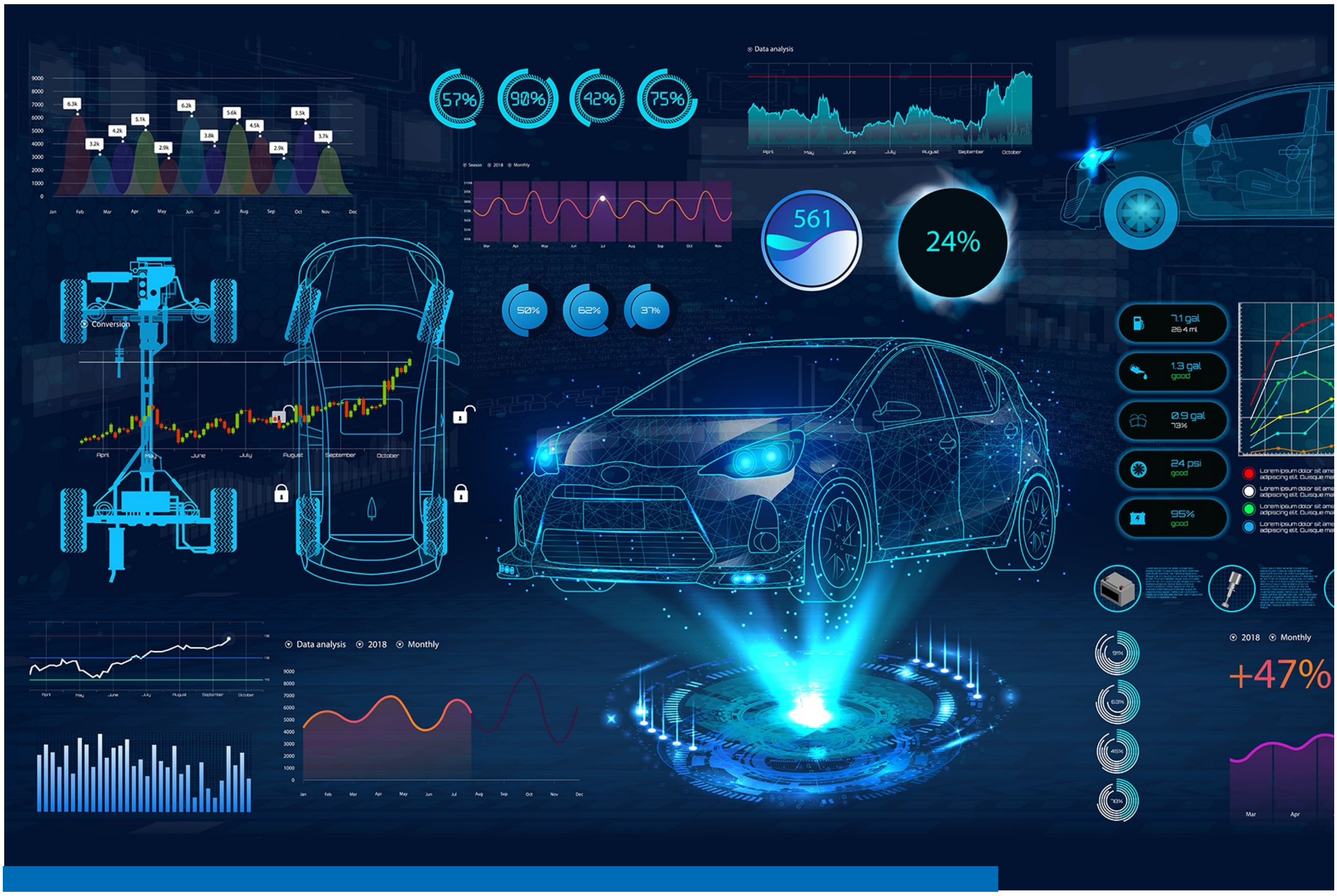

Lifecycle Analysis of UK Road Vehicles

Specialist Professional and Technical Services 2 (SPaTS2) Framework Lot 1 (Technical Consultancy, Engineering Advice, Research and Innovation for roads, vehicles, highway infrastructure and operations)

Work Order Ref: T0082 TETI0045

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Table of contents

Table of figures

Table of tables

Glossary

Abbreviation	Definition
AQP	Air Quality Pollutants
B7	7%vol biofuel blend in diesel
BAU	Business As Usual
BCEV	Battery Catenary Electric Vehicle (see also BEV-ERS)
BEV	Battery Electric Vehicle (fully electric)
BEV-ERS	Battery Electric Vehicle with Electric Road System (i.e. via vehicle pantograph and overhead catenary or other form of dynamic charging), also known as BCEV
BSi	British Standards Institute
CED	Cumulative Energy Demand
CEV	Catenary Electric Vehicle
CH_4	Methane
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
EC	European Commission
EoL	End-of-Life
EV	Electric Vehicle
FAME	Fatty Acid Methyl Ester (Biodiesel).
FCEV	Fuel Cell Electric Vehicle (running on hydrogen)
GHG	Greenhouse Gases
GWP	Global Warming Potential
GVW	Gross Vehicle Weight
H_2	Hydrogen
HD	Heavy Duty
HDV	Heavy Duty Vehicle (lorries, buses and coaches)
HCEV	Hybrid Catenary Electric Vehicle
HEV-D/P/H2	Hybrid Electric Vehicle, with Diesel / Petrol / Hydrogen ICE
HEV-D-ERS	Diesel Hybrid Electric Vehicle with Electric Road System (i.e. via vehicle pantograph and overhead catenary or other dynamic charging) (aka HCEV)
HVO	Hydrotreated Vegetable Oil (Renewable Diesel)
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ICEV-D/P/H2	Diesel/Petrol/Hydrogen ICE Vehicle
ISO	International Organisation for Standardisation

Abbreviation	Definition
kWh	kilo-Watt-Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCV	Light Commercial Vehicle (van)
LDV	Light Duty Vehicle (Car or LCV)
LHV	Lower Heating Value
Li-ion	Lithium Ion
LNG	Liquefied Natural Gas
LPG	Liquefied petroleum gas.
MD	Medium Duty
MJ	Mega-Joule
N_2O	Nitrous Oxide
NEDC	New European Drive Cycle
NH_3	Ammonia
NOx	Nitrogen Oxides (includes nitrogen monoxide and nitrogen dioxide)
OEM	Original Equipment Manufacturer
PCR	Product Category Rules
PEF	Product Environmental Footprints
PHEV	Plug-in Hybrid Electric Vehicle
PtX	Power-to-X (where X can be a variety of hydrocarbon liquid fuels or gases)
PV	[Solar] Photo Voltaic
RE	Renewable Energy/Electricity
RES	Renewable Energy Sources
REEV	Range Extended Electric Vehicle
RW	Real world
SMR	Steam Methane Reforming (Hydrogen production from natural gas)
SNG	Synthetic Natural Gas
SO_2	Sulphur Dioxide
SO_2e	Sulphur Dioxide equivalent
SoC	Available State-of-Charge percentage for battery
TCO	Total Cost of Ownership
TTW	Tank-to-Wheel
VOC	Volatile Organic Compound
WLTP	Worldwide harmonised Light vehicle Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheel

