

Article

Decarbonising Agriculture with Green Hydrogen: A Stakeholder-Guided Feasibility Study

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Abstract

Green hydrogen offers a promising yet underexplored pathway for agricultural decarbonisation, requiring technological readiness and coordinated action from policymakers, industry, and farmers. This paper integrates techno-economic modelling with stakeholder engagement (semi-structured interviews and an expert workshop) to assess its potential. Analyses were conducted for farms of 123 hectares and clusters of 10 farms, complemented by seven interviews and a workshop with nine sector experts. Findings show both opportunities and barriers. While on-farm hydrogen production is technically feasible, it remains economically uncompetitive due to high levelised costs, shaped by seasonal demand variability and low utilisation of electrolyzers and storage. Pooling demand across multiple users is essential to improve cost-effectiveness. Stakeholders identified three potential business models: fertiliser production via ammonia synthesis, cooperative-based models, and local refuelling stations. Of these, cooperative hydrogen hubs emerged as the most promising, enabling clusters of farms to jointly invest in renewable-powered electrolyzers, storage, and refuelling facilities, thereby reducing costs, extending participation to smaller farms, and mitigating risks through collective investment. By linking techno-economic feasibility with stakeholder perspectives and business model considerations, the results contribute to socio-technical transition theory by showing how technological, institutional, and social factors interact in shaping hydrogen adoption in agriculture. With appropriate policy support, cooperative hubs could lower costs, ease concerns over affordability and complexity, and position hydrogen as a practical driver of agricultural decarbonisation and rural resilience.

Keywords: green hydrogen; agricultural decarbonisation; techno-economic assessment; cooperative business models; net-zero farming



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1. Introduction

The urgent global imperative to achieve Net Zero emissions by 2050 has brought hydrogen (H₂) into sharp focus as a key energy vector for decarbonising hard-to-abate sectors [1]. Although H₂ currently accounts for just 0.1% of total global energy consumption, projections suggest it could contribute up to 10% by 2050, with the majority sourced from low-carbon emission technologies such as water electrolysis powered by renewables and natural gas reforming coupled with Carbon Capture Utilisation and Storage (CCUS) [1]. In 2020, nearly 80% of H₂ production—equivalent to 90 Mt—was derived from fossil fuels, generating over 900 Mt of CO₂ emissions [2].

Global hydrogen demand—currently around 90 million tonnes per year—is dominated by grey hydrogen, produced from fossil fuels (mainly natural gas via steam methane reforming) without capturing the resulting CO₂ emissions. It is used primarily in fertiliser production, oil refining, and chemical processes such as methanol production [3]. However, this status quo is incompatible with Net Zero ambitions, making a decisive transition to clean hydrogen urgently necessary. Green hydrogen, produced from water electrolysis powered by renewable energy, is near zero-carbon, while blue hydrogen, produced from natural gas with carbon capture and storage, offers a lower-carbon but transitional alternative. Under slower decarbonisation scenarios, where policy action and technology adoption progress more gradually, these incumbent sectors are likely to lead the initial shift by replacing grey hydrogen with cleaner options. Under more ambitious pathways, however, transformative applications such as green steel, synthetic fuels, heavy-duty transport, and low-carbon agriculture must drive the trajectory of hydrogen deployment.

The agricultural sector is increasingly recognised as a critical front for decarbonisation. Globally, it contributes nearly one-third of emissions (through farming, fertiliser use, and land-use change) [4]. In the UK, agriculture accounts for around 12% of emissions and is the largest source of nitrous oxide and methane. Progress toward the NFU's 2040 net-zero goal has been slow [5]. While mitigation of N₂O and CH₄ is essential, agriculture's ongoing dependence on fossil fuels—especially diesel in machinery—creates a significant CO₂ burden. Green hydrogen offers a pathway to cut this energy-related CO₂ and to produce low-carbon ammonia for fertilisers, bridging both energy and input decarbonisation [5]. Agriculture's heavy reliance on fossil fuels, especially diesel for heavy-duty vehicles, positions it as a high-impact candidate for green H₂ integration. In 2020, UK agriculture consumed approximately 473,000 tonnes of oil equivalent in petroleum products and 98,000 m³ of natural gas, with demand projected to rise by 2040 [6]. In response, the UK government has proposed new regulations to allow hydrogen-powered tractors, diggers, and forklifts to operate on public roads [7]. While such policies show momentum, these technologies are at different maturity levels. Hydrogen forklifts are the most advanced, with thousands already in commercial use. Tractors remain at the pilot stage with only a few prototypes, while diggers and other heavy machinery are largely experimental. This demonstrates both the promise and current limits of hydrogen in agriculture, highlighting the need for innovation and infrastructure to scale deployment [8,9].

Beyond decarbonising agricultural machinery, green H₂ holds significant promise in the production of low-carbon fertilisers, addressing one of the sector's most emissions-intensive inputs—and as a sustainable energy carrier for farms aiming to become self-sufficient. This aligns with the UK's ambition to achieve net-zero farming by 2040 [10]. However, despite its potential, the agricultural use of green H₂ faces substantial techno-economic challenges. High production costs, low competitiveness relative to fossil alternatives, and financial barriers such as the capital-intensive nature of electrolysis infrastructure currently limit its scalability [11,12]. In addition, land-use conflicts and water resource constraints raise further concerns, especially in rural regions where farming and hydrogen production need to coexist to avoid competition over resources. Without appropriate planning controls, hydrogen expansion could compete with farming, driving tensions over land and water use [13].

As hydrogen technologies advance and costs decline, clean hydrogen is expected to replace grey hydrogen, which still dominates supply today. Projections suggest that by 2050, clean hydrogen could meet 73–100% of global demand, reducing grey hydrogen to only a marginal role in all but the most conservative scenarios [3]. Achieving this transition will require urgent investment in infrastructure, large-scale electrolyser deployment, supportive policies, and effective market incentives. Global hydrogen production must scale up rapidly,

reaching around 200 Mt by 2030 and 585 Mt by 2050, with electrolyser capacity expanding from 0.3 GW today to about 3600 GW [3]. In the UK, hydrogen is expected to become a major part of the energy system by 2050, potentially supplying up to one-third of total demand [10].

This paper first reviews the techno-economic, social, and regulatory perspectives on green hydrogen in agriculture, highlighting key barriers and research gaps (Section 2). It then outlines the mixed-methods approach used in the study (Section 3), presents the results and discussion (Section 4), and concludes with recommendations for policy and practice (Section 5).

2. Evidence Synthesis

2.1. Techno-Economic Review of Green H₂ in Agriculture

Green hydrogen (H₂) is produced through the electrolysis of water using renewable electricity, ensuring minimal associated greenhouse emissions. Electrolysers—most commonly alkaline, proton exchange membrane (PEM), and solid oxide—differ in cost, efficiency, and maturity, but all operate by splitting water into hydrogen and oxygen using electricity [14]. In agricultural contexts, green hydrogen has two primary uses: (1) as a feedstock for fertiliser production (via Haber–Bosch), enabling a low-carbon ammonia pathway, and (2) as an energy carrier for farm machinery, via modified internal combustion engines or fuel cells [15].

However, its techno-economic feasibility in agriculture remains challenged. While conceptually promising, its deployment is constrained by high production costs, logistical complexity, and infrastructure requirements. Scaling use demands advances in electrolyser technology, lower renewable electricity costs, supportive policy frameworks, and investment in hydrogen supply chains. Janke et al. [16] conducted a focused techno-economic analysis of green H₂ integration within agricultural operations, specifically assessing on-site production for a 300-hectare wind-powered cereal farm in Sweden. Their analysis yielded a levelised cost of hydrogen (LCOH) ranging from USD 22.90 to USD 16/kg H₂. Although scaling the system across multiple farms produced a 28–35% cost reduction, the LCOH remained uncompetitive with diesel in most cases—only achieving economic viability in 9 out of 20 scenarios under favourable carbon pricing conditions. Furthermore, while the study accounts for ancillary revenue from oxygen by-products and land leasing, these contributions were minor and insufficient to offset the overarching cost barriers. This underscores Janke et al. [16]’s key argument: substantial policy intervention is essential to bridge the economic gap.

A growing body of research explores the integration of green hydrogen into ammonia production pathways, particularly as a decarbonisation strategy for the Haber–Bosch process, which currently accounts for between 1% and 2% of global CO₂ emissions [17–19]. Building on this evidence, a UK-based feasibility study by Tristan et al. [20] further supports this trajectory, revealing that ammonia-based H₂ transport could reduce the LCOH by up to 64%, from USD 11.77 to USD 4.22/kg H₂. This shift in economic performance signals a potentially transformative application for agricultural decarbonisation.

Further academic analyses categorise H₂ use into power-to-hydrogen-to-power (P2H₂P) and power-to-hydrogen (P2H) applications, with significant implications for cost. Several studies [21–24] demonstrate that P2H₂P systems, particularly those used as energy storage alternatives to batteries, offer increased reliability and economic value in grid-stabilising roles. Nonetheless, the LCOH for these systems remains relatively high, posing a barrier to widespread adoption. Production scale plays a crucial role: at 500 kg H₂/hour, the LCOH drops to USD 6.35/kg, whereas at just 50 kg H₂/hour, it rises steeply to USD 15.83/kg [25]. In addition, the capacity factor—representing the utilisation rate of

production assets—has a strong inverse relationship with the LCOH; lower capacity factors lead to disproportionately higher H₂ costs [26].

Collectively, these studies reveal a complex interplay of technical, economic, and infrastructural variables that must be navigated to render green H₂ viable in agriculture. While certain applications—such as green ammonia or large-scale on-site production—show economic promise, especially under supportive policy regimes, widespread adoption will depend on the strategic alignment of storage technologies, production scales, and targeted end uses.

This literature review indicates that, although green H₂ shows strong potential for agricultural decarbonisation, the current evidence base is fragmented and context-specific. Techno-economic studies have largely focused on isolated case studies, cost modelling, or infrastructure trials, without offering an integrated, sector-wide assessment. What is missing is a comprehensive evaluation of how production scales, storage technologies, and policy mechanisms interact to shape economic viability in agricultural contexts.

2.2. Social and Regulatory Perspectives of Green H₂ Implementation

Green hydrogen (H₂) is increasingly recognised as a cornerstone of future low-carbon energy systems, yet its diffusion is shaped not only by techno-economic barriers but also by significant social and regulatory challenges. Public perceptions of hydrogen are often characterised by uncertainty, low awareness, and safety concerns. In regions where infrastructure remains under-developed, such as parts of Eastern Europe, limited knowledge of production processes and benefits contributes to neutral or evasive attitudes [27]. Even in countries with advanced energy systems, familiarity with H₂ is still relatively low; where attitudes are positive, they are often superficial and based on limited exposure [28–30].

Safety perceptions remain decisive. Concerns around the risk of explosion at hydrogen refuelling stations persist, with Gordon et al. [31] noting that such fears are frequently linked to historical events (e.g., the 1937 Hindenburg disaster) or conflated with associations to hydrogen bombs. This legacy of fear continues to constrain acceptance, particularly in residential and agricultural applications [30].

