Zemo Partnership
Accelerating Transport to Zero Emissions

Hydrogen Vehicle Well-to-Wheel GHG and Energy Study

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Executive Summary

The recently published Government climate change policy documents, Decarbonising Transportation, a better, greener Britain and the UK Hydrogen Strategy, identify hydrogen as one of the zero emission technology options for decarbonising the UK road transport sector. Zemo Partnership has undertaken a WTW (Well-to-Wheel) study to increase understanding of the GHG emissions and energy efficiency performance of hydrogen vehicles using a range of low carbon hydrogen supply chains. The aim of this work is to help inform future policy development for the role of hydrogen in transport.

This study combines GHG and energy consumption data sets from Zemo Partnership's Low Carbon Hydrogen Well-to-Tank Pathways Study, with Tank-to-Wheel data sourced for a variety of hydrogen vehicles - trucks, buses, vans and cars. This report presents the WTW results for three hydrogen vehicle powertrain architectures FCEV, dual fuel ICEV and H_2 ICEV, along with BEV and ICEVs using diesel and renewable fuels for comparison. The low carbon hydrogen supply chains examined include electrolysis, biomass gasification with CCS and methane reformation with CCS. Consideration is also given to fossil hydrogen pathways. The study has explored the sensitivity of GHG emissions and energy consumption to a range of inputs and options, with more than 250 WTW scenarios being modelled in the 2020-2035 timeframe.

The study revealed the following findings

- Each of the hydrogen vehicle architectures analysed can deliver low carbon, and in some cases negative, WTW GHG emissions solutions[1] over the next decade. This outcome is identical across light and heavy-duty vehicle segments and is predicated on the use of low carbon hydrogen.
- When comparing the WTW GHG emissions performance of BEV, ICEV using renewable fuels (produced from waste-based feedstocks), and hydrogen HGVs using low carbon hydrogen, all technology options perform better than incumbent fossil fuelled diesel vehicles.
- The WTW energy efficiency of hydrogen vehicles is lower than diesel ICEV, BEV and ICEV using renewable fuels. The difference is most pronounced for heavy duty vehicles. In the case of HGVs, FCEV trucks are in the order of four to six times less energy efficient than BEV on a WTW basis. Irrespective of the low carbon hydrogen supply pathway, the hydrogen production process is energy intensive thereby influencing WTW energy efficiency. This finding highlights the importance of accounting for energy consumption along with WTW GHG emissions and ensuring an energy efficient transition to net zero GHG emissions.
- There are a variety of powertrains and fuels that can potentially achieve net zero WTW GHG emissions, but with limited biogenic resources and renewable electricity supplies, it is critical to adopt energy efficient solutions to maximise the benefits wherever possible. For example, hydrogen vehicles would need to demonstrate other benefits beyond WTW (e.g. superior payload, vehicle range, lower operational costs) to compensate for the increased energy consumption compared to alternative powertrain solutions such as BEV.

[1] Hydrogen production pathways utilising biogenic feedstocks and carbon capture and storage.

- WTW GHG emissions are dominated by the hydrogen supply chain production method, with distribution and dispensing having less impact. Green hydrogen supply chains deliver the lowest WTW GHG emissions for hydrogen vehicles. Vehicles using hydrogen produced from steam methane reformation and electrolysis using current grid electricity do not perform better than diesel ICEV; grey hydrogen is to be avoided.
- WTW GHG emissions are highly sensitive to the electricity grid carbon intensity; this is relevant for both hydrogen and battery electric vehicles. As a result, it is critical that consistent WTT GHG emissions factors for electricity are adopted by Government and industry when comparing different zero, and low carbon, vehicle technologies. This is especially important for hydrogen produced by electrolysis and in comparison to BEV.
- Care needs to be exercised with carbon accounting for low carbon hydrogen supply chains that achieve negative GHG emissions, notably BECCS. These pathways could inadvertently result in the promotion of energy inefficient technology.

Key recommendations

- A feasibility study to assess the suitability of different vehicles for different use cases is recommended to inform the role of hydrogen in the HGV sector. Relevant factors in such a study would include vehicle payload and capacity, range, refuelling/charging time and infrastructure. This could be integrated into the UK Government's Zero Emission Freight Trial. Monitoring of WTW GHG and energy efficiency performance of trial vehicles is strongly encouraged.
- Many low carbon hydrogen supply chains are immature or poorly characterised and the number of hydrogen vehicles in the market is very limited. More robust vehicle performance data, particularly chassis dyno and real-world vehicle data from hydrogen FCEV, ICEV and dual fuel vehicles, would improve the assessment of WTW GHG and energy efficiency.
- Focusing transport policy solely on mitigating tailpipe GHG emissions can risk neglecting upstream WTT GHG emissions and overall energy efficiency performance. As consideration of WTW GHG emissions and energy efficiency is seen as essential for achieving net zero transport emissions, it is recommended that both are embedded into emerging Government policy.
- Given the importance of electricity grid carbon intensity in accurately assessing WTW GHG emissions, it would be beneficial for the UK Government to address the differing data sets currently published in the UK (BEIS Company GHG Reporting and BEIS Energy and Emission Projections), agreeing upon and releasing a single set of figures. Furthermore, it's recommended to develop and integrate a set of WTT GHG emission conversion factors for different low carbon hydrogen supply chains specific to the UK, for inclusion in the BEIS Company Reporting GHG conversion factor database. In this area, Zemo's recently published Low Carbon Hydrogen Pathways study provides new data sets and defines pathway boundaries and methodology.

Acronyms and abbreviations

ATR	Autothermal Reforming
B100	Pure Biodiesel (waste biogenic feedstock)
BECCS	BioEnergy with Carbon Capture and Storage
BEIS	Dept for Business, Energy & Industrial Strategy
BEV	Battery Electric Vehicle
CBG	Compressed Biomethane
CCS	Carbon Capture and Storage
CR	Capture Rate of CO_2
DfT	Department for Transport
EEP	Energy and Emissions Projections
FCEV	Fuel Cell Electric Vehicle
FTIR	Fourier-Transform Infrared Spectroscopy
gCO_2e/km	grams of CO_2 equivalent per km
GHG	Greenhouse Gas
Grid-E	Grid Electricity
GWP	Global Warming Potential
H_2	Hydrogen
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
ICEV	Internal Combustion Engine Vehicle
JEC	Joint Research Centre of the European Commission
LCA	Life Cycle Assessment
LCV	Light Commercial Vehicle
LEB	Low Emission Bus (Zemo certification scheme)
LEFT	Low Emission Freight and Logistics Trial
LH_2	Liquefied Hydrogen
LHV	Lower Heating Value
LNG	Liquid Natural Gas
NEDC	New European Driving Cycle
NG	Natural Gas
PSA	Pressure Swing Adsorption
RDW	Residual Domestic Waste
RED	Renewable Energy Directive
Renew-E	Renewable Electricity
RTFO	Renewable Transport Fuel Obligation
SMR	Steam Methane Reformation
TTW	Tank-to-Wheel
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheel

1. Introduction

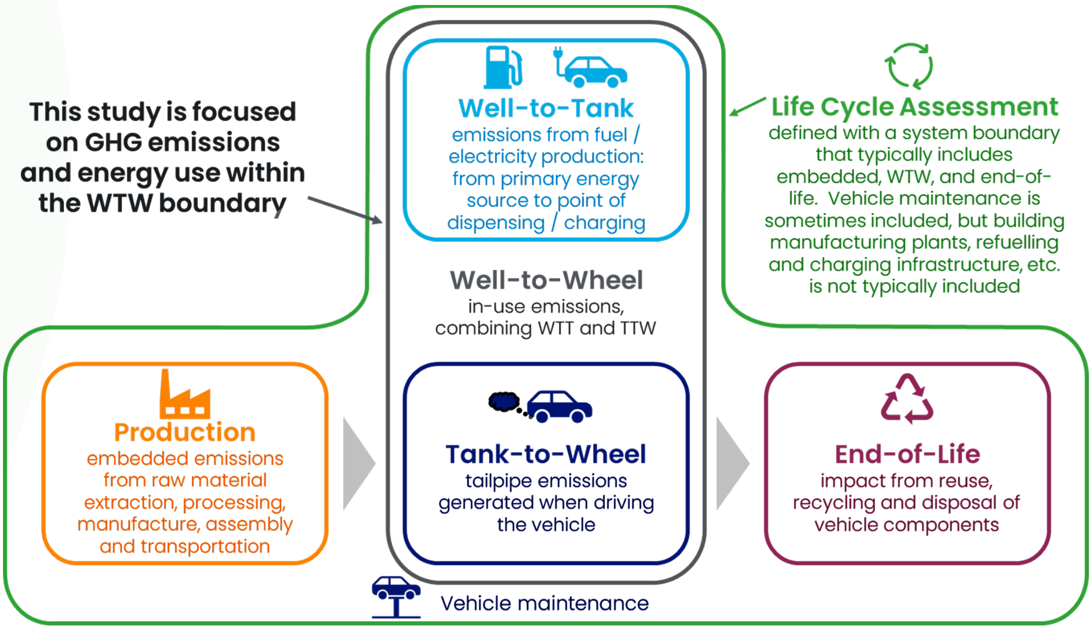
Hydrogen vehicles are expected to play a role in the long-term decarbonisation of the UK transport sector, with particular focus on hydrogen FCEV as a zero-emission technology option for HGVs. As such, UK Government will need to develop new policies which should be informed by a robust evidence base of hydrogen vehicle GHG emissions and energy efficiency performance. This data will also be highly valuable for fleet operators, to inform decision making with regards to hydrogen vehicles. Zemo have identified several areas which warrant building the evidence base to appreciate the role of hydrogen in net zero emission transport and fill key gaps in knowledge. This focuses on enhancing understanding of the carbon intensity and energy consumption of different low carbon hydrogen supply chains[2] specific to the UK, and WTW performance of hydrogen vehicles.

Zemo has subsequently undertaken a study to determine Well-to-Wheel GHG emissions and energy performance analysis of a range of hydrogen vehicles. The data sets presented enable an independent comparison of vehicles using hydrogen from a range of low carbon supply chains, with other zero and ultra-low carbon technologies and fuels, over the next decade.

1.1 Well-to-Wheel boundaries

This study is focused purely on GHG emissions and energy consumption within the Well-to-Wheel boundary shown in the centre of Figure 1.

Figure 1. Definition of Well-to-Wheel and vehicle Life Cycle Assessment system boundaries



² Zemo WTT study: https://www.zemo.org.uk/assets/reports/Zemo%20Low%20Carbon%20Hydrogen%20WTT%20Pathways%20-%20Summary%20(2).pdf.

WTW describes the in-use phase of the vehicle lifecycle. The GHG emissions and energy consumption are calculated by summing the Well-to-Tank contributions from the fuel / electricity production and the Tank-to-Wheel vehicle energy consumption and tailpipe emissions. WTW GHG emissions and energy are proportional to the vehicle fuel / electricity consumption.

WTW differs from a full life cycle assessment in that it does not include the vehicle production and end of life. Also, LCAs may include a range of environmental impact categories, such as global warming potential, air quality, toxicity, land transformation, resource depletion, etc. Other environmental, health and economic impacts are not within the current scope of this study. Zemo plan to use the WTW GHG emissions derived from this study in future LCA studies.

2. Methodology

Zemo have derived low carbon hydrogen supply chain data from their WTT model and collated TTW data to estimate the WTW GHG emissions and energy consumption for FCEV, dual fuel H_2 and ICEV H_2. The vehicle applications explored were medium sized passenger car, single decker bus, small light commercial van and rigid HGV truck (18t GVW). An Excel based WTW model was developed to run scenarios in the 2020 to 2035 timeframe for different hydrogen vehicle powertrains and low carbon hydrogen supply chains. A selection of comparator vehicle technologies and fuels have also been modelled to provide context.

