Zemo Partnership
Accelerating Transport to Zero Emissions

Vehicle life cycle GHG emissions study to show the role of renewable fuels in meeting net zero

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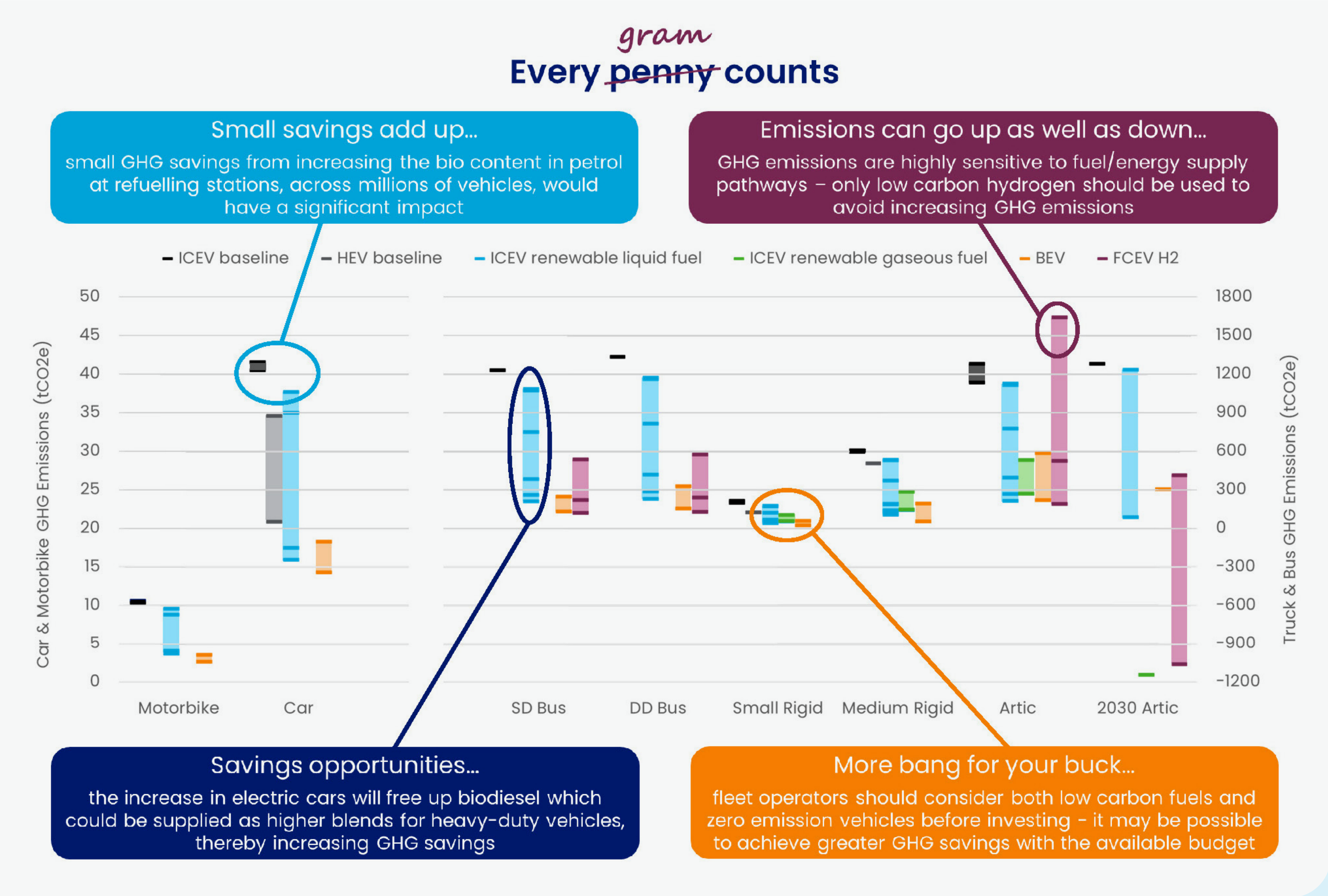
In a Nutshell

Zemo have modelled vehicle life cycle greenhouse gas (GHG) emissions across a broad range of vehicle segments, powertrains and fuel/energy pathways to demonstrate the complementary role that renewable fuels can play, alongside zero tailpipe emission technologies, in delivering GHG emissions savings. Renewable low carbon fuels have a vital contribution to make towards GHG emissions abatement, with the potential for large cumulative savings if implemented soon and at scale.



1. Executive Summary

Significant GHG emissions abatement will be required from the road transport sector to meet net zero by 2050. The Climate Change Committee's 6th Carbon Budget analysis estimates that about 96 million tonnes of GHG emissions abatement is needed for UK surface transport by 2035, rising to approximately 136 million tonnes by 2050. A portfolio of technologies, fuels and energy vectors will be needed to replace fossil fuels and deliver GHG savings at scale and within this timeframe.

Whilst the focus of Government policy is on the transition to zero (tailpipe) emission propulsion technologies, the merits of renewable fuels should not be forgotten. GHG emissions reductions that can be made today can accumulate over time, making them significantly more impactful than savings made in the future, in terms of limiting global warming. There is no reason why renewable fuels should not be employed alongside electric powertrain technologies. Renewable low carbon fuels have a vital and rapid contribution to make towards GHG emissions abatement – they can ease the transition for consumers, mitigate embedded carbon from new vehicle manufacture and help to bridge the gap for harder to decarbonise applications.

Renewable fuels can reduce the GHG emissions from the existing petrol and diesel vehicles which will continue to form a significant part of the UK vehicle parc for many years, even after bans on the sale of new internal combustion engine vehicles come into force. Combining renewable fuels with hybrid vehicles could also help to decarbonise applications for which a pure electric vehicle is currently unaffordable or unavailable, due to the power demand, vehicle range or recharging considerations.

Heavy-duty vehicles are at the early stages of the electrification journey. Renewable fuels can help to bridge the gap whilst the zero (tailpipe) emission heavy-duty vehicle market develops. With the increase in the uptake of light electric vehicles today, the volumes of liquid fuel being used are now beginning to reduce over time. This creates opportunities for increasing the proportion of renewable fuel content, particularly in the heavy-duty vehicle segment, thus increasing GHG emissions abatement.

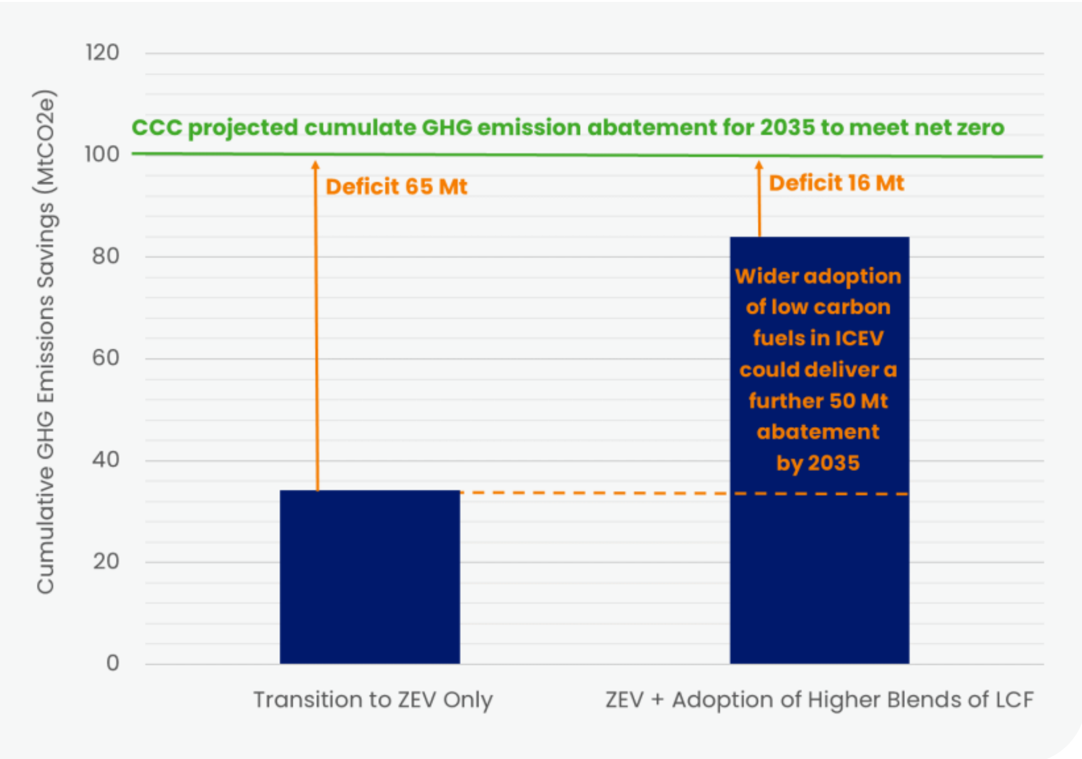


Figure 1. Modelled GHG emissions savings with and without the adoption of higher blends of low carbon fuels in heavy goods vehicles (HGVs)[1]

For this study, Zemo have used their vehicle life cycle GHG emissions tool to model a broad range of vehicle segments, powertrains and fuel/energy pathways. The modelling includes renewable fuel pathways available in the UK today and advanced fuel pathways that may be commercialised over the next decade. The study demonstrates the complementary role that renewable fuels can play, alongside zero tailpipe emission technologies, in delivering GHG emissions savings. By considering the whole vehicle life cycle, it has been possible to identify opportunities for maximising GHG abatement and potential unintended consequences.

[1] Decarbonising Heavy Duty Vehicles and Machinery, 2022: https://www.zemo.org.uk/work-with-us/fuels/projects/future-of-fuel-taxation.htm

Key findings

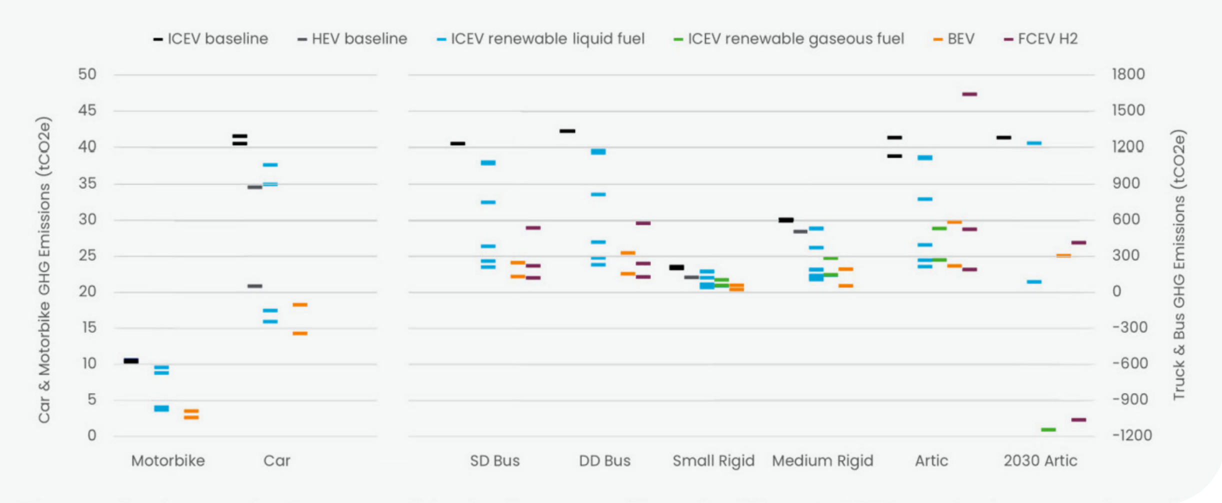


Figure 2. Total life cycle GHG emissions for all applications modelled

Figure 2 shows that renewable fuels can offer significant GHG emissions savings in comparison to conventional, predominantly fossil content fuels. In most of the vehicle segments modelled, there are some renewable fuels which show greater life cycle GHG emissions savings than current battery electric vehicles using grid electricity. For example, in heavy-duty vehicles renewable diesel shows life cycle GHG emissions savings in the range of 79 83%, whereas battery electric vehicles using grid electricity show savings in the range of 54 80% (compared to the baseline diesel vehicle using standard retail fuel and depending on the vehicle segment).

The relative vehicle life cycle GHG emissions for different powertrain/fuel/energy combinations differ depending on the vehicle application, indicating that a one-size-fits-all approach would not be optimum for road transport decarbonisation, at least in the short to medium term. For example, the modelled fuel cell bus operating on hydrogen produced via electrolysis with grid electricity, offers GHG emissions savings compared to the standard diesel bus, whereas the fuel cell articulated truck with the same hydrogen supply shows increased GHG emissions compared to the standard diesel truck. This is because the bus has comparatively lower fuel consumption and mileage, combined with a longer vehicle life, allowing it to benefit from improvements in hydrogen production emissions as the electricity grid decarbonises over time.

A sensitivity analysis of key model parameters shows that the vehicle lifetime GHG emissions are most sensitive to the carbon intensity of the fuel/electricity supply pathway (feedstocks, production and distribution). Today, trucks using biomethane from manure feedstocks can result in 'negative' life cycle GHG emissions ('methane credits' recognise the capture of fugitive methane emissions, a highly potent GHG, that would ordinarily be released into the atmosphere).