Drawing on socio-technical transition scholarship, social acceptance is increasingly understood as a multi-dimensional and dynamic process, shaped by interactions across macro- (policy/regulation), meso- (markets/communities), and micro-levels (households/individuals) [32–34]. From this perspective, hydrogen adoption depends not only on affordability or performance, but also on evolving social meanings, trust, and legitimacy. Recent evidence supports this view: a representative survey conducted through the Norwegian Citizen Panel found significantly higher support for *green hydrogen* (mean score 3.9 on a five-point scale) compared with *blue* (3.2) and *grey* (2.3) hydrogen once respondents were informed of their fossil origins. Acceptance was also influenced by broader social factors such as climate change concern, gender, and political affiliation, underscoring the importance of transparent communication strategies to avoid misunderstandings and resistance [35].

In agriculture, where hydrogen could play a transformative role in decarbonising farming operations and replacing diesel with clean fuel, these challenges are especially pronounced. Farmers' willingness to adopt new technologies is strongly influenced by trust, familiarity, and cultural practices [36] and without targeted engagement and incentives, the transition risks being delayed or resisted. At the same time, regulatory inertia remains a major barrier: many national governments still lack coherent strategies, policy support, and financial mechanisms to accelerate hydrogen adoption [37]. Such uncertainty, coupled with weak communication strategies, creates an environment where neither users nor investors feel confident committing to hydrogen technologies.

Although hydrogen is starting to get attention in agricultural contexts, the literature remains fragmented and still relatively limited. By contrast, more advanced techno-economic modelling has been carried out in other sectors [16,38,39]—for example, off-grid hydrogen production in Australia [40] and large-scale refuelling stations in Germany [41]. While such studies advance understanding of technical and economic feasibility, they remain sector-specific and do not address agriculture directly. Broader comparative analyses have begun to emerge [42], but these consider agriculture only indirectly. Few studies have engaged directly with farmers' perspectives or applied socio-technical transition theory, with Hahn et al. [43] in Sweden being one of the limited examples. This imbalance indicates a clear gap: while we know much about the costs and technical barriers of hydrogen in farming, we know far less about the social, cultural, and institutional factors that shape adoption.

While prior studies in contexts such as Australia and Germany have advanced techno-economic modelling of hydrogen systems, they remain largely sector-specific and technically focused. Against this backdrop, this paper investigates the potential and limitations of deploying green hydrogen in the agricultural sector. It combines techno-economic assessment at both the farm and cluster scales with stakeholder engagement through semi-structured interviews and an expert workshop, assessing not only cost-effectiveness but also the institutional, financial, and operational barriers to adoption. By doing so, the study moves beyond fragmented case-specific analyses to provide a more integrated understanding of how production scale, storage technologies, and policy mechanisms interact to shape feasibility. In addition, it addresses the underexplored social and regulatory dimensions of hydrogen adoption in rural contexts by engaging directly with farmers and sector experts to capture local acceptance, trust-building, and governance needs. This paper is guided by three key questions:

1. What are the techno-economic conditions under which green hydrogen becomes feasible at the farm and cluster scales in UK agriculture?
2. How do farmers, developers, and sector experts perceive the opportunities and barriers to hydrogen adoption in rural contexts?
3. Which business models (e.g., on-farm refuelling, ammonia-based fertiliser, or cooperative hubs) are most feasible?

3. Materials and Methods

This paper adopts a mixed-methods approach to evaluate the feasibility of green H₂ production in the farming sector, addressing both techno-economic and socio-institutional dimensions. Specifically, it combines the following:

1. Techno-economic assessment (quantitative)—to evaluate the cost-effectiveness of green H₂ systems through LCOH calculations under different farm-based scenarios.
2. Stakeholder analysis (qualitative)—to explore the socio-institutional dimensions of H₂ integration in farming, through semi-structured interviews and an expert workshop with professionals and practitioners.

The two components were closely connected. Insights from the interviews guided the design of scenarios and informed the assessment of different business models, helping to capture farmer priorities and institutional realities. These scenarios and business models were then presented in the workshop, where participants validated the results and reflected on their feasibility, costs, and practical challenges. This integration of quantitative modelling with stakeholder perspectives ensured that the analysis addressed both technical-economic viability and real-world acceptance.

3.1. Techno-Economic Assessment Methodology

The main purpose of the quantitative analysis was to assess the cost-effectiveness of green H₂ for farms, which is quantified by the LCOH. The analysis was implemented through three steps: (i) the conceptualisation of green H₂ systems in farms, (ii) the proposition of scenarios of H₂ use cases, and (iii) optimal sizing of H₂ systems to minimise the LCOH. These are described below.

3.1.1. Conceptualisation of Green H₂ Systems

The design of green H₂ systems in farms is conceptualised in this section, which includes the electrolyser, wind turbine, solar panel, compressor, H₂ storage, and H₂ refuelling stations. A schematic of the system is shown in Figure 1.

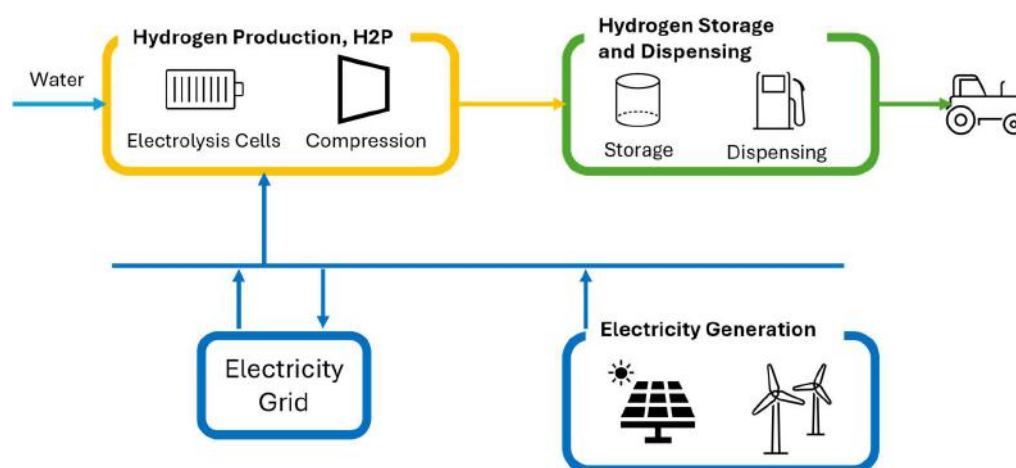


Figure 1. Schematic showing a typical green H₂ production system for farms.

As shown in Figure 1, the renewable power generation, including solar and wind generation, supports the production of green H₂ through electrolyzers. The system can import electricity from the grid when the renewable generation is insufficient, and export electricity back to the grid when there is surplus electricity generation. The compressor consumes electricity and compresses the pressure of the H₂ before it is sent to the H₂ storage. Considering the seasonality of farm-level H₂ demand and weather-dependent renewable generation, the H₂ storage can be used to balance the H₂ generation and demand in farms by storing excessive produced H₂ and retrieving it from storage to address generation shortages.

The H₂ production facilities include proton exchange membranes (PEMs), photocatalysis, alkaline electrolyzers, and polymer electrolysis; the H₂ storage technologies include compressed-air, cryo-liquid, cryo-compressed, metal hydride, and salt cavern technologies. The specific production and storage technologies to be applied for farms can be chosen by multi-criteria design analysis, such as the rank-sum method [44].

3.1.2. Proposition of Scenarios for H₂ Usage in Farms

H₂ usage (demand pattern) in farms can affect the optimal configuration and operation of the H₂ systems, and accordingly, the LCOH. In addition to supporting the machinery of farming activities, H₂ can also be used to refuel delivery vehicles or heavy goods vehicles surrounding the farm. This section presents two example scenarios for H₂ usage in farms; the H₂ demand in kg is obtained from historic diesel consumption of farm machinery, based on the assumption that hydrogen fuel cell vehicles will replace them. Each scenario will be assessed in the techno-economic analysis to identify the best scenario with a minimised LCOH. The H₂ demand profile of the scenarios is presented as follows.

(i) H₂ consumed by selected farms only

For a typical combinable cereal farm (an average size of 123 hectares) in Eastern England [5] the equivalent H₂ demand to carry out the required farming activities, including land preparation, seeding, fertiliser application, and harvesting, over a typical year is shown in Figure 2.

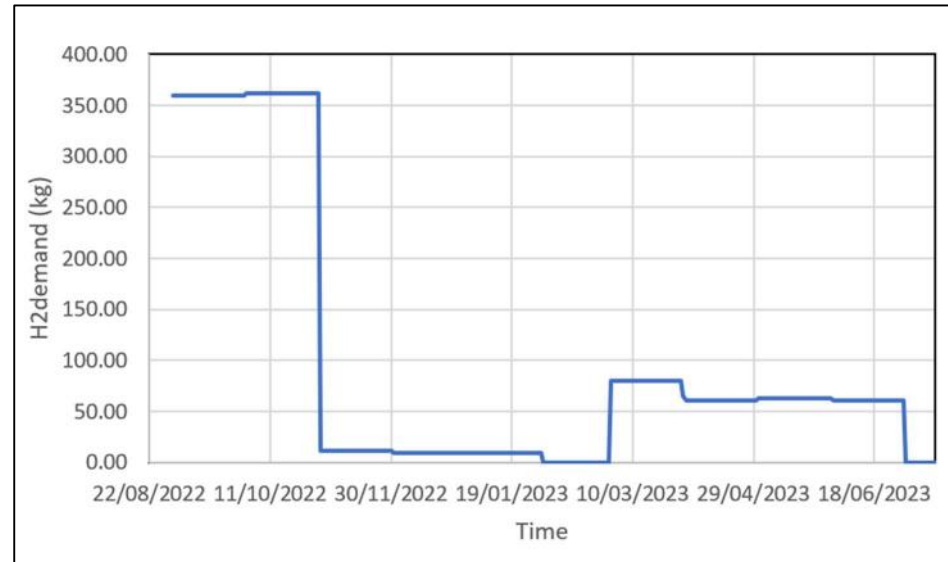


Figure 2. H₂ demand for a typical average-sized cereal farm in Eastern England.

As shown in Figure 2, peak demand occurs between mid-August and October, with extremely low demand in winter, and medium demand in spring. The seasonal demand renders high utilisation of H₂ systems during peak periods but low utilisation during periods of low demand. This imbalance would lead to an overall low utilisation rate, leaving the system underused, and driving up the LCOH.

(ii) H₂ consumed by heavy vehicles in the surrounding area

To minimise the LCOH, it is essential to flatten the seasonal demand; hence, the H₂ demand for the heavy vehicles in the surrounding area of the farm can be considered. An example is the use of haulage transport for delivering the harvested crops, assuming they are decarbonised and replaced by fuel cell trucks (such as XCIENT); their equivalent H₂ demand for delivering the crops to the processing facilities 40 km away is estimated as shown in Figure 3 [45]. For the combinable cereal farm analysed in this paper, crops like winter wheat and spring barley are typically harvested and stored in March and August, respectively; the transport demand is assumed to be constant following the harvesting activity and even between March and September.

