilise hydrogen to power systems • Utilise hydrogen in traditional manufacturing • Develop hydrogen utilisation in the marine sector (e.g., e-methanol, port facilities) • Upskill workforce in areas such as hydrogen vehicle maintenance, fleet management, and retrofitting • Practical demonstrations of hydrogen-powered technologies to gain public acceptance	**Threats** Production • Over-reliance on reforming and carbon capture may perpetuate the UK's dependence on fossil fuels • Grid capacity bottleneck, delays in grid connection and high cost associated with upgrades • Public acceptance Storage • Underground storage, liquid hydrogen carriers, and metal hydrides require significant investments and further development to achieve cost-effective scalability Transport • Lack of standardised protocols for hydrogen transport Utilisation • Limited potential for buildings and residential applications due to the presence of more mature alternatives (electric) • Lack of standardised policies for hydrogen transport • Public acceptance

provides useful information that could be tailored to guide hydrogen project development in other city regions with regard to the possible hydrogen-favourable sectors.

Specifically, converting the SWOT in Table 5 into an actionable agenda requires sequencing policy interventions so that early institutional moves unlock investable projects, mid-term build-out consolidation network effects, and longer-term options mature without stranding near-term assets. In the short term, policy should leverage existing strengths by anchoring offtake around technologies and assets that are already available or advancing through consent, notably reforming with CCS integrated into the HyNet system, the initial segments of the hydrogen pipeline and aboveground compressed gas storage. This implies concluding revenue-support arrangements for producers and networks consistent with the Low Carbon Hydrogen Agreement and regulated-asset models described in Section 3, finalising permits where development consents are already available, and using Local Area Energy Planning to prioritise hydrogen-ready zones that couple industrial clusters, the Port of Liverpool and public sector fleets. In parallel, visible end-use demonstrations in buses, HGVs, and port operations should be mobilised to turn a perceived strength in transport into bankable offtake, with a clear communications plan to build public confidence.

Addressing weaknesses requires early clarity on costs, standards and responsibilities. Over the next few years, a coordinated disclosure of levelised hydrogen costs for priority LCR applications, accompanied by standardised technical specifications for purity and pressure at the point of use, will reduce transaction costs for offtakers and financiers. The same time horizon should be used to agree interim safety and operational protocols for road transportation and site handling while the dedicated pipeline network is constructed, and to publish a skills and accreditation pathway for vehicle maintenance, depot operations and port handling so that workforce readiness keeps pace with deployments. In the medium term (three to five years), the focus shifts to commissioning contracted production capacity, bringing initial pipeline corridors into operation, and converting temporary logistics (tube trailers and tankers) into a predictable hybrid regime that progressively hands over to pipelines. Over the longer term (five to ten years), the cost gap for electrolysis can be narrowed by co-locating electrolytic projects with increasingly abundant offshore wind and by integrating large-scale storage, thus reducing exposure to electricity price volatility and enabling seasonal balancing.

Opportunities should be sequenced so that infrastructure readiness aligns with growing demand. In the short term, port-led demonstrations for heavy road transport and harbour equipment, together with preparatory steps for maritime fuels such as e-methanol and ammonia handling, can create early volumes and learning effects. In the medium term, the region can expand pipeline interconnections and progress subsurface storage appraisal so that salt-cavern capacity near the LCR becomes a practical balancing option rather than a distant prospect. In the longer term, scaling electrolysis alongside inter-seasonal storage would allow a gradual pivot from blue to green hydrogen while avoiding abrupt shifts in utilisation assets and network configuration. Throughout, the TH approach should be used to co-design projects, with academia supporting measurement, verification and safety cases, industry delivering projects at risk once revenue arrangements are in place, and the LCRCA convening planning, funding applications and public engagement.