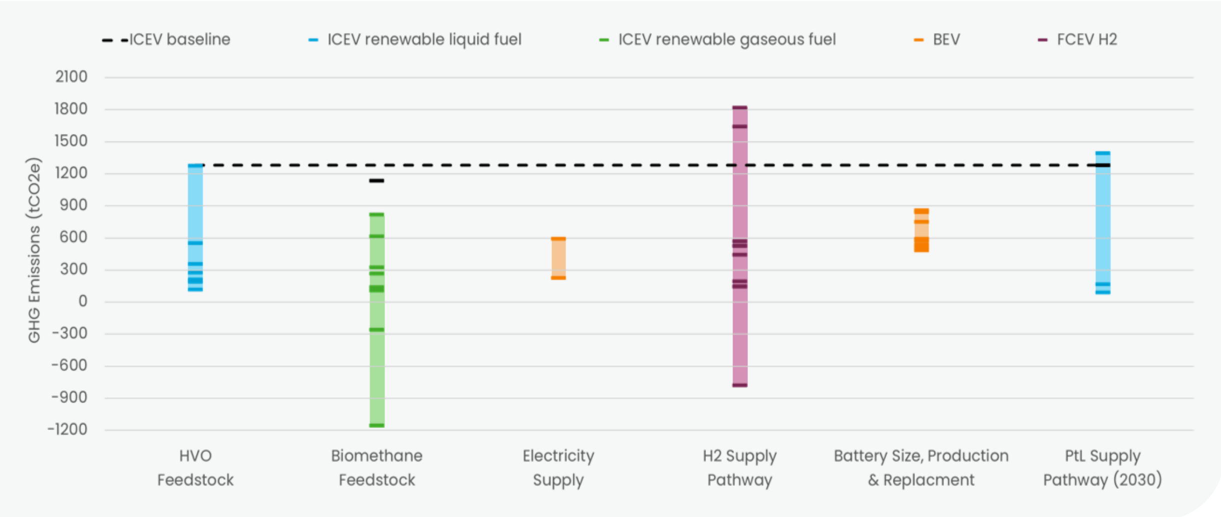


Figure 3. Parameters with the highest impact on articulated truck life cycle GHG emissions

For electric vehicles, characteristics of the battery (raw materials, production, size and number of replacements) also significantly impact lifetime GHG emissions. It is important to note that relatively small differences in emissions for a single vehicle can cumulate to significant fleet-wide emissions.

Key recommendations

Transport policy and legislation should be informed by vehicle life cycle GHG emissions data, rather than focused solely on mitigating tailpipe GHG emissions. This helps to avoid inadvertently increasing GHG emissions (e.g. by supporting 'zero emission' fuel cell vehicles without stipulating low carbon hydrogen) and facilitates a technology neutral approach to comparing decarbonisation options across different vehicle segments. This approach has additional benefits when combined with total cost of ownership and carbon abatement costs (the cost of an intervention to reduce GHG emissions). Wherever possible, life cycle emissions should be embedded into emerging Government policy.

Organisations developing their fleet decarbonisation strategy should consider vehicle life cycle emissions, rather than just the in-use or tailpipe emissions. Both low carbon fuels and zero (tailpipe) emission technologies should be considered before investing in new vehicles, as the relative savings are not always intuitive. By using low carbon fuels, it may be possible to achieve greater GHG emissions savings with the available budget. Low carbon fuels may also offer a faster route to reducing fleet GHG emissions in the near term. The economics and feasibility of particular powertrains for a given duty cycle and use case are also important[2].

Feedstocks and resources (for both low carbon fuels and electric vehicle batteries) should be allocated to maximise the overall GHG emissions abatement – Government needs to consider and monitor competing demands, and available decarbonisation solutions, across all sectors. Hopefully, this will be included within the Department for Transport's forthcoming Low Carbon Fuels Strategy. The supply and deployment of low carbon renewable fuels should be maximised, particularly in sectors that are more challenging to electrify in short to medium term, such as long haul HGVs.

[2] More information on renewable fuels can be found in The Renewable Fuels Guide and Appendix, 2023: https://www.zemo.org.uk/FuelsGuide2023

In the short to medium term, renewable fuels could make an absolutely vital contribution to GHG emissions abatement. However, for this to materialise, they need to be affordable and available. Zemo's previous study 'Decarbonising Heavy Duty Vehicles and Machinery'[1] showed that to significantly increase the uptake of higher blends of renewable diesel and biodiesel in the UK heavy-duty vehicle and non-road mobile machinery sectors, some policy changes are required. Firstly, the Renewable Transport Fuel Obligation (RTFO) targets will need to be increased, to ensure that there is an incentive to supply higher blends as the demand for diesel falls over time, due to increasing electrification. Secondly, a fiscal incentive, such as a reduction in fuel duty for renewable fuels, would help fleet operators with very tight financial margins make the switch to low carbon fuels, which are currently more expensive than diesel – either in terms of the cost per litre, or in terms of costs for modifying and maintaining the vehicles and fuelling infrastructure.

Companies purchasing renewable fuels and hydrogen in bulk should be aware of the very high sensitivity of vehicle life cycle GHG emissions to the fuel supply pathway, and scrutinise the information provided to them by potential suppliers. The GHG emissions savings and provenance of raw material feedstocks of renewable fuels from suppliers approved under the Renewable Fuels Assurance Scheme (RFAS)[3], are independently verified to give end users confidence and ensure they receive supply chain specific GHG emissions data.

For electric vehicles, the size and capacity of the batteries should be optimised for the vehicle use case wherever possible. Larger, heavier batteries may offer improved vehicle range, but they also result in higher GHG emissions during production, end-of-life and vehicle use. Furthermore, they may reduce the payload capacity of goods vehicles.

[3] Renewable Fuels Assurance Scheme: https://www.zemo.org.uk/RFAS

2. Acronyms & Abbreviations

AD	Anaerobic Digestion
ATR	Autothermal Reforming
AUS	Australia
B100	Pure biodiesel / FAME (waste biogenic feedstock)
B20, B30, etc.	20%, 30%, etc. biodiesel blended with fossil diesel
B7	Standard pump (retail) diesel, up to 7% biodiesel blended with fossil diesel
BE	Bioethanol
BEIS	Department for Business, Energy & Industrial Strategy, UK Government (now the Department for Energy Security and Net Zero)
BEV	Battery Electric Vehicle
BG	Biogasoline
BioSNG	Synthetic Natural Gas, from the gasification of biomass
BtG	Bioethanol to Gasoline, via dehydration and oligomerization
BtL	Biomass to Liquid, synthetic liquid fuel made from methane or syngas using the Fischer Tropsch process
BtL3	3% BtL blended with other fossil and renewable components
C	Carbon
CBG	Compressed Biomethane Gas, methane derived from biomass, either via anaerobic digestion (in a dedicated plant, sewage treatment works or landfill) or via gasification

cc	Cubic centimetres
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CO_2	Carbon dioxide
CNG	Compressed Natural Gas
DD	Double Decker bus
DESNZ	Department for Energy Security and Net Zero, UK Government (formerly the Department for Business, Energy & Industrial Strategy)
DfT	Department for Transport, UK Government
E5, E10	5%, 10% bioethanol blended with fossil gasoline, both available at standard refuelling pumps since 2021
e-fuel	A fuel produced using renewable electricity and sources of carbon, also known as PtL
FAME	Fatty Acid Methyl Esters
FCEV	Fuel Cell Electric Vehicle, fuelled with hydrogen
FT	Fischer Tropsch, chemical reactions that convert a mixture of carbon monoxide and hydrogen into liquid hydrocarbons
GHG	Greenhouse Gas
grid-e	UK grid electricity
GWP	Global Warming Potential
H_2	Hydrogen
HEV	Hybrid Electric Vehicle
HGV	Heavy Goods Vehicle

HT	Hydrotreatment
HVO	Hydrotreated Vegetable Oil, a type of renewable diesel
ICEV	Internal Combustion Engine Vehicle
ILUC	Indirect Land Use Change
JEC	Consortium made up of the European Commission's Joint Research Centre, EUCAR and Concawe
LCA	Life Cycle Assessment
LCF	Low Carbon Fuels, fuels that offer GHG savings compared to fossil fuels on a life cycle basis
LNG	Liquefied Natural Gas
MAR	Morocco
Mt	Million tonnes (metric)
MTBE	Methyl Tertiary Butyl Ether, a common additive to petrol
MtG	Methanol to Gasoline
PHEV	Plug-in Hybrid Electric Vehicle
PtL	Power to Liquid, a fuel produced using renewable electricity and sources of carbon, also known as e-fuel
RD	Renewable diesel, a paraffinic diesel made from renewable sources
RDF	Refuse Derived Fuel (biomass fraction)
RED II	Renewable Energy Directive II, a legal framework for the development of renewable energy across all sectors of the EU
renew-e	Renewable electricity
RFAS	Renewable Fuels Assurance Scheme, managed by Zemo Partnership

RFNBO	Renewable Fuels of Non-Biological Origin (includes hydrogen)
RTFO	Renewable Transport Fuel Obligation, UK Government's low carbon fuel policy for reducing GHG emissions from road transport
SD	Single Decker bus
SMR	Steam Methane Reformation
tCO_2e	Metric tonnes of CO_2 equivalent, unit of measurement for GHG emissions which also includes other GHGs such as N_2O and CH_4
tCO_2e/tkm	Metric tonnes of CO_2 equivalent per tonne transported over a distance of one kilometre
TTW	Tank-to-Wheel. TTW emissions are generated when driving the vehicle. For renewable fuels, TTW emissions are not the same as the emissions measured from the vehicle tailpipe. This is because the CO_2 emissions from combustion are offset by the CO_2 absorbed by the biomass feedstock during growth. Where biomethane is produced from biogenic waste feedstock comprising of manure, fugitive emissions of methane are prevented and a methane credit can be applied (as per RED II), resulting in a negative carbon intensity value
UCO	Used Cooking Oil
WTT	Well-to-Tank. WTT emissions are generated from fuel or electricity production, from the primary energy source to the point of dispensing or charging
WTW	Well-to-Wheel. WTW emissions are all the emissions generated by a vehicle in-use. This is the sum of the WTT and TTW emissions. This differs from the vehicle life cycle emissions which also include vehicle production and disposal/recycling at end-of-life
ZEV	Zero Emission Vehicle, zero emissions at the point of use

3. Introduction

The aim of this study is to demonstrate the complementary role that renewable fuels play alongside zero tailpipe emission technologies in delivering GHG emissions savings. With this in mind, Zemo's in-house vehicle life cycle GHG emissions tool has been used to model a range of vehicle segments, powertrains and fuel/energy pathways. The modelling is based on vehicle models currently on the market and considers renewable fuel pathways available in the UK today, along with some more advanced fuel pathways that have commercialisation potential over the next decade.

Scope

This study is focused purely on GHG emissions within the vehicle life cycle boundary shown in **Figure 4**. The model includes GHG emissions arising from vehicle production, fuel/energy production (Well-to-Tank, WTT), fuel/energy use (Tank-to-Wheel, TTW) and vehicle end-of-life. The model does not account for refuelling and charging infrastructure, or maintenance.

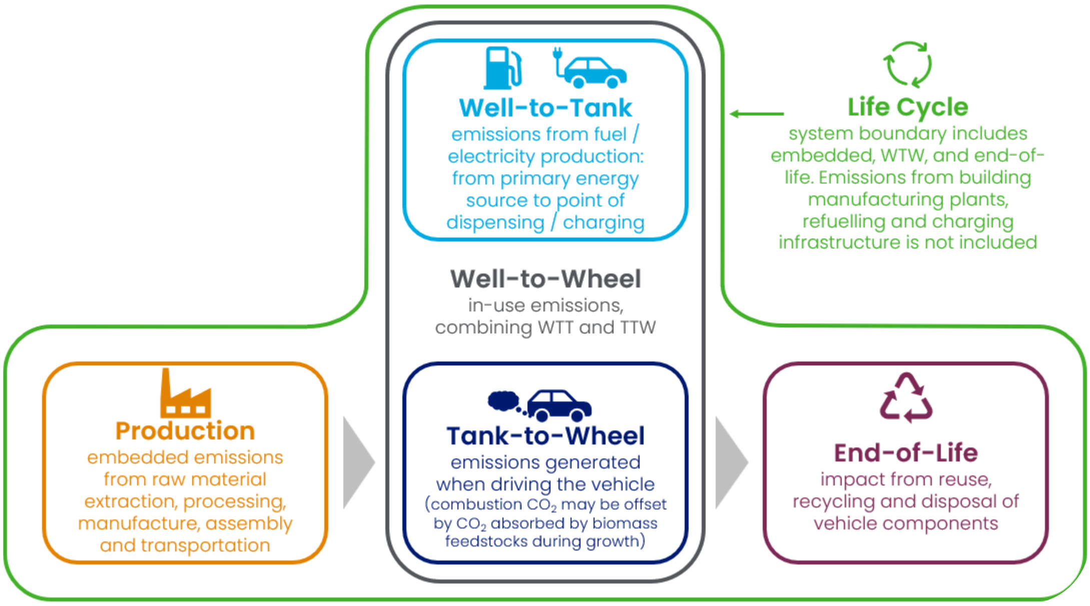


Figure 4. Vehicle life cycle system boundary

The WTT emissions factors for renewable fuel pathways include the cultivation of raw materials or collection of the organic waste/residue, fuel production, distribution, storage and dispensing.