3.1.3. Optimisation Model for H₂ System Sizing

The problem formulation of the H₂ system sizing is presented as below:

$$\text{Minimise } C_{Tot} = C_{P2H} + C_{HS} + C_{PV} + C_{WT} + C_{HRS} + C_{comp} + C_{op} \quad (1)$$

$$\text{Where } C_{P2H} = N_{P2H} \times U_{P2H} \quad (2)$$

$$C_{PV} = N_{PV} \times U_{PV} \quad (3)$$

$$C_{WT} = N_{WT} \times U_{WT} \quad (4)$$

$$C_{op} = LF \times \frac{365 \times 24}{T} \times \sum_{t=1}^T (E_{imp,t} \times P_{imp,t} - E_{exp,t} \times P_{exp,t}) \quad (5)$$

Subject to

$$E_{PV,t} + E_{WT,t} + E_{imp,t} - E_{exp,t} = E_{P2H,t} + E_{HS,t}, \forall t \quad (6)$$

$$H_{P2H,t} - H_{H2S,out,t} = H_{P2H,stor,t}, \forall t \quad (7)$$

$$E_{P2H,t} = H_{P2H,t} \left(\frac{H_{LHV}}{3600 * \eta_e} + e_c \right), \forall t \quad (8)$$

$$0 \leq \sum_{t=1}^T H_{P2H,stor,t} \leq N_{stor}, \forall t \quad (9)$$

$$H_{P2H,t} \leq Q_{P2H} * N_{P2H}, \forall t \quad (10)$$

In (1), C_{Tot} is the total cost of the H_2 system over its lifetime LF ; C_{P2H} , C_{HS} , C_{PV} , C_{WT} , C_{HRS} , and C_{comp} are the capital cost of the electrolyser, H_2 storage, PV panel, wind turbine, H_2 refuelling station, and compressor; and C_{op} is the system total operating cost. U_{P2H} , U_{PV} , and U_{WT} are the unit price of a single unit electrolyser, PV panel, and wind turbine, and N_{P2H} , N_{PV} , and N_{WT} are the numbers of those units, respectively. T is the total time step of an analysed time period of the system, $E_{imp,t}$ is the amount of electricity imported at time step t , $E_{exp,t}$ is the electricity export to the grid at time step t , and $P_{imp,t}$ and $P_{exp,t}$ are the prices of electricity importing and exporting. $E_{PV,t}$ and $E_{WT,t}$ are the electricity generation from solar PV and wind generation at time step t , and $E_{P2H,t}$ and $E_{HS,t}$ are the electricity powering the electrolyser and H_2 storage at time step t . $H_{P2H,t}$ is the H_2 output from the electrolyser at time step t , $H_{H2S,out,t}$ is the H_2 injected to the H_2 storage at time step t , and $H_{P2H,stor,t}$ is the H_2 supplied for end use for time step t . H_{LHV} is the net calorific value of hydrogen, η_e is the efficiency of the electrolyser, e_c is the compressor power consumption, and Q_{P2H} is the output capacity of the electrolyser.

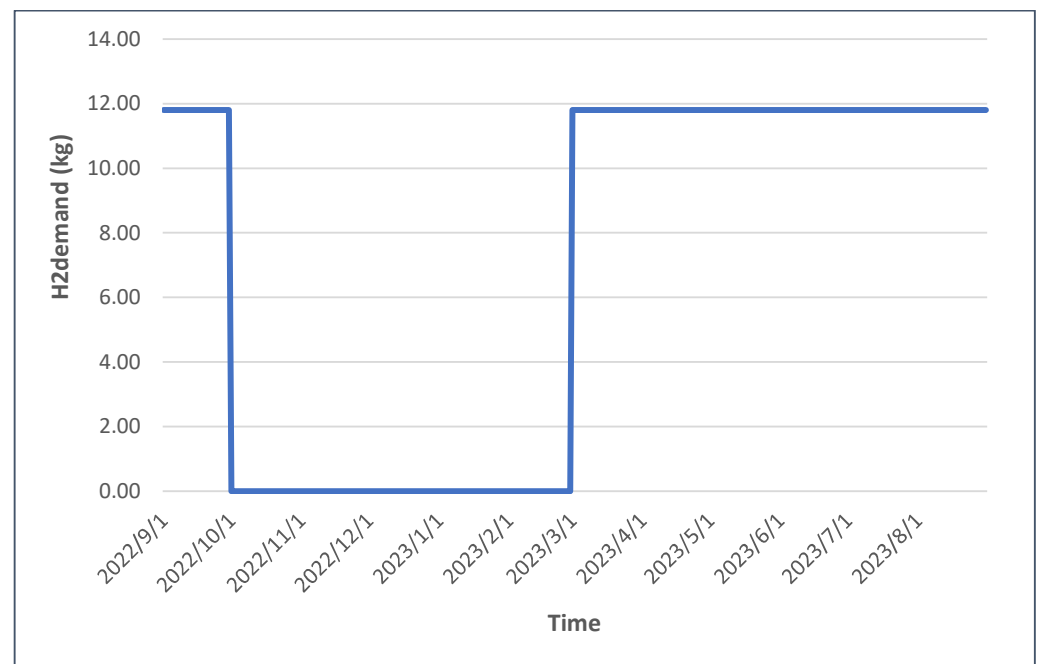


Figure 3. H_2 demand of high-duty delivery vehicles.

Within the context of the optimisation problem, the objective function (1) minimises the system total cost, including the capital and operating cost, over its lifetime. (2)–(4) detail the calculation of the components' capital costs. (5) expresses the calculation of the operating cost in terms of the cost of electricity minus the profit of exporting electricity over the system's lifetime. (6) expresses the balance of electricity supply and demand of the farm for all time steps, and (7) indicates the balance of H_2 supply and demand for all time

steps. (8) illustrates the relationship between the electricity input to the electrolyser and H₂ output. (9) means that the amount of H₂ stored in the storage at any time should be higher than zero and lower than the capacity. (10) means that the amount of H₂ produced by the electrolyser cannot exceed its capacity.

The optimisation problem is linear, which can be effectively resolved by linear programming solvers.

3.2. Qualitative Data Analysis

To explore the perspectives of key stakeholders in the farming sector regarding the implementation of green H₂ production in agricultural systems, we conducted seven online semi-structured interviews between June and August 2024. Online data collection gained significant attention during the COVID-19 pandemic and has remained popular since, primarily due to its adaptability in meeting diverse research needs and logistical efficiency [46]. This approach expanded access to participants across wider geographical regions, reducing travel time and costs while ensuring continuity in data collection. The convenience it offers to both researchers and participants has contributed to its ongoing popularity, making it a practical choice for various research settings today.

We employed snowball sampling, starting with established contacts in the hydrogen and agricultural sectors and then expanding through participant recommendations. Our final sample comprised a heterogeneous group of stakeholders with direct relevance to agricultural hydrogen adoption: an academic specialising in hydrogen technology, a hydrogen project development officer, a company founder working on hydrogen-powered farm machinery, two farmers, a water management specialist, and a representative from a national agriculture body (see Figure 4).

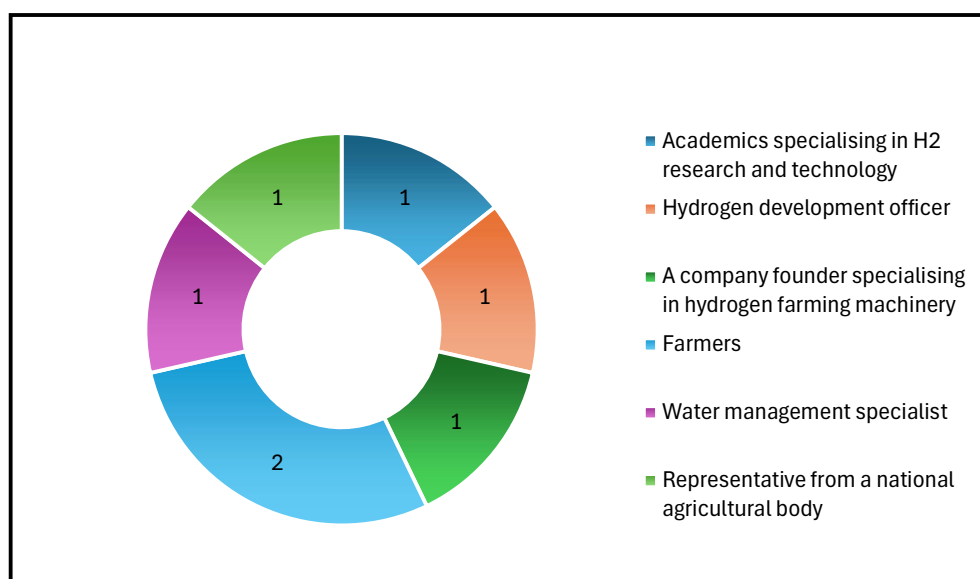


Figure 4. Sectoral representation of interviewees (N = 7).

While the sample size is modest, it brings together a range of perspectives across the hydrogen–agriculture interface, including farmers, technology developers, researchers, and policy representatives. This diversity enabled us to capture a breadth of insights into the opportunities and challenges of hydrogen in farming contexts. Given the exploratory scope and early stage of hydrogen adoption in agriculture, the interviews offer an initial evidence base to guide future research and policy. Methodological guidance also notes that saturation in focused stakeholder groups is often reached with 6–12 interviews [47].

An interview guide consisting of eight open-ended questions was developed to ensure consistency and facilitate focused discussions. The questions were organised around two main themes: (i) challenges and opportunities for implementing green H₂ in farming, including operational and logistical aspects of H₂ production, and (ii) financial and business considerations, such as identifying suitable business models and determining necessary policy support. All interviews were audio-recorded with explicit participant consent. Each interview was transcribed, assigned a unique identifying code, and reviewed twice by the primary researcher to ensure reliability. The coded transcripts were then consolidated and analysed using NVivo version 14 [48] for efficient keyword and thematic searches.

Findings from the techno-economic assessments and semi-structured interviews were presented and discussed in a virtual expert workshop held in September 2024, attended by nine participants from academia, the hydrogen industry, and the farming sector. The workshop aimed to share results with stakeholders, explore potential business opportunities for hydrogen in agriculture, and examine the policy landscape and required support for adoption. Discussions were recorded, transcribed, and incorporated into the thematic analysis to ensure that expert perspectives were fully captured. While the workshop added valuable depth to the study, the insights reflect a focused group of UK-based participants and should be considered indicative, offering exploratory guidance for future research and policy development.

4. Results and Discussion

This section integrates findings from the techno-economic analysis, semi-structured interviews, and the stakeholder workshop to address the study's three research questions within the broader policy context of the UK Hydrogen Strategy. Section 4.1 addresses RQ1 by analysing the techno-economic conditions under which hydrogen becomes feasible at the farm and cluster scales, highlighting cost drivers, seasonal demand patterns, and utilisation challenges—issues also recognised in the Strategy's emphasis on reducing costs and scaling up hydrogen production. Sections 4.2 and 4.3 address RQ2 by presenting stakeholder perspectives on opportunities and barriers, spanning the techno-economic, social, environmental, and institutional dimensions.

