Zemo Partnership
Accelerating Transport to Zero Emissions

Executive Summary

Low Carbon Hydrogen Well-to-Tank Pathways Study

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1. Introduction

In the transition to zero emission vehicles and net zero transport, one of the primary considerations is the carbon intensity of the fuel/energy used, and the efficiency of both the production and distribution of that fuel and its use in a vehicle.

Battery electric vehicles currently dominate the zero emissions market and many studies have been conducted to assess the carbon intensity trajectory of electricity and its transmission, and on electric vehicle efficiency.

The other clear zero emissions option is hydrogen fuel cell electric vehicles but there is very little agreed data on either the pathways for low carbon hydrogen supply or on the vehicle efficiency of FCEV. Specifically in the UK there is no GHG reporting data for companies using hydrogen vehicles.

With the increase in hydrogen vehicles, particularly in bus and truck applications Zemo identified several areas which warranted building an evidence base to improve understanding of the role of hydrogen in zero emission transport and to fill key gaps in transport sector's knowledge. This is based on performing a detailed examination of vehicle and fuel life cycle greenhouse gas emissions.

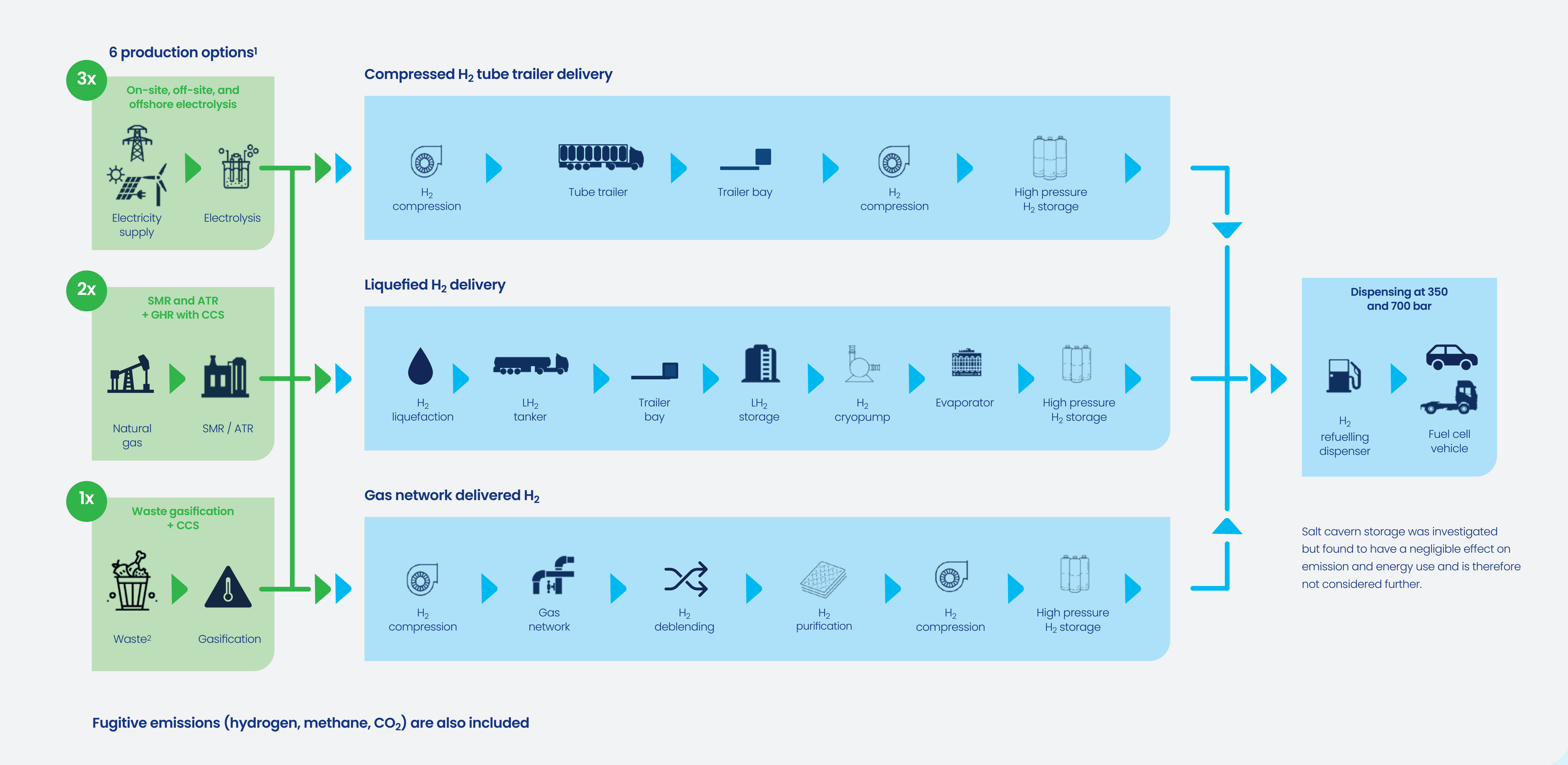
Zemo established that robust and representative data sets are urgently required to enable equitable comparison of low carbon hydrogen pathways with other zero and ultra-low carbon technologies and fuels over the next decade. The first key issue is the absence of Well-to-Tank GHG emission factors for different low carbon hydrogen supply chains specific to the UK, and an appreciation of energy consumption.