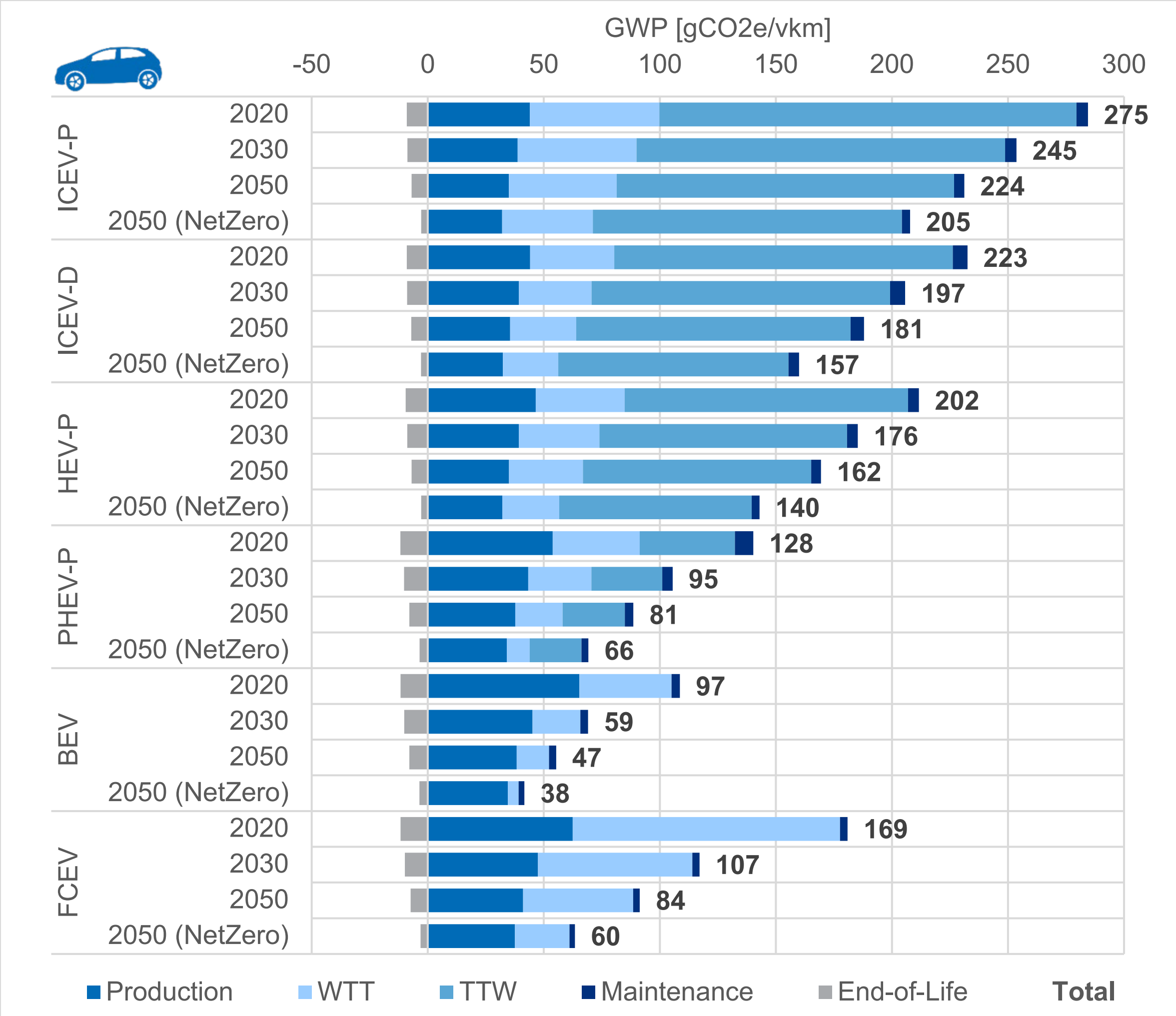
Abbreviation	Definition
xEV	Electric vehicles (includes BEVs, PHEVs, REEVs and FCEVs)
ZEV	Zero Emission Vehicle (includes BEV and FCEV)

Highlights/Summary

General points:

- The analysis shows that electric (xEV) powertrains used in UK road vehicles are expected to have significantly lower greenhouse gas (GHG) impacts across all vehicle types. Battery electric vehicles (BEVs) consistently perform better than all other powertrains.
  - Due to the UK's very clean electricity mix, already in 2020 a typical battery electric car is estimated to save ~65% GHG emissions compared to an equivalent conventional petrol car.
- Improvements in battery technology, battery manufacturing and end-of-life treatment are projected to significantly reduce the LCA GHG emissions of BEVs in the future:
  - By 2030, BEVs are estimated to deliver a ~76% GHG reduction compared to an equivalent conventional petrol car, due to a combination of improved battery technology and a further decarbonised UK electricity grid. By 2050, these savings could increase to 81%.
  - By 2050 BEV production emissions could reach close to parity with those of conventional vehicles.
- Hydrogen fuel cell electric vehicles (FCEVs) also offer the opportunity to deliver large GHG savings versus conventional vehicles. By 2050, a FCEV articulated lorry could save ~73% GHG emissions versus a conventional diesel lorry.
- The analysis did not include biomass plus carbon capture and storage (CCS) directly for hydrogen, nor for electricity production, which could result in further significant reductions in emissions (as this power combination delivers negative GHG emissions).
- The results support the current strategy for encouraging the move to zero emission road transport to reduce GHG emissions.
- Modelling indicates that PHEVs could deliver significant carbon savings versus petrol and diesel equivalents. However, this is subject to uncertainty due to the real world performance of batteries and owners charging behaviour (see Section 3.3 of the main report. for more detail).
- A battery replacement is not usually expected to be needed for BEV cars and vans over normal operational lifetimes with current technology, but is expected to be needed for heavy duty vehicles, which have much higher lifetime activity. However, this may not be necessary in the longer term, due to improvements in battery technology and higher capacity batteries.
- BEVs provide a much more efficient end-to-end use of renewable energy in their operation – using only around 35% of that of FCEVs in 2020, when hydrogen is produced from electrolysis. This is mainly due to losses in the production of hydrogen fuel and then in converting this back into electricity on-board the FCEV.
- Impacts on human health are also expected to be significantly lower from alternative and electric powertrains, as lifecycle air pollutant emissions are lower, and occur further away from highly populated areas compared to conventional ICEVs (even when these vehicles are complying the most recent Euro 6 or Euro VI emissions limits). This is particularly important for vehicles like urban buses and for vans and lorries on urban delivery operations.

