scottish science advisory council

SSAC Technical Briefing Note on:

Opportunities and challenges associated with hydrogen's role in the delivery of future energy systems in the context of a Just Transition

EXECUTIVE SUMMARY

The Scottish Government (SG) published Part 1 – Hydrogen Economy: Route Map to 2030 and 2045 - Hydrogen action plan: draft - gov.scot (www.gov.scot) in 2021 stating its commitment to developing a hydrogen economy in Scotland and has already supported trials to demonstrate the use of hydrogen in the transport, home heating and management of energy demand fluctuation sectors. This is an emerging economy, however, for which demand is still uncertain and the rate of growth will depend on decisions made beyond and within Scotland on how best to decarbonise the energy sector. Progress will also depend on the resolution of a number of technical problems to scaling up the generation and use of hydrogen in the transition to a lower carbon economy and the SG has recognised the importance of planning implementation in the context of a Just Transition. During 2022 the SG developed a draft Energy strategy and Just Transition Plan (ESJTP), to go out for consultation in late 2022. This study, together with the feedback from that consultation, will inform the revision of the draft ESJTP.

There are already many reports published and pilot trials underway related to the role of hydrogen (see links in Annex 1a) and the SSAC supplemented their own knowledge of the energy sector and role of hydrogen, with reviews of these and knowledge collated through interactions with stakeholders, drawn from academia, the energy sector and civil society via a questionnaire and virtual Roundtable. The approach considered both the technical and the socio-economic challenges.

Significant technical challenges remain in terms of the source, production systems, infrastructure for transportation, storage and supply routes for hydrogen, some of which are geological and engineering focused, but all of which form major hurdles to its deployment. Resolving these requires significant investment by both the public and private sectors during a time of multiple economic challenges and at an ambitious pace to meet the Net Zero target. Prioritisation is key and should be reached through partnerships between government (local as well as national), agencies, energy-intensive industries, academia and stakeholders which take account of the varying energy and economic demand and supply across Scotland.

Given that hydrogen plays only a very small part in the energy mix currently, and where it does it is in specialist, niche areas, a big challenge lies ahead in engaging with wider society. It will be very important to have a phased, transparent and inclusive communication strategy on the options for decarbonisation of the energy sector being considered by the SG and the likely timing of their decision making. This will enable informed investment decisions to be made across scales from householders to big industry.

Summary of priority actions informed by SSAC's stakeholder engagement:

Engagement with stakeholders and the general public:

1. A need for honesty, transparency and integrity in communications
2. Explanations to stakeholders and the public about current energy systems and their relationship to greenhouse gas emissions, compared to new systems, could help with public understanding of the relative costs and benefits.
3. The long-term scenarios (e.g. which sectors the SG thinks might use hydrogen, roughly to what extent and at what scale) need to be clear and explained in relation to infrastructure costs at both the household and national level.
4. Using case studies of past successes – e.g. the use of hydrogen in Orkney and Aberdeen – in messaging may help alleviate concerns, particularly about safety for local rural and city transportation.
5. Any known impacts of hydrogen generation, storage and use on other environmental indicators should also be transparent.
6. Academics and industry could help to communicate the risks and opportunities of different approaches.

Opportunities and challenges in different sectors and mutual dependences:

1. There is concern about the tight timelines set by the Net Zero Strategy, relative to the timing of decisions, given the need for investment in infrastructure – this emphasises the need for close working between government and industry.
2. The use of hydrogen in different sectors provides opportunities, but also challenges – freight transport and industry were considered to be a better place to start than domestic heating, marine transport or aviation.
3. The issue of having sufficient skilled workers available came up frequently – one point related to ensuring there is sufficient opportunity to re-skill and upskill workers to face the needs for the hydrogen sector.
4. The opportunity for hydrogen to compensate for the intermittency of other forms of low carbon energy such as wind and solar was raised e.g. through storage. This emphasises the need for a holistic energy strategy.
5. Stakeholders asked for a high-level cost/benefit analysis and for consideration being given to different ways of billing for infrastructure costs.
6. Reference was made to potential demand for hydrogen not just as a fuel, but also as a chemical feedstock (e.g. for fertilisers). The production of ammonia and synthetic fuel using green hydrogen were mentioned as two opportunities for Scotland.