Currently, there is significant uncertainty around the GHG impact of recycling and disposing of battery electric vehicle (BEV) batteries. Neither battery recycling credits nor battery second life have been considered in this study.

Cost of ownership, energy consumption, material and feedstock availability, air quality, and other environmental and health impacts are not within the scope of this study.

4. Modelling Approach

The vehicle life cycle modelling was carried out in 3 phases as shown in **Figure 5**.

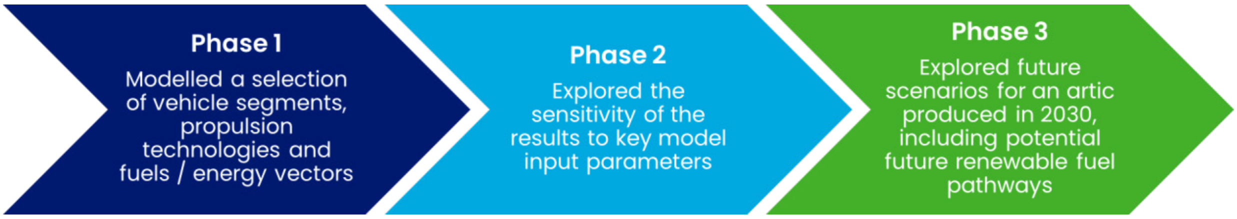


Figure 5. Phases of vehicle life cycle GHG emissions modelling

The vehicle segments, propulsion technologies and fuel/energy vectors modelled in Phase 1 are shown in **Table 1.** Zemo have focused on modelling the most relevant powertrain and fuel/energy pathway combinations for each vehicle segment (other combinations are possible but outside of the scope of this study). The renewable fuels selected are representative of feasible UK supply chains (e.g. high blend biodiesel from waste based feedstocks used in heavy-duty goods vehicles). Examples of low carbon fuel supply chains, covering fuel production, distribution and dispensing, can be found in the Appendix.

Vehicle segments	Propulsion technologies	Fuel/energy vectors
650cc motorcycle (L3) Medium passenger car (M1) Small rigid truck (N2) Medium rigid truck (N3) Articulated truck (N3) Single decker bus (M3) Double decker bus (M3)	ICEV (internal combustion engine) HEV (hybrid) PHEV (plug-in hybrid) BEV (battery electric) FCEV (hydrogen fuel cell)	Diesel: pump (retail B7), biodiesel, renewable, biosynthetic (BtL), renewable synthetic (PtL, e-fuel) Gasoline: pump (retail E5 and E10), bioethanol, biosynthetic (BtG, BtL) Gas: CNG, biomethane[4] (CBG), biosyngas (BioSNG) Hydrogen: various supply pathways Electricity: UK grid and renewable

Table 1. Phase 1 scenarios

[4] Biomethane can also be supplied as a liquid for use in LNG vehicles (not modelled in this study)

Input data

	ICEV	BEV	FCEV
Vehicle parameters	Zemo life cycle model and members' feedback (see Appendix for vehicle operational parameters)		
WTT and TTW GHG emissions factors	DESNZ (formerly BEIS) Company Reporting 2022[5] RTFO Statistics 2021 (final) and 2022 (2nd provisional)[6] JEC Well-To-Wheels v5 2020[7] Industry sourced	DESNZ Company Reporting 2022 and DESNZ Green Book Grid Average[8] Consumption Commercial/Public Sector values 2021 + a 25% uplift for WTT emissions (see Appendix for more details) (TTW GHG are zero)	Zemo WTT model[9] E4Tech/DESNZ hydrogen import chains report 2022[10] (TTW GHG are zero)
Battery carbon intensity	-	Minviro/T&E solid state and lithium-ion battery LCA report 2022[11]	-

Table 2. Model input data sources

All vehicles are assumed to be produced in Europe and operated in the UK. Vehicle fuel/electricity consumption is highly dependent on driving style, vehicle speed, vehicle payload, climate and so on. Wherever possible, consumption values for consistent drive cycles or driving conditions have been used for the vehicles powered by different energy vectors within a particular vehicle segment. Vehicle fuel/energy consumption was further explored during the sensitivity analysis in Phase 2.

5 DESNZ company reporting: https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2022
6 RTFO renewable fuel statistics: https://www.gov.uk/government/collections/renewable-fuel-statistics
7 JEC Well-to-Tank report v5: https://publications.jrc.ec.europa.eu/repository/handle/JRC119036
8 Green Book supplementary guidance: https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal
9 Zemo low carbon hydrogen WTT pathways study: https://www.zemo.org.uk/work-with-us/fuels/projects/examining-hydrogen-production-pathways-and-use-in-vehicles.htm. Hydrogen pathway WTT GHG emissions model includes production, distribution, dispense and fugitive emissions.
10 E4Tech/DESNZ hydrogen import chains report: https://www.gov.uk/government/publications/expansion-of-hydrogen-production-pathways-analysis-import-chains
11 Minviro/T&E battery LCA report: https://www.transportenvironment.org/wp-content/uploads/2022/07/2022_07_LCA_research_by_Minviro.pdf

5. Results & Commentary

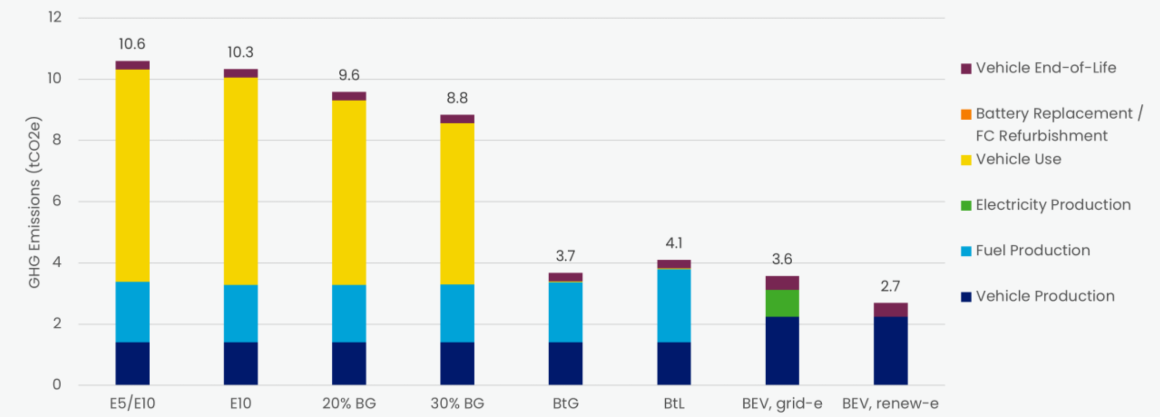
The modelled results presented in this section show the life cycle GHG emissions of ICE vehicles fuelled by a range of renewable fuels, along with conventional fuels, BEVs and FCEVs for comparison.

As mentioned in Section 3, this study is focused on vehicle life cycle GHG emissions. It is important to bear in mind that the results alone cannot be used to categorically select an optimum vehicle propulsion technology or fuel/energy vector for a given application. Firstly, due to time constraints, it has only been possible to model a selection of vehicle types, use cases and potential propulsion technologies. Secondly, there are many other factors that need consideration, which include, but are not limited to, the following:

- The feasibility of particular powertrains for a given duty cycle and use case (e.g. vehicle range and charging/refuelling time, vehicle payload and packaging constraints for on-board hydrogen storage).
- Vehicle availability and affordability (including the second-hand vehicle market and the availability of rare materials e.g. for battery manufacture).
- Fuel/energy availability and security (including the availability of feedstocks, fuel supplies and ease of access to refuelling/recharging infrastructure).
- The energy demand required to generate the fuel/energy vector.
- The cost of ownership (including fuel price and fiscal incentives, e.g. Bus Service Operators Grants).
- Operational requirements (e.g. maintenance schedule, warranty considerations and staff training).
- Organisations' decarbonisation and sustainability targets and policies (including procurement policies requiring contractors to reduce emissions).
- Developments in battery recycling and reuse.
- Other environmental and social impacts (including air quality and potential impacts of low emissions zones around cities).

Phase 1 – Vehicle scenarios

Motorcycle



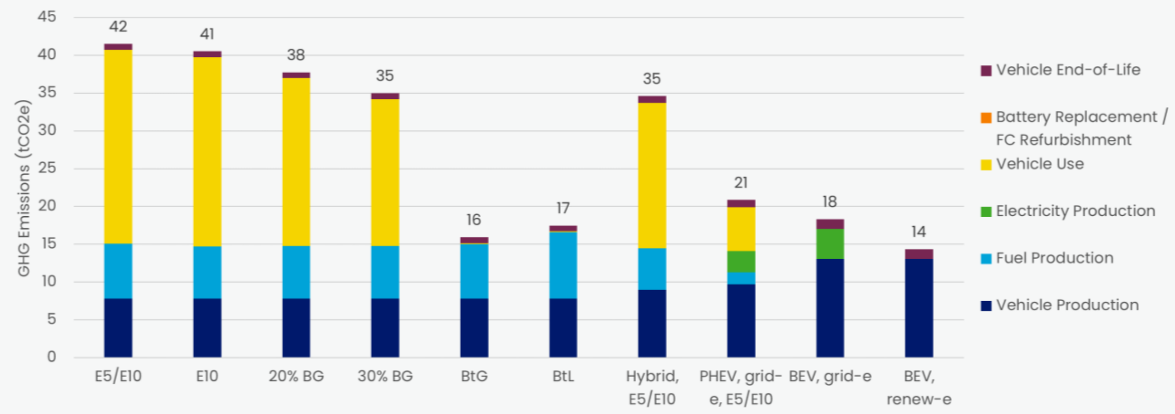
Note: 20% BG (biogasoline) is a blend of E10 and 10% BtG, similarly 30% BG is a blend of E10 and 20% BtG.

Figure 6. Total life cycle GHG emissions for 650cc motorcycle

The results show that the BEV offers the lowest life cycle GHG emissions for this scenario, despite higher emissions from vehicle production. The bio synthetic gasoline fuels (BtG and BtL) are at the early stages of market entry, with immediate opportunities in the motorsport sector. They offer significant savings compared to regular petrol and have the added advantage of being compatible with existing ICE vehicles.

Note that some renewable fuels have very low 'vehicle use' TTW emissions (shown in yellow in **Figure 6** and subsequent figures) because the CO_2 from combustion, measured at the tailpipe, is 'offset' by CO_2 absorbed during plant growth.

Passenger car



Note: 20% BG (biogasoline) is a blend of E10 and 10% BtG, similarly 30% BG is a blend of E10 and 20% BtG.

Figure 7. Total life cycle GHG emissions for medium sized (C-segment) passenger car

For this scenario, the bio synthetic gasoline fuels (BtG and BtL) offer slightly lower life cycle GHG emissions than the BEV using grid electricity. The hybrid vehicles also offer GHG savings compared to using pump petrol. Compared to the BEV, the PHEV has significantly lower embedded emissions from vehicle production – this means that for very low mileage applications, a PHEV can result in lower overall GHG emissions.

While the GHG savings from 20% and 30% biogasoline are not as great as the BEVs and bio synthetic fuels, the huge numbers of light-duty petrol vehicles in the UK vehicle parc means the savings would be substantial if these fuels replaced E10 petrol at refuelling stations. The additional cumulative savings (compared to using E10) from gradually increasing the bio content percentage in petrol to 20% (10% bioethanol plus 10% biogasoline) could reach around 26 $MtCO_2e$ by 2030.

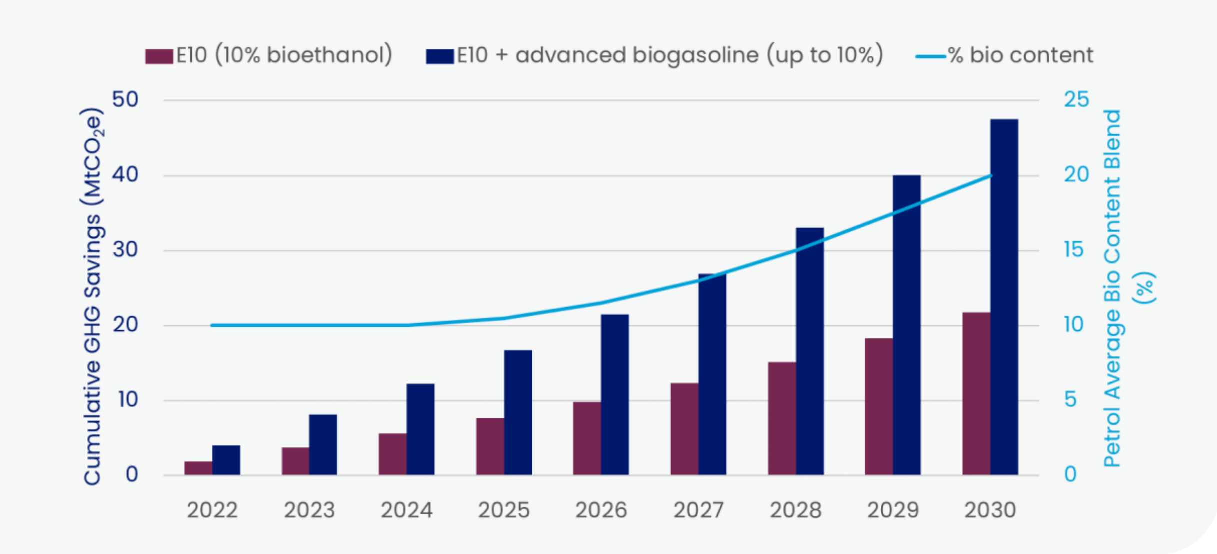


Figure 8. Modelled cumulative GHG emissions savings with increasing bio content in petrol

Note: increasing the amount of ethanol in petrol to more than 10% (E10) would necessitate updates in fuel supply infrastructure and vehicle engines – this is referred to as the 'blend wall'. However, by using BtG, it is possible to increase the % of renewable content without changing existing infrastructure and vehicles.