Figure ES1: Summary of breakdown of overall lifecycle greenhouse gas impacts for Lower Medium Cars for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power for 2050)



Notes: GWP = global warming potential for greenhouse gas emissions. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix.

1 Introduction and overview

1.1 Introduction

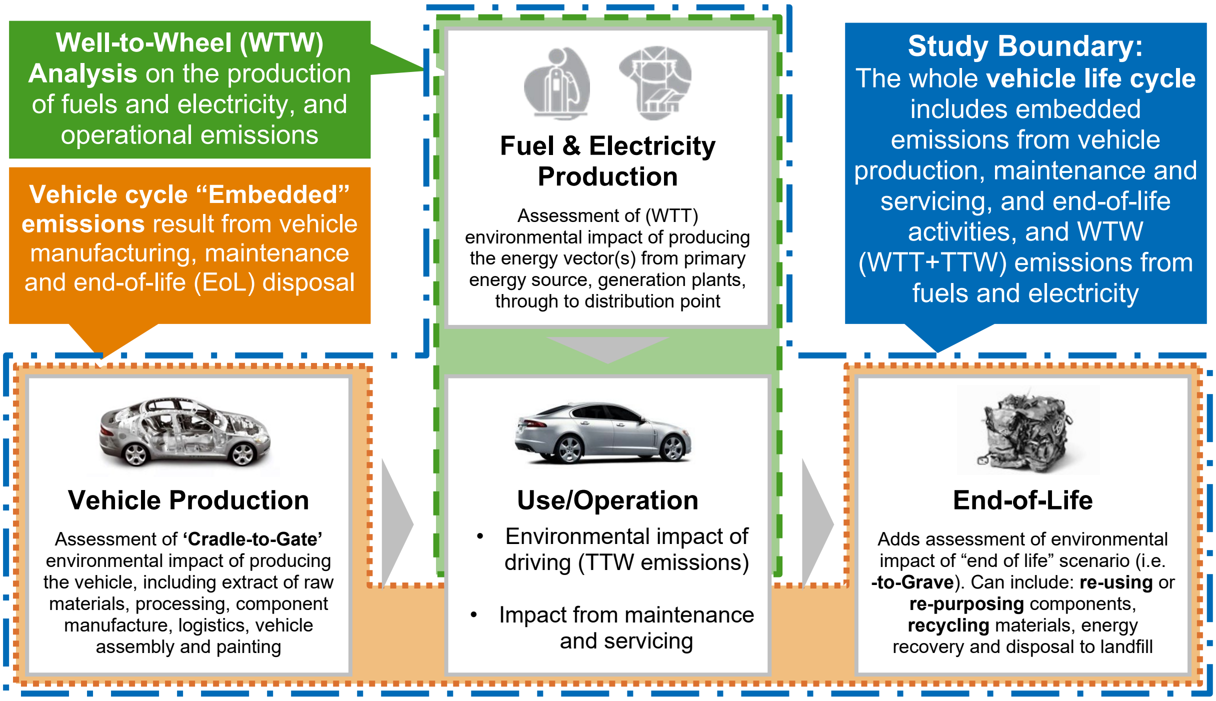
The Department for Transport (DfT) has commissioned Ricardo Energy & Environment ("Ricardo") to adapt its previous EU-centric road vehicle LCA (life-cycle assessment) analysis for the European Commission (EC, DG CLIMA) to be more specific to the UK context.

This final report provides the high-level summary of the UK vehicle LCA results. A complete dataset of the final results will also be submitted alongside the final report. An outline of the methodological basis of the work is provided in the following section, with a summary of the key results from the analysis provided in Chapter 2, and a discussion of a number of sensitivity scenario analyses provided in Chapter 3. Further information on key input data, and more detailed results are also provided in the Appendices.

1.2 Methodological basis

The LCA modelling analysis for this project was carried out using Ricardo's bespoke Vehicle LCA Modelling framework, which was used to provide results for our recent project for the European Commission (Ricardo et al., 2020). An outline of the scope of the LCA is provided in Figure 1.1. The underlying methodology and the majority of the input assumptions and datasets used in the analysis are the same as those, which are described in detail in our final report (published on the EC's website[1]).

Figure 1.1: Schematic scope of the assessment (system boundaries)



Note: Infrastructure for energy production (electricity and fuels) is also included. Electricity storage is excluded. WTT = Well-to-Tank; TTW = Tank-to-Wheel.

Since this EC work was completed, Ricardo have also made a range of refinements to our model to further extend its capability, and improve a range of underlying data and assumptions also informed by other recent work by Ricardo for the EC (e.g. on the future evolution of electric range, adjustments to the relative performance of a number of alternative powertrains, emissions from e-fuel production).

In addition, a number of updates were made to the model input datasets, to better align the vehicle LCA modelling to the UK-specific context, and were predominantly based on datasets provided by DfT and BEIS. The following elements were updated (with further information also provided in Appendix A1):

[1] Available for download from DG Climate Action's website at: https://ec.europa.eu/clima/policies/transport/vehicles_en#tab-0-1

- *Vehicle manufacturing*: UK-specific share of vehicle and xEV battery production origins.
- *Vehicle operation*: vehicle lifetime (years), lifetime activity (km) and share of driving on urban/rural/motorway roads (%).
- *Energy supply*: Projected UK electricity generation mix, net electricity imports, and energy storage losses. Projected future substitution of conventional fossil fuels with biofuels. Projected UK-specific mix of hydrogen production sources, and a change in the electricity source for e-fuel and hydrogen production to be based on UK electricity.

Outputs from the overall vehicle LCA modelling are provided aligned to specific overall scenario settings applied across all module calculations and a range of variable settings allowing for the exploration of sensitivities. The global/overall scenario settings directly impact in particular the electricity mix used, the future improvement in vehicle technical efficiency and biofuel substitution rates up to 2050. The two alternative scenarios included in the analysis are summarised in Table 1.1 below.