Finally, Section 4.4 responds to RQ3 by evaluating alternative business models—on-farm refuelling, ammonia-based fertiliser production, and cooperative hubs—and their feasibility from both the economic and social perspectives. By linking techno-economic feasibility with stakeholder perspectives and business model considerations, the results contribute to socio-technical transition theory by illustrating how technological, institutional, and social factors interact in shaping hydrogen adoption in agriculture.

4.1. Techno-Economic Analysis

4.1.1. Case Study Setup and Data Collection

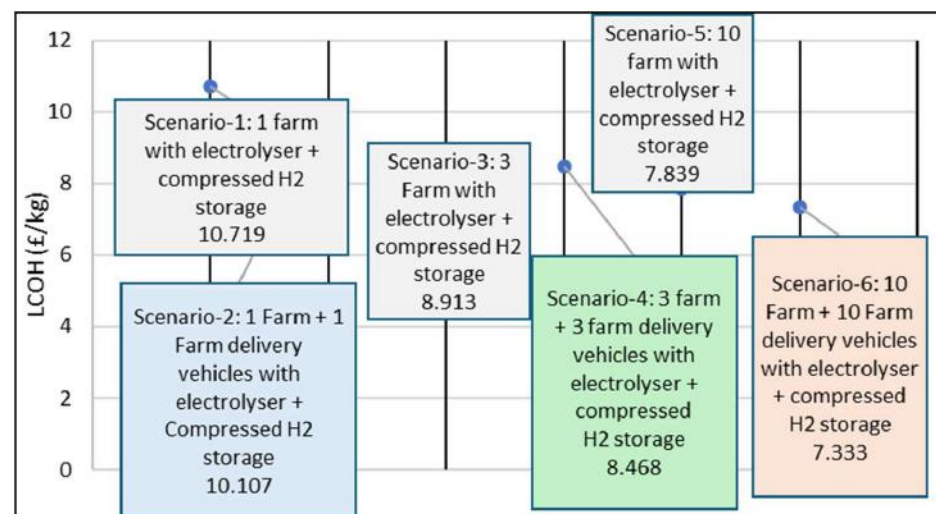
A case study was conducted for optimally planning the H₂ systems to support the demand of farms located in Eastern England by optimising the problem in (1). It was implemented for the scenarios proposed in Section 3.1.2 for three sizes of farms including (i) a 123-hectare farm (average farm size), (ii) a cluster of 3 × 123-hectare farms, and (iii) a cluster of 10 × 123-hectare farms. The demand data, solar irradiation, and wind speed for every 3 h over one year were collected for the optimisation. Some of the main data used for formulating the problems in (1) is presented in Table 1 based on [16,49–53].

Table 1. Case study data.

Name	Description	Value
U_{PV}	Capital cost of a single unit solar PV	712,000 GBP/MW
U_{WT}	Capital cost of a single unit 500 kW wind turbine	654,000 GBP/unit
U_{HS}	Capital cost of a single unit of H ₂ storage	500 GBP/kg
U_{HRS}	Capital cost of a dispenser	71,000 GBP/unit
$P_{imp,t}$	Price of grid electricity	240.6 GBP/MWh
$P_{exp,t}$	Price of exported electricity	0
Q_{P2H}	Operating capacity of an electrolyser	2.708 kg/hr
e_c	Power consumption of compressor	0.0063 MWh/kg
η_e	Electrolyser efficiency	58%
H_{LHV}	Lower heating value of hydrogen	120 MJ/kg

4.1.2. Case Study Results

To minimise the LCOH, some scenarios using the generated H₂ to support the heavy transportation in the surrounding area of the farms are simulated, such as the delivery vehicle for harvested crops as described in Section 3.1.2; the results are shown in Figure 5. It is obtained that the best LCOH is derived as 0.24 GBP/kWh for the scenario of planning the H₂ system for a cluster of 10 farms, supporting the demand of the farms and 10 delivering vehicles.

**Figure 5.** Levelised cost of hydrogen of scenarios.

Nevertheless, the future LCOH is projected to reduce due to (i) the increase of electrolyser efficiency to potentially 76% in 2050, and (ii) the reduction of the capital cost of electrolyser from 1000 USD/kW in 2020 to 307 USD/kW in 2050 [52], assuming the future diesel price increases to 144.2 pence/L by 2035 compared with 119.4 pence/L in 2020 [54]. Based on those price trends, the LCOH of 0.24 GBP/kWh derived from the 10-farm scenario was estimated to reduce to 0.17 GBP/kWh by 2050, while the price of diesel was estimated to increase to 0.205 GBP/kWh by 2050; the prices of the two energies could break even by 2040 as shown in Figure 6.

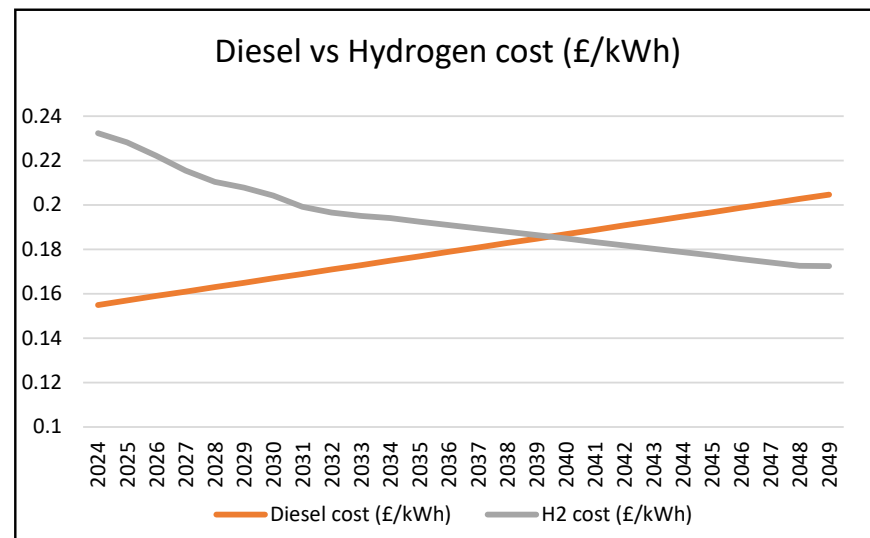


Figure 6. Projection of diesel and hydrogen costs towards 2050.

4.2. Key Opportunities from Producing Green H₂ in Farming

The majority of our interviewees see green H₂ production as offering various opportunities for the agriculture sector. Figure 7 highlights the key opportunities identified in farming. Some interviewees highlighted green H₂ as a promising solution for decarbonising the farming sector, which heavily relies on fossil fuels. As a clean fuel emitting only water vapor, H₂ can significantly reduce agriculture’s environmental impact [55]. With its high energy density, green H₂ offers potential as a sustainable energy source and an energy carrier for storing and transporting electricity, benefiting agricultural operations [56].

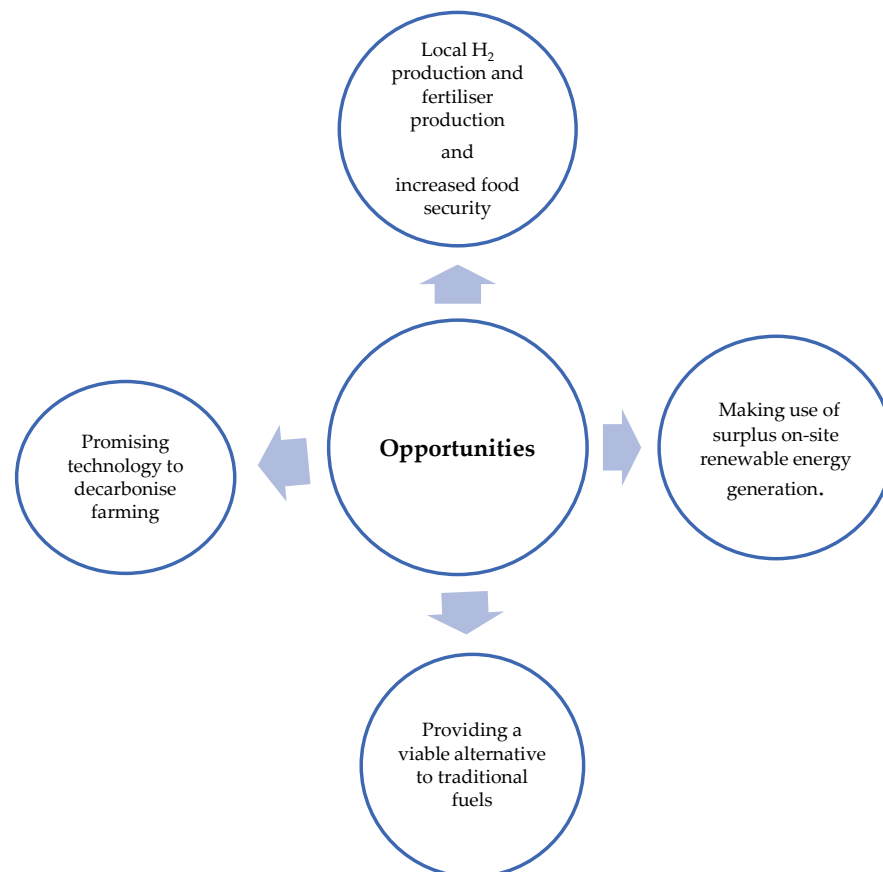


Figure 7. Key opportunities for green H₂ production in the UK farming sector.

A farmer stated the following:

“I believe H₂ gas produced through green electrolysis is the most promising technology for decarbonising the farming sector”. (i1, Farmer A)

Despite its potential, H₂ is currently primarily used in the petrochemical industry—mainly for synthesising ammonia for fertilisers, refining processes, and steel and iron production. Its application in other sectors, such as transportation, shipping, heating, electricity generation, and agricultural machinery, remains limited [57,58].

Several interviewees identified local H₂ and fertiliser production as a key opportunity for green H₂ generated via water electrolysis using renewable energy in the farming sector. Most countries’ fertiliser sectors rely heavily on imported natural gas and fertilisers. Geopolitical conflicts and supply chain disruptions have significantly increased costs [59]. Investing in domestically produced green H₂ and ammonia could reduce reliance on imports, enhancing economic resilience and food security [60]. One interviewee noted that historically, fuel and fertiliser have been the largest costs in farming, emphasising that green H₂ could mitigate these costs, particularly given recent price surges due to geopolitical uncertainties, supporting a more sustainable agricultural model.

Farmer A mentioned the following:

“The two biggest expenses on the farm have been fuel and fertiliser. Now, hydrogen has the potential to address both of these costs and could significantly alleviate the problem of high expenses on fuel and fertiliser . . . Fertiliser prices have been massively inflated by the fertiliser companies. With the added impact of the Ukraine war and other factors, it became almost unaffordable two years ago. This situation poses a serious threat to our food security”. (i1, Farmer A)

The literature supports interviewees’ statements, noting that fertiliser became nearly unaffordable two years ago, causing significant financial strain on farm production. Fertiliser prices increased by 78% from 2021 to 2022, followed by an additional 67% rise by 2023 [61]. This inflation highlights the potential benefits of local green H₂ and fertiliser production, reducing import dependency and stabilising supply chains. Green H₂ can also help to alleviate financial pressure on farmers and enhance food security [60].