Rigid truck

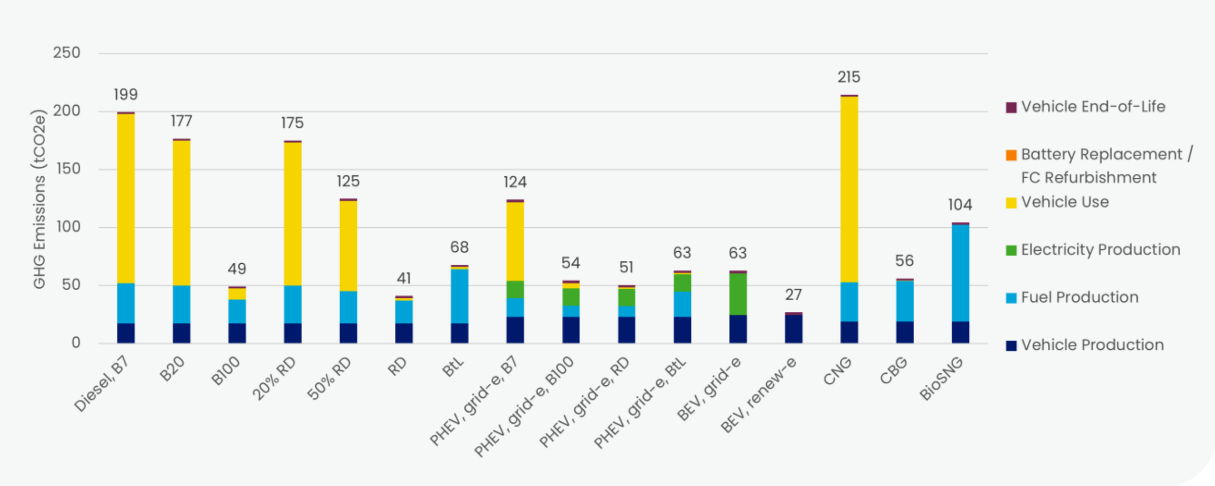


Figure 9. Total life cycle GHG emissions for small rigid truck (7.5 tonne)

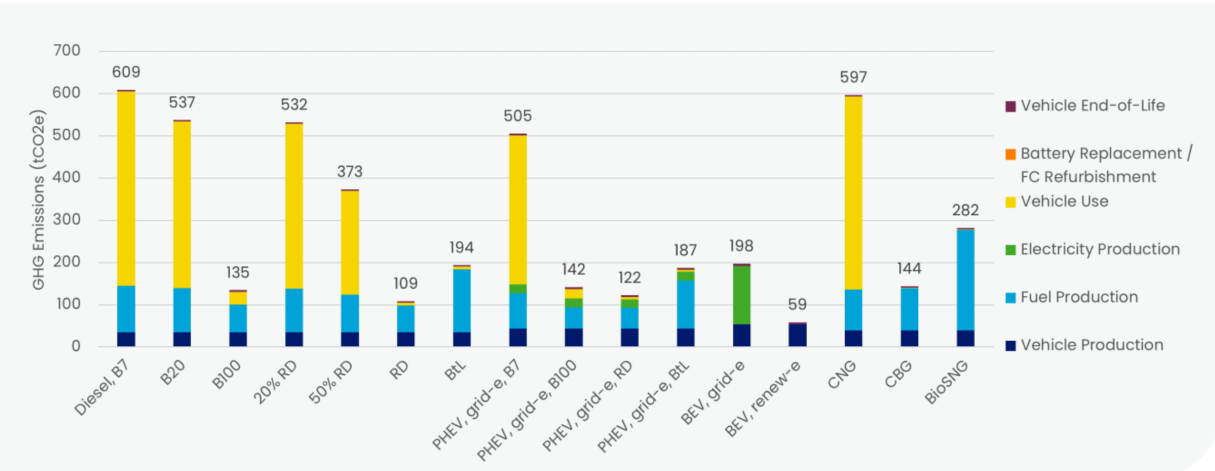


Figure 10. Total life cycle GHG emissions for medium rigid truck (12-32 tonne)

The small and medium rigid truck scenarios show similar trends. In both cases, 100% renewable diesel (RD) and biodiesel (B100) offer significant GHG savings, with lower life cycle GHG emissions than the BEV using grid electricity. The PHEV offers GHG savings compared to a conventional diesel truck when using B7 pump diesel and further GHG emissions savings if using RD or B100. However, when fuelled with RD or B100, the PHEV actually has higher GHG emissions savings than a conventional vehicle using the same fuel. Gas trucks using compressed biomethane (CBG) also show significant GHG savings.

Articulated truck

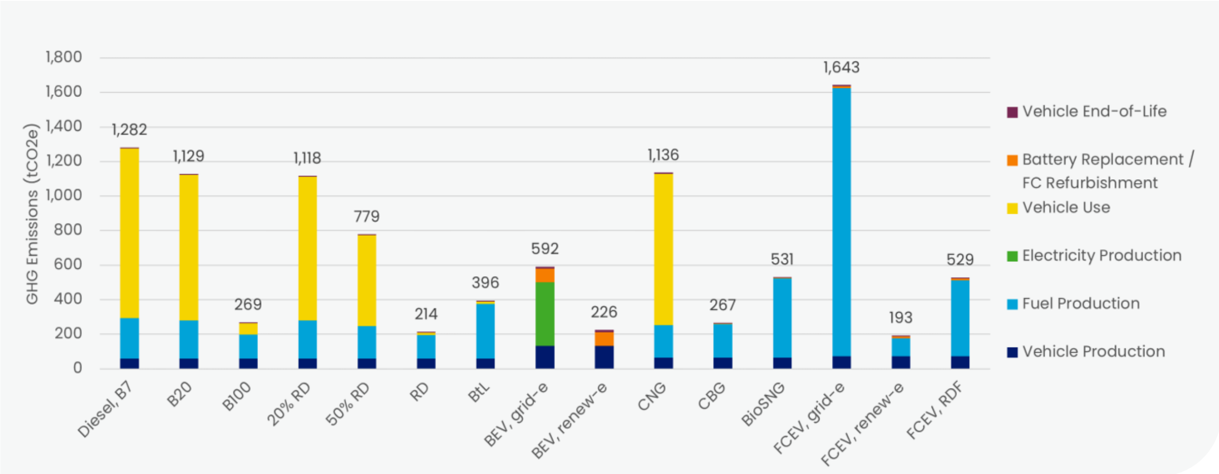


Figure 11. Total life cycle GHG emissions for articulated truck (30-44 tonne)

Given the high lifetime mileage of the articulated truck, it is assumed necessary for the BEV and FCEV battery to be replaced and the fuel cell to be refurbished part way through the vehicle life.

The results show that the FCEV using hydrogen, produced via electrolysis with renewable electricity, offers the lowest life cycle GHG emissions. However, the FCEV results are highly dependent on the source of hydrogen. The FCEV using hydrogen produced via electrolysis with grid electricity produces higher GHG emissions than the standard diesel vehicle. Currently, most commercial hydrogen is produced via Steam Methane Reformation of natural gas. Vehicle life cycle GHG emissions for this and other hydrogen supply pathways were modelled as part of the sensitivity analysis and are shown in **Figure 19**.

The 100% RD, B100, CBG and synthetic fuels (BtL and BioSNG) all offer significant GHG savings compared to the conventional diesel truck, with lower life cycle GHG emissions than the BEV using grid electricity.

While the GHG savings for B20 and 20% RD appear quite modest, these can still make a significant contribution to GHG abatement in the HGV sector, particularly in the short to medium term. A mix of blends across different fleet operators (with some operators using 100% and others using blends such as B20) is considered more likely than a significant increase in the renewable content in pump diesel.

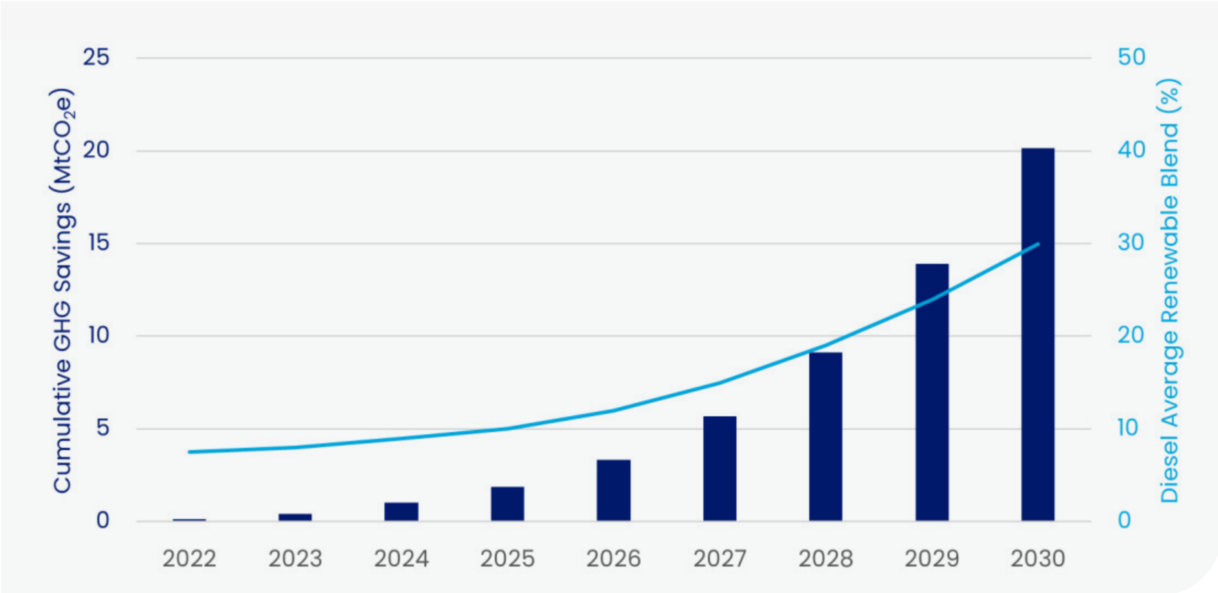


Figure 12. Modelled cumulative GHG emissions savings with increasing average renewable fuel content across the HGV fleet

The propulsion technology chosen can affect an HGVs payload (the mass of goods that can be transported). Even with an additional two tonne allowance in gross vehicle weight limit for certain zero (tailpipe) emission vehicles[12], BEVs may still have a reduced maximum payload compared to a conventional vehicle. **Figure 13** shows that the results in tCO_2e per tonne-kilometre follow broadly similar trends to those in tCO_2e, as shown in **Figure 11**.