In total, more than 250 WTW scenarios have been modelled, including:

- 4 vehicle applications (car, bus, van, truck)
- 7 vehicle powertrain / fuel combinations
- 3 electricity GHG emissions conversion factors
- 1 grey hydrogen production pathway
- 6 low carbon hydrogen production pathways
- 3 hydrogen distribution pathways
- 3 hydrogen dispensing options.

2.1 Input data

Table 1. Data used to determine WTW GHG emissions and energy consumption

	Hydrogen vehicles	Comparator vehicles
WTT energy consumption data for the fuel or electricity supply chain	Data not readily available in the public domain: values derived using Zemo hydrogen WTT model	Most WTT energy data available from JEC WTT 2019 data sets[3], biomethane and biodiesel values from Zemo members. Biodiesel and biomethane derived from biogenic waste feedstocks
WTT GHG emissions data for the fuel or electricity supply chain	Data not readily available in the public domain: values derived using Zemo hydrogen WTT model, created as a precursor to this study	Most WTT GHG conversion factors from BEIS Company Reporting[4] and Zemo Renewable Fuels Assurance Scheme
Vehicle fuel or electricity consumption	Data from members and the public domain, collated by Zemo for this study. Limited availability of chassis dyno data means that consumption data is not based on a consistent drive cycle for all comparator vehicles	Data from Zemo chassis dyno testing and public domain. TTW GHG conversion factors from BEIS Company Reporting[4]

[3] JEC WTT data sets: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC119036/jec_wtt_v5_119036_annexes_final.pdf

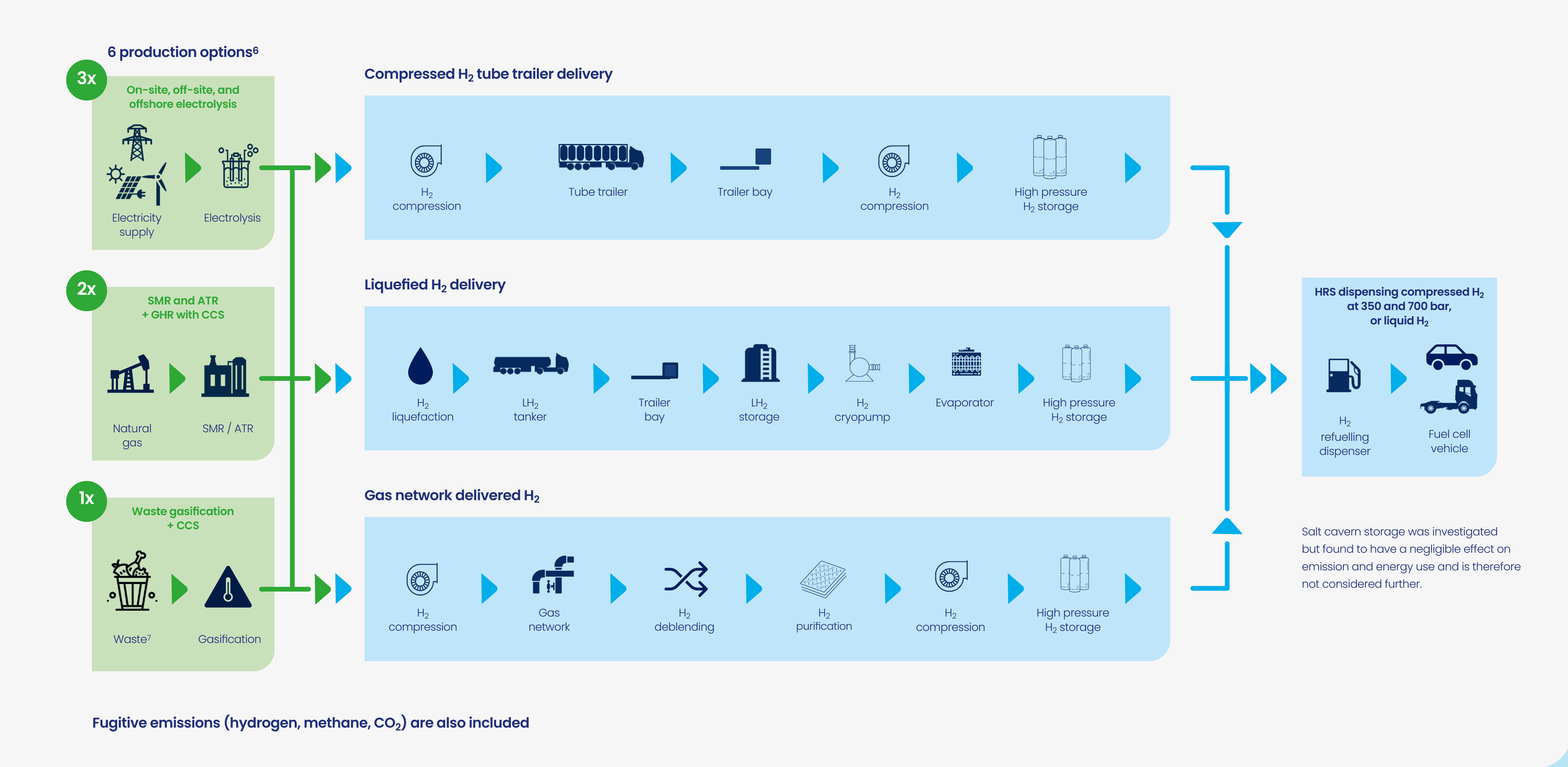
[4] BEIS company reporting: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

2.1.1 WTT energy consumption and GHG emissions

As Table 1 indicates, WTT energy consumption and GHG emissions data was not readily available for the low carbon hydrogen supply chain pathways. To address this, Zemo commissioned a WTT study to identify the emerging hydrogen supply chains and to create a model of WTT energy consumption and GHG emissions. The WTT study[5] was carried out by Element Energy and the pathways included the production, purification, distribution, transmission, storage, dispensing and fugitive losses of hydrogen via electrolysis, gas reformation and gasification.

Figure 2 illustrates the hydrogen supply chain modelled in the WTT study which includes 6 production configurations, 3 distribution pathways and 3 dispensing options. The gas network pathway assumes a blend of 20% H_2 and 80% CH_4 in the 2030 scenario, while from 2035 it assumes that the gas network can transport 100% H_2. Grey hydrogen produced by steam reformation of natural gas has also been modelled for comparison.

Figure 2. Low carbon hydrogen supply pathways modelled



[5] Zemo WTT study: https://www.zemo.org.uk/hydrogenwttsummary.

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

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

2.1.2 Fuel and electricity consumption

At the present time there are relatively few hydrogen vehicles in operation in the UK and most of these are passenger car FCEVs. As such, hydrogen vehicle consumption data is quite limited. Zemo carried out a literature survey and contacted members to request vehicle emissions test data and fleet operator data. The data was collated to give a 'typical' hydrogen consumption value for four different vehicle types: a passenger car, a small van, a single decker bus and a heavy goods truck. Fuel consumption data was also found for a selection of comparator vehicles, such as a diesel ICEV. The vehicle consumption values used for the study are shown in Table 2.

Vehicle fuel consumption is highly dependent on a wide range of parameters, including driving style, vehicle speed, vehicle payload and weather. Ideally, when comparing vehicles powered by different fuels or electricity, the figures should be for consistent drive cycles or driving conditions, vehicle loading, etc. Unfortunately, this was not always possible due to limited data availability.

2.1.3 TTW GHG emissions

The TTW GHG emissions (gCO_2e/km) for the comparator vehicles with non-renewable fuels were based on test data where available. Where test data only included CO_2 emissions (e.g. WLTP), the tailpipe gCO_2/km value was increased by 3%, to estimate the contribution of other GHGs. The Low Emissions Bus test data included FTIR measurements, so in this case TTW gCO_2e/km was estimated from CO_2, CH_4 and N_2O using GWP factors.

For renewable fuels such as biomethane, the tailpipe emissions are not used to calculate the TTW gCO_2e/km as the CO_2 emissions from combustion are offset by the CO_2 captured by the biomass feedstock. In these cases, and where tailpipe test data was unavailable, GHG conversion factors have been used (taken from BEIS 2021 Scope 1 UK Government GHG Conversion Factors for Company Reporting where available).

Table 2. TTW vehicle data sets

Vehicle	Powertrain	Fuel or grid electricity consumption	Basis for fuel / electricity consumption value	Source
Passenger Car D-segment	ICEV Diesel	4.5 L/100km	BMW 3 series, Euro 6, combined WLTP	https://www.cars-data.com/en/bmw-318d-specs/95188/tech
	BEV	14.9 kWh/100km	Tesla Model 3 standard range	https://ev-database.uk/car/1060/Tesla-Model-3-Standard-Range
	FCEV	0.8 kg/100km	Toyota Mirai, combined WLTP	https://www.grange.co.uk/technical-data/toyota/mirai/hydrogen-fuel-cell-design-4dr-cvt
LCV	ICEV Diesel	5.9 L/100km	Renault Kangoo van, combined WLTP	https://cdn.group.renault.com/ren/gb/transversal-assets/brochures/van-ebrochures/KANGOO-eBrochure.pdf.asset.pdf/1d67c84936.pdf
	BEV	19.3 kWh/100km	Renault Kangoo van	https://ev-database.uk/car/1101/Renault-Kangoo-Crew-Van-ZE33
	FCEV	0.9 kg/100km	Renault Kangoo ZE Hydrogen, combined NEDC or WLTP	https://en.media.groupe.renault.com/assets/2019-press-kit-groupe-renault-introduces-hydrogen-into-its-light-commercial-vehicles-range-press-kit-e043-989c5.html?dl=1
Bus Single Decker	ICEV Diesel	25.4 L/100km	Optare MetroCity efficient diesel, Low Emission Bus cycle	Zemo LEB test data
	BEV	83.1 kWh/100km	BYD eBus, Low Emission Bus cycle	Zemo LEB test data
	FCEV	6.5 kg/100km	Trial data and litre review	Zemo information
HGV 18t GVW	ICEV Diesel	28.0 L/100km	LEFT trial data and experience, regional delivery	Zemo information
	ICEV Biodiesel	28.0 L/100km	Diesel, regional delivery	Zemo information
	ICEV Biomethane CBG	25.0 kg/100km	LEFT trial data and experience, regional delivery	Zemo information
	BEV	130.0 kWh/100km	LEFT trial data and experience, regional delivery	Zemo information
	ICEV Dual Fuel	17.1 L/100km, 3.1 kg/100km	Diesel comparator and LEFT trial data (~40% diesel substituted)	Zemo information
	ICEV H_2	10.5 kg/100km	Aggregate with adjustment for ICEV v. FCEV	Literature review and shared data
	FCEV	9.0 kg/100km	Aggregate	Literature review and shared data