The Low Carbon Hydrogen Well-to-Tank Pathways study was commissioned by Zemo Partnership and a core group of member companies, and was delivered by Element Energy with oversight by a broad steering group from within Zemo.

The overarching aim of this study was to determine the WTT GHG emission and energy consumption values for six low carbon hydrogen supply chain pathways specific to the UK in the 2020 to 2035 timeline. The WTT pathway compromised of hydrogen production, distribution, storage and dispensing at the refuelling station. This work feeds into a wider study Zemo are undertaking involving Well-To-Wheel GHG emissions and the overall energy efficiency of hydrogen vehicles.

Figure 1 provides an overview of the WTT pathways examined in the study. The hydrogen production methods selected were electrolysis (on-site, large scale off-site and off-shore), methane reformation (ATR+GHR and SMR) with carbon capture and storage (CCS) and waste gasification with CCS. Three distribution routes were analysed, these being compressed hydrogen tube trailer delivery, liquified H_2 delivery and natural gas grid pipeline hydrogen delivery. For the pipeline delivery, this covered a blend of 20% hydrogen inserted into the gas network in 2030, increasing to 100% hydrogen from 2035. Two hydrogen refuelling station architectures were included – compressed hydrogen, dispensing at 350 bar and 700 bar and liquid hydrogen. Fossil fuel, renewable feedstocks and energy sources, were flexed in the analysis, an example being replacing natural gas with biomethane for SMR and ATR with CCS pathways. Upstream GHG emissions associated with electricity, natural gas and biomass production, plus transportation were also included in the study to give the most complete picture.

Figure 1 WTT pathways analysed - hydrogen production, distribution and dispensing options



[1] Only on-site electrolysis modelled for 2020 – other production options modelled from 2030 onwards

[2] Gasification uses municipal solid waste that is 65% biogenic by energy. For gas grid blending, a blending ratio of 20% is considered.

2. Methodology

The objectives of the low carbon hydrogen pathway study focused on:

- Providing a transparent and up to date analysis of the WTT GHG emissions and energy use for a range of low carbon hydrogen supply chains
- Accounting for fugitive hydrogen, carbon dioxide and methane emissions
- Identifying the key sensitivities influencing carbon intensity and energy use
- Creating an in-house WTT low carbon hydrogen pathways model for ongoing Zemo use

The study collated data from a range of published literature sources and directly from companies across the hydrogen supply chain. An expert steering group of Zemo members contributed to peer reviewing assumptions, modelling inputs and outputs. A GHG emissions and energy use model was created comprising of more than thirty combinations for various production, distribution and dispensing pathways. Low, central and high values were identified for a range of parameters, including plant and equipment energy consumption plus hydrogen losses across the supply chain. Central values were used to derive final WTT GHG emission and energy consumptions figures for the various low carbon hydrogen supply chains. Timelines for specific WTT values were aligned with anticipated technology commercialisation and deployment, resulting in 2020, 2030 and "from 2035" being selected.

The modelling work itself included numerous specific assumptions, the most relevant are listed below:

- Hydrogen is produced at hydrogen fuel cell purity (99.999%), with 'Hydrogen reported as the Low Heating Value'
- SMR retrofitted with CCS equipment, assumed a capture rate of 60%
- ATR equipped with gas heated reformer technology and CCS plant with capture rate of 95%
- Municipal solid waste gasification, with a CCS plant capture rate of 97%
- Energy required for CO_2 compression and transportation is included within production emissions
- Hydrogen compression included with production energy and GHG emissions
- Electrolysers based on PEM technology
- Electrolyser energy, and GHG emissions, take into account requirements for water purification, drying and deoxygenation
- Electrolyser efficiency improves from 2020 to 2035
- On-site electrolyser (reference scenario) is powered by grid electricity
- Off-site and off-shore electrolysers are powered by renewable electricity
- Municipal solid waste feedstock for gasification has a biogenic content of 65%
- BEIS EEP 2019 GHG emission factors adopted for electricity carbon intensity
- National Grid FES 2020 Steady Progression scenario adopted for natural gas GHG emissions. BEIS 2019 Company GHG Conversion Factors Scope 3 (upstream) for LNG and pipeline natural gas were combined with the proportions of LNG and pipeline natural gas in the UK gas mix from FES to calculate natural gas WTT GHG emissions
- Hydrogen assumed to have a GWP of 5.8, applied to fugitive hydrogen losses
- From 2035, the gas network deblending requirement is removed as a consequence of 100% hydrogen delivery, purification energy use is retained