Another benefit of green H₂ production in farming, as highlighted by interviewees, is the opportunity to utilise surplus on-site renewable energy. In the UK, balancing supply and demand across the electricity network is challenging due to transmission capacity constraints, often leading to curtailment of excess renewable generation to avoid overload [62]. For example, in 2020, 3.5 TWh of wind generation was curtailed, which is enough to power 800,000 homes, and in 2022, 4% of wind generation was curtailed, equivalent to 1 million households’ consumption. Between 2021 and 2023, GBP 1.5 billion was spent curtailing over 6.5 TWh of wind power [63]. Instead of wasting this energy, it could be used to produce green H₂.

A H₂ development officer stated the following:

“There are many farmers, particularly in Scotland, who have existing wind turbines that are frequently curtailed, meaning they’re not fully utilising the renewable electricity they generate on-site. This presents a viable option for these farms to act as hubs for H₂ production, similar to a microgrid model. In this setup, the curtailed energy can be used to produce something valuable rather than being wasted. Wind farms that face curtailment could be particularly suited for hydrogen production, helping to ensure that renewable electricity isn’t wasted”. (I6, a hydrogen development officer)

Local green H₂ production offers a solution to transmission constraints by converting surplus renewable energy into H₂, reducing curtailment and improving the economic

benefits of on-site generation [64]. This approach supports energy-intensive farming operations, with H₂ fuelling equipment like tractors and heavy machinery, enhancing sustainability [65].

Several interviewees noted that green H₂ presents a viable alternative to diesel for powering heavy agricultural machinery. It can be used in internal combustion engines (ICE) and offers a high energy content, making it an attractive diesel substitute. The literature shows that H₂ fuel has better thermal efficiency than conventional fuels due to its higher auto-ignition temperature [66].

A company founder specialising in H₂ farming machinery stated the following:

“Hydrogen can be used to power a combustion engine, though further development is still needed for these engines, which is why it hasn’t yet gone mainstream. However, using hydrogen in combustion engines is a realistic option, especially if the hydrogen is produced through electrolysis on the farm, which is relatively straightforward. This process requires a renewable energy source to power the electrolyser, making on-farm renewable energy crucial for hydrogen production”. (i5, hydrogen farming machinery specialist)

4.3. Barriers to Green H₂ Production Across the Farming Sector

Despite the promising opportunities, this paper identifies various barriers, including techno-economic, social, environmental, institutional, and legal barriers, that hinder widespread H₂ adoption. Although H₂ has a long history, green H₂ makes up only 4% of the total H₂ output [67]. This low adoption mirrors broader challenges in the energy sector, where renewable energy accounts for just 6% of the global energy mix [68]. By combining the feedback from the stakeholder analyses, Figure 8 summarises their reported perspectives on key challenges and their interdependencies to H₂ production across the farming sector.

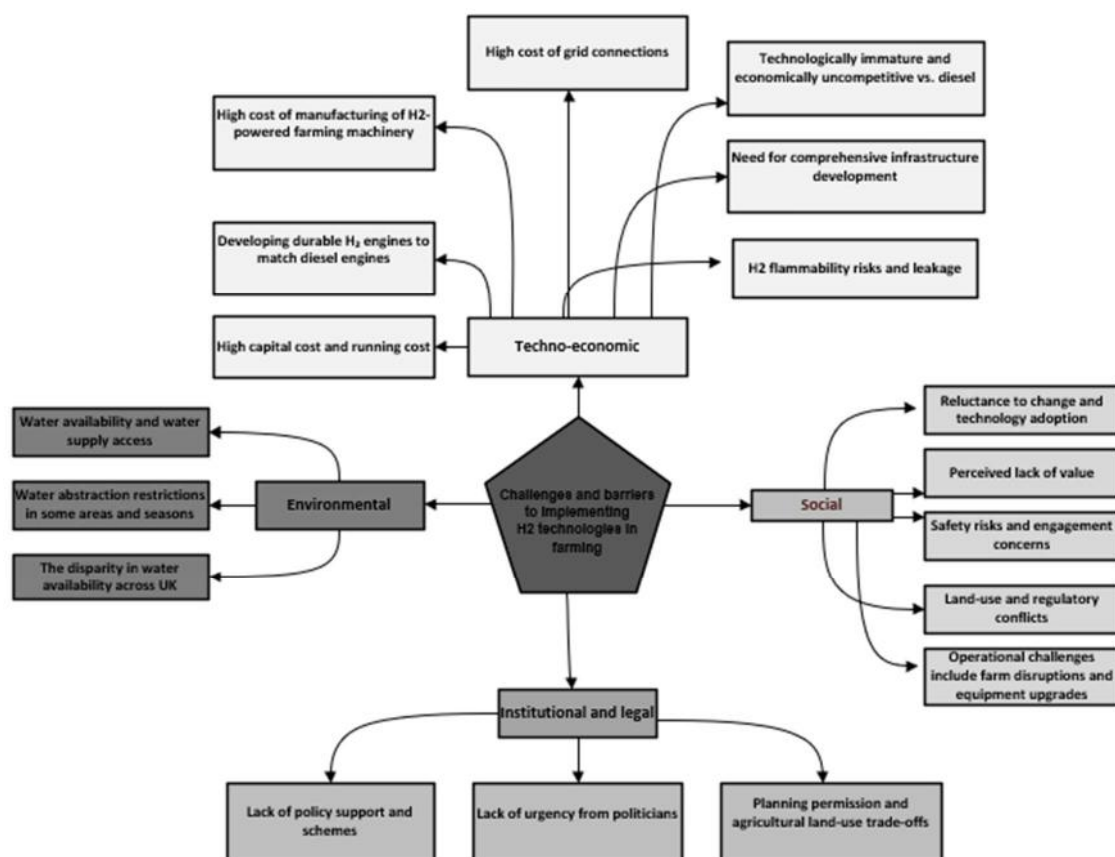


Figure 8. Challenges to implementing H₂ technologies in farming.

4.3.1. Techno-Economic Challenges

This section explores the techno-economic challenges of green H₂ production in farming, summarised in Figure 9. Despite four decades of research, an economically viable H₂ economy remains elusive, with economic and technical barriers being key obstacles to global adoption [68,69]. While the existing literature acknowledges these barriers, this section focuses on the specific challenges within the farming sector that must be addressed for green H₂ adoption.

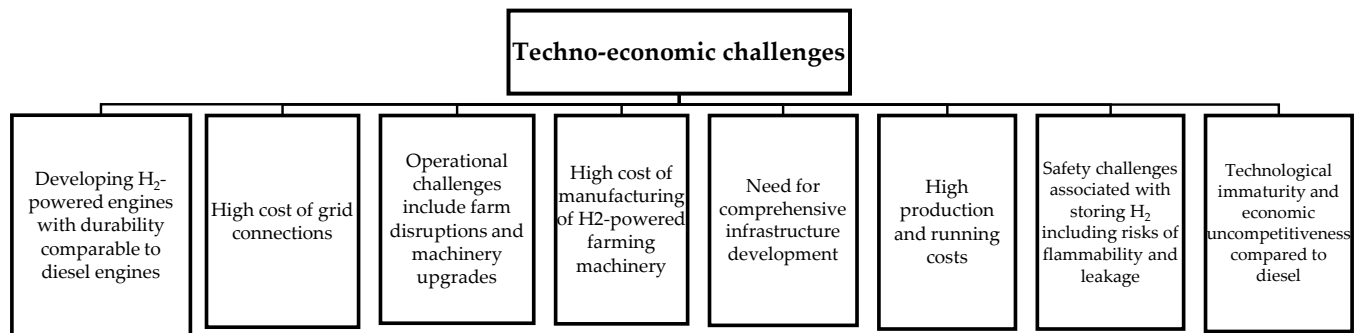


Figure 9. Key techno-economic challenges to H₂ implementation in the agricultural sector.

Cost emerged as one of the significant barriers by our interviewees. The majority of our interviewees (five out of seven) identified cost as a key barrier to deploying H₂ production in farming.

Interviewees stated the following:

“Farm machinery and other equipment powered entirely by hydrogen is feasible, but current costs are slightly too high. Additionally, there are still very few hydrogen engines available”. (i1, a farmer)

“The biggest barrier to any new technology is often its cost. The key question is how the cost compares to existing solutions”. (i7, representative from an agriculture body)

Interviewees emphasised the high cost of green H₂ production as a major barrier to adoption. Currently, green H₂ costs USD 4–6 per kilogram, which is two to three times higher than grey H₂ [70]. This cost difference is mainly due to the price of renewable energy, which, despite declining annually, has not yet reached the competitiveness needed for a market breakthrough. A key challenge is the high cost of electrolyzers, the technology needed for green H₂ production [70]. Electrolyzers are still costly and technologically immature, lacking the scale needed to lower prices. Achieving economies of scale is crucial for making green H₂ feasible. One interviewee, a company founder specialising in H₂-powered farming machinery, pointed out the following:

“The main issue now is reducing costs to improve efficiency and make H₂ competitive with diesel.” (i5, founder specialising in hydrogen-powered farming machinery)

For green H₂ adoption, cost competitiveness with traditional fuels is essential [71]. Unless economic barriers are addressed, green H₂ uptake will remain limited despite its environmental benefits. Experts in this study noted that developing H₂-powered engines with similar durability as diesel is challenging, making technological readiness a barrier to adoption. While H₂ technologies have matured, green H₂ production remains commercially unviable and lacks price competitiveness [72].

The best LCOH derived from the techno-economic assessment is 0.24 GBP/kWh when investing in H₂ systems for 10 farms, and supporting the demand of farms and delivery vehicles, compared to the price of diesel of 0.153 GBP/kWh. However, as discussed in Section 4.1., the price of diesel is projected to increase, and the LCOH is estimated to

decrease as electrolyser efficiency is forecasted to increase with the costs reduced; thus, the prices of the two energies could break even in 2040. Additionally, the break-even point can be advanced by considering other scenarios or financing schemes, with examples including using the H₂ system to supply the wider transportation demand of the local area, and the incorporation of a carbon tax scheme.

The high cost of producing H₂-powered machinery also presents financial hurdles. This stems from the significant capital investment required for development and low initial production volumes, leading to high costs similar to early electric vehicles [73]. Scaling up production and technological improvements are crucial to enhancing performance and reducing costs [68].

In addition to these cost barriers, intellectual property (IP) constraints may further increase expenses and limit access. Many patents related to hydrogen internal combustion engines are held in jurisdictions such as Japan, potentially imposing licensing fees or design restrictions on tractors and other heavy-duty equipment. These IP barriers add to the financial and potentially institutional challenges already constraining hydrogen adoption in agriculture.

In addition to previously mentioned challenges, this study identified a major barrier to green H₂ production: the need for comprehensive infrastructure development. Key components include (i) H₂ storage costs and space requirements, (ii) pipeline construction, (iii) storage facilities, (iv) refuelling stations, and (v) grid connections, which are crucial for reliable H₂ production, especially where renewable energy falls short.