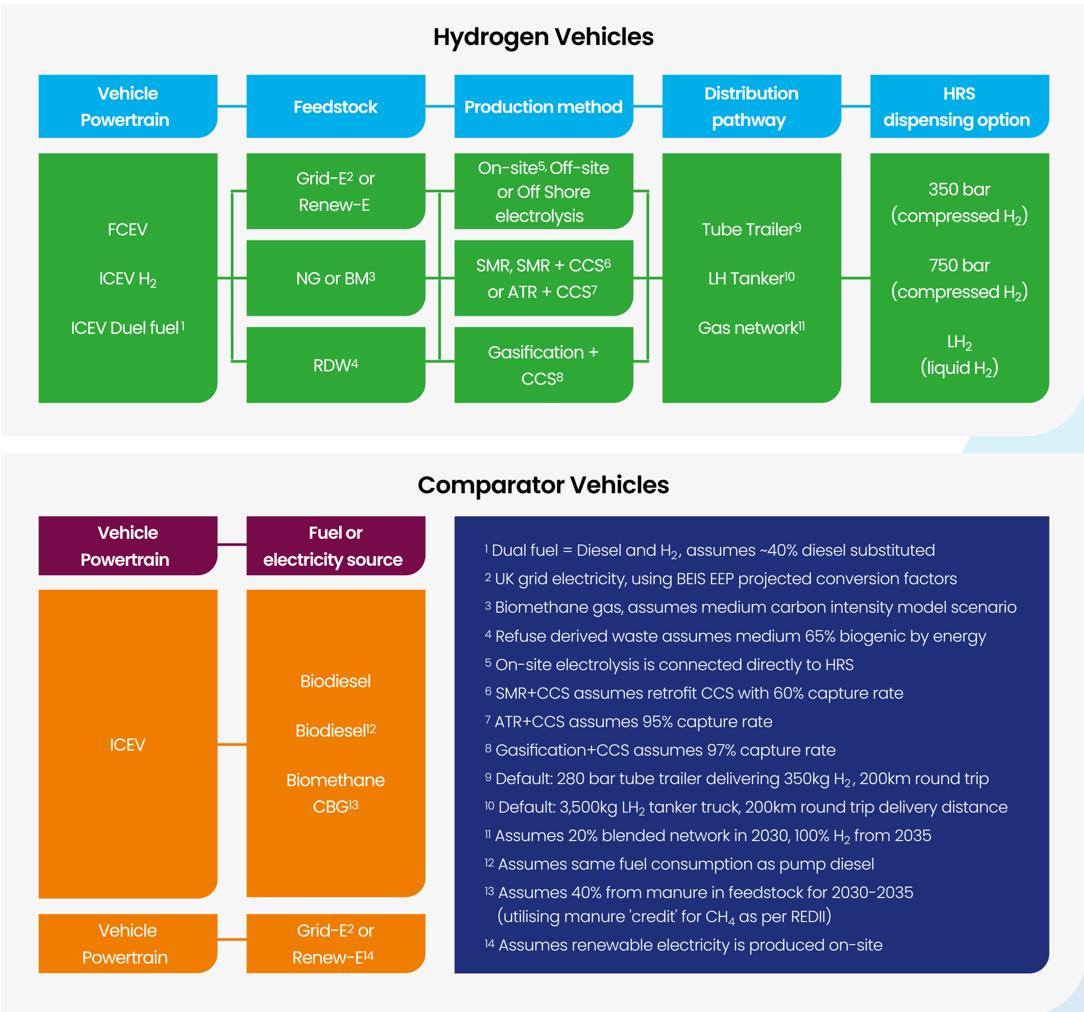
2.2 Assumptions

The relative immaturity of hydrogen vehicles means that it has been necessary to make assumptions which, for transparency, are listed in Appendix 6.1. Further details of the hydrogen supply model assumptions can be found in the WTT report[8]. Some margin of error in the absolute values of the results is to be expected, but it is believed that the results offer valid insights into trends and key sensitivities. Caution should be exercised if comparing data from other studies, which may have different system boundaries and assumptions.

It is not the intention of this study to assess the feasibility of different vehicle powertrains for different applications, nor select an optimum. To following are not within the current scope:

- Changes in payload between different powertrains, for example, due to BEV battery size and weight, or hydrogen storage tank size and weight.
- Vehicle range, refuelling time and cabin heating requirements.
- Changes in vehicle performance over time e.g. FCEV and lithium battery.
- Embedded emissions and energy usage from vehicle production and end-of-life.

Figure 3. Notation used to label hydrogen and comparator vehicles within report



[8] Zemo WTT study: https://www.zemo.org.uk/assets/reports/Zemo%20Low%20Carbon%20Hydrogen%20WTT%20Pathways%20-%20full%20report.pdf.

2.3 Calculations

The calculations for WTW energy consumption and GHG emissions are shown in Figure 4.

Figure 4. Calculations for WTT, TTW and WTW energy consumption and GHG emissions

Energy Consumption

WTW energy (MJ/km) = **WTT energy (MJ/km)** Energy used to produce, distribute and dispense fuel used + **TTW energy (MJ/km)** Energy used in combustion

Hydrogen Vehicles

WTW energy (MJ/km) = WTT energy (MJ/kg H_2) x TTW H_2 consumption (kg H_2/km) + H_2 LHV (MJ/kg H_2) x TTW H_2 consumption (kg H_2/km)

Comparator Vehicles

WTW energy (MJ/km) = WTT energy (MJ/MJ $_{fuel}$) x [LHV (MJ/kg) x fuel density (kg/m^3) / 1000] x TTW fuel consumption (L/km) + [LHV (MJ/kg) x fuel density (kg/m^3) / 1000] x TTW fuel consumption (L/km)

GHG Emissions

WTW GHG emissions (gCO_2e/km) = **WTT GHG emissions (gCO_2e/km)** From producing, distributing and dispensing fuel used + **TTW GHG emissions (gCO_2e/km)** Produced when driving the vehicle

Hydrogen Vehicles

WTW GHG emissions (gCO_2e/km) = WTT GHG emissions (gCO_2e/kg H_2) x TTW H_2 consumption (kg H_2/km) + Assumed to be zero

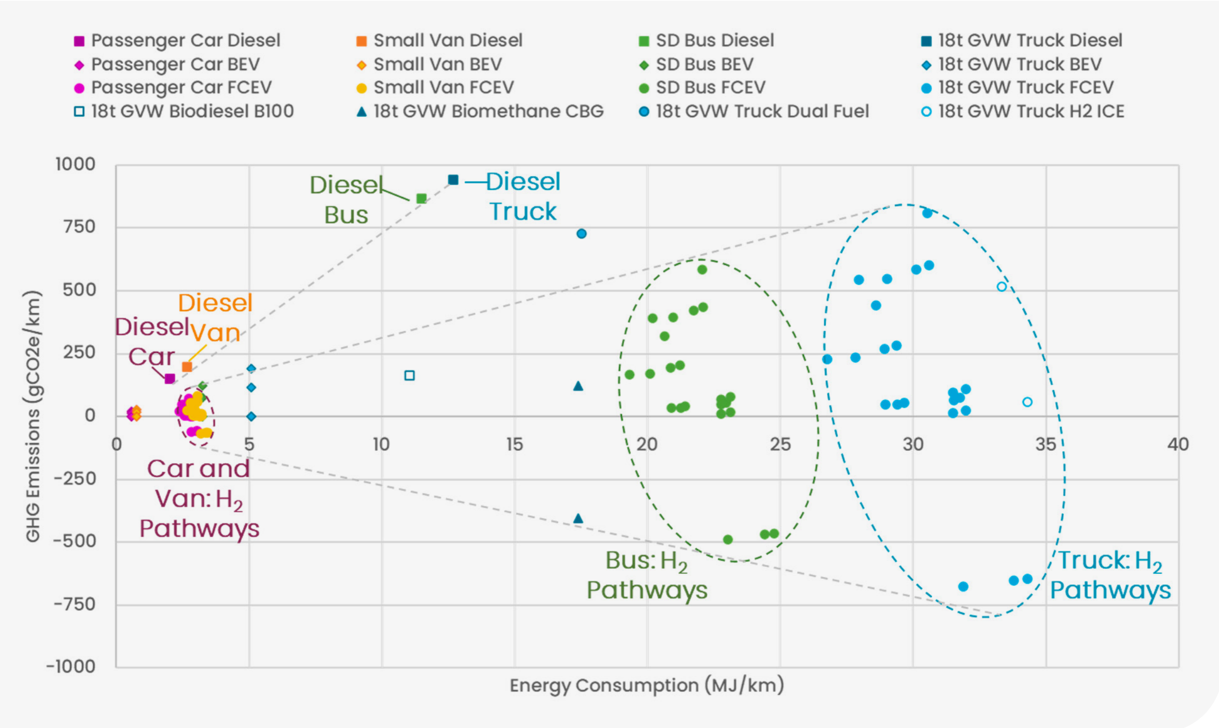
Comparator Vehicles

WTW GHG emissions (gCO_2e/km) = WTT emissions factor (gCO_2e/L) x TTW fuel consumption (L/km) + Measured tailpipe emissions (gCO_2e/km) or calculated from TTW emissions factor (gCO_2e/L) x TTW fuel consumption (L/km)

3. Model Results & Commentary

The WTW scenarios modelled include four vehicle applications: D-segment passenger car, small van, single decker bus and a fully laden 18t GVW heavy goods vehicle. While the absolute values vary, Figure 5 shows that the trends between scenarios with different powertrains and hydrogen supply pathways are similar for each of the vehicle categories modelled. As such, this report focuses primarily on the HGV data to illustrate these trends. A selection results for the passenger car, van and bus are provided in Appendices 6.2 to 6.4.

Figure 5. Trends in WTW GHG emissions and energy consumption for different vehicles

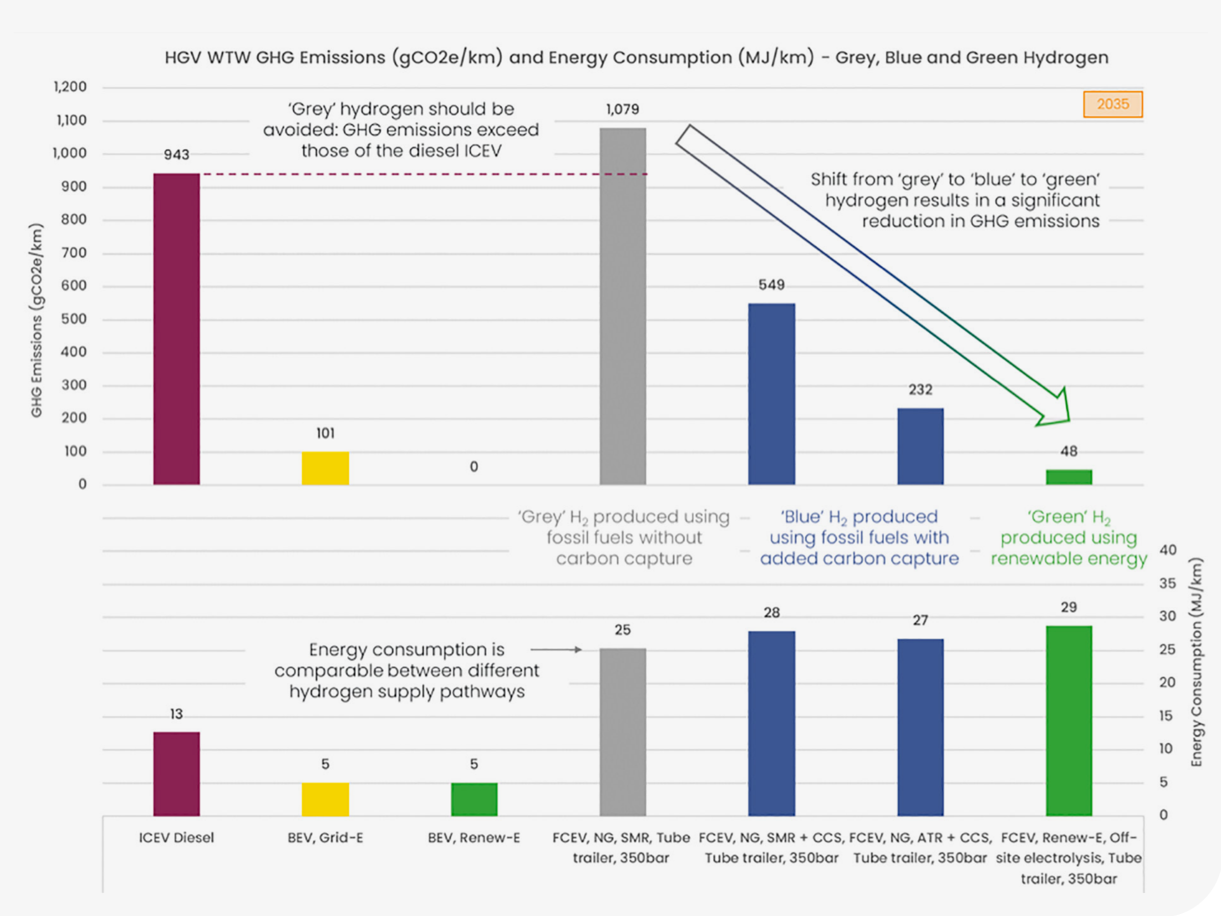


3.1 Decarbonising hydrogen supply chains

Current UK hydrogen production is predominantly from the reformation of natural gas, but to meet net zero, it is critical that low carbon hydrogen production pathways are commercialised. Hydrogen produced from fossil fuels without carbon capture is often referred to as 'grey hydrogen'. Low carbon hydrogen can be 'green hydrogen', produced using renewable energy, or 'blue hydrogen', from non-renewable energy source with added carbon capture and storage (CCS). The supply of hydrogen is expected to decarbonise over the next decade.