3. Low Carbon Hydrogen Pathways WTT GHG Emissions and Energy Consumption Values

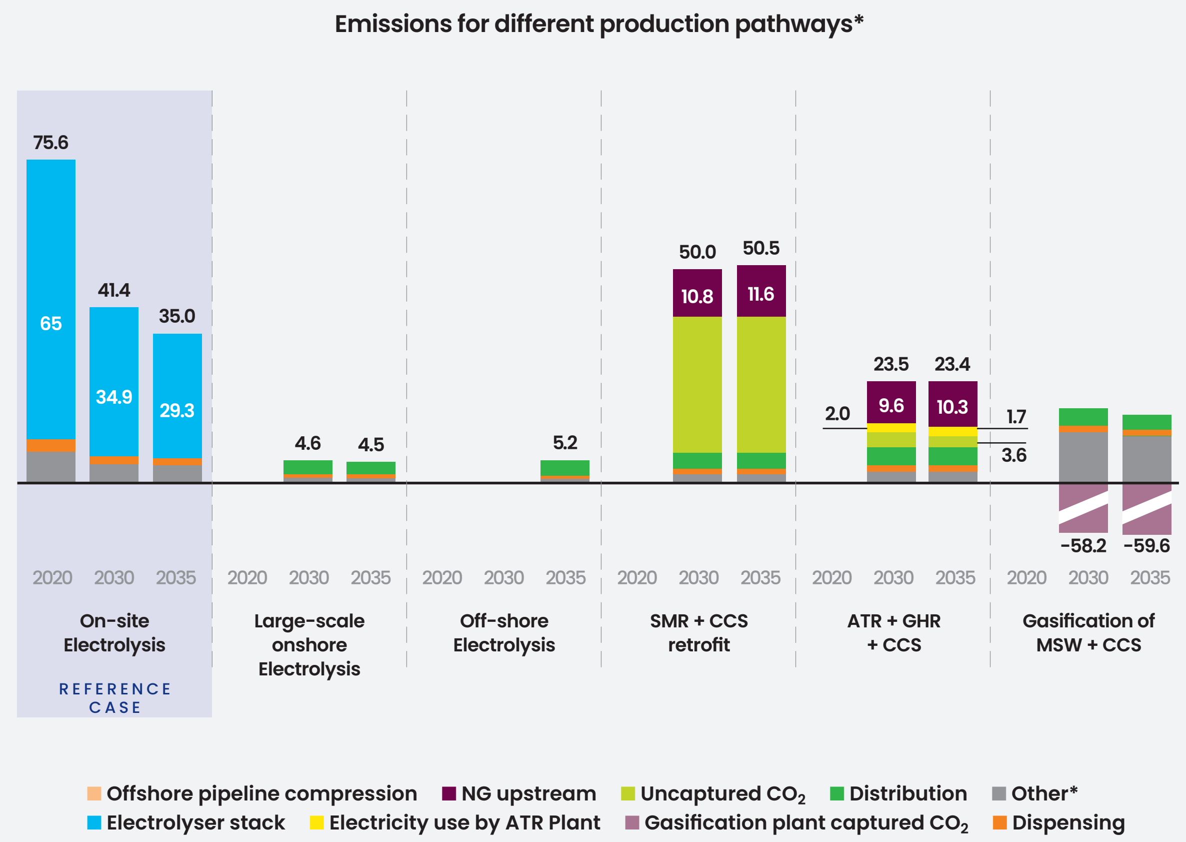
The initial "baseline" for today, with on-site electrolysers powered by the current electricity grid demonstrated the highest GHG emission intensity considered at 75 gCO_2e/MJ, see Table 1. Moving forward in time, WTT GHG emission values for the low carbon hydrogen pathways in 2030 and 2035 ranged from -108.2 gCO_2e/MJ (100% biogenic biomass gasification with CCS, gas grid distribution) to 54.3 gCO_2e/MJ (SMR with retrofit CCS, liquified tanker distribution). Forecast improvements in electrolyser efficiency over the next fifteen years, combined with a reduction in the UK electricity grid carbon intensity, were shown to reduce GHG emissions for the on-site electrolyser pathway by approximately 50%.

Table 1: WTT GHG emissions (gCO_2e/MJ) for different low carbon hydrogen production and distribution pathways, based on compressed HRS at 350bar dispensing.

	2020	2030			2035 +		
Hydrogen production pathway	CH_2	CH_2	LH_2	Gas Grid 20% H_2	CH_2	LH_2	Gas Grid 100% H_2
On site electrolysis (grid)	75.6	41.4		35.0			
On-shore electrolysis (renewable)		4.6	2.1	6.2	4.5	1.8	3.2
Off-shore electrolysis (renewable)			5.2	8.4	3.3		
SMR with retrofit CCS, natural gas feedstock		50.0	54.3	50.8	50.5	53.5	48.7
SMR with retrofit CCS, biomethane feedstock		-18.1	-13.9	-17.4	-18.4	-15.0	-20.6
ATR+GHR with CCS, natural gas feedstock		22.9	25.1	21.8	22.8	24.2	19.2
ATR+GHR with CCS, biomethane feedstock		-39.6	-35.7	-38.8	-40.1	-37.0	-42.3
MSW gasification with CCS (65% biogenic)		-57.5	-57.4	-54.9	-59.0	-59.4	-62.5
Biomass gasification with CCS (100% biogenic)		-104.7	-102.3	-103.6	-105.9	-104.4	-108.2

The method of producing hydrogen has the greatest influence on WTT GHG emissions across all hydrogen pathways, due to the influence of electricity grid carbon intensity and CCS effectiveness, as can be seen in Figure 2. However, in the cases of electrolysis powered by 100% renewable electricity, or BECCS pathways, the emissions contribution from distribution becomes the parameter of most influence in terms of overall WTT GHG emissions.