Interviewees highlighted that the fact that some farms are located in remote areas poses challenges for H₂ delivery, requiring extensive infrastructure for consistent supply. Despite these challenges, gradual infrastructure development can support rural farming needs. This aligns with the literature citing the need for extensive technologies and infrastructure as a barrier to green H₂ deployment [68,74].

A key aspect of the infrastructure challenge is the high cost of grid connections, which adds complexity to developing reliable H₂ systems. To reduce grid connection costs, off-grid solutions could be explored. However, the feasibility depends on factors such as location, energy demand, and production capacity. Off-grid systems are generally more suitable for remote areas, but their practicality varies depending on each farm's specific requirements.

Another key challenge in deploying H₂ in farming is the cost and space requirements for H₂ storage. H₂ can be stored in gaseous, liquid, or combined forms, with liquid storage mitigating some volumetric challenges due to its higher density [75]. Lower energy density requires more space per unit of energy compared to conventional fuels, and the need for pressurisation or liquefaction means H₂ storage requires larger, stronger systems. The use of high-pressure cylinders for large-scale H₂ storage is both technically challenging and extremely costly [75]. Participants in our study suggested potential solutions, such as storing only small amounts of H₂ for direct use (e.g., vehicle refuelling) or on-site production and consumption to eliminate the need for large-scale storage, thus reducing costs and logistical complexity. Adequate space is also crucial, as storage facilities should be positioned away from core farm operations to minimise impact. Due to H₂'s low energy density, numerous large canisters are required, making space a key factor for successful implementation.

Gradual infrastructure development could help address these barriers, allowing H₂ technology to contribute effectively to sustainable farming. Our findings align with the existing literature, which highlights infrastructure development as a major challenge for H₂ production, transport, storage, and distribution [76].

Another key techno-economic challenge for implementing green H₂ production in farming is the safety concerns, particularly with storing H₂ at high pressure, which poses risks of flammability and leakage. Some participants in our study underscored the unique challenges of managing H₂ due to its distinct properties. Handling H₂ involves several risks, but with a clearer understanding, these risks can be effectively managed. Unlike natural gas, H₂ requires distinct risk management and mitigation strategies, which adds complexity to its handling given the relatively new nature of the technology. Appropriately managing H₂ will require careful handling and storage procedures, especially under high pressure. As a farmer stated,

“It can be very dangerous if in the wrong hands, but so can certain fuels we use today. Handling things under very high pressure is difficult. Where do we source it from? How does it arrive on the farm? Are we going to produce it ourselves, or will we form collaborations?” (i3, farmer)

Our findings align with Calabrese et al. [76], who have similarly identified H₂ handling as a major challenge. To minimise leakage risks, specialised equipment and procedures are required. Calabrese et al. [76] also highlighted that transporting H₂ over long distances poses safety issues due to its low energy density, necessitating the use of specialised pipelines and containers.

The key challenge lies in managing the transition from fossil fuels to H₂ in a way that is both practical and financially viable. A gradual phase-out of existing equipment as it reaches the end of its lifespan may be more feasible for farmers, whereas immediate replacement would impose significant upfront costs. Most crop-drying systems currently rely on diesel or gas, prompting questions about the extent of modifications needed for H₂ use. While major overhauls may not be necessary, any required adaptations could still present obstacles. As one agricultural representative observed,

“Farmers are unlikely to immediately discard their current equipment and replace it with new technology. The transition would likely occur over time, as the existing equipment reaches the end of its working life and requires replacement”. (i7, representative from an agriculture body)

H₂-powered farming machinery is still emerging, with costs significantly higher than traditional diesel-powered tractors and equipment. The upfront capital expense for H₂-powered tractors can be substantially greater than for conventional models, making the switch economically challenging for farmers [77,78]. Therefore, a phased approach is likely the most feasible path, requiring careful coordination to mitigate costs and disruption.

One key operational challenge raised by interviewees is the long lead time for acquiring electrolyzers, which could delay H₂ implementation and disrupt farm operations. To minimise this risk, it is essential that H₂ infrastructure development does not interfere with agricultural activities. Interviewees stressed the importance of close collaboration with farm managers. As one H₂ development officer noted,

“The design, construction, or operation of the hydrogen infrastructure should not impact the day-to-day workings of the farm... we’re working closely with our farm manager to mitigate that risk and ensure clear communication about when certain buildings are in use throughout the year”. (i6, hydrogen development officer)

4.3.2. Social Challenges

In this section, we present the social challenges identified by our study for implementing green H₂ in the farming sector, as summarised in Figure 10. The acceptance of energy technologies hinges significantly on public support; without it, the adoption process can be severely hindered or even brought to a halt. Thus, understanding these social challenges

and public perspectives is not merely beneficial but essential for shaping effective policies and industry standards [68].

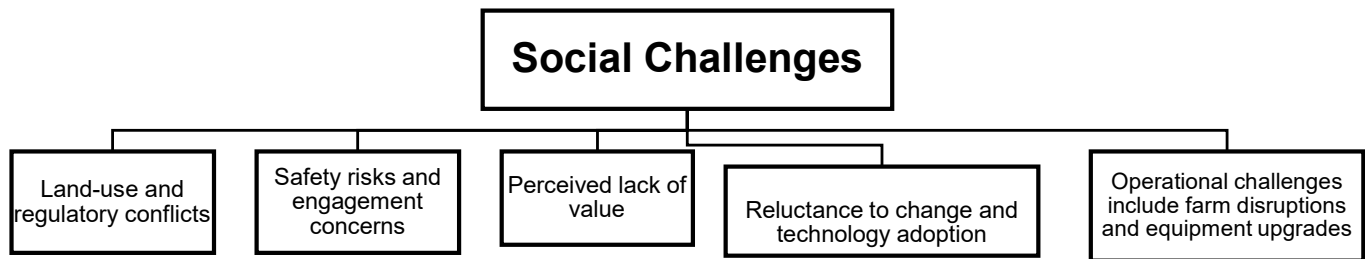


Figure 10. Social challenges to the implementation of green H₂ in farming.

Our interviewees emphasised that there will likely be initial reluctance and scepticism among farmers regarding the adoption of new technologies, such as switching to H₂-powered machinery. This hesitation is not unexpected, as farmers are often traditional and slow to adopt new techniques. However, some groups are quick to seize new opportunities when they see the potential benefits. A critical driver for engaging farmers and stakeholders in adopting green H₂ technologies in agriculture is the promise of financial benefits, which could significantly accelerate adoption. A representative from a national agricultural body stated the following:

“I think initially, there would be some reluctance, some scepticism. Farmers, or a group—groups of farmers—tend to be slow to adapt to different techniques, different technologies. But having said that, there are other farmers, other groups of farmers, who are very quick to adapt them and seize new opportunities. And so, if there is a significant benefit”. (i7, representative from an agriculture body)

The adaptation of green H₂ in farming faces multiple challenges, particularly due to resistance to new technology and the complexities involved in transitioning from established practices. Interviewees emphasised that the fundamental differences between current technologies and green H₂ make it difficult to convince farmers to adopt this new approach. One interviewee suggested that a demonstration farm showcasing the technology could play a pivotal role in persuading farmers by overcoming their natural conservatism and resistance to change. This demonstration would also provide an opportunity to refine the technology and ensure safety, aligning with the notion that effective communication fosters trust in green H₂, as emphasised by [27,79]. Thus, demonstration farms, dissemination, and education emerge as practical strategies to strengthen communication and promote acceptance of green H₂ [80,81].

Another identified obstacle to the adoption of green H₂ in farming was stakeholder engagement, especially considering safety concerns. Some participants highlighted that H₂'s perceived explosiveness is a significant barrier for farmers. One H₂ development officer illustrated this concern, stating the following:

“Key part of stakeholder engagement is to really hit home about this safety piece as well, because also that’s a concern for some farmers is that you’re storing what is deemed as a, you know, highly explosive flammable gas on an agricultural site, and it’s really just making sure that those safety measures are in place, but also say that when they are in place that there isn’t, there’s quite reduced risk”. (I6, a H₂ development officer)

This finding aligns with existing research on social acceptance of H₂, which shows that the public commonly views it as a highly explosive substance [82]. Therefore, implementing appropriate safety measures and effectively communicating the mitigated risks are crucial for engaging stakeholders. The literature indicates that when the public

has a higher level of knowledge, their perception of H₂ tends to be more positive. This underscores the importance of effective communication in alleviating concerns related to this technology [27]. Demonstration farms can showcase green H₂ technology, alleviate concerns, build trust, and enhance stakeholder engagement.

Adoption of green H₂ in agriculture hinges on its ability to compete with diesel on cost. Without economic parity, convincing farmers—who operate within tight margins and tend to be risk-averse—to transition remains unlikely. Energy costs are a decisive factor, and while recent price hikes have forced farmers to adapt, a similar leap in cost from H₂ would likely face resistance.

As expressed by one interviewee, the shift from electricity at GBP 0.08 to GBP 0.30 per kWh was once unthinkable but is now a reality—albeit a difficult one. This underscores that adaptation is possible, but only when alternatives remain viable for business continuity.

“If you said to someone when they were paying 8 pence per unit for electricity, ‘How would you feel if you had to pay 30 pence per unit?’ they would say, ‘Oh, that’s ridiculous, we wouldn’t have a business, life would grind to a halt.’ And here we are. We’re there, and life is difficult, but it hasn’t ground to a halt.” (i3; a farmer)

The real barrier, however, is not just cost but confidence. Farmers emphasise the need for straightforward, practical comparisons: if diesel is readily available and affordable, H₂ must offer clear advantages. Without transparent communication, demonstrable savings, and systems that integrate seamlessly into existing operations, green H₂ risks being perceived as an impractical solution—regardless of its environmental benefits. This research also identified operational challenges, such as farm disruptions and the need to upgrade existing machinery, which present significant barriers to the adoption of green H₂ in farming. Most farms currently rely on diesel- or gas-powered equipment, and transitioning to H₂ would require costly modifications. Given these costs, it is unlikely that farmers will immediately discard their current machinery in favour of new H₂-powered technology. Instead, a more gradual replacement approach might face less resistance.

This study underscores that the successful adoption of green H₂ in agriculture depends on its economic viability. Farmers prioritise cost savings and profitability, often above environmental considerations, making financial incentives and the affordability of H₂-powered machinery essential to overcoming resistance. At present, the lack of clear financial benefits limits uptake. According to the techno-economic assessment, H₂ could reach cost parity with diesel by 2040, enabling wider adoption. In the near term, however, an estimated GBP 19 million in incentives would be required in 2024 to support H₂ system investment across 10 farms (a total of 1230 hectares) to make H₂ competitive with diesel.

Furthermore, some participants highlighted land-use conflict as a key barrier to green H₂ deployment in farming. The core issue is competition between energy and food production. As the global food demand grows, the pressure to preserve agricultural land intensifies. Balancing land for H₂ versus crops complicates decisions for farmers and raises critical questions about prioritisation. Reduced farmland could also impact regional economies and disrupt existing trade flows [13].