Messages around storage and export:

1. The potential of Scotland, the north in particular, to produce more renewable energy than current demand required was referenced, alongside the potential for this excess to be stored and exported as hydrogen.
2. There are major challenges surrounding safe geological storage given the lack of salt deposits in Scotland and unproven potential to use depleted gas fields in offshore waters.
3. Technology and engineering issues around hydrogen storage and transportation (e.g. issues resulting from its small molecular size increasing the risk of leakage and pipe embrittlement due to the diffusion and dissolution of hydrogen in the microstructure of

metal piping or infrastructures), however, mean that caution is required re scaling up, given the costs of refitting the whole system.

4. Caution also needs to be exercised in quantifying Scotland's hydrogen export opportunities, given the uncertainties regarding storage, excess production, identification of long-term markets and the extent of competition.

Challenges associated with investment and markets:

1. Achievement of export potential will require support for hydrogen technology start-ups and spinouts in Scotland and encouragement for larger players to invest in Scotland.
2. There is a need for more clarity from government on their priorities for hydrogen use to manage demand, e.g. to stimulate demand for hydrogen as a chemical feedstock.
3. Perceived insufficient R&D investment in Scotland at present to lead any hydrogen industry developments, which in turn suggests that Scotland will not play a key part in structuring export markets.

Projects are already underway to provide evidence in support of decisions to address some of these challenges and links to key projects are given in the main text.

Summary of concerns and recommended actions on any foreseeable impacts of incorporating hydrogen in the energy mix on Scotland's eight Just Transition Outcomes ([Just Transition - A Fairer, Greener Scotland: Scottish Government response - gov.scot (www.gov.scot)](https://www.gov.scot).

Citizens, communities and place: Participants agreed that the risks and opportunities are strongly connected to local circumstances and commended the commitment to regional hubs of hydrogen activity outlined in the draft Hydrogen Action Plan.
Action recommended: Partnerships between government (local as well as national), agencies, energy-intensive industries and stakeholders which take account of varying energy and economic demand and supply across Scotland will be crucial.

Jobs, skills and education**:** The opportunity for retraining and upskilling of those at risk from the downscaling of the oil and gas industry was highlighted at university, college and operational levels.
Action recommended: Clear and early guidance from SG on priority uses of hydrogen and associated strategy for skills and training, including fair pay and orientation to equality, diversity and social inclusion.

Fair distribution of costs and benefits: Possible opportunities in coastal areas and where hydrogen hubs might be located, were mentioned in terms of manufacturing jobs and access to cheaper energy, but may also lead to negative impacts if major new infrastructure is required.
Action recommended: Collaboration between key stakeholders, industrial partners and local communities will be essential to define opportunities and trade-offs, including methods to secure economic returns to key regions.

Business and Economy*:* There will be winners and losers with respect to economic opportunities depending on the balance between blue and green hydrogen investment.
Action recommended: SG financial support, transparent and timely planning processes, experienced workforce and good infrastructure.

Adaptation and Resilience: In terms of resilience with increased risk of storms associated with climate change, remote areas may be able to access hydrogen fuelled generators.
Action recommended: SG to engage with BEIS on the parameters for Capacity Market auctions and the interface with hydrogen strategy. How might a prospective 'local' hydrogen generator business engage in the GB capacity market?

Environmental protection and restoration**:** Blue hydrogen was viewed as environmentally negative since technologies for carbon capture and storage are only at an early stage of development and the technology still relied upon a gas field source. More generally the life cycle environmental impact of different decarbonisation technologies needs to be considered.
Action recommended: The move to green hydrogen should be accelerated where socio-economic and environmental benefits coincide. This requires scenario analysis which is sensitive to place-based variations.