Figure 6 shows that emerging low carbon hydrogen supply pathways offer significant improvements in GHG emissions for comparable energy consumption. However, WTW GHG emissions from a FCEV using 'grey' hydrogen can exceed those of a diesel vehicle, as in this HGV scenario. It is also worthwhile highlighting that a FCEV using hydrogen supplied by electrolysis using today's grid electricity, will not deliver improvements in WTW GHG emissions performance compared to a diesel ICEV (as shown in Figure 10).

Figure 6. Shift to low carbon hydrogen pathways in 2035

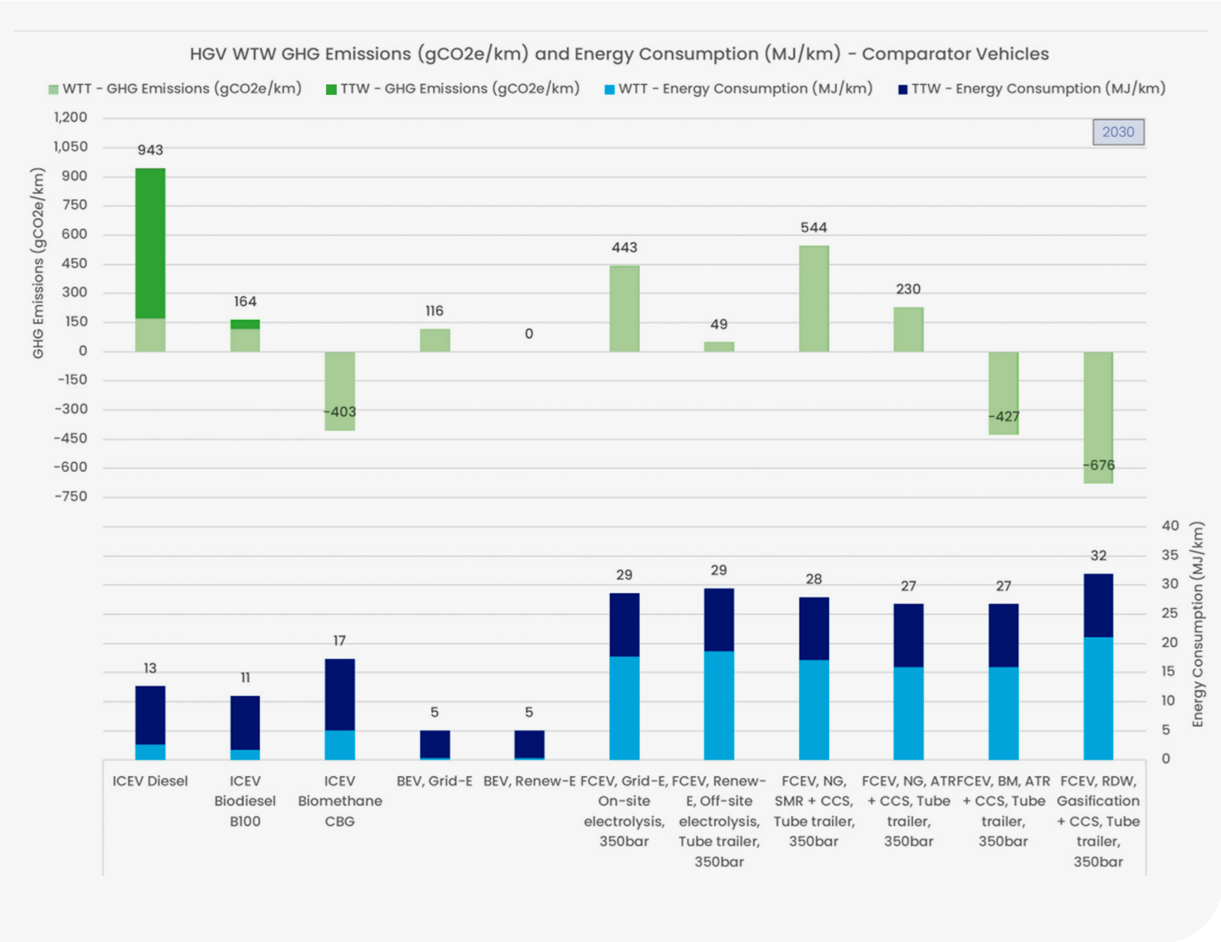


Hydrogen vehicles can provide low carbon WTW GHG emissions solutions, with 'green' hydrogen resulting in the largest reduction in GHG emissions for H_2.'Grey' hydrogen must be avoided in transport.

3.2 Meeting net zero GHG emissions

The upper section of Figure 7 shows that there are several different vehicle technologies and fuel pathways with the potential to achieve low, zero or even negative WTW GHG emissions. FCEV combined with low carbon hydrogen is clearly a promising option. The lower section shows the corresponding energy consumption. The main drawback with hydrogen FCEVs, is that irrespective of the supply pathway, the hydrogen production process is energy intensive compared to electricity and alternative fuels. As a consequence of this, the WTW energy performance of FCEV is much lower than incumbent diesel ICEV and BEV. In the HGV example the WTW energy efficiency of the BEV truck is four to six times better than the FCEV operating on different low carbon hydrogen supply chains.

Figure 7. Hydrogen FCEVs and comparator vehicles in 2030



It is vital to consider GHG emissions and energy consumption together to deliver an efficient net zero energy and transport system.

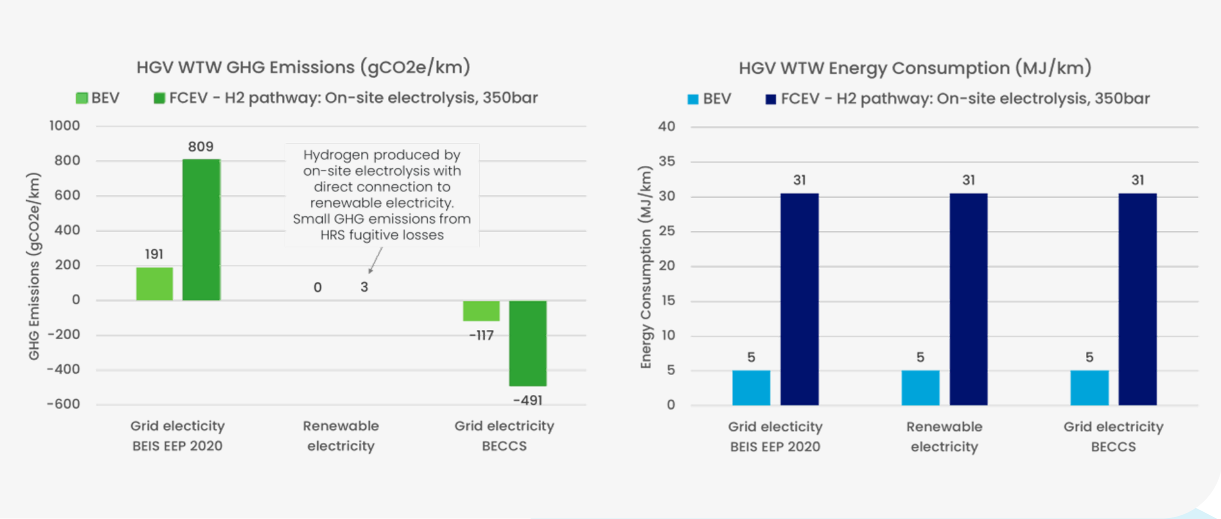
Hydrogen vehicles need to demonstrate other benefits that justify the increased energy consumption. It is possible that hydrogen vehicles might be the optimum solution for some applications, but additional data would be required to assess the feasibility of different vehicles for different usage cases. Examples of other factors that should be considered are cost of ownership, vehicle payload (gCO_2e/tkm), capacity, range, refuelling/charging time and infrastructure.

A wider range of factors would need to be considered to assess the feasibility of different hydrogen vehicle technologies for specific applications and identify where the sweet spot of this technology resides, given its high energy requirement.

3.3 Negative carbon accounting

GHG emissions are highly dependent on the carbon intensity of the electricity used to charge a BEV or, in the case of a FCEV, generate the hydrogen using electrolysis. Figure 8 shows three electricity source scenarios: grid electricity, renewable electricity and grid electricity generated using BECCS. Due to the carbon offsetting associated with using biomass as an energy source, electricity produced from BECCS, can result in negative WTW gCO_2e/km. This can be seen in the left-hand section of Figure 8. If viewed in isolation, this could be misleading as the FCEV with BECCS electricity appears to be better than the BEV in terms of GHG emissions (more negative). The right-hand section of Figure 8 shows that the BEV truck is more energy efficient, having significantly lower WTW energy consumption than the FCEV, irrespective of the source of the electricity. With negative carbon accounting, less energy efficient scenarios and increased vehicle mileage can result in apparently larger negative GHG emissions, but clearly this should be avoided.

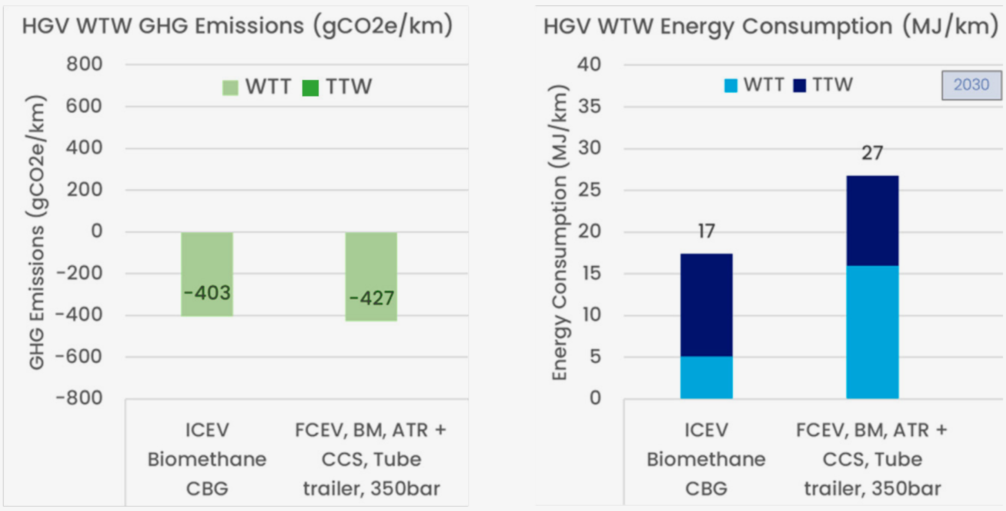
Figure 8. BEV and FCEV with different sources of electricity



Negative carbon pathways could lead to unintended consequences by promoting energy inefficient options. Caution must be exercised when utilising carbon offsetting in GHG emissions accounting for BECCS pathways.

A similar phenomenon is evident in Figure 9 which compares an ICEV CBG truck using biomethane (biogenic waste feedstock comprising of 40% manure resulting in a methane credit) with a FCEV using hydrogen produced from ATR+CCS with biomethane as a feedstock. While the FCEV has more negative GHG emissions, the right-hand side of Figure 9 shows that in this example, the CBG truck has lower energy consumption. Bioenergy supplies are limited and should be allocated strategically to maximise GHG savings.