Table 1.1: Summary of vehicle LCA modelling scenarios

Scenario	Description
Baseline	Baseline policy scenario including all currently planned / implemented UK policies.
Net Zero Power	Scenario with energy mix and biofuels assumptions consistent with UK government modelling meeting the UK's 2050 'Net Zero' objective. Improvements in future vehicle efficiency are aligned with the 'Tech1.5' scenario from Ricardo's analysis for EC DG CLIMA*.

Notes: * Scenario consistent with the EU contribution to meeting the Paris Agreement objective of keeping global temperature increase to a maximum of 1.5 ºC, from the European Commission's 'Long-Term Strategy to reach a climate-neutral Europe by 2050' (European Commission, 2018) (Ricardo et al., 2020).

It should be noted the modelling does *not* project forward the environmental impacts of all processes aligned with Net Zero, e.g. it does not include full decarbonisation of aluminium production in the creation of vehicles (as this is beyond the scope of the initial report). What is included in the Net Zero Power scenario includes activities directly related to the energy sector and the vehicles, i.e.:

- Significant improvements to the UK (and global) electricity production mix (see Appendix A1.2), and the effects of this on:
    - Impacts resulting from electricity used directly in xEVs.
    - Impacts from electricity used in the production of liquid and gaseous fuels.
    - Impacts from the use of electricity in production of the raw materials used in vehicles.
    - Impacts from the use of electricity in the manufacturing of vehicles, batteries and other components.
    - Impacts from the use of electricity in end-of-life activities (e.g. recycling processes) and accounting (e.g. credits from energy recovery), etc.
- Higher levels of end-of-life vehicle (and battery) recycling/material recovery, including shifts to more efficient/lower impact hydrometallurgical processes for battery recycling.
- Increased (but limited) levels of uptake of bio-/low-carbon fuels in the fleet (see Appendix A1.2).
- Significant improvements to the energy consumption (per km) of all vehicle powertrain types (i.e. due to the application of a range of efficiency measures, including mass reduction, etc.).

Other economy-wide actions likely to be necessary to meet Net Zero objectives are not included in the scenario. This is because the focus of the original study was on the key elements that would directly/meaningfully affect the comparison of different vehicle powertrain and fuel types, and this would have very significantly increased complexity. For example, the following were not included/covered:

- Non-electricity related improvements in the extraction and processing of raw materials, e.g. also changes in processing/manufacturing technologies, e.g. so-called 'Fossil-fuel free steel' processes, aluminium production, lower GHG polymers/plastics, textiles, etc.

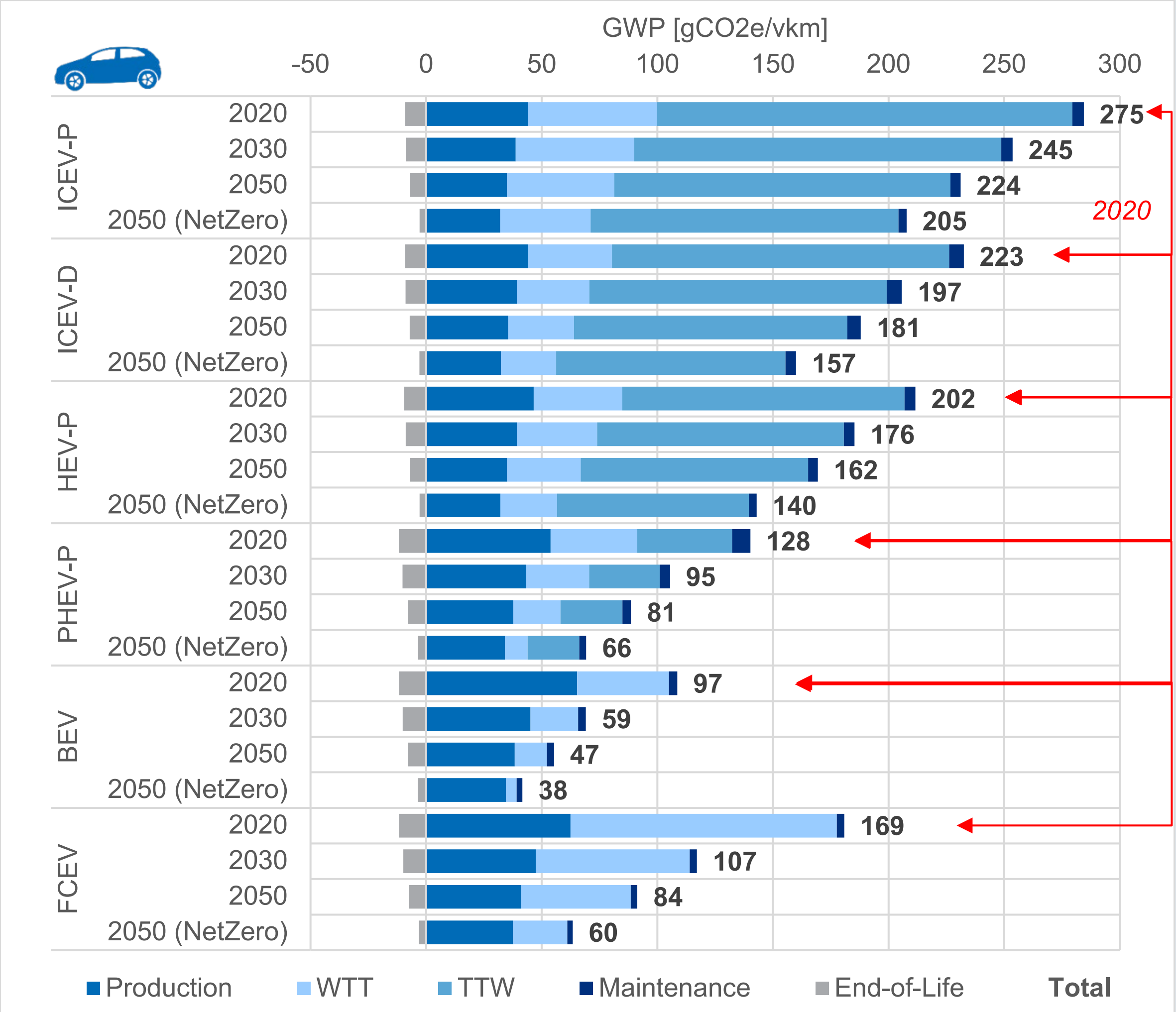
- Shifts to low-carbon or net zero fuels used in manufacturing, logistics activities, and in other sectors across the economy.
- Other improvements to manufacturing vehicles, their components, and end-of-life processes.