Decarbonisation and efficiencies**:** Risks associated with hydrogen leakage from storage sites or infrastructure and its release, or of other gases such as methane, into the atmosphere need to be avoided. Recent evidence points to the Global Warming Potential of Hydrogen as being more powerful than previously estimated.
Action recommended: the Hydrogen Action Plan needs to cover avoidance of the release of **all** greenhouse gases.

Further equality and human rights implementation and preventing new inequalities from arising**:** There is a risk that funding for investment in green hydrogen will come from customers' bills.
Action recommended: Stakeholders recommended that taxes or levies in the energy sector should be used to fund development of green hydrogen; such a decision would have to be taken by the UK Government.

CHALLENGES TO REALISING THE OPPORTUNITIES OF HYDROGEN CONTRIBUTING TO THE TRANSITION TO A LOW CARBON ECONOMY

Introduction

Hydrogen production is a proven technology, on a small scale and currently for niche markets such as for small-scale power supply in off-grid modes, large-scale chemical energy exports and through production of fertilisers. Since hydrogen rarely occurs naturally in its pure form, industries that rely on it (e.g. oil refining and fertiliser production plants) have sourced it through gasification and reforming of fossil fuels both of which are emission-intensive.

Although the deployment of hydrogen as an alternative energy vector has long been discussed, it has yet to be realised because of the lack of low-cost and conversion technologies. Hydrogen Generation - an overview | ScienceDirect Topics The recent tipping point in the cost of some renewable energy technologies such as wind and photovoltaics has mobilised continuing sustained interest in use of renewable hydrogen, produced by electrolysis, which splits water into hydrogen and oxygen.

Although some suggest that hydrogen production does not lead to CO2 emissions during combustion, this is disputed, and recent work suggests that it is a much more powerful greenhouse gas than previously thought. UK government study | Recharge (rechargenews.com); Atmospheric implications of increased hydrogen use (publishing.service.gov.uk); Fugitive hydrogen emissions in a future hydrogen economy (publishing.service.gov.uk)

The UK Government issued its Net Zero Strategy in April 2022, in which it detailed its plans to accelerate secure clean, green, UK-made energy. The new commitments contained in the Net Zero Strategy proposals are hugely ambitious and the UK Climate Change Committee (CCC) have suggested that Government, business and industry will need to focus relentlessly on delivery at a scale and pace as yet unseen for the ambition to be fulfilled.

The CCC have highlighted the potential role that hydrogen could play in decarbonising electricity generation and to provide a Balanced Net Zero Pathway for Fuel Supply in their three reports: Hydrogen-in-a-low-carbon-economy-CCC-2018.pdf (theccc.org.uk), Net Zero - Technical Report - Climate Change Committee (theccc.org.uk) and Sixth Carbon Budget - Climate Change Committee (theccc.org.uk)

In their publications, the CCC propose that hydrogen (as either ammonia or as hydrogen itself) can be used as a low-carbon fuel in the buildings, industrial, transport (including shipping) and power sectors. The CCC have previously suggested that hydrogen could be produced at low cost with low emissions, by the development of advanced methane reformation facilities with CCS. However, the ongoing energy price crisis fuelled by increases in the gas price have meant that blue hydrogen production is adversely affected and is no longer low cost.

The CCC believe that hydrogen can provide a flexible form of dispatchable generation such as unabated gas and encourage Government to support the early demonstration of the everyday uses of hydrogen to establish the practicality of switching from natural gas to hydrogen.

In the Balanced Pathway, they envisage some gas power plants starting to switch to hydrogen in the 2020s. They suggest that hydrogen gas plants could provide 20 TWh of generation by 2035, to meet 5% of demand and state that significant volumes of low-carbon hydrogen should be produced in a carbon capture and storage (CCS) 'cluster' by 2030 to help the industry grow.