[12] https://www.gov.uk/government/speeches/the-road-vehicles-authorised-weight-amendment-regulations-2023

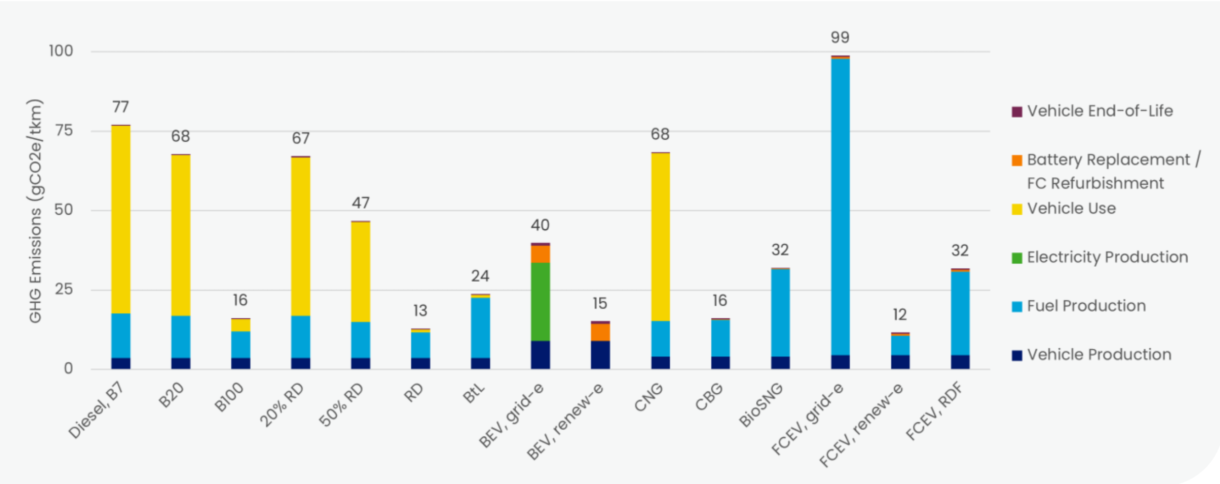


Figure 13. Total life cycle GHG emissions per tonne-km for articulated truck (30-44 tonne)

Bus

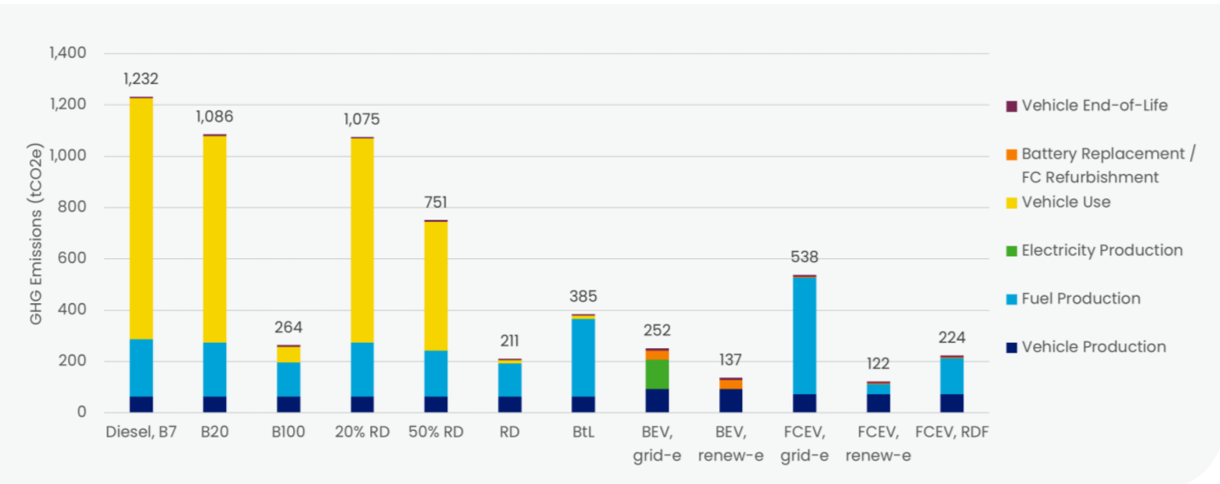


Figure 14. Total life cycle GHG emissions for single decker bus

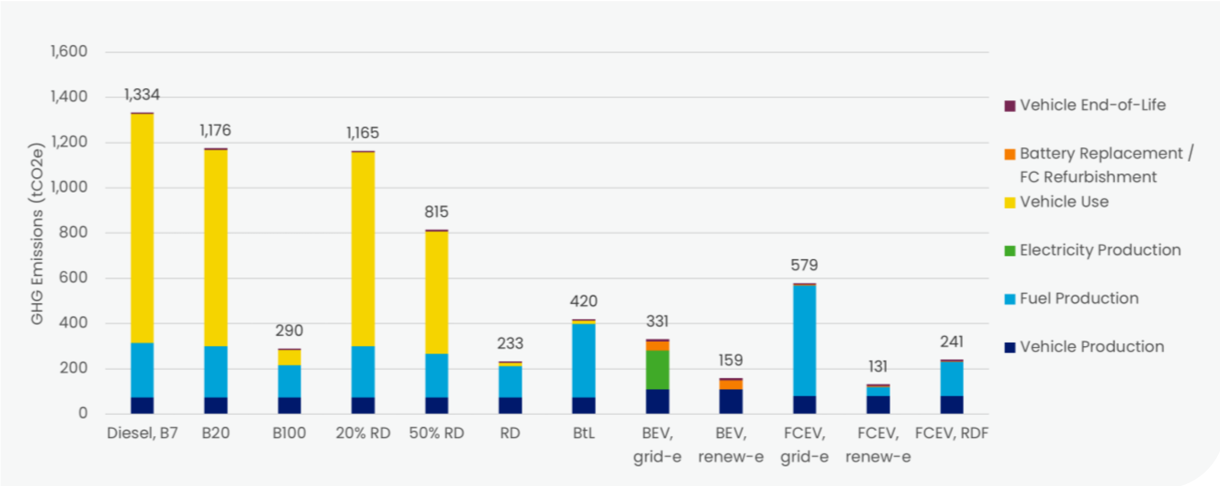


Figure 15. Total life cycle GHG emissions for double decker bus

The single and double decker bus scenarios show similar trends. The FCEV using hydrogen produced via electrolysis with renewable electricity offers the lowest life cycle GHG emissions for these scenarios. Unlike the articulated truck, the bus FCEV using hydrogen produced via electrolysis with grid electricity produces lower GHG emissions than the standard diesel vehicle. Compared to the articulated truck, the bus has lower consumption, lower lifetime mileage and a longer vehicle life, hence the average hydrogen WTT emissions factor is lower, as the electricity grid is forecast to decarbonise over time.

The BEV using renewable electricity offers the second lowest GHG emissions. It is worth noting that on a WTW basis, the BEV is more energy efficient than the FCEV; it requires less electricity to power a BEV than produce the hydrogen required for the FCEV.

100% RD, B100 and BtL also offer significant GHG savings compared to the conventional diesel truck, with RD and B100 showing lower or similar life cycle GHG emissions to the BEV using grid electricity.

For some use cases, it may not be possible to make a direct replacement of an existing diesel vehicle with a BEV, due to the downtime needed for recharging. For example, additional vehicles might be required in a fleet of buses to allow sufficient time for charging between use. In this scenario, the GHG savings from a fleet of BEVs may be less than anticipated. **Figure 16** shows that on a fleet basis, if 20% more buses were required to accommodate for BEV charging downtime, B100 could potentially offer greater GHG savings than a fleet of single decker BEVs, while RD offers even greater savings.

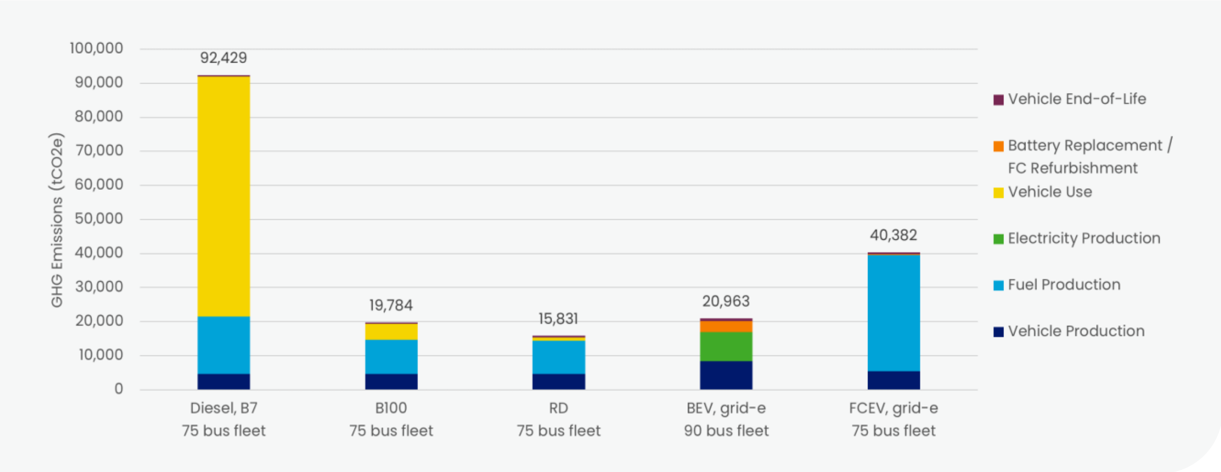


Figure 16. Total life cycle GHG emissions for a fleet of single decker buses

Bus operators may need to consider adopting a range of technologies and vehicle types within their fleet according to their routes. For example, a BEV might be optimal for city operation, while an ICEV using renewable low carbon fuels might be optimal for rural routes.

Phase 2 – Sensitivity analysis

Summary of key sensitivities

For the most part, the sensitivity analysis used the articulated truck (artic) model. **Table 3** provides a summary of the key sensitivities explored. Lifetime GHG emissions were found to be most sensitive to the carbon intensity of the fuel/electricity supply pathway (feedstocks, production and distribution). For the BEV, the battery characteristics (raw materials, production, size and number of replacements) also has a significant impact on the lifetime GHG emissions. However, it is important to note that relatively small differences in emissions for a single vehicle become highly significant when considering the entire UK vehicle fleet.

Sensitivity to...	Impact
Renewable diesel (HVO) feedstocks	High
Biomethane feedstocks	High
Hydrogen supply pathway	High
Electricity supply	Medium-High
BEV mileage profile	Medium
BEV battery size	Medium-High
BEV battery replacement	Medium-High
BEV battery pack carbon intensity	Medium-High
FCEV fuel cell refurbishment/replacement	Low
Hydrogen global warming potential (GWP)	Medium-Low
Fuel production	Medium-Low
Vehicle production location (EU or UK)	Low
Fuel consumption	Medium-High
Electricity consumption	Medium
PtL supply pathway (2030 onwards)	High
Vehicle production (2030)	Medium-Low

Table 3. Sensitivity of total life cycle GHG emissions to key input parameters

Renewable diesel feedstocks

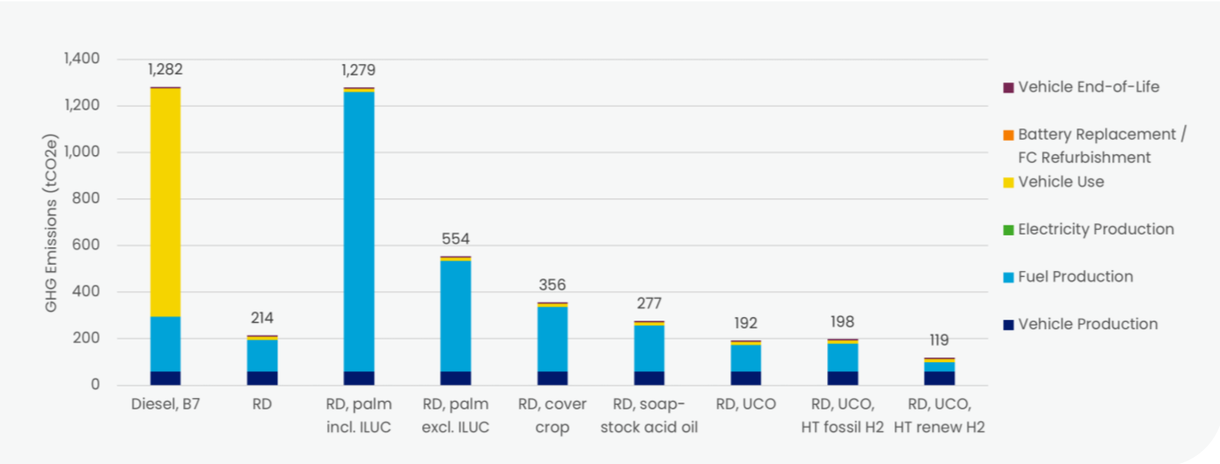


Figure 17. Impact of renewable diesel feedstock on artic total life cycle GHG emissions

The results show that the renewable diesel feedstock has a considerable impact on the vehicle life cycle GHG emissions. If renewable diesel (in this case HVO) is produced using palm oil and the indirect land use change (ILUC)[13] factor is included, the renewable diesel offers no significant GHG savings compared to pump diesel. This is an extreme case and it is worth noting that the 2021 RTFO statistics[14] showed that no HVO supplied in the UK was produced using palm oil as a feedstock. The HVO from other feedstocks all offer significant GHG savings, although some will be less than the savings from other scenarios such as B100.

Zemo recommends purchasing renewable fuels from renewable fuel suppliers approved under the Renewable Fuels Assurance Scheme (RFAS)[15], which independently verifies the GHG emissions savings and provenance of raw material feedstocks of renewable fuels supplied in the UK.

[13] To address ILUC, the RTFO includes additional rewards for waste feedstocks, a development fuel target, and a crop cap to limit the max contribution from crop-derived biofuels - biofuels from dedicated energy crops do not count towards the crop cap or the development fuel target.