4.3.3. Environmental Challenges

Our findings emphasised that the key environmental challenges for H₂ deployment in farming, as shown in Figure 11, are primarily related to water availability and access.

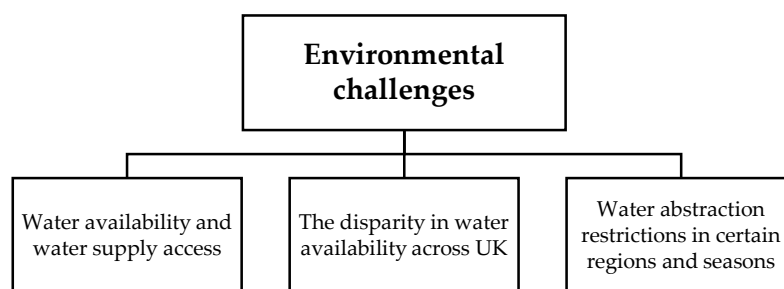


Figure 11. Environmental challenges to the implementation of green H₂ in farming.

One of the key challenges facing H₂ production is the availability of water resources, which is further complicated by the competing demands from other sectors, particularly agriculture. Our study indicates a growing concern regarding whether sufficient water is available to support H₂ production, especially considering the high quality of water required. Water sourced from non-public supplies often presents quality issues, while relying on public water supplies involves increased costs, making water accessibility a significant barrier for H₂ production.

If H₂ production is integrated into the farming sector, the challenge of water availability becomes even more pronounced. Agriculture, as the largest consumer of water, accounts for 70% of water withdrawals, primarily for irrigation [13]. Despite 95% of agricultural land relying on rainfall, the substantial water consumption by agriculture places additional pressure on already scarce water resources [83]. Combining H₂ production with farming activities would intensify the demand for water within the agricultural sector, potentially creating a conflict between crop irrigation needs and H₂ production requirements. This competition between agriculture and H₂ production exacerbates the challenge, particularly in regions such as Southeast and Eastern England, where high population densities further strain water availability. Historical events, such as the 2012 drought following two consecutive dry winters and the 2018 heatwave across Europe, have highlighted the vulnerability of regional water supplies [84]. These regional disparities underscore the critical need for strategic water management to support H₂ production without compromising other essential water needs.

Water availability for H₂ production varies significantly by location; while some areas have abundant resources, others face substantial shortages, making H₂ production challenging. Additionally, the insufficient quality of non-public sources often necessitates reliance on costly public supplies, affecting the overall feasibility of H₂ production.

It has been highlighted that the feasibility of water use for H₂ production depends significantly on the level of water stress in a region. Due to limited water availability, obtaining a water abstraction license in many water-stressed areas presents a considerable challenge. Eastern England is one of the most water-stressed regions in the country but also a major producer of horticultural and combinable crops, requiring substantial agricultural machinery. This combination of high-water demand and low availability further complicates the process of securing abstraction licenses [85].

This study highlights two critical aspects of H₂ production: the seasonal fluctuations of water availability and the potential alignment with energy production periods. Water availability, particularly from non-public supplies, is often seasonal, typically influenced by rainfall, with greater availability in winter. This makes water storage management essential, especially in regions where farmers rely on non-public water sources. As noted by a water management specialist,

“When using non-public water supply sources, farmers’ ability to abstract water is often seasonal. There’s typically more water available in winter, which means you need to consider the amount of storage required”. (i2, a water management specialist)

Moreover, H₂ production may align with seasonal energy availability, such as increased solar energy in summer. Therefore, balancing water storage, energy availability, and H₂ storage is crucial to ensure efficient H₂ production. As the specialist further pointed out,

“If you can store water and take advantage of greater solar energy availability during summer, hydrogen production becomes easier during that period”. (i2, a water management specialist)

This interdependence of water and energy resources underscores the importance of strategic management to align peak production periods with both water and energy availability.

4.3.4. Institutional and Legal Challenges

The empirical results from the workshops and interviews identified three key institutional challenges to implementing hydrogen in farming, which are outlined in Figure 12.

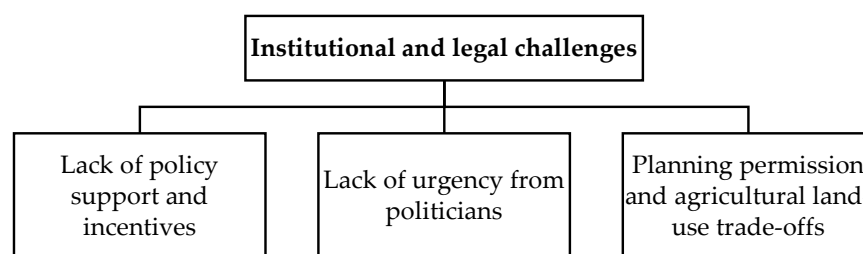


Figure 12. Institutional and legal challenges to the implementation of green H₂ in farming.

A key challenge highlighted by participants is the lack of targeted policy support and incentives for hydrogen adoption in agriculture. While government programmes such as the Hydrogen Allocation Rounds, the Hydrogen Business Model, and the Net Zero Hydrogen Fund provide support for low-carbon hydrogen production, none are specifically designed for farm-level applications [86,87]. Government capital grants for hydrogen-related infrastructure could improve financial viability, yet no such grants currently exist for agricultural hydrogen production. Participants also emphasised that future incentives—such as capital grants or tax breaks—should be inclusive across sectors to encourage a broad transition from fossil fuels to hydrogen, while addressing the unique needs of agriculture.

Policy support is essential for hydrogen production to become cost-competitive with fossil fuels and to enable its effective deployment in farming. Government intervention—through tax breaks, subsidies, or other incentives—is needed to make hydrogen technologies financially attractive to farmers. Capital grants for demonstration farms could further showcase hydrogen production at the farm level, demonstrating feasibility and cost-effectiveness. Several participants emphasised that without targeted government involvement, achieving cost competitiveness with fossil fuels would be unlikely. One of our interviews highlighted the following:

If we really want to implement hydrogen adoption, the government must be involved. Policies need to make hydrogen or green energy more affordable, for example, by cutting taxes for those using these technologies in crop production. Offering incentives, such as tax breaks, would make it more attractive for people to install electrolyzers and other hydrogen-related equipment, thereby facilitating the transition to green energy. (i4, an academic specialising in hydrogen research and technology)

Some participants also highlighted the lack of urgency from politicians and policy-makers to promote H₂ adoption in the farming sector, which acts as a significant barrier to large-scale implementation. Another challenge raised by several interviewees concerns potential planning permission issues and the farming community's worry about the trade-off between using land for energy production versus food production. A water management specialist specifically emphasised the following:

"I think it becomes more of an issue when you need to balance agricultural land use for hydrogen energy production instead of food production. That then becomes a much more complex decision."

This highlights a wider societal dilemma: dedicating land and resources to hydrogen production may compete with food security objectives, particularly in regions where arable land is scarce. The food–energy–water nexus literature notes that renewable energy projects have sometimes displaced agricultural activities or altered rural landscapes, leading to tensions within local communities. The Kipeto wind project in Kenya illustrates both the risks and complexities of such trade-offs: although compensation and consultation enabled communities to maintain some access to land, concerns remained over fairness and long-term outcomes, reflecting how land negotiations can generate ongoing contestation [88]. These experiences suggest that land-use competition in energy transitions is not only a technical consideration but also a societal and governance challenge. In the agricultural hydrogen context, such trade-offs may become particularly sensitive, as pressures on land for food production intersect with emerging demands for energy infrastructure. Together with limited political momentum and planning uncertainties, these land-related challenges may present significant barriers to wider adoption of hydrogen in farming.

4.4. Alternative Stakeholder-Driven Business Models for Green H₂ Deployment

Stakeholders identified three business models to support the economic integration of green H₂ in agriculture: fertiliser production via ammonia synthesis, cooperative-based models, and local hydrogen refuelling stations (Figure 13). Among these, cooperative-based models emerged as particularly promising. Cooperatives—organisations jointly owned and democratically governed by their members—are already well embedded in farming systems through mechanisms such as machinery rings and supply co-ops, which have historically improved access to infrastructure, reduced costs, and enabled economies of scale [89,90].

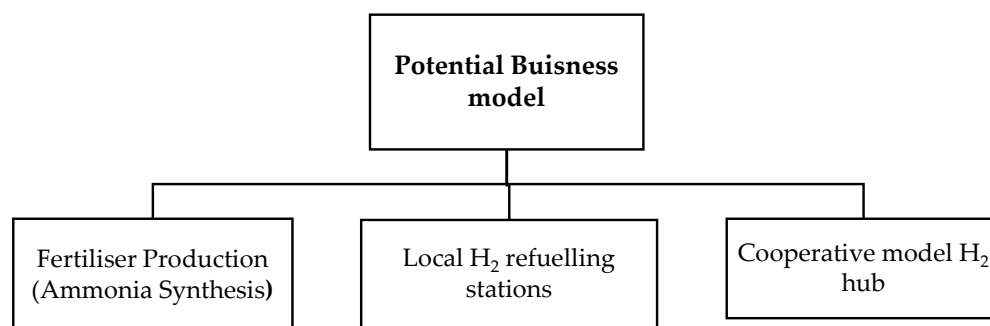


Figure 13. Alternative stakeholder-driven business models for green H₂ deployment.

In the context of H₂, a cooperative model entails clusters of farms collectively investing in and managing electrolyzers, storage facilities, and refuelling infrastructure. Powered by renewable sources (e.g., wind or solar), these systems would enable the local production, storage, and distribution of hydrogen for both stationary (e.g., irrigation, chilling, and heating) and mobile (e.g., tractors and farm vehicles) applications. By leveraging collective ownership and shared infrastructure, cooperative arrangements can reduce costs,

improve system utilisation, and enhance the economic viability of green hydrogen in agriculture. Key benefits include the following: (i) access to shared infrastructure, allowing small and resource-constrained farms to participate without incurring prohibitive costs; (ii) economies of scale, improving performance and reducing the levelised cost of hydrogen; and (iii) risk mitigation through pooled investment and distributed operational responsibility. Although challenges remain around governance, coordination, and equity, cooperative models present a viable and inclusive pathway for integrating smallholders into the hydrogen value chain. For example, the HydroGlen pilot [91] demonstrates the technical and economic feasibility of a hydrogen-powered farming community, showing how farms can become energy self-reliant through modular on-site renewable generation and hydrogen systems. While it serves as a demonstrator for rural resilience and replicability, the project does not operate under a cooperative governance model; rather, it lays the groundwork for future implementation by farming communities or cooperatives.

Cooperative-led hydrogen projects are particularly well-suited to blended finance models, which combine capital grants or concessional loans (e.g., a zero interest loan) with membership-based equity or contributions to help de-risk investments. This approach has been widely used in community energy initiatives, especially in underserved markets where upfront risks deter private investors [92]. In addition, membership-based equity contributions—where farmers invest proportionally in the cooperative—along with targeted grants or subsidies can provide critical early-stage support. Evidence from community energy financing shows that such projects typically rely on a mix of equity, debt, and grants depending on their maturity stage, with cooperative loans also offering a viable instrument for scaling infrastructure [93]. Together, these mechanisms make cooperative financing a promising pathway to support hydrogen adoption in agriculture, as they lower entry barriers while embedding democratic ownership and shared responsibility.