2 Overall road vehicle lifecycle impacts

2.1 Passenger cars

- Electric powertrain vehicles (xEVs) have been found to provide significant lifecycle greenhouse reductions compared to conventional petrol and diesel vehicles operating in UK conditions.
  - Already in 2020 a typical battery electric car is estimated to save ~65% GHG emissions compared to an equivalent conventional petrol car.
  - GHG benefits of xEVs increase with electrification level with battery electric vehicles (BEVs) showing the highest benefits and full hybrid electric vehicles (HEVs) the lowest.
  - Production emissions for BEVs are around 50% higher than petrol cars in 2020 (mainly due to the batteries), and make up 67% of total estimated lifecycle GHG emissions. By 2050 BEV production emissions could reach close to parity with those of conventional vehicles.
  - WTT (Well-to-Tank) emissions of petrol and diesel can be significant (mainly from oil extraction, refining). These make up 20% of emissions for a conventional petrol car in 2020.
- BEVs GHG benefits increase in future years reaching ~76% reduction by 2030 compared to an equivalent conventional petrol car, due to a combination of improved battery technology and a further decarbonised UK electricity grid. By 2050 these savings could further increase to 81%.
- Modelling indicates that PHEVs could deliver significant carbon savings versus petrol and diesel equivalents. However, this is subject to additional uncertainty due to the real world performance of batteries and owners charging behaviour (see Section 3.3 for more detail).
- Hydrogen fuel cell electric vehicles (FCEVs) also offer the opportunity to deliver large savings versus conventional vehicles. By 2050 a FCEV could save 71% versus a conventional petrol car.
- The analysis did not include biomass plus carbon capture and storage (CCS) directly for hydrogen, nor for electricity production, which could result in further significant reductions in emissions from FCEV or BEV (as this power combination delivers negative emissions).
- BEVs provide a much more efficient end-to-end use of renewable energy in their operation – using only around 35% of that of FCEVs in 2020 (when hydrogen is produced from electrolysis). This is mainly due to losses in the production of hydrogen fuel and in converting this back into electricity on-board the FCEV.
- Electric powertrains also provide significant reductions in direct air pollutant emissions - up to 100% for many pollutants for BEV and FCEV. This is particularly important to reduce human health impacts in urban environments. On a life-cycle basis BEVs also reduce total air pollutant emissions by between 42% to 90%, depending on the pollutant.
- Recycling and recovery of critical materials (and electronic components) are important to maximise the benefits of BEVs, as well as other xEVs.

Figure 2.1: Summary of breakdown of overall lifecycle greenhouse gas impacts for Lower Medium Cars for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power for 2050)



Notes: GWP = global warming potential for greenhouse gas emissions. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix.

Figure 2.2 provides a summary of the main results for the lifecycle greenhouse gas (GHG) emissions for typical Lower Medium segment passenger cars (i.e. VW Golf size or similar) for a selection of key powertrain types. Some high-level results are also shown in Figure 2.2 for the CED (cumulative energy demand) LCA indicator – which provides a good indication on the overall efficiency of the use of primary energy (important in the context of limited renewable energy sources). Further details for other powertrain types and for Large SUVs are provided in Appendix A2.

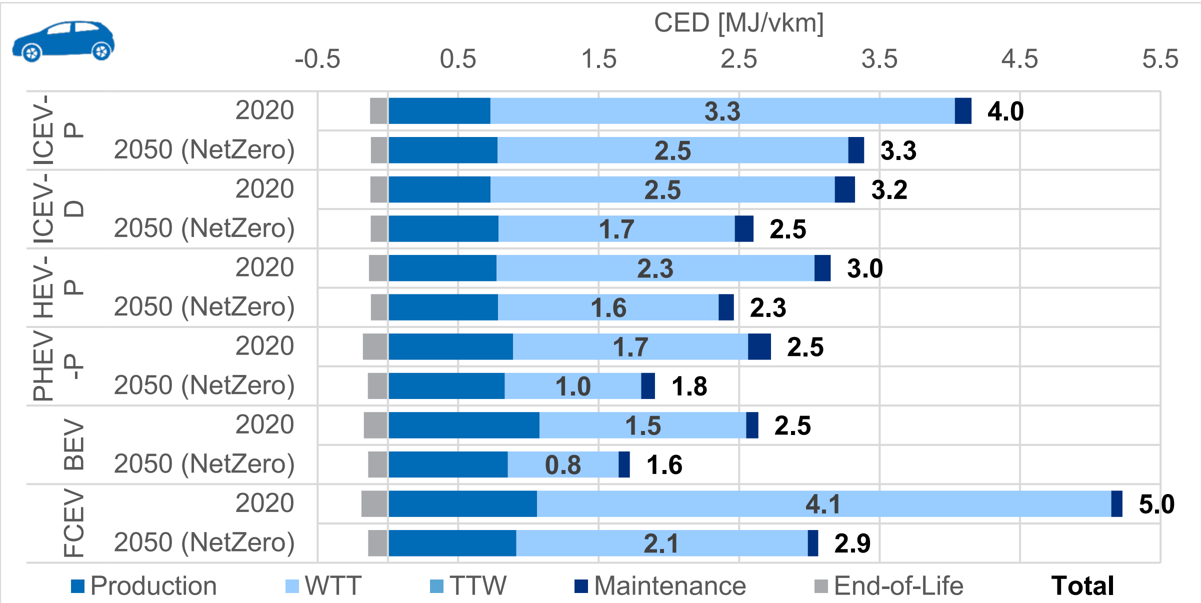
The results for GHG emissions (in CO_2 equivalents for the GWP metric – global warming potential) clearly show the significant benefits of hybrid and electric powertrain vehicles (i.e. HEV, PHEV, BEV and FCEV) in comparison to conventional petrol and diesel internal combustion engine vehicles (i.e. ICEV-P and ICEV-D). Already in 2020, a new battery electric vehicle (BEV), is expected to reduce GHG emissions by 65% compared to a conventional petrol vehicle, when operating in real-world conditions over 14 years and 200,000 km lifetime. This is an even greater saving than previously found for a BEV operating in EU-average conditions / electricity mix in our analysis for DG CLIMA (Ricardo et al., 2020), mainly due to the significantly cleaner UK electricity generation mix, compared to the EU-average.