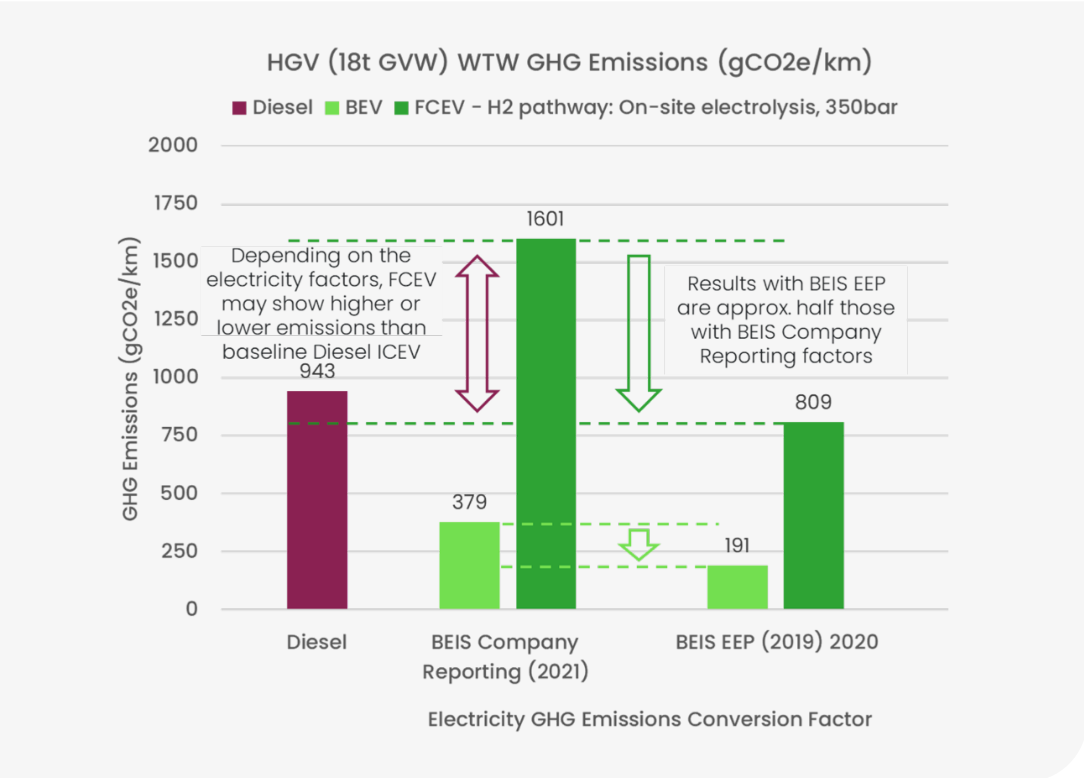
Figure 9. ICEV and FCEV with biomethane in 2030



3.4 Grid electricity GHG emission conversion factors

Zemo's WTT low carbon hydrogen pathways model uses BEIS EEP 2019 GHG emissions conversion factors for deriving grid electricity carbon intensity, and for consistency, these have also been applied to the BEV comparators. Zemo traditionally use the BEIS Company Reporting WTT GHG emissions conversion factors for electricity consumption (combining the factors for electricity generation and transmission & distribution grid losses). There is significant disconnect between BEIS EEP and BEIS Company Reporting GHG emission factors, with the current BEIS company reporting value being approximately twice that of the BEIS EEP forecast. Figure 10 shows that the electricity grid carbon intensity factor used in calculating the WTW GHG emissions has a significant impact on the results and as such, should be specified by Government in the forthcoming low carbon hydrogen standard to ensure a consistent approach.

Figure 10. Sensitivity of GHG emissions to electricity grid conversion factor



A 'standard' set of GHG emissions conversion factors for grid electricity should be adopted in carbon accounting used in Government policy: this will ensure consistency in the data sets used to inform decision making and policy creation.

3.5 Hydrogen production

The upper section of Figure 11 shows that the hydrogen production pathway has a significant impact on the overall WTW GHG emissions. The scenarios show a large variation in GHG emissions, with the 'green' electrolysis pathways showing the lowest emissions without applying negative GHG offsets. The lower section of Figure 11 shows that the production pathway has a relatively small impact on energy consumption.

Figure 11. Comparison of low carbon hydrogen production pathways in 2030

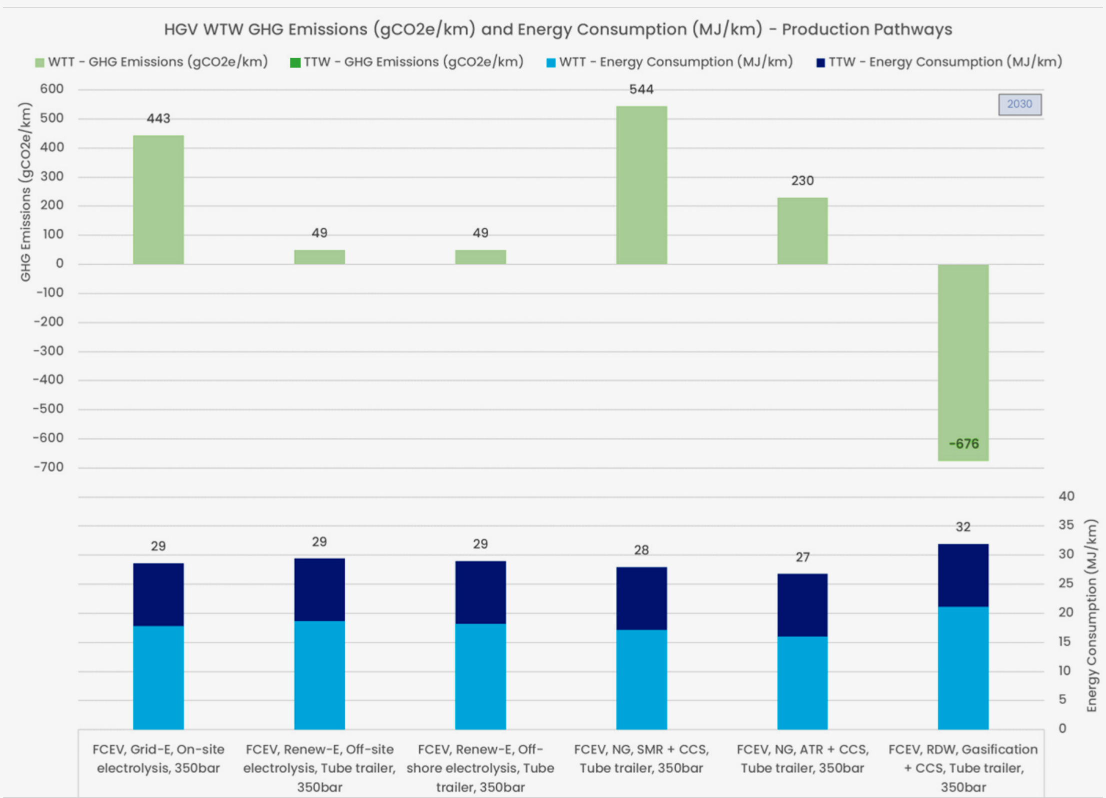
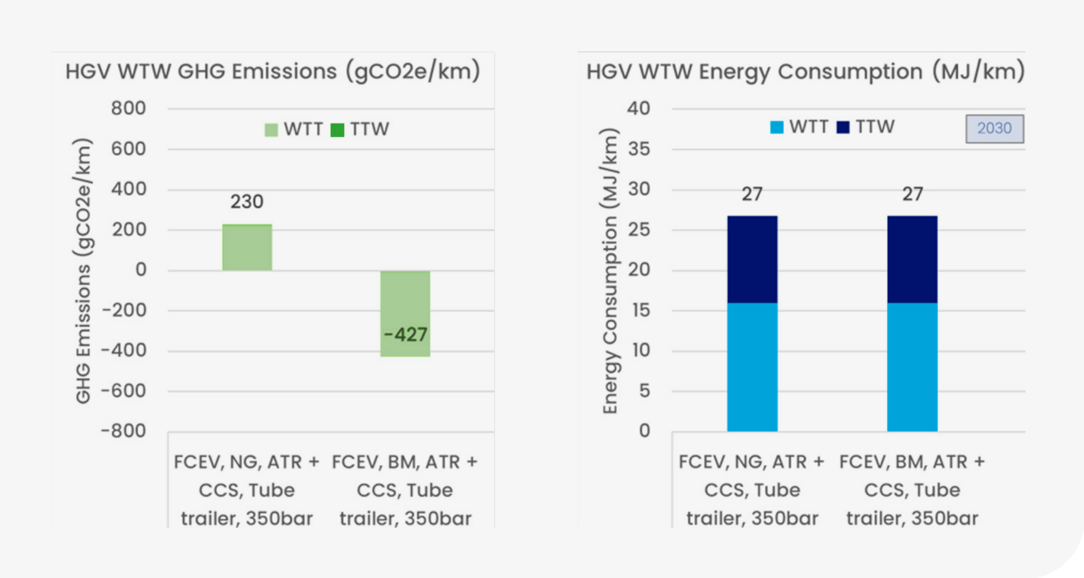


Figure 12 shows the results for two hydrogen supply pathways, both using ATR+CCS but with different feedstocks: natural gas and biomethane. The left-hand section of the figure shows that GHG emissions are highly dependent on the choice of feedstock, its corresponding carbon intensity and eligibility to use of carbon offsetting in the GHG emissions accounting.

Figure 12. Choice of feedstock for hydrogen production in 2030

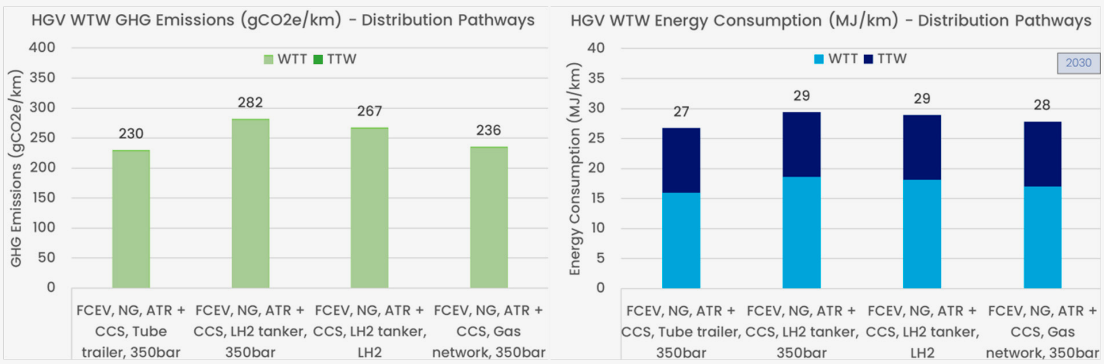


The hydrogen production process and feedstock dominate GHG emissions and energy use arising from the hydrogen supply chain.

3.6 Hydrogen distribution and dispensing

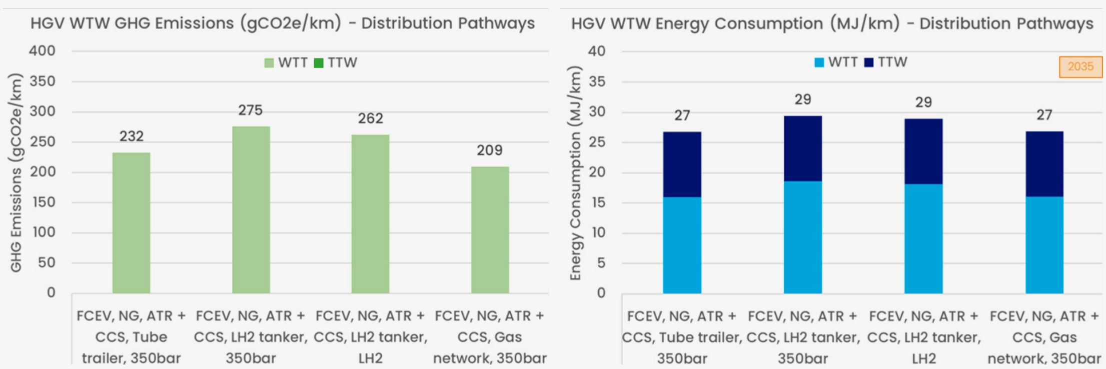
The following figures show that the distribution and dispensing of hydrogen have a less significant impact on GHG emissions and energy consumption than the production process. Figure 13 shows that the tube trailer and gas network pathways result in lower WTW GHG emissions than liquified tanker delivery and dispensing. For the 2030 scenario the gas network is assumed to consist of 20% H_2 and 80% CH_4, with additional energy requirements for deblending.