Developing small-scale H₂ refuelling stations on farms is a promising strategy to expand H₂ use in transportation, especially in rural areas. By producing fuel on-site, these facilities can serve both farm machinery and nearby transport vehicles, creating a new revenue stream for farmers while boosting local hydrogen utilisation [94]. A notable example is a pilot project in Steyning, West Sussex, where the company Engas Global deployed a compact “plug-and-play” hydrogen refuelling unit on a working farm. This unit uses surplus electricity from the farm’s biogas combined heat and power plant to run a containerised electrolyser, which produces, compresses, stores, and dispenses green hydrogen on-site without the need for grid power or external fuel deliveries. The system generates roughly 20 kg of hydrogen per day—enough to refuel about 60–70 small fuel cell cars—and regularly fuels a Riversimple Rasa hydrogen car as a demonstration. This independent on-farm setup exemplifies how green hydrogen can be produced and used locally, providing the farmer with clean fuel for personal use and the opportunity to sell fuel to others in the community [95]. Industry observers note that such decentralised hydrogen refuelling models could be replicated across other rural and semi-rural sites, turning farms into energy hubs and diversifying income for landowners [95].

As Table 2 outlines, despite the potential benefits, several challenges hinder the wider deployment of farm-based hydrogen refuelling stations:

- **High Capital Cost and Reliability:** Hydrogen refuelling stations are expensive, often costing millions for a single installation. They are complex, bespoke systems, with even advanced designs achieving only about 95% uptime, making rural investment financially challenging [96].
- **Regulatory and Planning Hurdles:** Strict safety regulations and lengthy approval processes for hydrogen infrastructure can delay projects for years, particularly in remote areas where permitting and compliance are more complex [97].

- **Demand Uncertainty and Underutilisation Risks:** Demand uncertainty in sparsely populated rural areas poses a significant risk to hydrogen refuelling infrastructure, as insufficient local demand can lead to underutilisation, higher unit costs, and poor economic viability. Studies indicate that small on-farm H₂ stations are unlikely to be viable without a consistent baseload demand [97,98].

For hydrogen refuelling stations, international experience suggests that significant public support is often needed to offset high upfront capital costs. In many instances, government programmes offer grants covering 70–85% of installation expenses, thereby lowering the financial barrier for deployment [99]. Additionally, public–private partnership models are commonly used in infrastructure finance, distributing the risks and responsibilities between government bodies and private developers. Such arrangements underscore the value of multi-stakeholder collaboration, enabling the formation of comprehensive hydrogen ecosystems that integrate public authorities, private firms, and research institutions across the value chain [100].

Table 2. Summary of alternative stakeholder-driven business models for green hydrogen deployment in agriculture.

Business Model	Advantages	Challenges	Source
Cooperative-Owned Hydrogen Infrastructure	<ul style="list-style-type: none"> • Promotes collective investment and cost-sharing • Builds on familiar cooperative structures like machinery rings • Enhances local energy independence and resilience 	<ul style="list-style-type: none"> • Requires coordination among multiple stakeholders • Needs optimised infrastructure planning (e.g., storage/system scale balancing) • Financial and institutional complexity 	[91,101]
Local H ₂ Refuelling on Farms	<ul style="list-style-type: none"> • Enables use of hydrogen for farm vehicles and local transport • Dual revenue stream potential • Can leverage renewable energy and increase local resilience 	<ul style="list-style-type: none"> • High setup and equipment costs • Regulatory, safety, and planning hurdles • Low demand in sparsely populated areas 	[96,102,103]
On-site Ammonia/Fertiliser Production	<ul style="list-style-type: none"> • Leverages hydrogen for fertiliser use, aligning with existing farm needs • Improved storage and energy density—reduces dependence on global supply chains • Modular solutions (e.g., containerised systems) are emerging 	<ul style="list-style-type: none"> • Initial capital investment needed for reactors and systems • Technical know-how required • Lacks tailored policy support 	[104,105]

A compelling entry point for the H₂ economy in agriculture lies in on-site fertiliser production via green ammonia synthesis. With approximately 67% of agricultural nitrogen currently supplied by industrial ammonia [106,107], integrating compact, containerised ammonia reactors into farm operations represents a logical and potentially transformative application of green hydrogen. Such systems would allow farms to produce their own nitrogen fertiliser using renewable hydrogen, directly meeting fertiliser needs while reduc-

ing exposure to volatile global supply chains and fossil fuel markets [107]. By decoupling fertiliser supply from external price shocks and import disruptions, decentralised ammonia production could significantly enhance rural resilience and food security.

Ammonia's material advantages further strengthen this proposition. Unlike hydrogen, which requires cryogenic or high-pressure storage, ammonia liquefies under moderate conditions and benefits from extensive existing infrastructure, including pipelines, storage tanks, and global shipping networks. Farmers are already familiar with ammonia-based fertilisers, lowering adoption barriers and enabling multifunctional use: green ammonia can be stored, applied directly as fertiliser, or reconverted to hydrogen, making it a versatile enabler of agricultural decarbonisation.

The economic potential is equally compelling. Recent studies suggest that decentralised ammonia could be cost-competitive with conventional production once transport costs and supply risks are factored in, potentially supplying up to 96% of global demand by 2030 [107]. This would not only reduce fertiliser costs but also mitigate reliance on imports and fossil fuels. However, this opportunity is far from guaranteed. High capital requirements, lack of economies of scale, and inefficiencies in current small modular systems continue to impede deployment [108]. Without policy intervention—through low-cost renewable energy, targeted incentives, and investment in catalyst and modular manufacturing innovation—these barriers will persist.

Global progress underscores what is possible. Large-scale green ammonia projects in Denmark, Europe, and the USA [109], alongside infrastructure integration trials such as [110], demonstrate technical feasibility and improving economics at scale. However, this study shows that translating such advances to UK agriculture is not straightforward: farm-based hydrogen production remains economically uncompetitive due to high costs, seasonal demand variability, and limited institutional support. Unlocking the potential of on-site green ammonia therefore demands coordinated policy action to de-risk investment, stimulate early adoption, and bridge the gap between global innovation and local agricultural realities. For financing green ammonia fertiliser production, the Green Hydrogen Contracting Guidance underscores that public sector grants and concessional funding are critical to de-risk hydrogen projects and make them more bankable, particularly during early-stage development phases [111].

5. Conclusions and Recommendations

Despite its potential, H₂ use remains concentrated in the petrochemical industry—primarily for ammonia synthesis, oil refining, and steel production—while applications in transport, heating, electricity generation, and agriculture remain limited [57,58]. This paper examined the potential of integrating green H₂ into agriculture through a combined techno-economic assessment and stakeholder analysis. The results show that farm-based H₂ production is technically feasible but currently economically uncompetitive. In a 10-farm cluster, the LCOH is around GBP 0.425/kWh—almost six times higher than diesel—driven by seasonal demand variability and low utilisation rates. Expanding demand by incorporating additional users, such as local delivery fleets, can reduce costs to GBP 0.24/kWh. This highlights the importance of multi-user integration and cross-sectoral planning.

However, cost competitiveness alone will not ensure adoption. Farmers are highly cost-sensitive and risk-averse, requiring solutions that are not only affordable but also reliable, simple to operate, and compatible with existing equipment. While stakeholders acknowledged hydrogen's potential to reduce dependence on volatile fuel and fertiliser markets, they also raised concerns over affordability, operational complexity, and limited institutional support. These findings highlight that successful deployment depends as much on social and institutional conditions as on technological progress.

Three business models were considered: on-farm hydrogen refuelling stations, small-scale fertiliser production via ammonia synthesis, and cooperative-based models. While refuelling and fertiliser production may offer niche opportunities, both face high capital costs and uncertain demand. In contrast, cooperative hydrogen hubs emerge as the most promising option, supported by the results from this research:

- Techno-economic assessment demonstrates that multi-user systems improve the utilisation rate of hydrogen production systems and therefore reduce the LCOH, making cooperative ownership more attractive than isolated farm systems.
- Stakeholder analysis shows that collective ownership can mitigate farmers' cost sensitivity and risk aversion, ensuring a fairer distribution of costs and benefits.
- Institutional precedent in UK agriculture—through machinery rings, supply co-ops, and renewable energy cooperatives—demonstrates that shared ownership has historically helped farmers overcome affordability constraints, operational risks, and lack of support in other domains [89,90].

Crucially, cooperatives are not only a way to reduce costs but also a proven mechanism for overcoming the very barriers farmers perceive today: affordability, operational complexity, and adaptability. With supportive policies and coordinated action, cooperative hydrogen hubs can transform hydrogen from a theoretical option into a practical driver of agricultural decarbonisation, rural resilience, and prosperity. Based on the techno-economic and stakeholder evidence presented in this paper, it is clear that cooperative hydrogen hubs offer the most viable pathway for agricultural hydrogen adoption in the UK. However, significant barriers remain around cost, governance, and practical implementation.

To realise the full potential of green hydrogen in agriculture, several enabling measures must be put in place. Addressing these challenges demands both targeted policy interventions and sustained research efforts. In particular, greater attention is needed regarding cooperative governance structures, financing models, and farmer engagement strategies to ensure hydrogen systems are not only technically and economically viable, but also socially acceptable and resilient. Without such an integrated approach, the UK risks missing a crucial opportunity to align agricultural practices with national climate commitments and strengthen rural resilience.

Recommendations:

- Provide targeted incentives (capital grants, tax breaks, and contracts-for-difference) to lower upfront costs and de-risk cooperative investment.
- Streamline planning and safety approval processes to accelerate rural hydrogen hub deployment.
- Expand cooperative hydrogen pilots to refine governance, financing, and business models in diverse agricultural contexts.

Taken together, these measures could support the UK in advancing agricultural decarbonisation, while also offering benefits for rural communities and contributing to the wider net-zero transition.

Avenues for Further Research

This study focused on the UK agricultural context, where farm-based renewable energy is the primary source for green hydrogen production. Future research could extend the analysis to international settings, such as China, where large-scale renewable projects (e.g., offshore wind and hydropower) may create different opportunities for hydrogen integration and deployment.

In addition, this study did not include formal uncertainty quantification, as this was beyond the intended scope. Future work could address this by incorporating systematic

uncertainty and sensitivity analyses of key parameters (e.g., diesel and electricity prices, electrolyser costs and efficiency, and hydrogen storage assumptions) to capture the variability in costs, performance, and external conditions. Doing so would enhance the robustness of techno-economic modelling and provide more reliable evidence to guide investment and policy decisions.

Finally, extending the analysis to larger and more diverse stakeholder groups across different regions would allow testing the transferability of results and provide stronger comparative evidence on the opportunities and barriers to agricultural hydrogen adoption.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
H ₂	Hydrogen
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
LCOH	Levelised Cost of Hydrogen
P	Pence

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