Since hydrogen is synthesised from fossil fuels or renewable energies, its cost will be dependant upon the price of its source. If hydrogen is made from natural gas, it will cost more than the gas itself and similarly, hydrogen derived from electrolysis will cost more than the electricity source.

In 2022 however, the Russian invasion of Ukraine resulted in major price increases in the European gas market, and there is continuing uncertainty about the near-term future of fossil fuel gas in the energy system. There are also known conversion losses in the methane reformation process. In combination, these two factors significantly change the cost equation for blue hydrogen. A key policy question now is where is best (whole system) value achieved from blue or green hydrogen production, relative to direct use of power from renewable generation.

Aims and objectives of this SSAC study
Given the potential significance of hydrogen in the delivery of the energy strategy and Just Transition plan, the SSAC's Energy sub-group undertook an analysis to identify the challenges, barriers and hurdles to the deployment of hydrogen, and to securing its economic contribution, compatible with the SG's mission to meet the net zero emission target by 2045.

The framing of engagements was co-designed with the SG Whole Systems and Technical Policy Unit . The aim was to provide a high level overview of some of the potential barriers to the role of hydrogen in delivering a fast, socially inclusive energy transition and to suggest pathways to overcome these barriers.

The SSAC study recognised the research being undertaken by other organisations that are active in this space in particular the Committee for Climate Change (CCC), but sought to complement that work by highlighting issues in a Scottish context.

Sources of evidence
To add to knowledge in the scientific literature, a questionnaire (Annex 1b) was sent out to 83 organisations of whom around a third responded. These responses helped to inform the structure of the Roundtable and the questions posed for discussion in 3 Breakout groups (Annex 1c). Twenty six stakeholders, together with 3 SG policy officials and the SSAC sub-group attended the virtual Roundtable which was held on 5 July 2022.

The contents of this paper take into account the written responses to the questionnaire, presentations that framed the discussion and the interactions on the day under two sub-headings:

i) Source, Transportation, Storage and Supply of Hydrogen; and
ii) Socio-economic questions about hydrogen as an energy vector.

Technical questions on source, transportation, storage and supply

Energy vectors are defined as **energy forms derived from natural resources,** which are converted to enable transportation, storage and use of a quantity of energy in another location and time. For use of any vector, its source, transportation, storage and reliable supplies must be guaranteed.

Production of hydrogen
There are a number of sources for hydrogen. Whist some sources rely upon gas, oil or coal (fossil fuel), one relies solely on the electrolysis of water from renewable power (e.g. wind energy).

The different sources of hydrogen are commonly "colour-coded" for clarity (Fig.1). Whilst **Black, Brown** and **Grey** hydrogen rely on fossil fuels as their feedstock, **Blue** Hydrogen requires a gas field, a secure carbon store to avoid CO2 emissions to the atmosphere and a hydrogen export route to be spatially close. With an ever-increasing awareness that more climate compatible energy sources are required, attention has turned to **Green** hydrogen, which is derived from electrolysis of fresh water to produce hydrogen and oxygen but no carbon by-product.