Whilst there are significant emissions resulting from the manufacturing of electric vehicle batteries (leading to much higher manufacturing emissions for BEVs compared with ICEs in 2020), the technical performance of these batteries has seen extremely rapid improvement in recent years. In addition, there has been an increase in the scale of xEV battery manufacturing, leading to efficiencies and reduced impacts. The higher manufacturing emissions of xEVs may also be offset (with credits – shown as negative emissions) by vehicle and battery recycling (which also provide important benefits from the recovery of key critical materials) and potential second-life applications for xEV batteries. The importance of this is also further explored in a sensitivity on end-of-life assumptions in later Section 3.4. The net result of this is that manufacturing related emissions are close to parity between BEVs and ICEs by 2050. The cumulative energy demand (CED) for conventional ICEV production rise in 2050 due to the assumptions on significant vehicle lightweighting using carbon-fibre reinforced plastic in the long-term to improve vehicle efficiency (which is applied to all powertrain types).

Full hybrid electric vehicles (HEVs) show significant lifecycle GHG benefits over conventional petrol and diesel vehicles. This is due to improved operational efficiency (particularly in urban stop-start traffic) and a relatively small relative increase in manufacturing emissions. Mild/48V-hybrid vehicles (which have smaller batteries and less powerful electric motors, and are less expensive to manufacture) would be expected to perform slightly less well on a lifecycle perspective due to a lower operational efficiency.

The results for plug-in hybrid electric vehicles (PHEVs) are in-between those of HEV and BEV, assuming these are charged regularly, achieving over 50% reduction in lifecycle GHG emissions versus a conventional petrol vehicle. The real-world performance of PHEVs relies significantly on the electric range available (which can also be affected by climate and driving conditions) and user behaviour/vehicle charging. The uncertainties in this regard are explored further in later Section 3.3.

Figure 2.2: Summary of breakdown of overall lifecycle cumulative energy demand (CED) impacts for Lower Medium Cars for selected powertrain types (Baseline scenario for 2020, Net Zero Power for 2050)



Notes: Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2020' are for the Baseline scenario conditions (e.g. improved future energy mix) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with significant improvements in vehicle efficiency and long-term energy mix.

For hydrogen fuel cell electric vehicles (FCEV), the results show a reduction in lifecycle GHG impacts versus ICEVs that are very significant, but around 60-70% higher than for an equivalent BEV for most of the timeseries. This is due to the lower overall efficiency of the full energy chain (including vehicle efficiency) for hydrogen produced from electricity (versus using it directly in a PHEV or BEV). In 2020, FCEVs show similar GHG savings between those of HEV and PHEVs, assuming hydrogen produced 100% from grid electricity. The assumed hydrogen production mix is summarised in Figure A3 in Appendix A1.2. Operation in 2050 for FCEVs in the Net Zero Power scenario assumes 43:57 ratio (from BEIS) of production using electrolysis (grid average electricity mix) and SMR+CCS (SMR production from natural gas with carbon capture and storage). As noted earlier, one of the limitations of the analysis is that BECCS (biomass energy plus carbon capture and storage) technologies, are not included in either the electricity mix, nor for hydrogen production in our analysis. These technologies offer the potential for significant net negative GHG emissions when applied in the UK energy system according to (Bui, Zhang, Fajardy, & Mac Dowell, 2021). Whilst this analysis found the conversion efficiency to be slightly higher (at 40%) for BHCCS (biomass to hydrogen + CCS) versus BECCS (biomass to electricity +CCS) (at ~30-36%), the direct use of electricity in BEVs and PHEVs is far more efficient than hydrogen used in FCEVs (which has to be converted back into electricity on-board the vehicle).

Our analysis shows also that FCEVs may have a similar manufacturing impact to BEVs. The most significant component responsible for additional manufacturing emissions for FCEVs is actually the high-pressure compressed H_2 storage vessel, since the carbon-fibre reinforced plastic (CFRP) used in these vessels has extremely high GHG production emissions. It is possible the use of recycled CFRP may have the potential reduce these impacts. However CFRP recycling technology is not yet mature/significantly commercialised. In addition, stronger and more lightweight carbon-fibre is needed for hydrogen storage vessels compared to wind turbines and aircraft materials, which account for most of the current use of this material (NikkeiAsia, 2020).

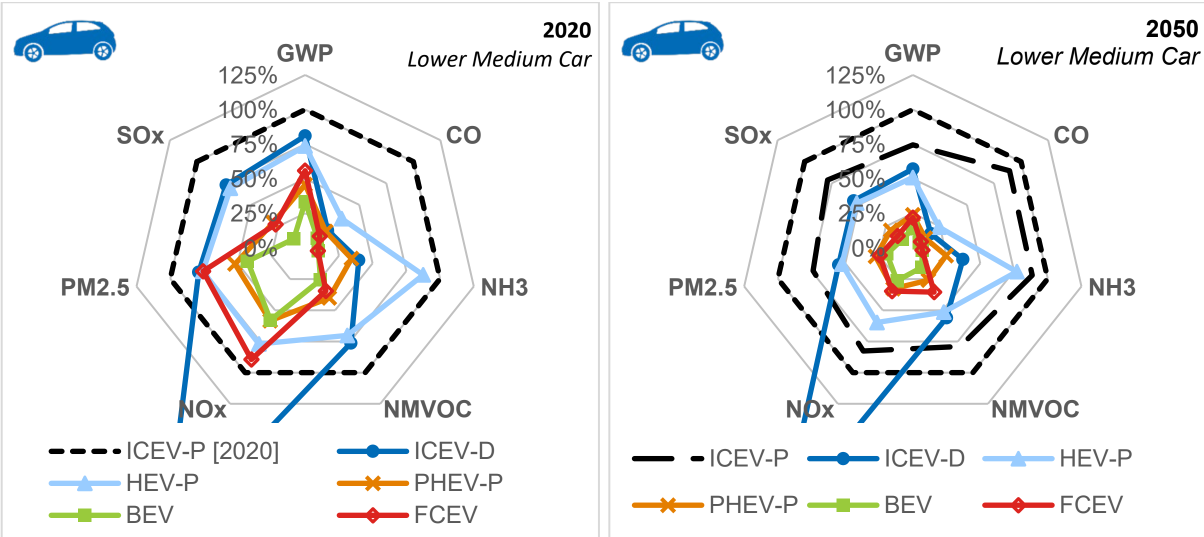
In future years the GHG emissions are projected to improve from all powertrain types, due to a combination of technical improvements to vehicle efficiency and xEV batteries, and also decarbonisation of UK fuel and electricity supply. However, improvements to the performance of vehicles with combustion engines does not improve to the same degree as xEVs. DfT projections show a modest increase in deployment/substitution of biofuels (or other low carbon fuels) into public refuelling stations/supply, while these fuels are assumed to be increasingly used to reduce emissions in sectors where zero tailpipe emission technologies are less likely to be available (e.g. aviation). Sensitivities on the lifecycle performance of different powertrain types using 100% biofuels or e-fuels[2] are provided in later Section 3.2, which show BEVs remain lower in all cases.