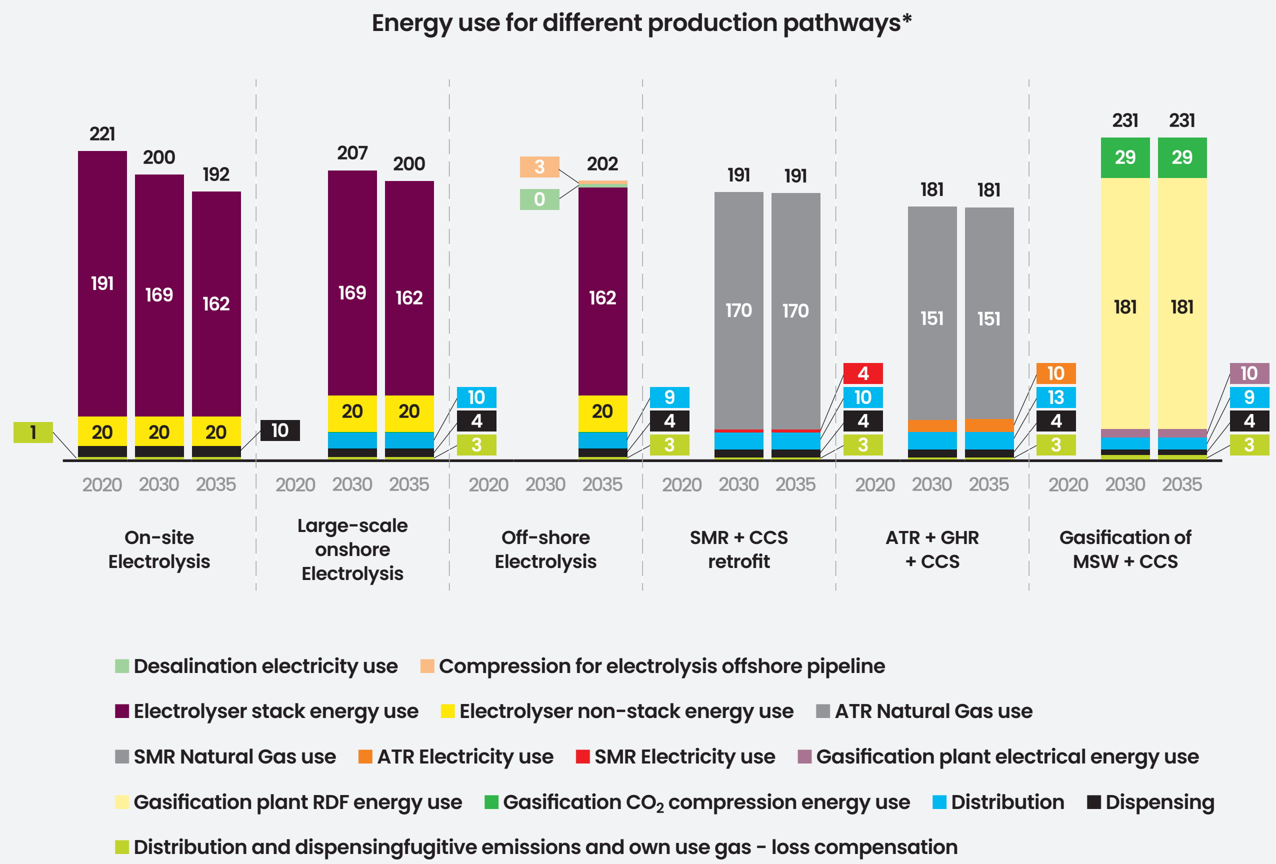
Figure 2: GHG emissions (gCO_2e/MJ) compressed tube trailer delivery dispensing at 350 bar all production pathways



*All results presented are the central case.

Looking at the overall pathway energy consumption a different picture emerges, where all production methods show the significant energy required (>180MJ) to make and deliver a kg of hydrogen (assumed to have an energy content of 120MJ) to a vehicle, irrespective of carbon intensity.

Figure 3: Energy use ($MJ/kg\ H_2$) compressed tube trailer delivery dispensing at 350 bar all H_2 production pathways



*All results presented are the central case.

Figure 3 shows that, for compressed hydrogen tanker delivery, energy consumption ranged from 181 to 231 $MJ/kg\ H_2$ across the six main low carbon hydrogen pathways in 2030. The production phase of the WTT pathway is responsible for the highest contribution in energy demand. For CCS plant, energy demand is mainly attributed to compressing CO_2 for dense phase transportation. Liquified H_2 transportation is associated with the highest energy demand across the distribution methods. Dispensing energy requirements, compression and cooling, represent the smallest energy demand element across the overall WTT pathway for all hydrogen production methods. Dispensing at 700 bar requires around 40% more electricity and therefore results in higher GHG emission impacts than 350 bar dispensing. Liquified HRS were determined to have the lowest energy requirement.

When accounting for hydrogen distribution by road tanker (compressed and liquified) and pipeline using the gas network, total pathway WTT GHG emissions vary by less than 5% across all production pathways. Similar outcomes materialise for the different HRS architectures.

When methane reformation with CCS hydrogen pathways utilise biomethane as a feedstock, GHG emissions reduce significantly. Hydrogen production pathways involving BECCS resulted in the lowest (most negative) GHG emission intensities, However, care must be taken when considering negative carbon accounting, to avoid encouraging energy use. From 2035 onwards, GHG emissions associated with pipeline hydrogen delivery reduce by over 60% due to a predicted transition to a 100% hydrogen grid and the associated removal of deblending. This distribution method has the potential to deliver the lowest WTT GHG emissions, and energy consumption, values across all the hydrogen distribution pathways considered.