Threats identified in Table 5 require proactive governance. Over the next two years, reliance on reforming with CCS should be managed by transparent performance metrics for capture rates and by publishing a forward schedule that shows how electrolytic capacity will be integrated as costs fall, thereby addressing concerns that blue hydrogen could entrench fossil fuel dependence. In the same time horizon, perceptions of safety and a lack of standardised transport protocols should be countered by adopting a consistent regional code of practice for hydrogen handling and by coordinating public-facing trials in everyday settings. From years three to five, grid-connection delays and electricity price risk should be mitigated through early queue management and by locating electrolysers where they can access low-congestion nodes or a dedicated renewable supply. Over five to ten years, the regulatory framework for underground storage and for marine transport of hydrogen or carriers should mature in step with projects, avoiding a policy lag that would otherwise slow capital deployment.

Bringing these strands together, the near-term agenda transforms strengths into immediate projects and neutralises the most critical weaknesses through clear costs, standards and skills. The medium-term agenda consolidates opportunities by commissioning production, activating pipelines and piloting subsurface storage. The long-term agenda broadens the technology base and deepens system flexibility so that the LCR can pivot to higher shares of green hydrogen without stranding assets. This time-bounded translation of the SWOT is intended to guide the LCR towards an investable pathway that is technically credible, institutionally feasible and publicly legitimate.

5. Summary

This study systematically reviews the readiness of the hydrogen supply chain infrastructure within the LCR, which highlights four sectors in the hydrogen economy, i.e., production, storage, transportation, and utilisation. Based on the TH model, industry-academia-governmental stakeholders offer first-hand data to assess the strengths, weaknesses, opportunities, and threats of hydrogen development in the LCR. Overall, based on the evidence reviewed in Section 3 with the roundtable perceptions in Section 4, a comparison shows where the literature aligns with stakeholder views, and these commonalities offer the future trends for hydrogen development in the LCR:

1) On production, Section 3 shows that near-term capacity growth in the LCR is anchored in reforming with CCS through the HyNet programme (HPP1/HPP2), while many electrolytic schemes remain at concept or feasibility stages. Nevertheless, stakeholders still perceived electrolysis as more developed than SMR, reflecting the visibility of planned electrolytic pilots, even if most are pre-FEED and several years from operation. This divergence indicates a need to clarify sequencing, i.e., blue hydrogen as a bridging supply with green projects scaling later.
2) On storage, the review highlights substantial theoretical potential in neighbouring salt caverns but also low technology maturity and geographic constraints for subsurface options at present. Consistent with this, participants rated aboveground compressed gas as the most suitable current option and scored underground storage more modestly, signalling cautious realism about deployment timelines.
3) On transport, Section 3 documents the HyNet plan for a dedicated hydrogen pipeline and growing port-based capabilities. Correspondingly, stakeholders rated pipelines highly for effectiveness within the LCR, while also recognising roles for road transportation during the build-out phase, showing close alignment between infrastructure plans and perceived practicality.
4) On utilisation, the evidence base emphasises early opportunities in the maritime cluster and heavy road transport associated with the Port of Liverpool. Stakeholders similarly ranked transport highest among end uses, reinforcing the case for near-term, visible demonstrations in fleets and port operations to create bankable offtake.
5) Section 3 underscores cost, regulatory and public-acceptance constraints, and participants' scores mirror these concerns, with costs, safety and acceptance all rated as weaknesses, indicating that financing frameworks, safety standards and engagement will be decisive enablers of the regional pathway.

Furthermore, this study is subject to a few limitations associated with the limited data sources and research scope. First, insights from the facilitator-led roundtable and the use of Likert scoring are subject to perception biases arising from the composition of the 31-participant samples, the self-reporting tendencies and the regional characteristics in hydrogen development. A follow-up investigation is necessary to update the findings and extend the datasets. Second, the evidence review and workshop capture a time-bound study within a rapidly evolving regional context, so some judgments may shift as projects advance through consents and contracting, e.g., electrolytic production timing, storage options and network build-out. Third, part of the regional evidence base necessarily draws on grey literature such as project documentation and industry reports, which can vary in transparency and update frequency. Although this study mitigates this by triangulating with academic and public sources and by using the roundtable to validate or challenge specific claims, these factors still suggest that the findings should be interpreted as indicative rather than definitive, while motivating future longitudinal follow-ups and closer linkage to comprehensive datasets.