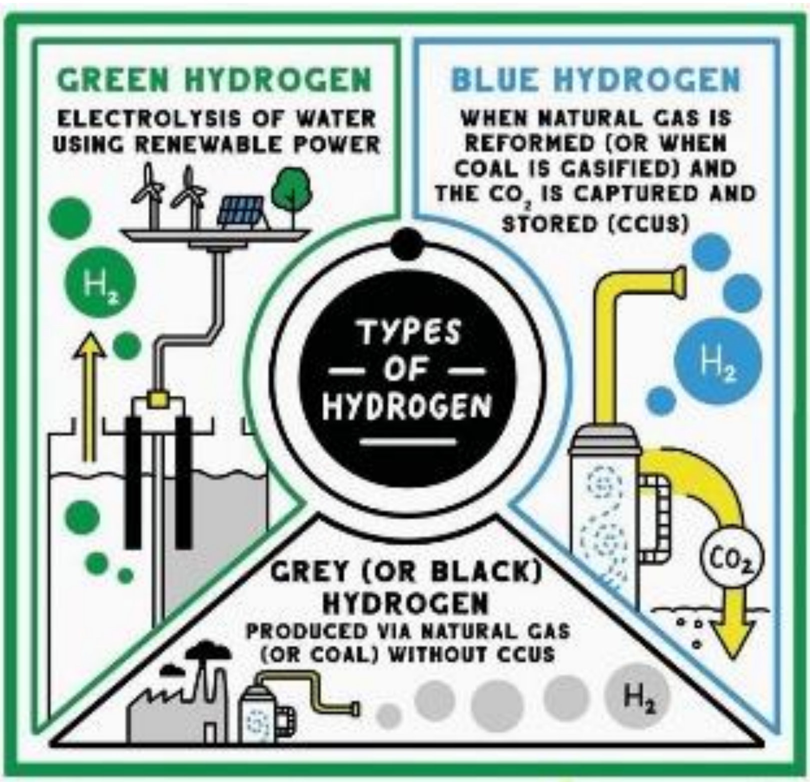

Fig.1: Sources of Hydrogen (Image shown courtesy of BP)

Since hydrogen is synthesised from fossil fuels or renewable energies, its cost is dependent upon the price of its source. When hydrogen is made from natural gas, it will cost more than the gas itself and similarly, hydrogen derived from electrolysis will cost more than the electricity source. As a consequence, hydrogen production is energy intensive, expensive and inefficient, with more energy needed to get less out.

Whilst electrolysis driven by offshore wind energy is being promoted as a viable source, the nature of sea water would necessitate the inclusion of a desalination plant, something that would lead to additional costs for hydrogen production.

The need for a gas field, carbon store and hydrogen export pathway for the production of blue hydrogen depends on continued gas production, the three elements all being spatially close to one another and linked, and agreement and alignment between the various stakeholders.

The production of hydrogen also depends on regulatory compliance and agreement between the Crown Estate/Crown Estate Scotland and the North Sea Transition Authority (NSTA) and management of the trade-offs resulting from co-location of competing interests (e.g. the competition for offshore "real estate") such as those that exist between wind farms, carbon storage licensees and oil and gas ventures.

Storage of hydrogen

The potential for storing hydrogen for use as an energy source to compensate for the intermittency of renewable energy or back-up supply in remote rural areas is seen as an opportunity. However, as regards long-term storage and containment, it is important to emphasise that hydrogen is a small, nimble and highly diffuse molecule that rarely occurs naturally. Its physical and chemical properties mean that it is hard to ensure that leakage is minimised; the most successful means of storage are through geological means exemplified by hermetically sealing in evaporite (rock salt; halite) deposits in which caverns have been dissolved out; an alternative is storage in manufactured containers.

The lack of any salt-deposits in Scotland means that onshore subsurface storage is not an option. The nearest sites where salt occurs in the subsurface are in Cheshire, along the east coast in Lincolnshire and Yorkshire, where storage repositories exist (Teesside) or are being planned (e.g. H2H Saltend - Equinor), and Northern Ireland, where feasibility studies are underway.

Some observers have suggested that offshore oil and gas fields represent an opportunity for storage especially those that have an evaporitic top seal and research is being undertaken to investigate the suitability of depleted fields for safe subsurface hydrogen storage (HyStorPor Project Hydrogen Storage in Porous Rocks (copernicus.org)). However, the absence of any naturally occurring hydrogen in 60 years of oil and gas exploration in the UK Continental Shelf (UKCS) provides a challenge and raises the immediate questions: Was the hydrogen once there and leaked? Or, if one were to inject it into the subsurface reservoirs, what confidence would one have that it wouldn't escape? One, other or both issues need to be addressed before subsurface hydrogen storage is undertaken.