[14] RTFO statistics: https://www.gov.uk/government/statistics/renewable-fuel-statistics-2021-final-report

[15] Renewable Fuels Assurance Scheme: https://www.zemo.org.uk/RFAS

Biomethane feedstocks

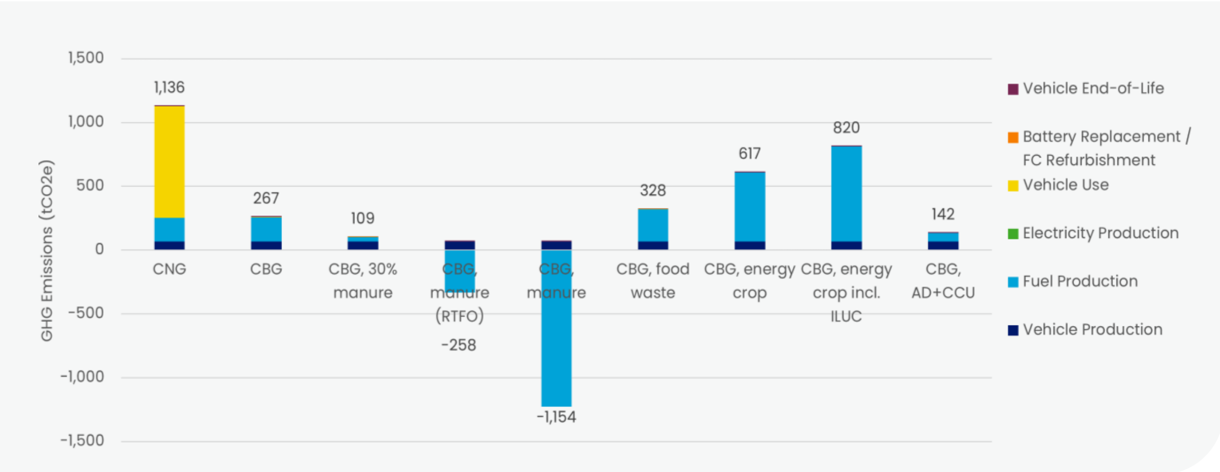


Figure 18. Impact of biomethane feedstock on artic total life cycle GHG emissions

The vehicle life cycle GHG emissions are even more sensitive to biomethane feedstocks than HVO feedstocks. All the CBG scenarios modelled offer significant savings compared to fossil fuels (CNG and B7). Biomethane produced using manure feedstocks enables negative GHG emissions over the vehicle's lifetime due to the methane captured. Manure slurry from farms generates fugitive methane, which is a more potent GHG than CO_2. Under RED II it is possible to apply a methane credit, resulting in negative GHG emissions. Using this feedstock also provides benefits to local economies and supports decarbonisation in the agricultural sector. While this source of biomethane should obviously be encouraged and used in applications that maximise carbon abatement, the supplies of CBG from manure feedstocks are limited and will not be sufficient for the entire vehicle fleet.

While it is likely to be more efficient to use biomethane as compressed gas in CNG vehicles or as liquid in LNG vehicles, it can also be used as a component in renewable liquid fuels (biomethanol, MtG) and as a fuel additive (MTBE).

Hydrogen supply pathway

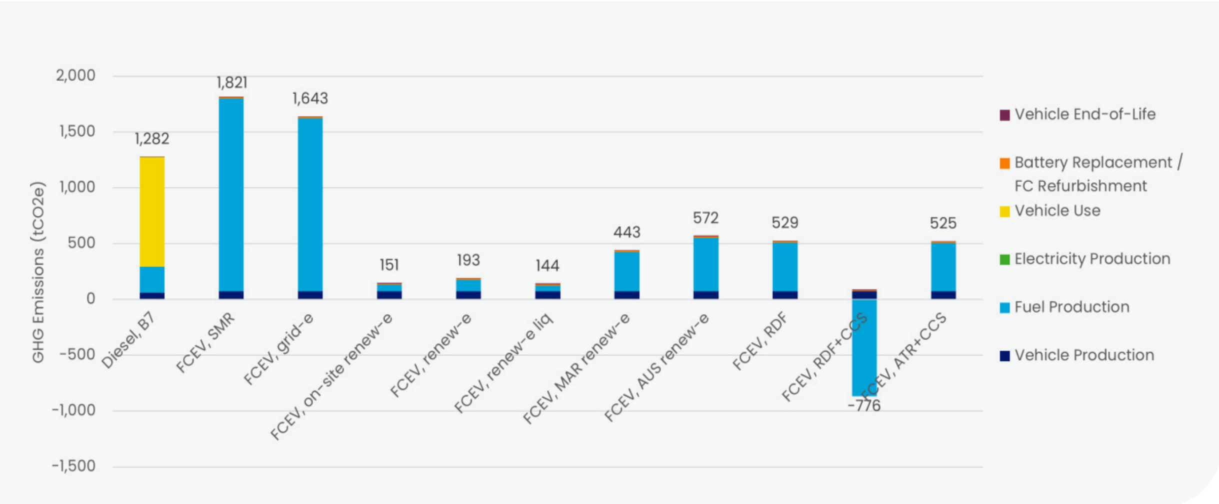


Figure 19. Impact of hydrogen supply pathway on artic total life cycle GHG emissions

The results show that the source of hydrogen also has a considerable impact on the vehicle life cycle GHG emissions. Hydrogen produced from Steam Methane Reformation (SMR) of natural gas, or via electrolysis using UK grid electricity (which currently uses significant volumes of natural gas), results in a significant increase in GHG emissions compared to the baseline ICEV with B7 diesel. Hydrogen produced via electrolysis using renewable electricity, or from the gasification of Refuse Derived Fuel (RDF), offers vehicle life cycle GHG emissions savings compared to conventional diesel.

When commercialised, carbon capture and storage (CCS) may be able to provide further reductions in emissions, with the potential for RDF plants to become carbon negative due to the credit for the biogenic carbon captured.

Several scenarios for hydrogen produced via electrolysis using renewable electricity have been presented, to give an idea of the impact of transporting hydrogen. For the on-site production scenario, the hydrogen is compressed at the refuelling station prior to dispensing using grid electricity. Hydrogen produced from off-site renewable electricity and transported as compressed gas in a tube trailer (within the UK) has slightly higher GHG emissions. Hydrogen produced from off-site renewable electricity and transported as liquid hydrogen in a tanker (within the UK) results in lower emissions than compressed hydrogen due to the increased volume per truck (in the scenario modelled, the liquefaction process uses renewable electricity - if this used grid electricity, the reverse would be true).

The imported hydrogen, produced from renewable electricity in Morocco or Australia and then transported as ammonia, highlights the significant impact that transportation can have on the overall GHG emissions.

Zemo's 'Hydrogen Vehicle WTW GHG and Energy Study' report[16] highlighted the importance of considering GHG emissions and energy consumption together to deliver an efficient net zero energy and transport system. The main drawback with hydrogen FCEVs, is that irrespective of the supply pathway, the hydrogen production process is energy intensive compared to electricity and some renewable fuels. The report showed the WTW energy efficiency of a BEV truck to be four to six times better than the FCEV, depending on the low carbon hydrogen supply chain pathway.

Note that to be eligible under the RTFO[17], hydrogen and other renewable fuels of non-biological origin (RFNBO) must be produced using 'additional' renewable electricity: i.e. renewable electricity that would not have been produced, or would have been wasted, if not consumed by the RFNBO production site.

It is also worth noting that there is huge existing and future demand for hydrogen from other sectors (e.g. oil refining, ammonia production, steel production) that also require decarbonisation, therefore the availability of renewable hydrogen for the transport sector may be limited.

[16] Hydrogen Vehicle WTW GHG and Energy Study, 2021: https://www.zemo.org.uk/work-with-us/fuels/projects/examining-hydrogen-production-pathways-and-use-in-vehicles.htm

[17] RTFO Guidance: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1164946/rtfo-guidance-for-renewable-fuels-of-non-biological-origin.pdf

Electricity supply

The Phase 1 results for BEVs using UK grid and renewable electricity show the significant impact of the electricity supply on the vehicle life cycle GHG emissions. Of the scenarios modelled, BEVs using renewable electricity offer some of the lowest life cycle GHG emissions. However, where the BEVs entering service today are relying on UK grid electricity, there are lower carbon alternatives amongst renewable fuels.

The results for BEVs using UK grid electricity (and FCEVs using hydrogen via electrolysis with grid electricity) are highly dependent on the forecasted UK grid decarbonisation. The electricity grid is expected to become less carbon intensive year on year (as shown in **Figure 32** in the Appendix). Hence the mileage profile for a BEV would have an impact on the total life cycle GHG emissions. The phase 1 modelling assumes a consistent annual mileage throughout the vehicle's lifetime. However, it is common for vehicles to have higher annual mileage when new and lower mileage as they get older.

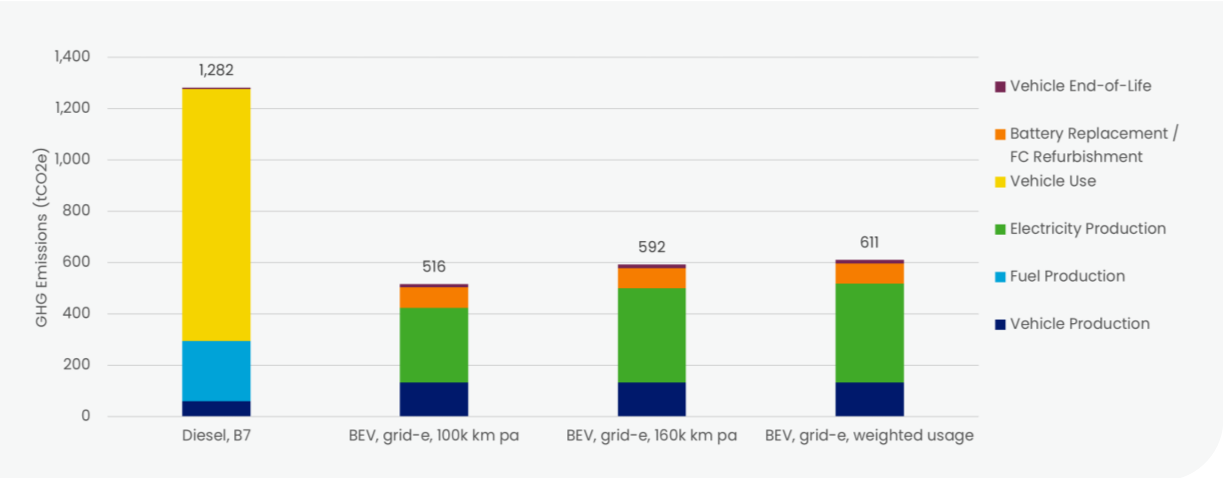


Figure 20. Impact of BEV mileage profile on artic total life cycle GHG emissions

Figure 20 shows three scenarios, all with the same total lifetime mileage. The first BEV truck has an annual mileage of 100,000 km with a 12.8 year vehicle life, the second has an annual mileage of 160,000 km and an 8 year life, and the third assumes a linear reduction in annual mileage throughout the 8 year vehicle life (30% higher than average in the first year and 30% lower than average in the last year). The life cycle GHG emissions savings are highest for the vehicle operating over a longer period due to grid decarbonisation over time.

BEV

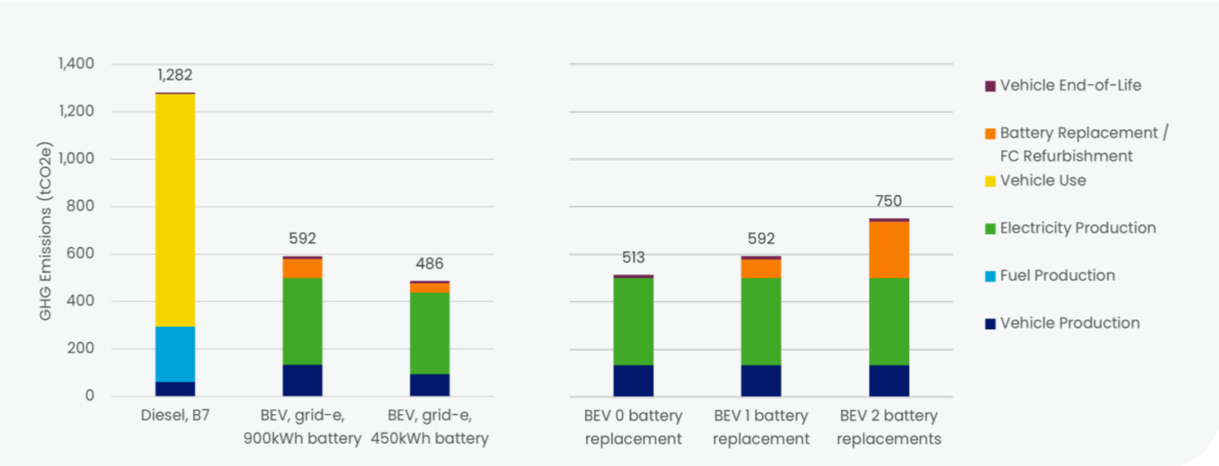


Figure 21. Impact of battery sizing and replacement on artic total life cycle GHG emissions

The sensitivity of vehicle life cycle GHG emissions to battery capacity/size and the frequency of battery replacements was investigated. The 900 kWh battery scenario represents a truck with depot-based charging, while the 450 kWh battery scenario assumes a combination of depot and public fast charging. The results show that while the relative 'rankings' of the comparator fuels and technologies do not change that much, both parameters have a significant impact on vehicle life cycle GHG emissions. To minimise GHG emissions, the battery should be sized for the vehicle use case wherever possible.

Advances in battery technology may reduce BEV life cycle GHG emissions for future vehicles. However, it is worth noting that previous improvements have not always resulted in lower GHG emissions; improvements in energy density have generally led to extended vehicle range and battery life, rather than smaller battery packs.