CRediT authorship contribution statement

Yuhao Cao: Writing – review & editing, Writing – original draft, Project administration, Methodology, Data curation, Conceptualization. **Reuben Singh Darshan Singh:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Scott Caldwell:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Richard Clarke:** Project administration, Funding acquisition. **Chia-Hsun Chang:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Zhuohua Qu:** Supervision, Project administration, Funding acquisition. **Zaili Yang:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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. Round table discussion tasks

Table A1
The seven-point likert scale for round table discussion tasks.

Section	Question	1	2	3	4	5	6	7	Skip
Production	**1. Based on your knowledge, which one of the following Hydrogen Production Technologies is well developed within the LCR**	**Completely Not Developed** The technology is not implemented or recognised within the LCR; minimal to no research or development efforts exist.	**Moderately Not Developed**The technology has limited recognition or implementation in the LCR; some initial research or small-scale projects may be underway.	**Slightly Not Developed** The technology shows signs of development but is not widely adopted; ongoing research efforts exist, but practical applications are rare.	**Neutral** The technology is gaining traction within the LCR; there are several research projects, pilot programs, or early-stage commercial applications.	**Slightly Developed** The technology is well established and increasingly utilised in the LCR; there are multiple successful projects and a growing industry presence.	**Moderately Developed** The technology is widely adopted and integrated into various sectors within the LCR; numerous successful applications and a robust support network exist.	**Completely Developed** The technology is a leading method for Hydrogen production in the LCR; it is fully integrated into the economy with extensive research, commercial applications, and widespread industry usage.	No Idea
	2. In your opinion, to what extent are the following factors a Strength or Weakness for local production of Hydrogen	**Strong Weakness**This factor is a significant barrier to local Hydrogen production; it severely limits feasibility or viability.	**Moderate Weakness**This factor poses challenges for local Hydrogen production; it negatively impacts implementation or development.	**Slight Weakness**This factor presents some issues, but is not a major hindrance; it may slow progress or create minor complications.	**Neutral**This factor is neither a strength nor a weakness; it has a neutral impact on local Hydrogen production.	**Slight Strength**This factor provides some benefits for local Hydrogen production; it can support development, but is not a primary enabler.	**Moderate Strength**This factor significantly contributes to the success of local Hydrogen production; it enhances feasibility and encourages development.	**Strong Strength**This factor is a major enabler for local Hydrogen production; it creates substantial advantages and greatly facilitates implementation.	
Storage and Distribution	**1. Based on your knowledge, at present, which one of the following Hydrogen storage methods is most suitable for Hydrogen Storage within the LCR**	**Strongly Unsuitable**This storage method is not appropriate for the LCR; it presents significant challenges or risks that make it impractical.	**Moderately Unsuitable**This storage method has considerable limitations for use in the LCR; it may hinder effective Hydrogen storage and distribution.	**Slightly Unsuitable**This storage method has some drawbacks, but it may still be used in specific contexts; its effectiveness is limited.	**Neutral**This storage method is neither suitable nor unsuitable; it has a mixed impact on Hydrogen storage in the LCR.	**Slightly Suitable**This storage method offers some advantages for the LCR; it can be effectively utilised in certain applications.	**Moderately Suitable**This storage method is well-suited for the LCR; it provides a practical and effective solution for Hydrogen storage needs.	**Strongly Suitable**This storage method is highly appropriate for the LCR; it represents an optimal solution with numerous advantages for Hydrogen storage.	
	2. Which one of the following existing transport methods is the most effective to implement within the LCR	**Completely Ineffective** The method is seen as having almost no potential for effective implementation.	**Moderately Ineffective** The method is largely ineffective, with significant limitations.	**Slightly Ineffective** The method has some limitations, but could work in certain situations.	**Neutral** The method is neither particularly effective nor ineffective; it could go either way.	**Slightly Effective** The method is somewhat effective and has more advantages than disadvantages.	**Moderately Effective** The method is generally effective and suitable for implementation.	**Completely Effective** The method is seen as the best and most effective option for implementation.	
	3. To what extent is the following a strength or weakness in the development of an effective transport of Hydrogen within the LCR	**Strong Weakness** The factor is a major barrier to the development of Hydrogen transport.	**Moderate Weakness** The factor poses some challenges to development.	**Slight Weakness** The factor is a minor hindrance to development.	**Neutral** The factor is neither a strength nor a weakness.	**Slight Strength** The factor provides some support for development.	**Moderate Strength** The factor is considerably supportive of development.	**Strong Strength** The factor is a major enabler for the development of Hydrogen transport.	
Utilisation	**1. Rate each one of the following sectors in terms of their potential for Hydrogen utilisation within the LCR**	**Very Low Potential**This sector shows little to no potential for Hydrogen utilisation; significant barriers exist that hinder any development.	**Low Potential**This sector has limited potential for Hydrogen utilisation; few opportunities exist, and challenges outweigh benefits.	**Slight Potential**This sector shows some potential for Hydrogen utilisation; there are isolated opportunities, but the overall impact is minimal.	**Moderate Potential** This sector has a reasonable potential for Hydrogen utilisation; some initiatives or projects exist, but widespread adoption is still limited.	**Considerable Potential**This sector shows strong potential for Hydrogen utilisation; there are several initiatives, projects, or applications demonstrating feasibility.	**High Potential**This sector has significant potential for Hydrogen utilisation; it is actively exploring various applications and opportunities for integration.	**Very High Potential**This sector is a leader in Hydrogen utilisation; it has numerous successful projects, strong cooperation, and a clear path toward widespread adoption.	
	2. To what extent is the following a strength or weakness in improving the utilisation of Hydrogen within the LCR	**Strong Weakness** The factor greatly hinders the utilisation of Hydrogen.	**Moderate Weakness** The factor presents noticeable challenges to utilisation.	**Slight Weakness** The factor has some minor negative impacts on utilisation.	**Neutral** The factor neither contributes to nor detracts from Hydrogen utilisation.	**Slight Strength** The factor offers some minor positive influence on utilisation.	**Moderate Strength** The factor provides substantial support to utilisation.	**Strong Strength** The factor is a major enabler for the improved utilisation of Hydrogen.	