The study found hydrogen losses to be relatively minor across the WTT pathway for all low carbon hydrogen supply chains analysed. Methane losses were accounted for in the upstream natural gas supply chain. In the case of fugitive CO_2 emissions, the main sources identified were the pipeline transportation of CO_2 to geological storage from the CCS plant, and gas grid network distribution for 20% hydrogen blend. The study revealed CO_2 emissions from these sources to be extremely low.

For ATR+GHR and SMR with CCS, upstream GHG emissions were the second most important contributing factor, responsible for approximately 15% of WTT pathway GHG emissions. Here, the distribution method has less influence on overall WTT pathway GHG emissions and energy consumption. Variability between distribution methods is most apparent from 2035 onwards, specifically for hydrogen pipeline distribution. The type of HRS architecture (dispensing) has the least impact on WTT GHG emissions and energy consumption; however fugitive hydrogen losses, were found to be most relevant for this element of the WTT pathway.

4. Key Sensitivities Influencing WTT GHG Emissions and Energy Demand

4.1 Hydrogen Production

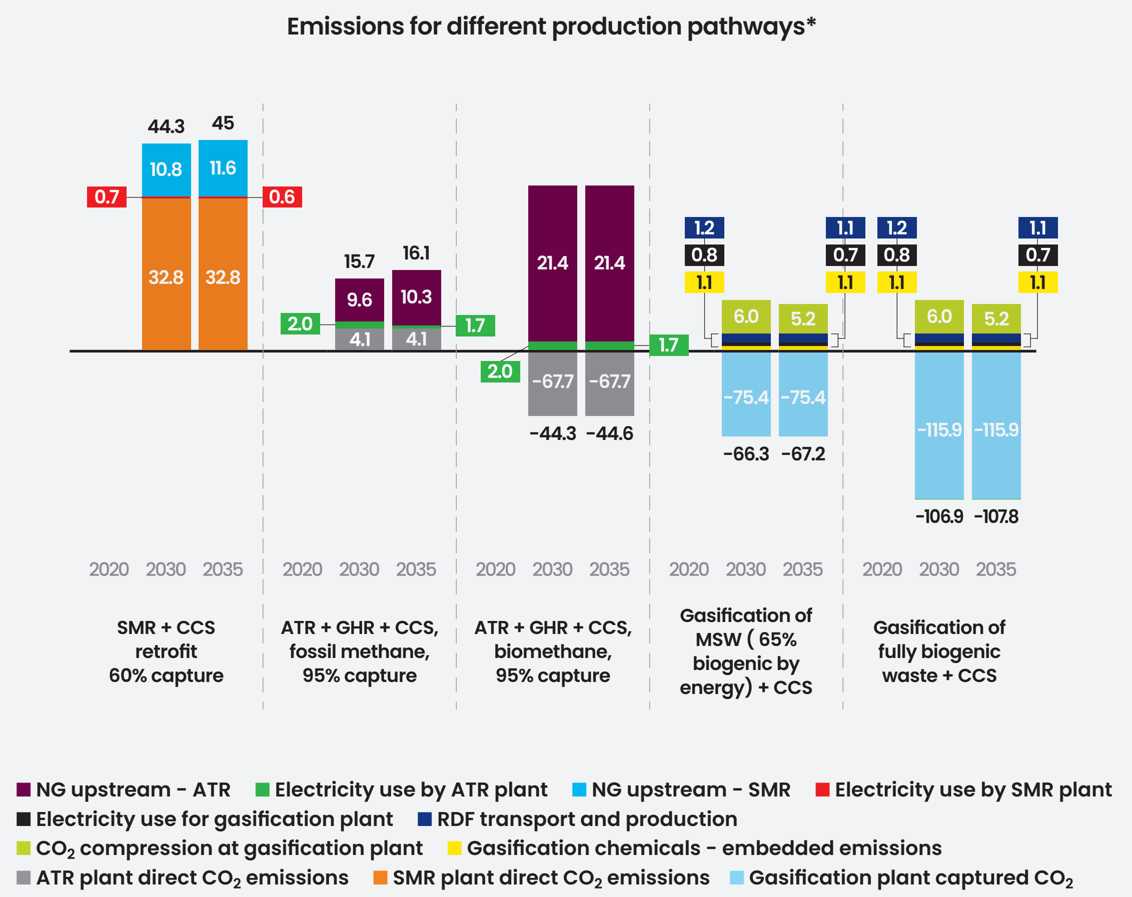
Energy source used for producing hydrogen

The energy source, whether fossil fuel or renewable, has a material impact on WTT GHG emissions for low carbon hydrogen supply chains. This is influenced by GHG emissions generated directly from energy use in the production process (electricity and heat) and upstream GHG emissions associated with energy production and distribution.

The carbon intensity of the electricity used has the greatest impact on the carbon footprint of hydrogen produced by electrolysis. As can been in Figure 2, 34.9 gCO_2e/MJ for an on-site electrolyser using average grid electricity in 2030, to 0 gCO_2e/MJ when 100% renewable electricity is used for an on-shore electrolyser. The GHG emission grid factor used to determine the carbon intensity of electricity is a critical sensitivity when calculating the carbon intensity electrolysis pathways.