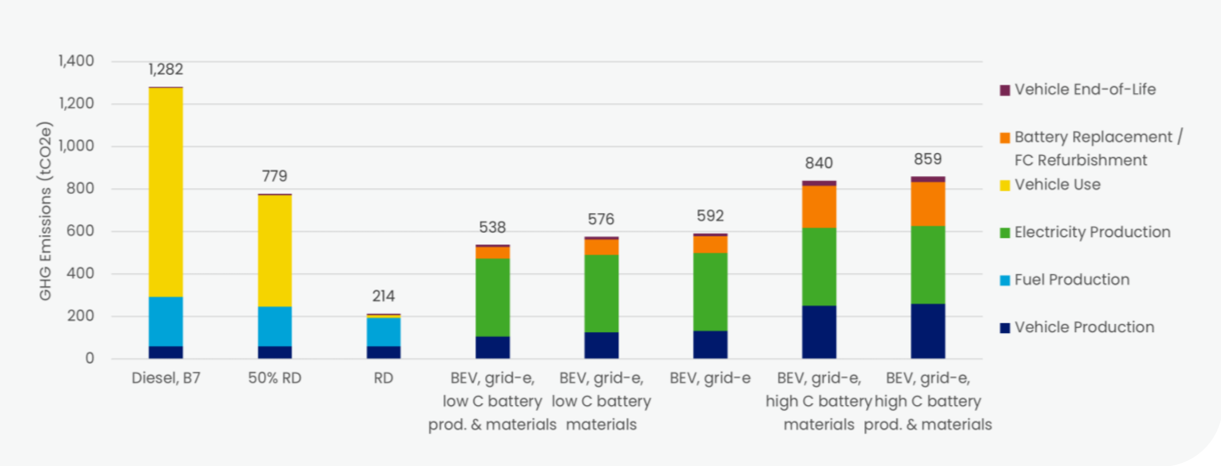


Figure 22. Impact of battery carbon intensity on artic total life cycle GHG emissions

Figure 22 shows that the carbon intensity of the battery itself, both in terms of raw materials and manufacture, also has a significant impact on GHG emissions. Sourcing materials with a lower carbon footprint is expected to have more of an impact than the location of production.

FCEV

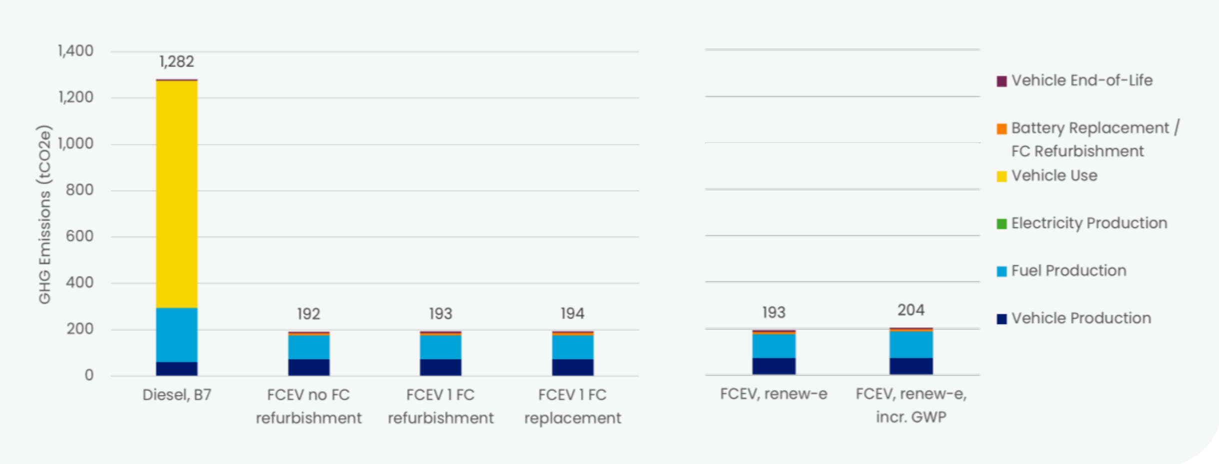


Figure 23. Impact of fuel cell refurbishment/replacement and hydrogen GWP on artic total life cycle GHG emissions

The results show that vehicle life cycle GHG emissions are less sensitive to the frequency of fuel cell refurbishments/replacements. The three scenarios modelled all include one battery replacement (the FCEV battery is significantly smaller than that of the BEV, hence the reduced impact on GHG emissions compared to **Figure 21**).

There is uncertainty around the global warming potential (GWP) of hydrogen as a greenhouse gas. Increasing the hydrogen GWP from 5.8 to 11[18] in the model increased the overall vehicle life cycle emissions by about 6% for this scenario.

[18] 11+/-5 suggested in Frazer-Nash Consultancy report, 2022: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1067137/fugitive-hydrogen-emissions-future-hydrogen-economy.pdf

Production

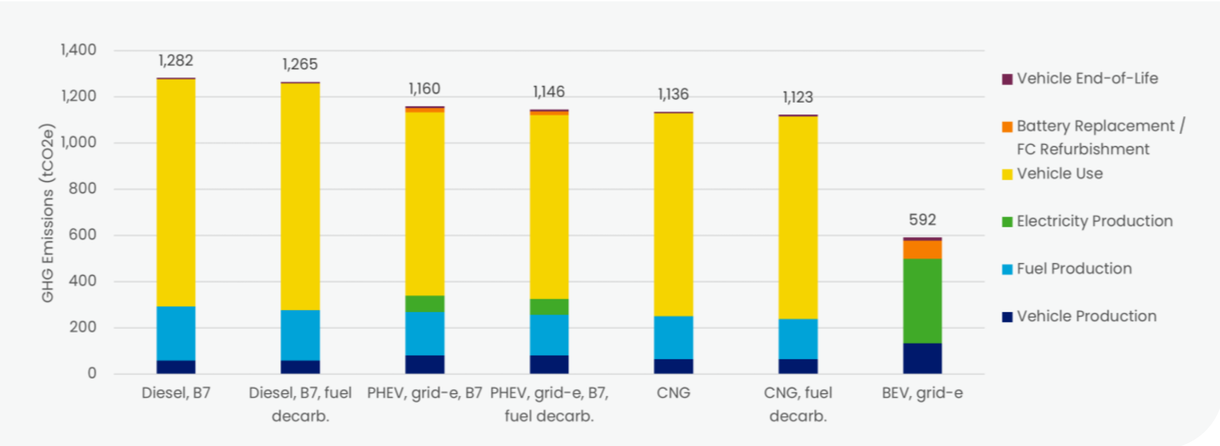


Figure 24. Impact of fuel production decarbonisation on artic total life cycle GHG emissions

Unlike the BEV, the emissions from fuel production (excluding hydrogen) are not expected to reduce much during the vehicle lifetime. Applying a reduction for fuel processing decarbonisation results in only a small change in vehicle life cycle GHG emissions.

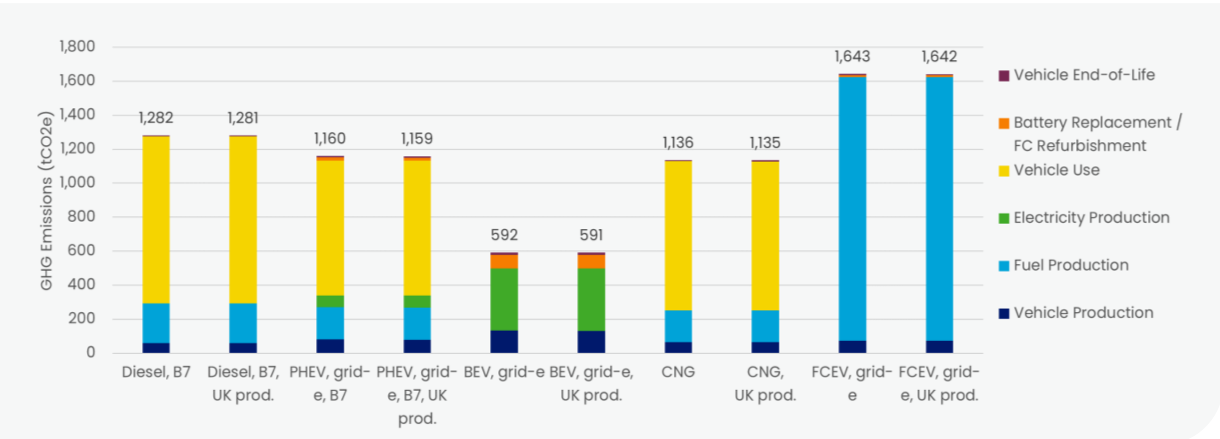


Figure 25. Impact of vehicle production location on artic total life cycle GHG emissions

The grid electricity emissions factor was varied from the baseline (an average for the EU) to the UK value. While this had very little impact on the vehicle life cycle emissions, it would be expected that producing the vehicle in other countries, for example China, would have a more pronounced impact.

Fuel consumption sensitivities

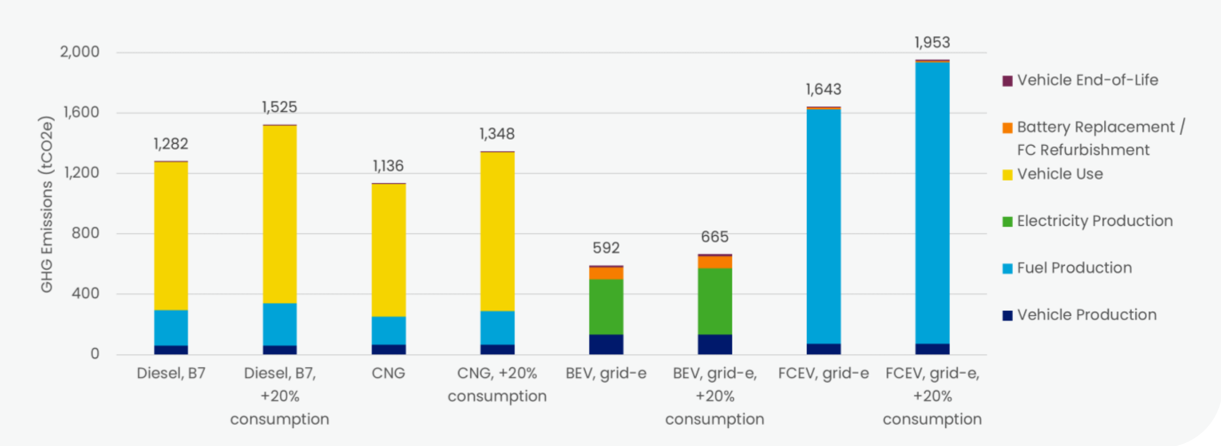


Figure 26. Impact of fuel consumption on artic truck total life cycle GHG emissions

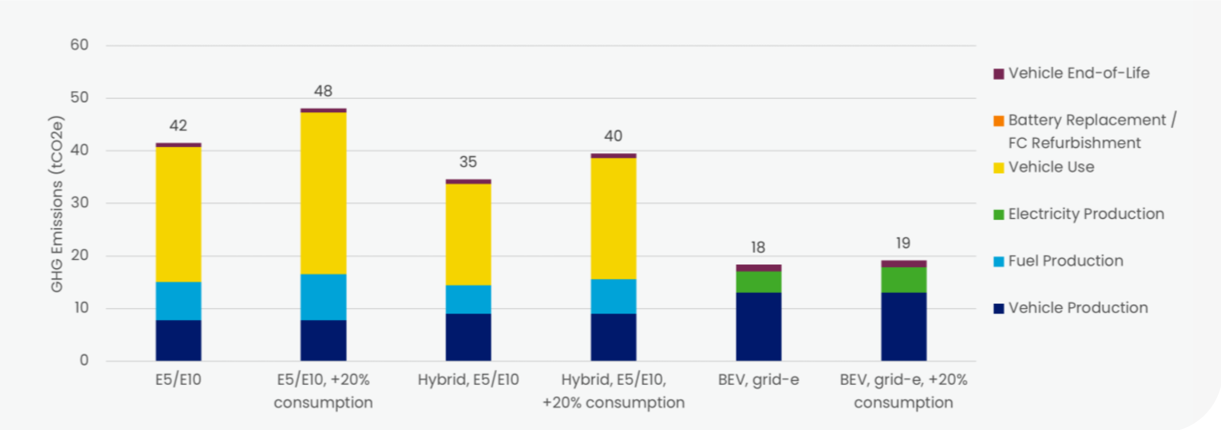
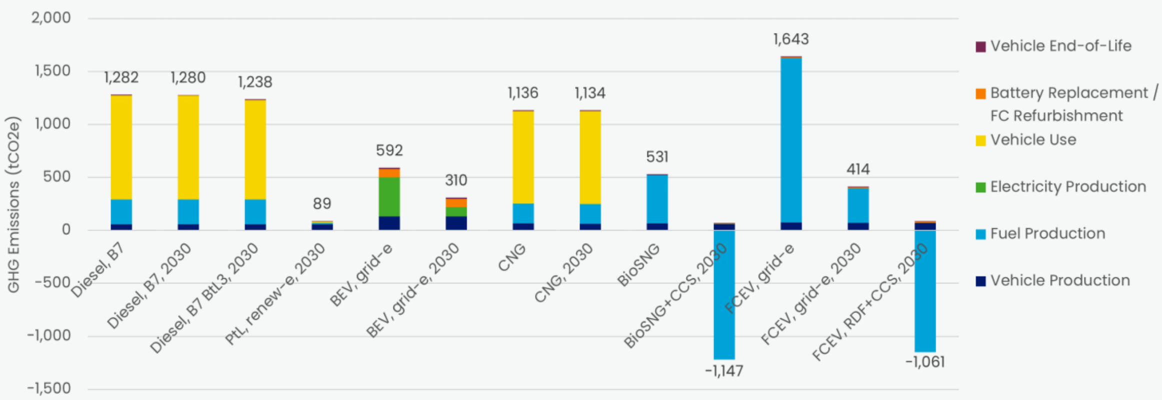


Figure 27. Impact of fuel consumption on passenger car total life cycle GHG emissions

Given the larger proportion of emissions from production, BEV results are less sensitive to a percentage increase in consumption. Increasing the consumption of any single technology by 20% does not change the 'rankings'. It is worth noting that the results are dependent on the usage profile. For example, compared to diesel engines, gas engines tend to have higher fuel consumption for urban operations, similar consumption for regional and lower consumption for long distance.