Figure 13. Comparison of hydrogen distribution pathways in 2030



From 2035 it is assumed that the gas network can transport 100% H_2, eliminating the need for deblending. (It is assumed that some regional sections of the network could be converted to 100% H_2, rather than full conversion of the UK gas network by this date.) Hence, as shown in Figure 14, the gas network pathway shows lower GHG emissions than the tube trailer for 2035.

Figure 14. Comparison of hydrogen distribution pathways in 2035



The results in Figure 13 and Figure 14 have been generated using the 'default' model values for distance and capacity of road transportation. Figure 15 illustrates the sensitivity of the GHG emissions and energy consumption to varying the transportation distance and tube trailer capacity. The 'default' scenario, shown in the central column, assumes a 200 km round trip and 350 kg H_2 trailer capacity. Comparing this to the left-hand column, shows that increasing the distance to a 1000 km round trip, results in a substantial increase in GHG emissions. Similarly, comparing the central and right-hand columns, shows a reduction in GHG emissions from increasing the trailer capacity to 1000 kg H_2.

Figure 15. Sensitivity to tube trailer distance and capacity in 2030

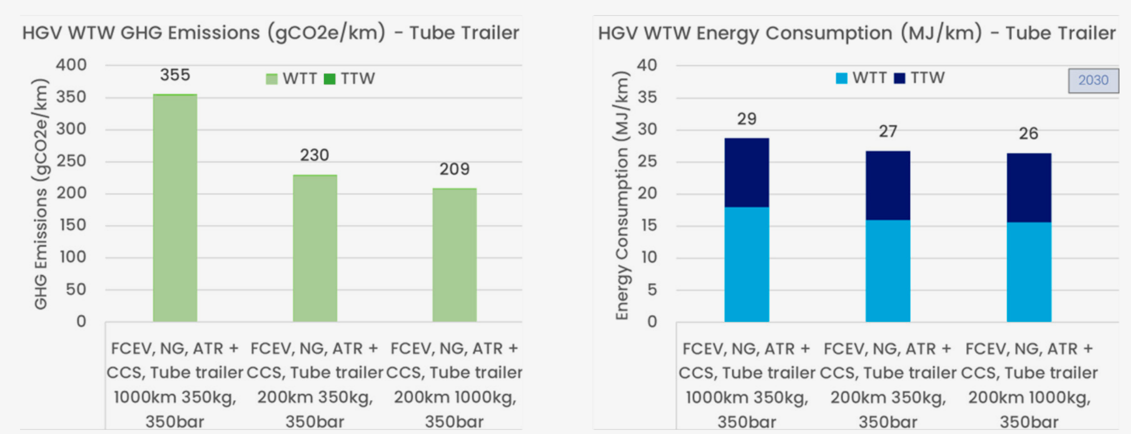
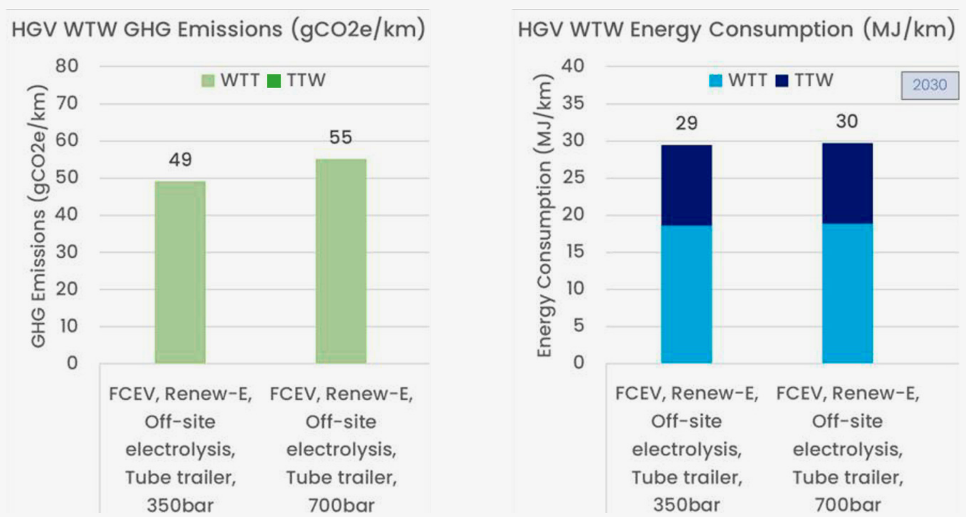


Figure 16 shows that varying the dispensing pressure has a much smaller impact on GHG emissions and energy consumption than hydrogen production.

Figure 16. Comparison of hydrogen dispensing pressures in 2030

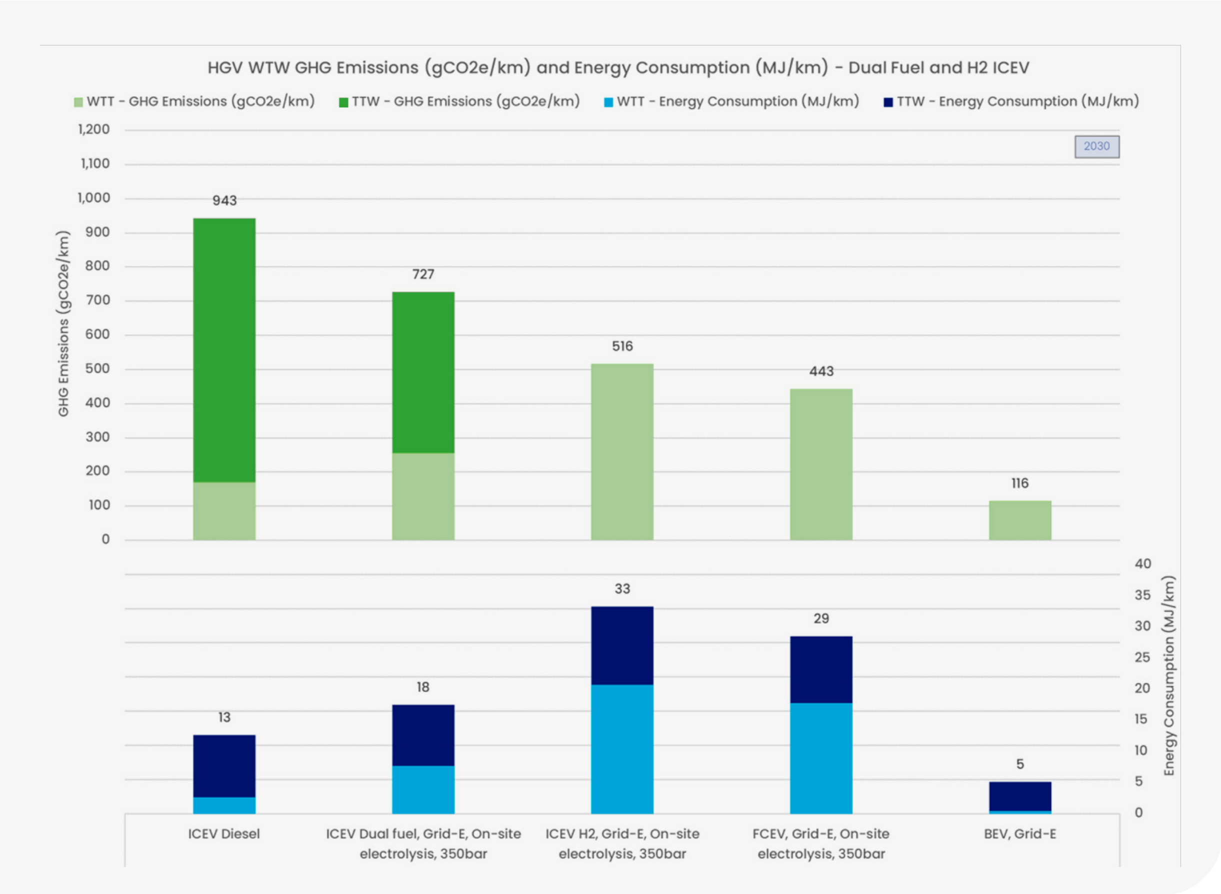


3.7 Dual fuel and hydrogen ICEV

The results presented so far have focused primarily on hydrogen fuel cell vehicles (FCEV) but it is worth considering hydrogen ICEVs and dual fuel (diesel and hydrogen) vehicles. The lower purity requirements for ICEV H_2, compared to FCEV, have not been accounted for in the hydrogen supply chain WTT modelling for this study. H_2 ICEV consumption was estimated to be a factor higher than the FCEV, based on limited data for an HGV scenario. Hence, the H_2 ICEV shows higher GHG emissions and energy consumption than the FCEV.

Figure 17 shows that hydrogen ICEVs can produce significantly lower GHG emissions than the diesel vehicle when using a low carbon hydrogen supply. It follows that the GHG emissions and energy consumption for dual fuel ICEVs fall part way between the diesel and pure hydrogen ICEVs.

Figure 17. Hydrogen and dual fuel ICEVs in 2030



When supplied with low carbon hydrogen, dual fuel ICEV, hydrogen ICEV and FCEV, can all exhibit lower WTW GHG emissions than a traditional diesel ICEV.

3.8 Overview of key sensitivities

By modelling a range of scenarios, and varying individual parameters within the model, it has been possible to determine which of the parameters explored have the greatest impact on WTW GHG emissions and energy consumption. These relative sensitivities are summarised in Table 3 and are useful for:

- Highlighting key factors that need to be considered by Government when creating policies relating to zero emission vehicles and low carbon hydrogen.
- Directing where to target efforts to minimise GHG emissions and energy use.
- Prioritising the gathering of data required to fill key gaps in knowledge.

Table 3. Summary of WTW GHG emissions and energy consumption key sensitivities

	GHG Emissions	Energy Consumption
Vehicle fuel / energy source	High	High
Grid electricity carbon intensity	High	None
Electricity source	High	None
Powertrain: H_2 ICEV v. FCEV	Low	Low
Fuel feedstock	High	None
H_2 production pathway	High	Low
H_2 distribution pathway	Low	Low
H_2 tube trailer distance & capacity	Medium	Low
HRS H_2 dispensing pressure	Low	Low

Table 3 shows that while there are several factors that have a large impact on WTW GHG emissions, the vehicle fuel / energy source has the greatest impact on GHG emissions and energy efficiency simultaneously. This highlights the need for more data to support informed decisions regarding the optimum solution for different vehicle applications and usage cases.

The high sensitivity of GHG emissions to the grid electricity conversion factors is useful in highlighting the importance of using an informed consistent approach, on which to base emerging Government policy and the impending low carbon hydrogen standard.

To minimise GHG emissions from the hydrogen supply pathway, the key areas to focus on are the production process and feedstock. The sensitivity to tube trailer distance shows that hydrogen supplied from a more local source (using the same production method) is beneficial in terms of GHG emissions. This becomes even more apparent in the case of hydrogen produced by electrolysis powered by 100% renewable electricity or BECCS pathways, where the GHG emissions contribution from distribution has the most influence in terms of overall WTW GHG emissions.