GHG emissions are highly influenced by the feedstock used for methane reformation with CCS and waste gasification with CCS pathways. The use of biomethane rather than natural gas as a feedstock in ATR or SMR with CCS could deliver carbon-negative hydrogen, estimated at -44.3 gCO_2e/MJ in 2030, see Figure 4. The feedstock composition of biomethane will influence GHG emissions, with waste derived feedstocks resulting in the lowest GHG emission intensity. In the case of hydrogen produced by municipal solid waste gasification, the proportion of biomass in the waste feedstock impacts the WTT GHG emissions value. As can be seen in Figure 4, the gasification of full biogenic waste stream with CCS has much lower GHG emissions intensity then the MSW feedstock.

Figure 4: GHG emissions (gCO_2e/MJ) for methane reformation and gasification pathways varying energy feedstocks.



All results presented are the central case.

Upstream GHG emissions associated with SMR+CSS and ATR+CCS were found to be highly influenced by the natural gas supply chain, with LNG associated with a higher carbon intensity. GHG emissions for natural gas are expected to increase over time, as the UK supply chain shifts towards a higher proportion of LNG imports. Key sources of CO_2 emissions include liquefaction plant, leakage and shipping vessels transporting LNG. However, the increase in LNG proportion only accounted for a 2% increase in emissions from methane reformation and CCS pathways in 2030.

4.2 Carbon Capture Rate for CCS Plant

The CO_2 capture rate of CCS technology has a major impact on GHG emissions for low carbon hydrogen produced by methane reformation with CCS. This was reflected in the case of SMR retrofits which could achieve only 60% capture. Very low GHG emission intensities can only be achieved by technologies with significantly higher capture rates, such as new ATR + GHR with CCS, with a predicted capture rate of 95% among the announced UK projects.

4.3 Hydrogen Distribution and Dispensing

The carbon intensity of the electricity required for compression and liquification greatly influences GHG emissions for hydrogen distribution and dispensing, as can be seen in Figure 5. However, the impact on overall WTT pathway GHG emissions is determined to be largely inconsequential. For gas grid delivery, the proportion of hydrogen transported in the gas network was shown to impact energy requirements, and therefore GHG emissions. Energy use for deblending hydrogen from a 20% hydrogen and 80% natural gas blend is identified as the influencing factor, as illustrated in Figure 5. The location of hydrogen off-take along the gas network for dispensing at the HRS was also shown to affect energy requirements for compression.

Compressed and liquified hydrogen road tanker distribution is influenced by the volume of hydrogen that is stored on the road tanker, in conjunction with the distance travelled. Efficiency improvements could be achieved by increasing the amount of compressed hydrogen delivered per shipment, e.g. 350kg to 1000kg. The larger energy requirements for liquified hydrogen truck delivery are apparent in Figure 6, mainly due to the high energy demand associated with liquification. The size and utilization of HRS using liquid hydrogen has a particularly significant impact on supply chain fugitive hydrogen emissions, with higher capacity stations associated with increased fugitive losses.

Figure 5: GHG emissions (gCO_2e/MJ) associated with different distribution options and different electricity sources, electrolyser example.