Whilst it may appear attractive to re-purpose the North Sea's infrastructure for hydrogen export, use of the existing oil and gas network is not a given as hydrogen may in some circumstances cause pipe embrittlement (What is Hydrogen Embrittlement? - Causes, Effects and Prevention - TWI (twi-global.com)), the degree to which it occurs being dependent upon the amount of hydrogen absorbed and the microstructure of the material. Redressing the embrittlement issue will add significant new costs in either lining the pipelines with compliant materials or else, investing in new systems including line-packing strategies. The National Grid has a project underway to consider repurposing the existing gas transmission system. (National Grid Project Union)

In the absence of geological storage solutions, an alternative option for Scotland is to design gasometer-like repositories of the type that used to house town gas before the advent of the North Sea gas and conversion of the gas network for methane. Given the scale of construction and urban planning needed to build the repositories there would be a challenge to gain the social licence to operate.

Distribution of hydrogen

The aforementioned issue with pipe embrittlement is not restricted to hydrogen transportation offshore, but equally applies to the onshore gas network and the whole system would need to be reconfigured and potentially replaced for hydrogen to be used exclusively. SGN are working to replace older iron mains gas pipelines with polyethylene in some locations and are targeting 2032 for the whole network to be compliant. {Iron mains risk reduction (hse.gov.uk)}

Work is ongoing on the end-to-end process needed for hydrogen's deployment, (e.g. including leakage, water shortages in Scotland, suitability of existing network) and there remains a need to check if the current network can transport hydrogen securely and efficiently, or if upgrades are needed.

The National Grid are also undertaking a comprehensive programme of work to connect hydrogen production, storage and demand to enable net zero and empower a UK hydrogen economy. National Grid Project Union

Use of hydrogen for heat

From a domestic heat perspective, the decisions on the future of the gas grid are reserved to Westminster. As a consequence, progress in Scotland's transition relies on decisions made by BEIS and for decarbonisation targets to be met by gas. An evidence-base is being gathered by BEIS to investigate this issue.

Heat is arguably the most challenging energy decarbonisation issue, because of the huge variation between winter and summer demand, as well as daily and weekly peaks and troughs. It may be impractical to electrify heat in totality because of the huge amount of infrastructure needed, much of which would be underutilised. Even with a high electrification solution using hybrid heat pumps with facility for gas combustion during peak demand periods all of the gas grid would be retained, albeit less utilised because of the use of hybrid boilers.

Hydrogen can be blended with methane to around 20% for domestic uses, but at higher concentrations, the flame on existing gas-cookers and boilers will not light and all gas appliances would need to be modified or replaced by new or hybrid ones.
Whilst challenges exist around the scale-up of hydrogen use and its deployment in the sectors that are hard to abate, it is an existing product, with some small-scale storage in existence, and is being tested through key projects such as the H100 project in Fife (About H100 Fife - SGN), at Winlaton in NE England (Hydrogen blending begins on the public gas network in Winlaton - HyDeploy), and on the Keele University campus, where the 20% blend is being trialled (HyDeploy - Keele University).

Use of hydrogen for transport
The highest value industry for hydrogen use is likely to be heavy goods transport, but there is concern from hauliers about the challenges of refuelling and the need for a country-wide consistent network to enable hydrogen to serve as an alternative to diesel.

Hydrogen may well provide a local transport solution, and it is already being deployed in some transportation schemes (e.g. in Aberdeen) where some hydrogen-fuelled buses are already in operation (H2 Aberdeen | Aberdeen City Council). Trials are extending to rail- (Scotland unveils hydrogen trains project (energy-reporters.com) and ferry-travel (Study into hydrogen powered ferries fuels green transport ambitions | Wood (woodplc.com).