Appendix B. Co-operative projects mentioned for future work

1. HyNet (https://hynet.co.uk/)
2. Levidian LOOP tech to support Hydrogen for transportation (https://www.levidian.com/loop)
3. New UK research council PBIAA project (https://www.ukri.org/opportunity/place-based-impact-acceleration-account/)
4. CPC maritime flagship project in LCR (https://cp.catapult.org.uk/event/martimeworkshop1-2/)
5. Liverpool-Belfast green corridor prioritised projects (https://www.royalhaskoningdhv.com/en/newsroom/news/2024/a-feasible-green-shipping-corridor-for-the-irish-sea)
6. National Highways Project Rapid – aligning infrastructure network to pair up with EV. Clean energy solutions (https://nationalhighways.co.uk/our-work/environment/environmental-sustainability-strategy/)
7. Freeport innovation fund (https://www.great.gov.uk/international/content/investment/how-we-can-help/freeports-in-the-uk/)
8. Future fuels project (https://futurefuels.imo.org/)
9. Clean Hydrogen innovation programme run by carbon trust (https://programmes.carbontrust.com/chip/)
10. Hydrogen UK (https://Hydrogen-uk.org/wp-content/uploads/2024/05/Hydrogen-UK-Imports-and-Exports-Report-2024.pdf)
11. EU research grants on climate change and net zero (https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/environment-and-climate/european-green-deal_en)

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