Phase 3 – Future scenarios

Articulated truck produced in 2030



Note: B7 BtL3 refers to a blend with 10% renewable content: 7% biodiesel and 3% BtL.

Figure 28. Total life cycle GHG emissions for artic truck produced in 2030

The results show that BioSNG and RDF gasification plants equipped with CCS have the potential for negative life cycle GHG emissions. PtL (e-fuels) have the potential for low life cycle GHG emissions, depending on the supply pathway.

The 2030 future BEV shows improved GHG savings, assuming that the predicted grid decarbonisation is realised. Future improvements in battery life may also reduce the need for a battery replacement during the vehicle lifetime, allowing further GHG savings.

The future FCEV using hydrogen produced via electrolysis with grid electricity shows even greater improvements, due to the grid decarbonisation and expected improvements in electrolysers. However, the 2030 FCEV GHG emissions are higher than the 2030 BEV.

The embedded emissions from vehicle production are expected to become more and more significant over time, as the GHG emissions from vehicle use decrease (e.g. from decarbonisation of the electricity grid).

PtL supply pathway

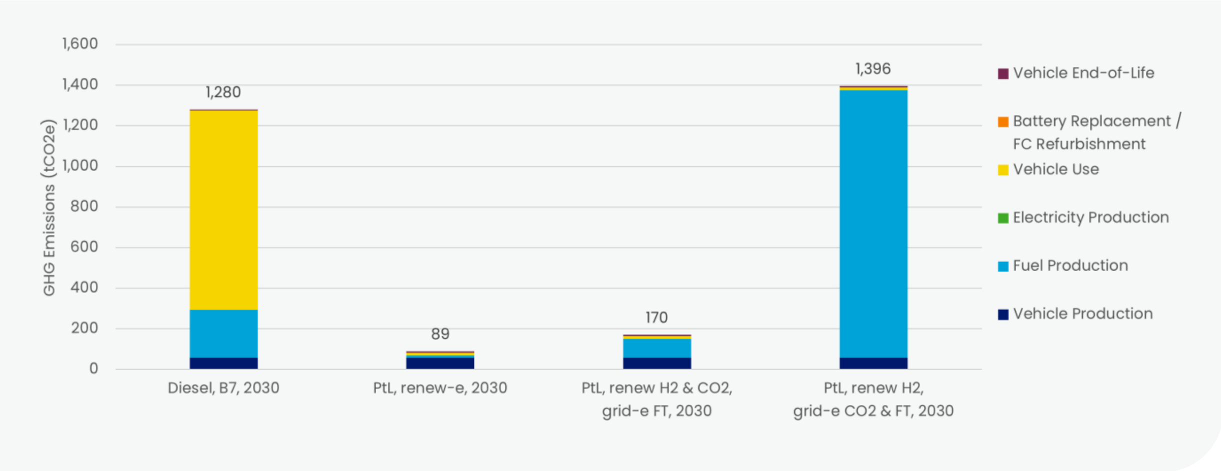


Figure 29. Impact of PtL supply pathway on artic (2030) total life cycle GHG emissions

The results show that PtL (e-fuels) have the potential for very low life cycle GHG emissions but could also be worse than conventional pump diesel depending on the production pathway, for example, if grid electricity is used for the Fischer Tropsch (FT) processing and CO_2 via direct air capture (DAC). It is important to note that the production of e-fuels is energy intensive. Consequently, e-fueled vehicles are less energy efficient than the BEV equivalent, as more electricity is used to produce the fuel than is required for direct electrification.

Production

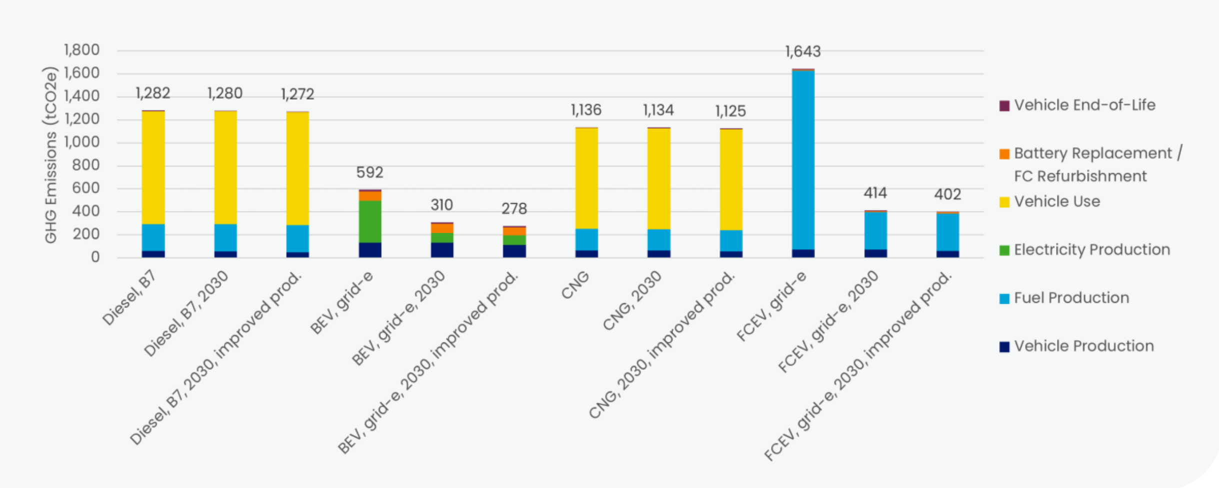


Figure 30. Impact of production emissions on artic (produced in 2030) total life cycle GHG emissions

Improvements in vehicle production by 2030 are expected to reduce the vehicle life cycle GHG emissions compared to a vehicle produced today. Of the vehicles modelled, the BEV is most sensitive to this because the embedded GHG emissions from production are higher.

End-of-life

The GHG impact of recycling and disposing of conventional vehicles (including those using renewable fuels) when they reach the end of their life is well understood and quantifiable. By contrast, there is still uncertainty around the GHG impact of recycling and disposal of BEV batteries, and their potential for second life uses in other sectors. More work is required to understand the full impacts of lithium battery critical mineral supply chains and battery recycling. The introduction of the EU battery directive[19] will support greater granularity of battery life cycle emissions.

[19] https://environment.ec.europa.eu/news/new-law-more-sustainable-circular-and-safe-batteries-enters-force-2023-08-17_en

6. Appendix

Example low carbon fuel supply chains

Renewable Fuel	Feedstock and production	Distribution and dispense
Biodiesel (FAME)	Waste vegetable oil - transesterification	Transported by road tanker, mostly dispensed at fleet depots
HVO, Renewable Diesel	Waste vegetable oil - hydrotreatment	
BtL, Biomass to Liquid	Waste wood - pyrolysis with FT	
PtL, Power to Liquid (e-fuel)	Renewable electricity and H_2, CO_2 flue gas - electrolysis, FT and methanol synthesis	
BtG, Bioethanol to Gasoline	Waste wood - dehydration and oligomerization	
CBG, Biomethane	Waste biomass - anaerobic digestion	Transported through gas grid or by cylinder tanker at 200-250 bar
BioSNG, Biosyngas	Waste wood and biomass - gasification	
Renewable Hydrogen	Waste biomass from refuse - gasification	Transported as compressed gas by tube trailer, dispensed at 350bar
	UK renewable electricity - off-site electrolysis	
	Overseas renewable electricity - electrolysis	Transported by ship as ammonia, then as above

Vehicle operating inputs

Vehicle category	Vehicle lifetime (years)	Annual mileage (km)	BEV / FCEV battery replacements
650cc motorcycle	12	6,000	0
Medium passenger car (C-segment)	15	13,000	0
Small rigid truck (7.5t)	10	30,000	0
Medium rigid truck (12-32t)	10	60,000	0
Articulated truck (30-44t)	8	160,000	1
Single decker bus	15	60,000	1
Double decker bus	15	60,000	1

Previous life cycle studies carried out by Zemo assumed a BEV battery replacement for most vehicle categories. Data from lighter vehicles has now shown that batteries often last for the entire vehicle lifetime. At this time, there is insufficient data on the durability of batteries in heavy-duty applications, hence it was assumed that one replacement was required for the articulated truck and buses. In these cases, the GHG emissions from battery replacement are assumed to be the same as the embedded emissions from the initial battery production when the vehicle was produced.

Grid electricity emissions factors

There are multiple UK grid electricity factors available in the public domain. The differences include geographical boundary (e.g. the inclusion or exclusion of imported electricity), temporal (lag real data, forecasts, backcasts), the inclusion or exclusion of WTT, the inclusion or exclusion of transmission and distribution losses, the accounting method used (e.g. grid average, marginal), and whether the grid is constrained or unconstrained. Zemo's 'Hydrogen Vehicle WTW GHG and Energy Study' study[20], showed that the WTW GHG emissions results are highly sensitive to the grid electricity factors used and that using different factors can change the relative GHG savings between comparator powertrains.

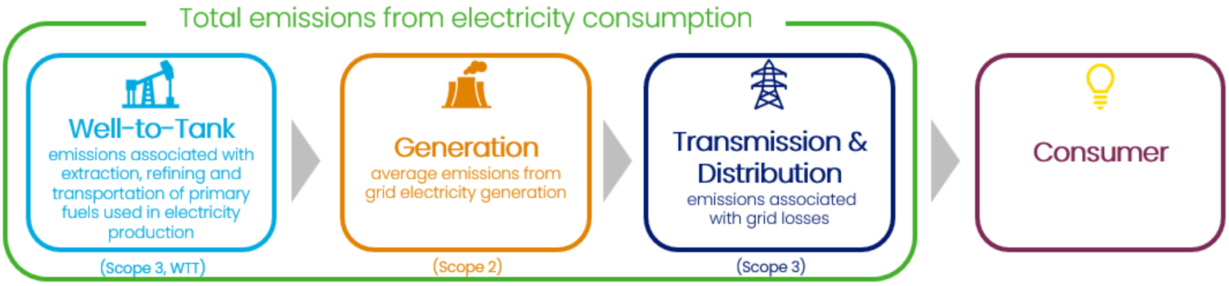


Figure 31. GHG emissions factors include WTT, generation and transmission and distribution

[20] Hydrogen Vehicle WTW GHG and Energy Study, 2021: https://www.zemo.org.uk/work-with-us/fuels/projects/examining-hydrogen-production-pathways-and-use-in-vehicles.htm

After consulting with BEIS (now DESNZ) and comparing the published grid emissions factors, Zemo adopted the following approach. For previous years, the emissions factors are calculated by summing the values for UK electricity generation, transmission and distribution, and WTT from the DESNZ company reporting data (allowing for the lag in the data being published). For future years, the emissions factors are based on the DESNZ Green Book Grid Average Consumption Commercial/Public Sector values. As these do not include WTT emissions, a 25% uplift was then applied (the 25% was estimated from the ratio of WTT to generation plus transmission and distribution losses in DESNZ company reporting data).

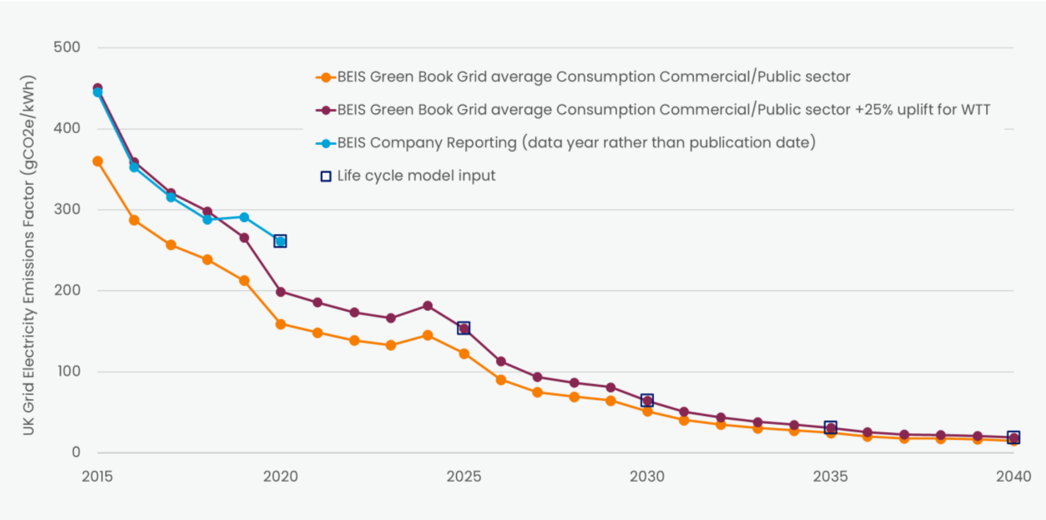


Figure 32. GHG emissions factors used in life cycle modelling

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