In terms of the other environmental and health impacts, Figure 2.3 also provides a summary of the lifecycle emissions of a range of regulated air quality pollutants for different fuels/powertrains in comparison to a typical 2020 Lower Medium petrol car. Whilst electric vehicles don't have exhaust emissions when operating on electricity (or hydrogen), there are still non-exhaust particulate emissions (from tyre and brake wear) and emissions associated with the vehicle manufacturing and electricity (or hydrogen) production. The non-exhaust emissions of xEVs are assumed to be similar to other vehicle types as there are currently no robust datasets available on their emissions versus conventional vehicles. Tyre wear emissions from xEVs are likely to be higher due to their higher weight, but brake wear emissions are likely to be lower due to regenerative braking. Overall in our analysis, total emissions of most pollutants are found to be also significantly reduced versus conventional vehicles (and further improve in future periods). The level of human exposure is also particularly important for the actual health impacts resulting from air quality pollutants, and most of the emissions from xEV powertrains occur in lifecycle stages (i.e. manufacturing, electricity generation) that are largely outside of heavily populated areas (unlike for direct exhaust emissions from vehicles with combustion engines).

A key concern for xEVs are scarce mineral & metal resources; in LCA these impacts are assessed with the abiotic resource depletion (ARD) indicator, where most of the impacts are due to certain materials (particularly copper and electronic components). However, critical materials used (in relatively very small quantities, by mass) in batteries and electric motors (notably lithium, cobalt and rare earth metals) do not appear to significantly influence the results. However, these materials are very important to consider at a wider system/fleet level, where effective recycling is important to recover them for reuse.

[2] e-fuels, also known as 'power-to-x' (PtX) fuels, are synthetic fuels produced from captured CO_2 (either from industrial processes or air capture) and hydrogen produced from electrolysis using renewable electricity.

Figure 2.3: Summary of the relative impacts for Lower Medium Cars for GHG (GWP) and air quality pollutant emissions (CO, NH_3, NMVOC, NOx, $PM_{2.5}$, SOx) for 2020 and 2050 powertrains (Net Zero Power scenario).

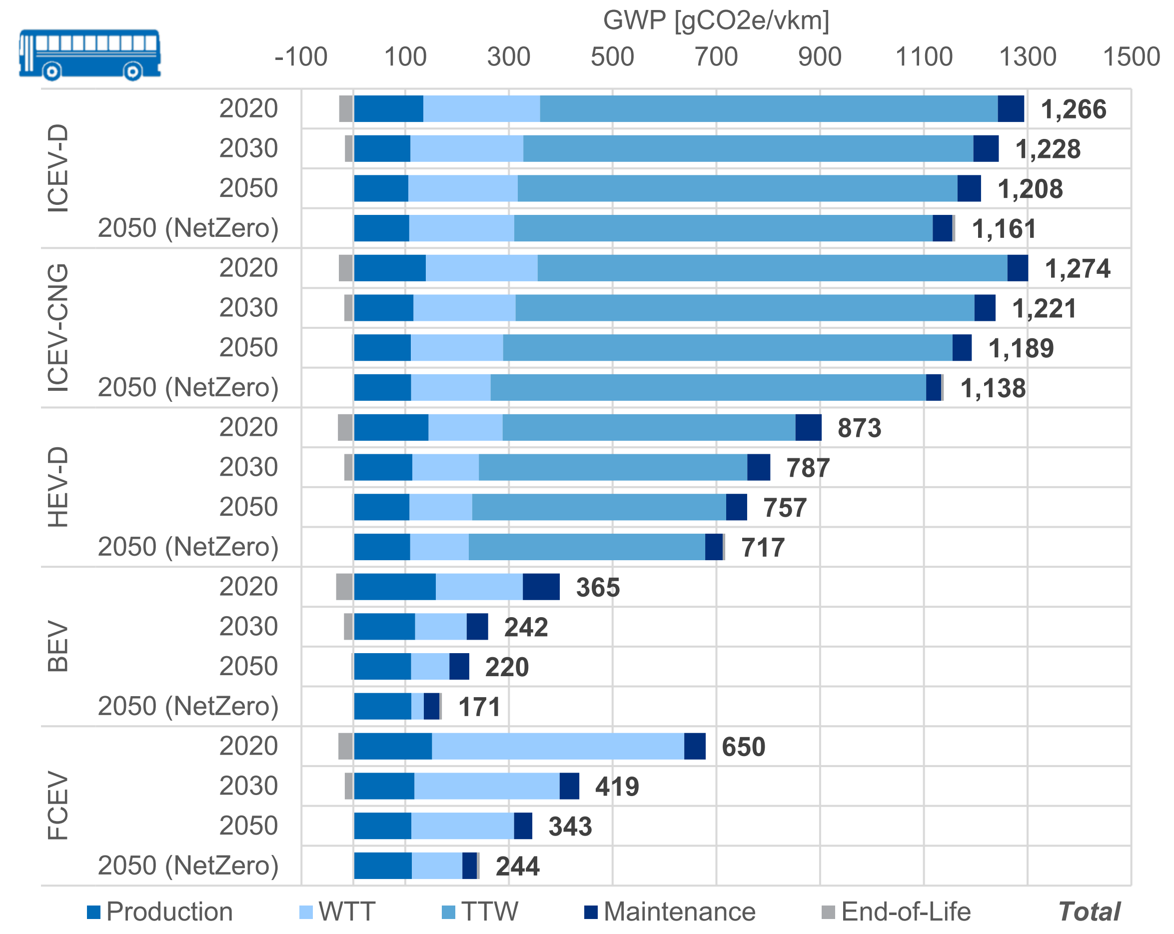


Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. Exhaust (TTW) air pollutant emissions are based on the version of COPERT current at the time this report was prepared, and assuming new vehicles meet the most stringent Euro 6 emission standards in place.