4. Recommendations

Based on the work performed in this study, the following recommendations are made:

1. Government should consider both WTW GHG emissions and energy consumption when setting policies relating to zero emission vehicles, rather than tailpipe GHG emissions in isolation. It is proposed that DfT's forthcoming trials of hydrogen and electric long-haul HGVs ensure WTW GHG emissions and energy consumption are accurately determined.
2. Caution should be exercised with negative GHG pathways using BECCS for hydrogen and other fuels: safeguards should be put in place to avoid promoting energy inefficient options and to make the best use of limited biomass and renewable energy resources.
3. The differing data sets released by BEIS for UK grid electricity carbon intensity should be addressed. BEIS are recommended to integrate a set of WTT GHG emission conversion factors for different low carbon hydrogen supply chains in their Company Reporting GHG emission factor database. These steps will ensure consistency in the data sets used by policy makers and industry. Zemo's work provides these new data sets and defines pathway boundaries.
4. It is essential that fleet operators receive robust GHG emissions data specific to their hydrogen supply chain from fuel suppliers, in order to have confidence in WTW GHG emissions performance. Renewable hydrogen is included within Zemo's Renewable Fuels Assurance Scheme.
5. A feasibility study to assess the suitability of different vehicles for different usage cases would be helpful to inform the role of hydrogen in the HGV sector. Additional data would be required to assess key factors such as vehicle payload and capacity, range, and refuelling/charging time and infrastructure. Payload is particularly important in determining feasible and optimal technology solutions for HGV applications: calculating the results in gCO_2e/tkm (gCO_2e from transporting one tonne of goods, one kilometre) may offer further insights.
6. Many of the low carbon hydrogen supply chain technologies analysed in this study are immature and the number of hydrogen vehicles in the market is very limited. More performance data, particularly chassis dyno and real-world vehicle test data from hydrogen FCEV, ICEV and dual fuel vehicles, would be useful in continuing to build the evidence base for hydrogen in net zero transport.

The WTW results from this study will feed into Zemo's life cycle GHG analysis workstream, which will aim to build upon the current evidence base by incorporating GHG emissions from vehicle production and end-of-life. Zemo's in-house life cycle GHG emissions tool has recently been expanded to incorporate hydrogen FCEVs. It is planned that the LCA work will include a broader range of vehicle applications, including a 44t GVW HGV truck.

5. Further Reading

The following publications may be of interest to the reader.

Low Carbon Hydrogen Well-to-Tank Pathways Study - Executive Summary, Zemo Partnership, August 2021
https://www.zemo.org.uk/hydrogenwttsummary

Low Carbon Hydrogen Well-to-Tank Pathways Study - Full Report, Element Energy, August 2021
https://www.zemo.org.uk/hydrogenwttreport

UK Hydrogen Strategy (and accompanying documents), BEIS, August 2021
https://www.gov.uk/government/publications/uk-hydrogen-strategy

Consultation on a UK Low Carbon Hydrogen Standard, BEIS, Closing date 25 October 2021
https://www.gov.uk/government/consultations/designing-a-uk-low-carbon-hydrogen-standard

JEC Well-to-Tank report v5, Joint Research Centre, 2020
https://publications.jrc.ec.europa.eu/repository/handle/JRC119036

Greenhouse gas reporting: conversion factors 2021, BEIS, June 2021
https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

6. Appendix

6.1 Assumptions

6.1.1 WTT hydrogen supply model

- A 100-year GWP of 5.8 is used for hydrogen, meaning that over 100 years 1 kg of hydrogen has the same warming effect as 5.8 kg of carbon dioxide. Note that hydrogen is an indirect greenhouse gas.
- A 100-year GWP of 28 is used for methane. GWP of methane remains consistent for future scenarios.
- Greenhouse gas emissions include emissions of CO_2, N_2O and CH_4.
- Lower Heating Value is used for hydrogen, natural gas and diesel, while Higher Heating Value is used for refuse derived fuel (biomass gasification).
- Fugitive hydrogen emissions are included: these contribute to the emissions through the direct global warming potential of the emitted hydrogen and through the increase in upstream emissions associated with production of the hydrogen that is lost.
- Hydrogen is produced at hydrogen fuel cell purity (99.999%).
- BEIS EEP 2019 projected electricity grid carbon emissions factors are used for the central scenario. Grid losses are included.
- Natural gas WTT upstream emissions of the UK average gas mix are obtained using a weighted average of the BEIS LNG and non-LNG emission factors. The weighting factors for the relative proportion of LNG in future are obtained from the National Grid FES 2020 Steady Progression (medium LNG is the central scenario). The model includes low, medium and high LNG scenarios, with 0%, 50% and 100% LNG 'generic imports' fraction (FES scenarios include some LNG as well as a 'generic imports' category). LNG upstream emissions remain consistent for future scenarios.
- Biomethane is not included in the main NG upstream emissions scenarios.
- On-site electrolysers are the only hydrogen production technology considered in 2020.
- All electrolysers use PEM electrolysis. Improvements in terms of energy use are expected by 2030 as the technology matures, then some further improvements by 2035, with energy use remaining constant from 2035.
- Renewable electricity is used for desalination in offshore electrolysis and for compression/ liquification for on- and off-shore electrolysis.
- SMR and ATR include a very small contribution from methane in the flue gas.
- Carbon capture rates for retrofit SMR, new ATR and gasification are 60%, 95% and 97% respectively.
- CCS energy use and emissions for CO_2 compression and transport are very small and are included within the production plant electrical energy use figures. Fugitive emissions of CO_2 during transport are negligible.
- Results for 'grey' hydrogen, from SMR without CCS, are modelled using 0% carbon capture rate and an estimated 15% reduction in WTT energy consumption to account for the CCS plant energy and the energy for CO_2 compression and injection.

- Waste Gasification data is based on one single technology. Municipal Solid Waste used to form the Refuse Derived Fuel feedstock for gasification is 65% biogenic by energy. For gasification with CCS, emissions from the fossil fraction are ignored, and negative emissions are credited for the biogenic fraction only.
- Truck for hydrogen distribution is a diesel Euro VI.
- Compressed H_2 central case: 280 bar tube trailers delivering 350 kg H_2, 200 km round trip delivery distance.
- LH_2 central case: 3,500 kg LH_2 tanker truck, 200 km round trip delivery distance.
- Gas network: H_2 injected at transmission level (80 bara), HRS connected to distribution network (2 bara). Energy for deblending is only required in 2030 when the gas network supply is assumed to be from a 20% blended network. From 3025 it is expected to be 100% H_2 (only available in some regions). H_2 delivered by a '100% H_2' gas network is 98% pure (impurities from the pipeline and odorants), requiring purification by PSA before dispensing. Energy for purification is negligible compared to compression. Unrecovered H_2 in PSA tail gas is re-injected into the gas network.
- Model includes purification, compression, pumping and cooling at HRS for dispensing H_2 at 350 or 700 bar.
- For compressed H_2 distribution, energy use is dominated by compression which does not vary significantly with station size per unit of H_2 dispensed and so this is not included as a variable.
- For LH_2 distribution, H_2 boil-off is substantially higher for smaller stations. The central scenario is a medium sized station with 1,500 kg H_2 /day.
- For compressed H_2 tube trailer deliveries, the tube trailer is left at the HRS, providing medium pressure storage. Compression is modelled from the halfway point between the delivery pressure and 20 bar, at which point the trailer is depleted and is returned for refilling.
- The WTT hydrogen supply model was manually overwritten to enable some scenarios in the 2020-2030 timeframe: off-site electrolysis in 2020 and off-shore electrolysis in 2030. Data may be less robust for these scenarios.

6.1.2 Electricity supply

- In order to be more consistent with the hydrogen supply model, WTT energy expenditure for electricity is based on transmission and distribution losses only: omitting the energy required for generation.
- WTT energy expenditure is the same for grid and on-site renewable electricity.
- WTT GHG emissions for on-site renewable electricity are zero.
- In order to be consistent with the hydrogen supply model, the 2020, 2030 and 2035 WTT GHG conversion factors for grid electricity are taken from BEIS EEP 2019 forecasts. The BEIS 2021 UK Government GHG Conversion Factors for Company Reporting have also been used in the 2020 comparison.
- For BEV TTW energy expenditure, grid energy consumption is used: this accounts for any charging losses.

6.1.3 Fuel supply

- WTT energy values for comparator fuels are taken from the JEC WTT 2019 data sets.
- WTT GHG conversion factors for comparator fuels are taken from BEIS 2021 Scope 3 UK Government GHG Conversion Factors for Company Reporting and Zemo Renewable Fuels Assurance Scheme (RFAS) where available.
- Biomethane and biodiesel WTT energy values and GHG conversion factors are from engagement with biofuel community members.
- Where available, fuel densities and LHVs are taken from BEIS 2021 UK Government GHG Conversion Factors for Company Reporting. Estimates have been made for fuel properties where data is not available.
- Diesel is a 'pump' blend and includes an element of biofuel (accounted for in the BEIS conversion factors).
- Except for biomethane, fuel properties remain consistent for future scenarios (no forecasts in blend changes have been applied).
- Biomethane feedstock for 2030-2035 includes 40% from manure, utilising manure 'credit' for CH_4 as per REDII; this gives rise to a negative carbon intensity value. While it is possible to produce biomethane from 100% manure this is likely to be small scale.

6.1.4 Vehicle fuel consumption

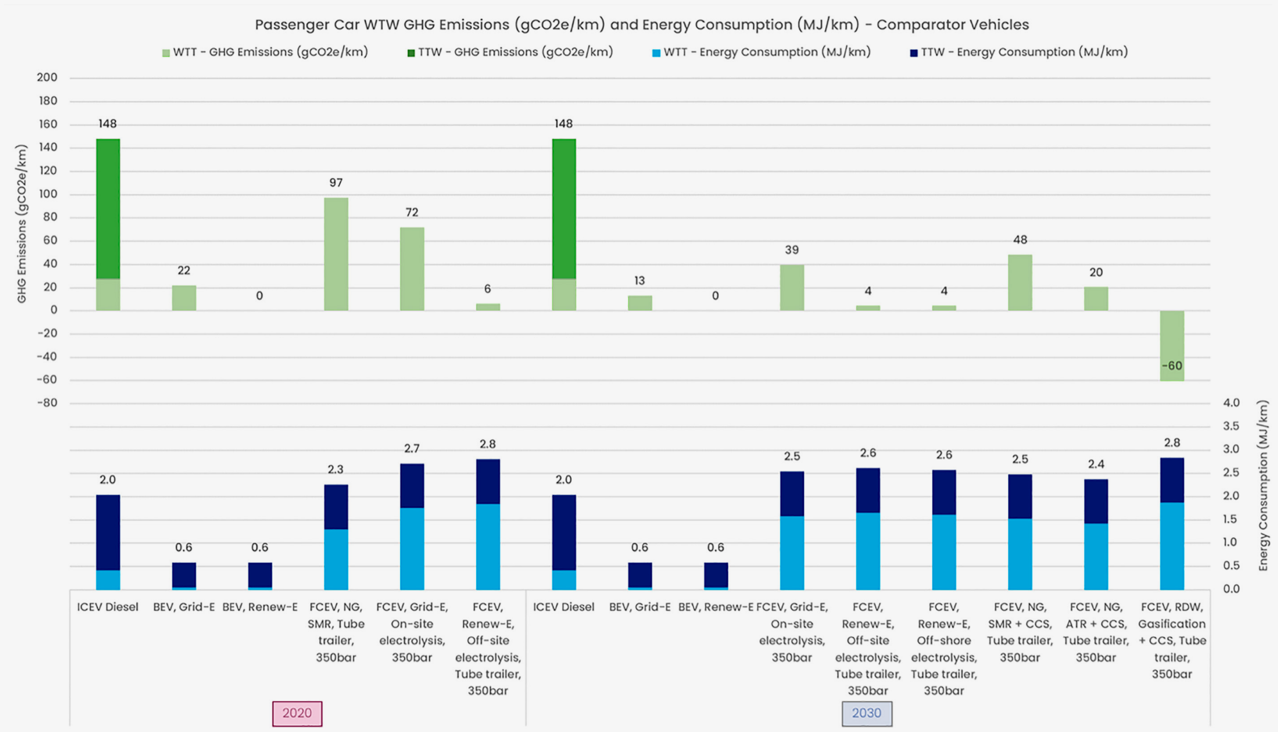
- Vehicle performance remains consistent for future scenarios (no forecasts in efficiency have been applied).
- Vehicle deterioration factors have not been applied.
- Hydrogen ICEV fuel consumption is estimated to be a factor higher than FCEV, based on limited data for the HGV scenario. ICEV and FCEV efficiency are dependent on the powertrain load so the difference in energy consumption between the two vehicles may vary with vehicle type. The lower purity requirements for ICEV H_2, compared to FCEV, has not been accounted for in the hydrogen supply modelling.
- Dual fuel vehicle hydrogen consumption, diesel consumption and tailpipe emissions are estimated as a proportion of the diesel comparator vehicle values. Using factors calculated from the LEFT trials, ~40% of diesel is substituted.
- An effort has been made to use vehicle energy/fuel consumption values corresponding to a consistent drive cycle or similar real world conditions for comparator vehicles. However, this was not always possible due to limited data availability.
- Biodiesel is estimated to have the same fuel consumption as pump diesel.
- HGV results have not been adjusted for potential changes in payload between different powertrains, for example, BEV battery size/weight or hydrogen storage tank size/weight.