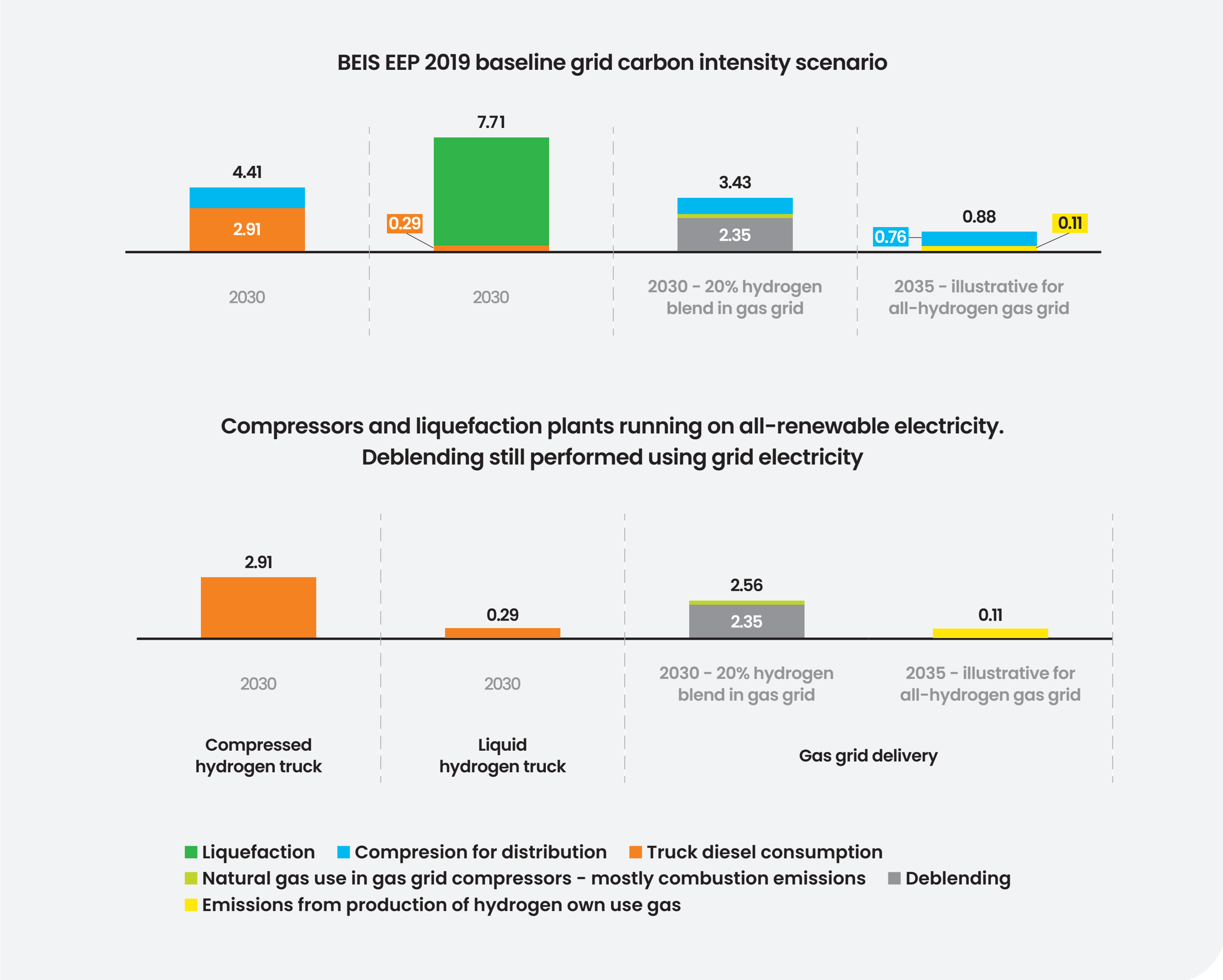
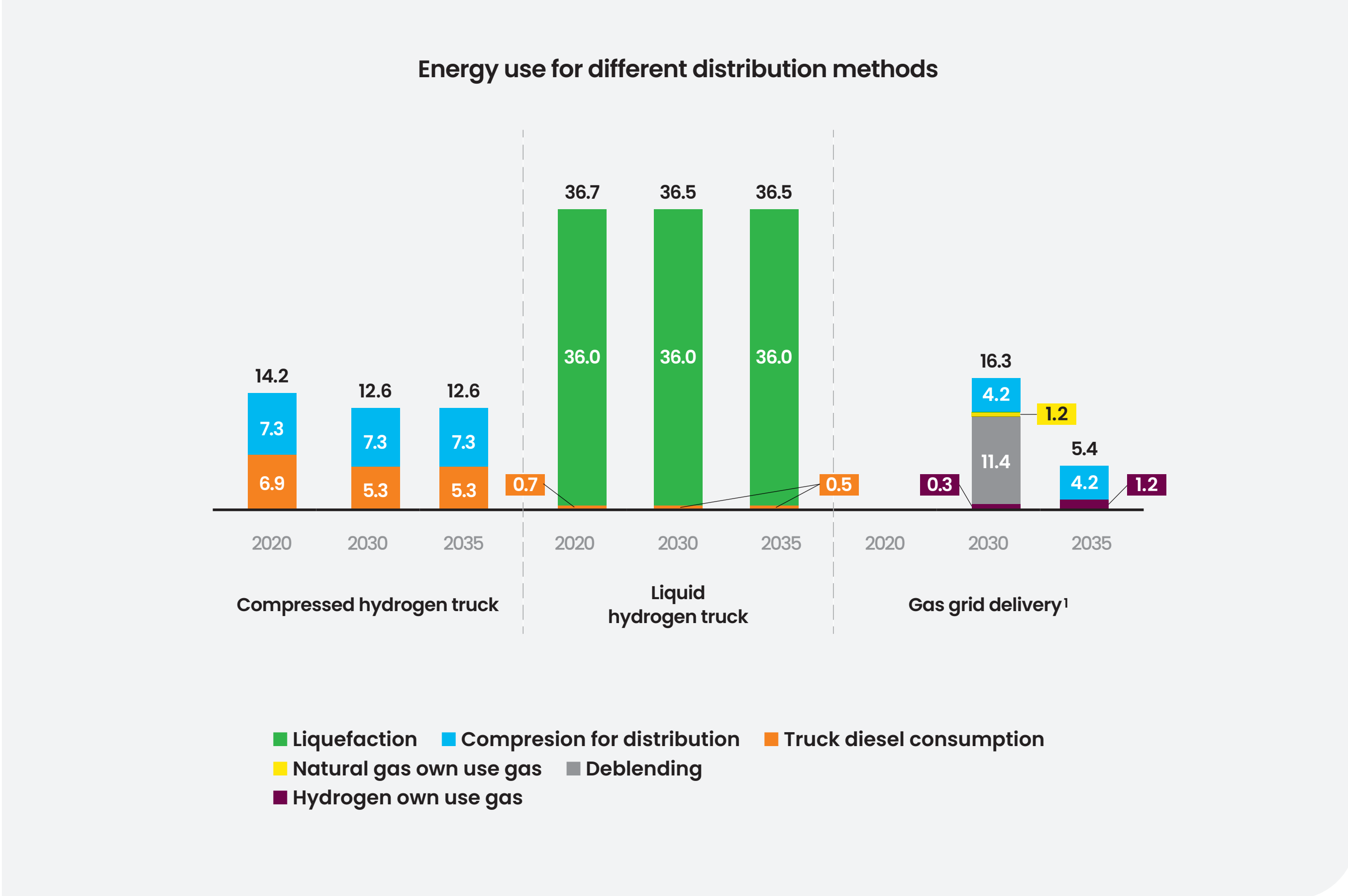


Figure 6 Energy use ($MJ/kg\ H_2$) for different distribution methods.