Use of hydrogen within energy network
Having highlighted the issues, a highly decentralised hydrogen grid still has potential in Scotland with local balancing of supply and demand to manage the high energy demands of heat, making a greater degree of electrification possible. The energy system operator (ESO) future energy scenarios (FES) provide a supportive starting point; 2021 FES envisage hydrogen heating for homes as possible only after 2035, which is too late as a timetable to support SG targets. UK Government have however stated that they will make a decision on the prospective use of hydrogen for domestic heating by 2026, based on outcomes of current hydrogen heating trials (see https://www.gov.uk/government/publications/heat-and-buildings-strategy).

Export of hydrogen
Production at scale will need port and vessel infrastructure; hence identification of the most suitable harbour locations is required Green Freeports in Scotland: bidding prospectus - GOV.UK (www.gov.uk) . Decisions regarding Freeport status awards may be relevant in making sites more competitive as renewable manufacturing hubs.
Questions exist about the level of investment and geographical constraints of supply which would affect Scotland's ability to compete in a European market for carbon. In terms of close neighbours, Belgium, Denmark, France, Germany, the Netherlands and Norway are all developing hydrogen strategies Hydrogen in North-Western Europe – Analysis - IEA and their decisions will impact on Scotland's competitiveness.

Socio-economic questions about hydrogen as an energy vector

There is a lack of awareness across society that blue and green hydrogen are being considered as a major energy vector. Evidence on societal concerns is lacking, and there is a need to develop a social licence for emerging production and supply systems. Given the aforementioned issues associated with the potential deployment of hydrogen, two principal questions are likely to be: is it safe? And what will it cost?

Safety of hydrogen

First, with respect to safety, there is a need for education about the technical aspects of a hydrogen system compared with the existing fossil fuel gas system. This would help to address public questions about viability, and potentially reassure any customers/communities where hydrogen may be tested, ultimately allowing informed decisions to be made.

Cost of hydrogen

Second, cost was an area of concern not only for the domestic sector, but also for industries that may aim, or may be expected, to switch to hydrogen for high temperature heat, where a key issue is the price of hydrogen compared to alternatives.

For the domestic sector, the SGN-led H100 Fife project (Buckhaven and Denbeath) will provide a critical feasibility test of safety and affordability of renewable hydrogen for heating and cooking, and evidence on user satisfaction https://www.h100fife.co.uk. [1] There is some uncertainty about progress, but commitment from sponsors to proceeding, as reported in https://www.theguardian.com/environment/2022/sep/20/world-first-hydrogen-project-raises-questions-about-its-role-in-fuelling-future-homes

Scottish fuel poverty policy and just transition plans aim to ensure that no one is left behind in, and that all benefit from, the energy transition, including island and rural communities. This policy commitment creates a test of financial feasibility of hydrogen for domestic supply, with current evidence from systematic review indicating that hydrogen for heating is likely to be more expensive than, for example, electric heat pumps http://www.janrosenow.com/uploads/4/7/1/2/4712328/is_heating_homes_with_hydrogen_all_but_a_pipe_dream_final.pdf .

With cost-effectiveness in question, care is needed to avoid the risk that discussion about hydrogen for heating acts as a distraction from the urgent work of upgrading building stock to retain warmth, as well as developing efficient community heat schemes and district heat networks, and stand-alone electric heating.

[1] With £28 million total funding from Ofgem (£18 million Network Innovation Competition), Scottish Government (£6.9 million) and gas network operators, the first phase of the project aims to produce hydrogen from electrolysis powered by a nearby offshore wind turbine. The intention by 2023 is to supply hydrogen to around 300 houses, via a new hydrogen network.