6.1.5 TTW GHG emissions

- TTW gCO_2e/km is zero for pure hydrogen vehicles and BEVs.
- TTW gCO_2e/km for comparator vehicles with non-renewable fuels is based on test data where available. Where test data does not include other GHG emissions (e.g. WLTP), TTW gCO_2e/km is equal to tailpipe CO_2 x 1.03 (additional 3% to estimate for other GHG emissions). Where test data for other GHG emissions is available (e.g. Low Emissions Bus testing with FTIR measurements), TTW gCO_2e/km is estimated from CO_2, CH_4 and N_2O using GWP factors.
- For renewable fuels such as biomethane, the tailpipe emissions are not used to calculate the TTW gCO_2e/km. CO_2 emissions from combustion are offset by the CO_2 captured by the biomass feedstock.
- For comparator vehicles with renewable fuels, or where tailpipe test data is unavailable, GHG conversion factors are used: taken from BEIS 2021 Scope 1 UK Government GHG Conversion Factors for Company Reporting where available.

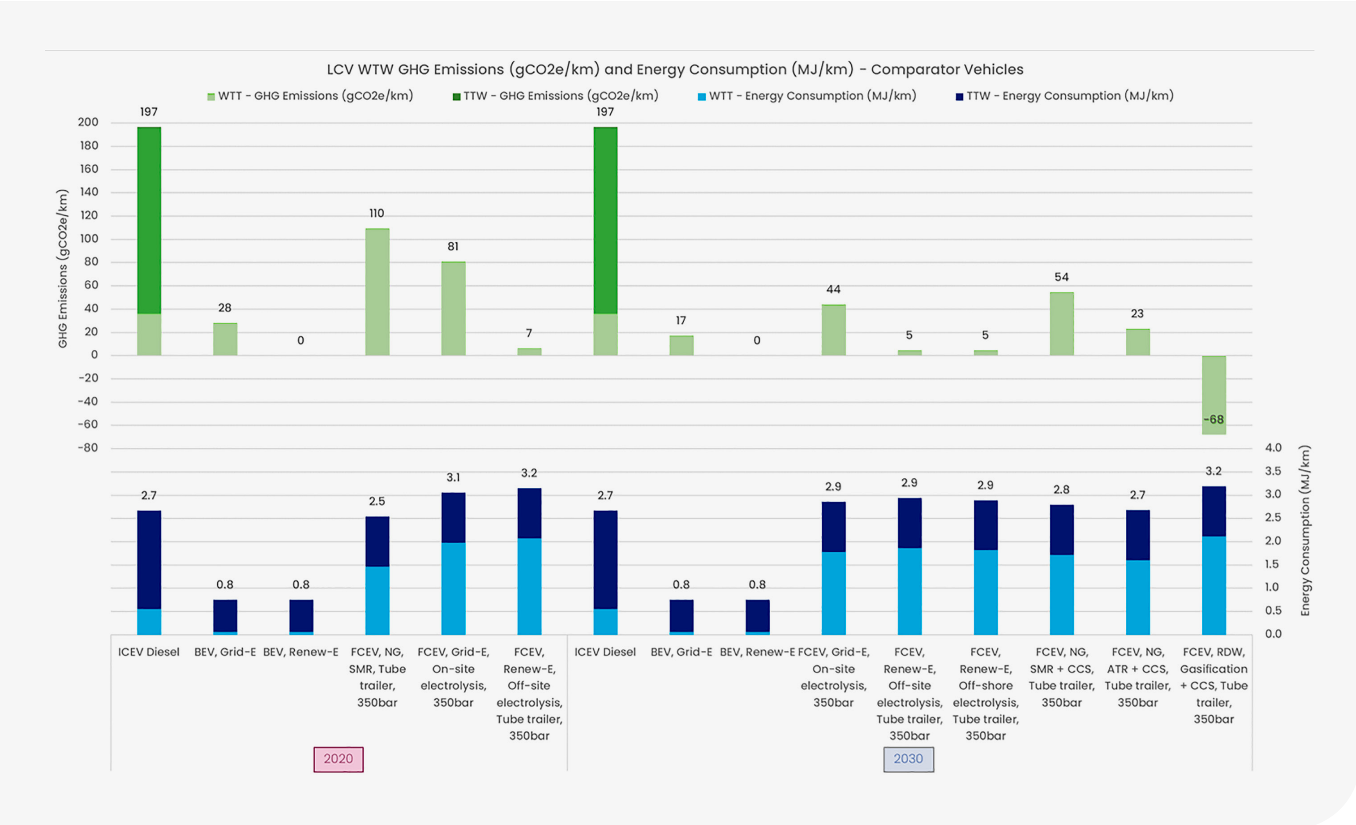
6.2 Passenger Car Overview

Figure 18. D-segment passenger car: hydrogen FCEVs and comparators in 2020 and 2030



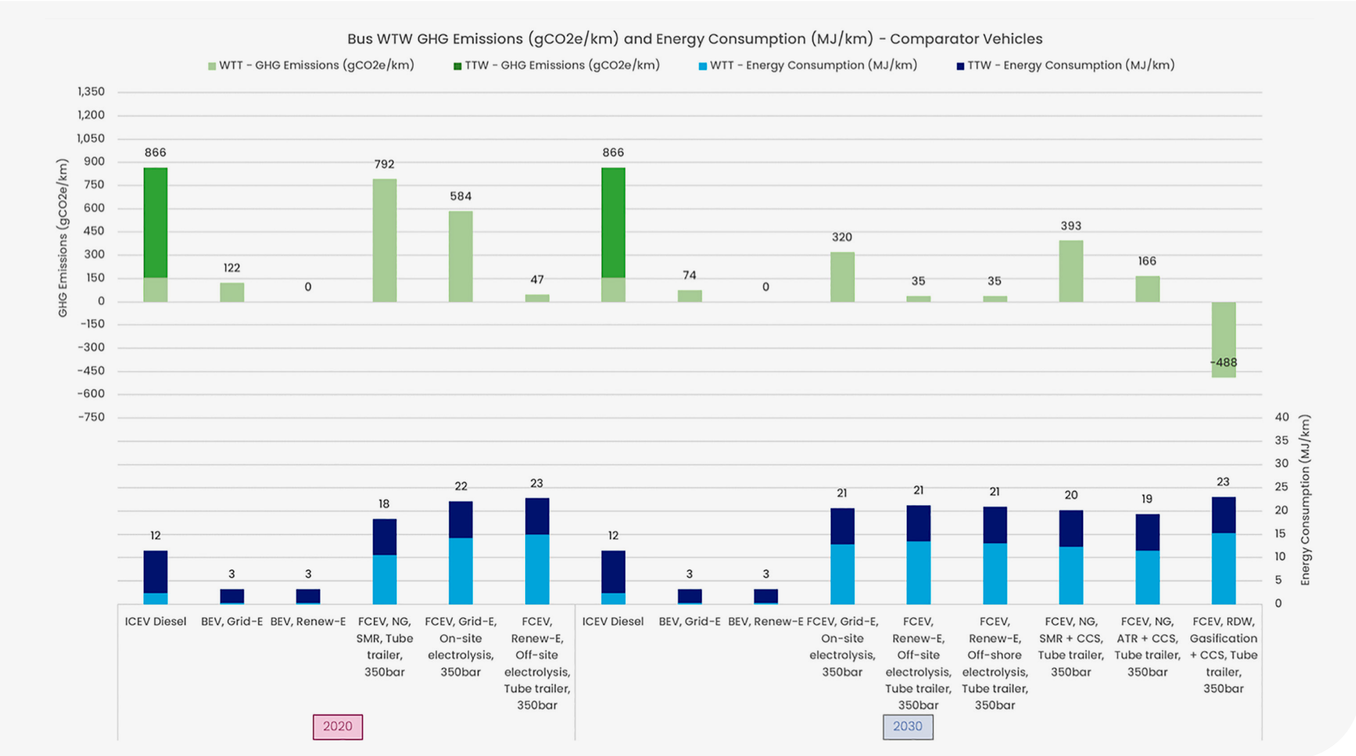
6.3 LCV Overview

Figure 19. Small van: hydrogen FCEVs and comparators in 2020 and 2030



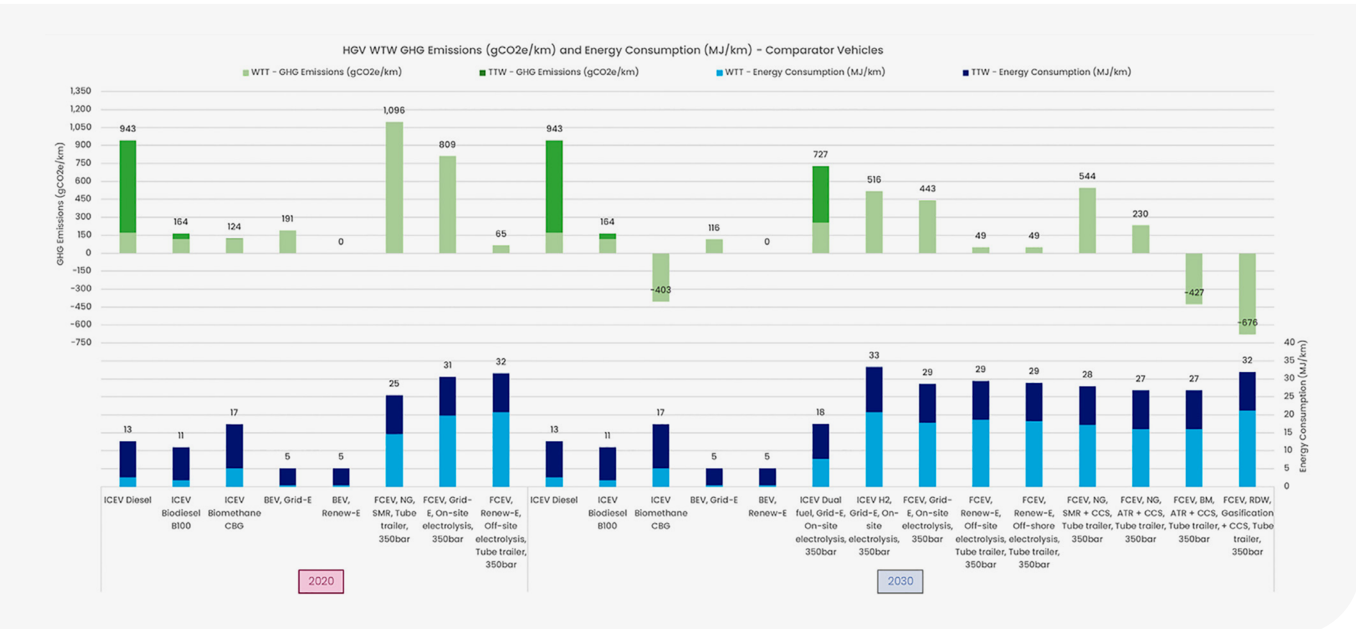
6.4 Bus Overview

Figure 20. Single decker bus: hydrogen FCEVs and comparators in 2020 and 2030



6.5 HGV Overview

Figure 21. 18t GVW truck: hydrogen FCEVs and comparators in 2020 and 2030



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