5. Conclusions and Recommendations for Further Work

- The study provides a new and robust series of WTT GHG emission and Energy factors for current and future Low carbon Hydrogen production pathways for use in comparative transport analysis and policy.
- The GHG intensity of hydrogen used in transport is highly variable but there are clear pathways for very low and even negative carbon hydrogen to be produced at scale with existing and emerging technology.
- Hydrogen used in transport consumes significant energy in production and distribution and this is only predicted to reduce by around 20% over the next 15 years in the best case. However the lowest GHG hydrogen does not reduce energy consumption significantly from the current level.
- Future policy for all fuel and energy options in transport must consider both GHG and energy consumption aspects (and in future, resource and other environmental considerations) in order to deliver an efficient net zero energy and transport system.

This study has strengthened the understanding of the WTT GHG emissions and energy consumption performance of a range of low carbon hydrogen supply chains specific to the UK, analysing multifarious production methods, distribution and dispensing options.

Hydrogen supply chains involving BECCS - gasification of biogenic waste with CCS, plus biomethane SMR and ATR+GHR with CCS, result in negative carbon emissions and delivered the lowest WTT GHG emission intensities. Availability of sustainable biomass over the next two decades will be a key factor influencing the scale of deployment of these pathways.

The electricity grid carbon intensity has a significant impact on low carbon hydrogen WTT GHG emissions, particularly for electrolysers running on grid average electricity. The lowest GHG emission intensity for electrolysis pathways was identified through use of renewable electricity. The scale up of new renewable electricity capacity is integral to the wide scale deployment of electrolysis and the delivery of green hydrogen supply chains. The increasing decarbonisation of the UK electricity grid will reduce GHG emissions across all low carbon hydrogen pathways over time – benefitting production, distribution and dispensing.

The carbon footprint of hydrogen produced from methane reformation with CCS is heavily dependent on the carbon capture rate of the CCS plant. SMR retrofitted with CCS was associated with the lower capture rates, and therefore higher GHG emission intensities than new build ATR+GHR with CCS. Both pathways hinge on the successful deployment of CCS. Upstream GHG emissions were found to be influenced by the natural gas supply chain, an increasing contribution of LNG in future years could raise overall WTT GHG emissions. When biomethane is used as a renewable feedstock, significant reductions in GHG emissions materialise.

The method of producing hydrogen was shown to be the dominant factor influencing overall WTT GHG emissions and energy consumption, constituting approximately 90% of the overall pathway. In cases where hydrogen production plants are completely decarbonised, the contribution of hydrogen distribution was revealed to be the dominant element of the WTT pathway with regards to GHG emission impacts. The difference between compressed hydrogen and liquid hydrogen dispensing was shown to have a negligible effect on overall WTT pathway GHG emissions and energy use, although careful management of fugitive hydrogen emissions will be necessary for liquid hydrogen HRS.

Energy demand was determined to be comparable across all production pathways. Hydrogen liquefaction was identified as the most energy intensive step in the distribution value chain. The most energy efficient distribution pathway, and showing the lowest GHG emission impact, was identified as hydrogen at 100% blend transported by the gas network pipeline from 2035. The greatest benefits were associated with hydrogen extracted at a higher pressure (reducing HRS compression duties). The blending of hydrogen at 20% is seen as a stepping-stone in enabling full grid conversion but involves significant energy use for deblending and purification. Significant investment will be required to achieve the full decarbonisation of the gas grid.

The study identified areas where further work is required to improve GHG emissions and energy demand data fidelity, and confidence in technology performance. These include:

- Real world performance data of hydrogen production technologies including capture rates for CCS plants.
- Energy use for CCS plant and transportation of CO_2, energy use for liquid HRS.
- More robust data sets for fugitive hydrogen and CO_2 emissions.
- For hydrogen pipeline distribution, energy use for deblending plants and variation between manufacturers should be monitored as the technology is rolled out.
- It is currently assumed that the CO_2 captured and stored via CCS will remain captured indefinitely. This should be monitored as projects are deployed and real-world data becomes available.

Low Carbon Hydrogen Well-to-Tank Pathways Study Full Report

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6. Abbreviations

ATR+GHR	Autothermal reforming with gas heated reformer
BECCS	Bio Energy with Carbon Capture and Storage
BEIS EEP	Department of Business, Energy and Industrial Strategy Energy and Emissions Projections
FES	Future Energy Scenarios
CCS	Carbon Capture and Storage
CH_2	Compressed Hydrogen
GHG	Greenhouse Gas
GWP	Global Warming Potential
HRS	Hydrogen Refuelling Station
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
MSW	Municipal Solid Waste
NG FES	National Grid Future Energy Scenarios
PEM	Proton Exchange Membrane
SMR	Steam Methane Reformation
WTT	Well-to-Tank (refers to whole H_2 pathway emissions from feedstock and production up to the point of dispensing to the vehicle's tank)

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