In the wider economy, where GHG externalities are not yet sufficiently embedded in cost comparisons, there is no short term economic case for production and use of clean hydrogen, instead of fossil fuels. Scottish and UK government policy statements, which situate hydrogen in the context of net zero GHG emission targets, anticipate creation of the necessary market institutions and financial flows, governing production, contracting, pricing and trade. Hence there are key socio-economic questions about market formation & regulation. These centre on the investors, supply chains, producers and customers needed for viable hydrogen production in what locations and the consequences for shares of costs and benefits. Scottish Government £10 million Hydrogen Innovation Scheme is intended to provide capital support over the next four years (2022-26). This aims to unlock additional private investment in the technology, and enable new companies to enter the sector. UK Government has committed up to £300 million until 2024 to pilot hydrogen programmes and innovation schemes. In this wider context of clean hydrogen policy, market development and economics, an important metric will be the levelized cost of hydrogen (LCofH), a **methodology used to account for all capital and operating costs of production** (see for example https://www.gov.uk/government/publications/hydrogen-production-costs-2021)**.**

This enables costs of different production routes to be compared against a common metric, in the context of whole system integration (i.e. costs of all energy sources/vectors). In the case of blue hydrogen (using fossil fuel gas and steam methane reformation with carbon capture and storage), cost estimates indicate that new infrastructure, scale and interdependencies of production entail significantly higher costs than fossil fuel gas.

At present the evidence base to evaluate costs and benefits of large-scale deployment of hydrogen is under-developed. There is an urgent need for objective, publicly available and accessible research data, situating hydrogen in the context of whole system decarbonisation scenarios, and using comparable cost formulae for the different options. It is critical to offset any risk that influential organisations may promote hydrogen to benefit commercial interests, but not necessarily the interests of consumers or wider publics. Concerns about this have been voiced. https://www.theguardian.com/business/2022/oct/15/the-great-hydrogen-gamble-hot-air-or-net-zeros-holy-grail?CMP=Share_AndroidApp_Other

Given the tight timeline to implement Scottish 2030 emission reduction targets, clarity over hydrogen policy priorities is important. Clean hydrogen has potential for use in a number of areas and sectors, notably marine, aviation, freight and heavy industry. Technical-economic challenges, however, suggest that freight transport and industry are likely to be the most useful starting points. Hydrogen may also be used as a 'storage' system for renewable power during periods when supply exceeds demand; it could in turn be used in combustion to supply electricity, although conversion losses need to be considered and costed. In all cases, there are consequences for electricity grid capacity and reinforcement costs.

At present, given the absence of a market for blue or green hydrogen, near-term hydrogen developments will benefit from attention to the sequencing of information to the relevant stakeholders, in line with progress in the supply chain. Early customers/users need to be identified, while avoiding possibly misleading information about short-term prospects for wider industry supply.

Conclusion

Hydrogen is actively being explored as an alternative energy vector to replace fossil fuels as part of efforts to decarbonise the energy sector and transition to a low-carbon economy. Hydrogen deployment relies on the resolution of numerous and challenging technical issues, improved efficiency and reduction in costs to scaling up its generation, safe storage and transportation and the social and economic challenges of ensuring a Just Transition.

It is unclear from the evidence tabled for this study how realistic or wide an application hydrogen will have for industry, domestic heat, road transport and agriculture, which contribute the highest emissions. If it proves to be impractical or too costly to deploy hydrogen in these sectors, however, those options should be removed at an early stage to reduce uncertainty for the public and business investment, and to enable greater clarity about their decarbonisation options and pathways.

Alternative low-carbon solutions also need to be sought via electric heating systems, district heating and electrical vehicles, shared transport and active travel. The highest priority action in the domestic sector remains building retrofit to reduce the need for heating. Hydrogen does potentially provide a new opportunity for some rural locations and to help compensate for the intermittency of renewable energy generation, but it will be important for government (at all levels) to work in partnership with the private sector whilst being open and transparent with wider society. Science has a role to play as an honest broker ensuring that relevant knowledge is subject to a thorough test, critically evaluated and objectively discussed.

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