2.2 Urban buses

- Urban buses are well suited to electric powertrain vehicles (xEVs) and provide the highest lifecycle GHG reductions compared to conventional combustion engine alternatives:
  - Already in 2020 a typical battery electric single-decker urban bus is estimated to save ~73% GHG emissions compared to an equivalent conventional diesel bus. By 2050 these savings could further increase to 82%.
  - GHG benefits of xEVs increase with electrification level with battery electric vehicles (BEVs) showing the highest benefits (73%) and full hybrid electric vehicles (HEVs) the lowest (31%).
  - Production emissions for BEVs are around 18% higher than diesel buses in 2020 (mainly due to the batteries), and make up 44% of total estimated lifecycle GHG emissions. By 2050 BEV production emissions could reach close to parity with those of conventional vehicles.
- Hydrogen fuel cell electric vehicles (FCEVs) also offer the opportunity to deliver large savings versus conventional vehicles. Already in 2020 the lifecycle GHG savings are estimated to save ~50% compared to a conventional diesel bus, and by 2050 a FCEV could increase to 72%.
- The analysis did not include biomass plus carbon capture and storage (CCS) directly for hydrogen, nor for electricity production, which could result in further significant reductions in emissions (as this power combination delivers negative emissions).
- Total maintenance emissions are 62% higher for electric buses in 2020 due to the need for a mid-life replacement of the traction battery, increasing their overall lifecycle emissions. This is likely not to be necessary in the longer term, due to improvements in battery technology and higher capacity batteries.
- Electric powertrains also provide significant reductions in direct air pollutant emissions - up to 100% for many pollutants for BEV and FCEV. This is particularly important to reduce human health impacts in urban environments. On a life-cycle basis BEVs also reduce total air pollutant emissions by between 42% to 91%, depending on the pollutant.

Figure 2.4: Summary of breakdown of overall lifecycle greenhouse gas impacts for urban buses for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power scenario for 2050)



Notes: GWP = global warming potential for greenhouse gas emissions. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix.

Figure 2.4 provides a summary of the main results for the lifecycle greenhouse gas (GHG) emissions for a typical single-decker urban bus operating in UK conditions for a selection of key powertrain types. Figure 2.5 also provides a comparison of cumulative energy demand (CED) for BEV and FCEV. (Further details for other powertrain types are provided in Appendix A2).

The results for GHG emissions (in CO_2 equivalents for the GWP metric – global warming potential) clearly show the significant benefits of hybrid and electric powertrain vehicles (i.e. HEV, BEV and FCEV) in comparison to conventional diesel internal combustion engine vehicles (i.e. ICEV-D). Urban buses operate in conditions that are more ideally suited for electric vehicles than for other vehicle types, as they have known/set routes and electric powertrains are particularly efficient in the lower speed stop-start environments for urban operations. Conversely, conventional diesel vehicles are generally least efficient in urban traffic conditions. These factors, together with the significantly higher lifetime activity of buses versus passenger cars means that the lifecycle GHG benefits of increasingly electrified bus powertrains are even greater due to significant fuel (WTT + TTW) emissions savings. As for passenger cars, the greatest GHG (and cumulative energy) savings are achieved by battery electric buses, with already ~73% GHG emissions reduction compared to an equivalent conventional 2020 diesel bus (and rising to over 86% reduction for a 2050 new bus in the Net Zero Power scenario case).

Hybrid diesel (HEV-D) and hydrogen fuel cell electric (FCEV) urban buses also show significant GHG reduction benefits over conventional diesel buses (31% and 54% for new 2020 vehicles, respectively). However, as indicated earlier for passenger cars, buses fuelled mainly by hydrogen produced from electrolysis have a much higher lifecycle cumulative energy demand compared to battery electric buses – shown in Figure 2.5. This also has an economic impact that is not covered in this study but should be taken into consideration for energy and transport policy. The assumed hydrogen production mix is also summarised in Figure A3 in Appendix A1.2.

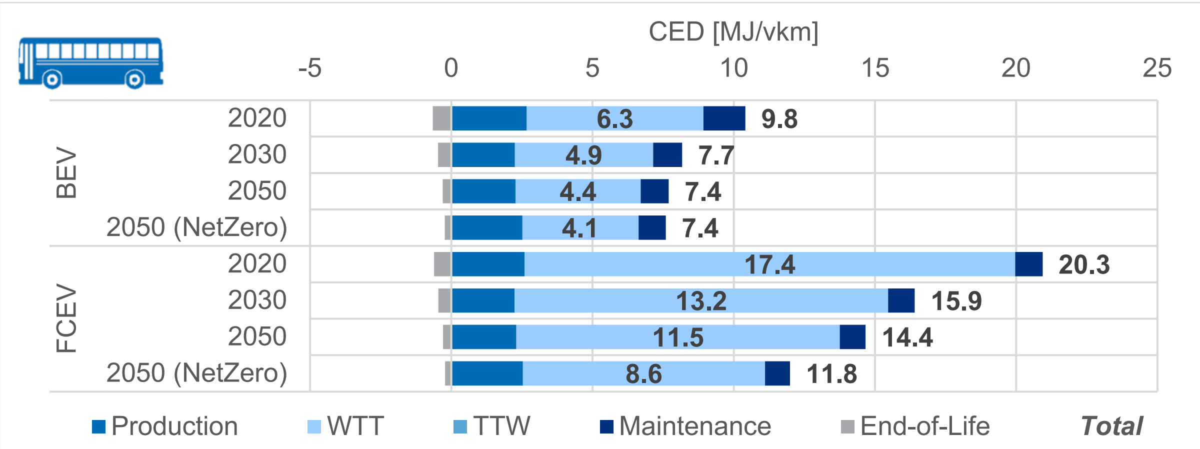
As also noted for passenger cars earlier, BECCS (biomass energy plus carbon capture and storage) technologies, are not included in either the electricity mix, nor for hydrogen production in our analysis. These technologies offer the potential for significant net negative GHG emissions for the UK.

For hybrid and electric buses the maintenance impacts in 2020 are higher than for other vehicle types due to the requirement for a mid-life battery replacement. However, no replacements are calculated to be required for later years from 2030 onwards, due to a combination of improved battery cycle life and higher capacity battery packs (i.e. which require fewer charge/discharge cycles to cover the same lifetime km).

The results also show that in these urban conditions, conventional compressed natural gas (CNG) fuelled buses (i.e. ICEV-CNG) do not provide GHG savings over conventional diesel buses. However, significant GHG savings are possible if the bus is operated on biomethane: ~51% using the 100% biofuel mix for 2030 (see Appendix A1.2 for further information on the 100% Biofuel blend, also discussed further in Section 3.2), compared to a conventional diesel bus.

The overall lifecycle emissions of air quality pollutants are in most cases also significantly reduced for the gas and electric powertrain buses compared to conventional Euro VI diesel buses (see Appendix A2 for further details). Importantly, particularly in urban environments, so-called 'zero-emission' powertrain buses (i.e. BEV and FCEV) generally only result in non-exhaust particulate emissions (from tyre and brake wear) at their point of use. Their use therefore significantly reduces human exposure to other harmful pollutants compared to vehicles with combustion engines.

Figure 2.5: Summary of breakdown of overall lifecycle cumulative energy demand impacts for urban buses for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)

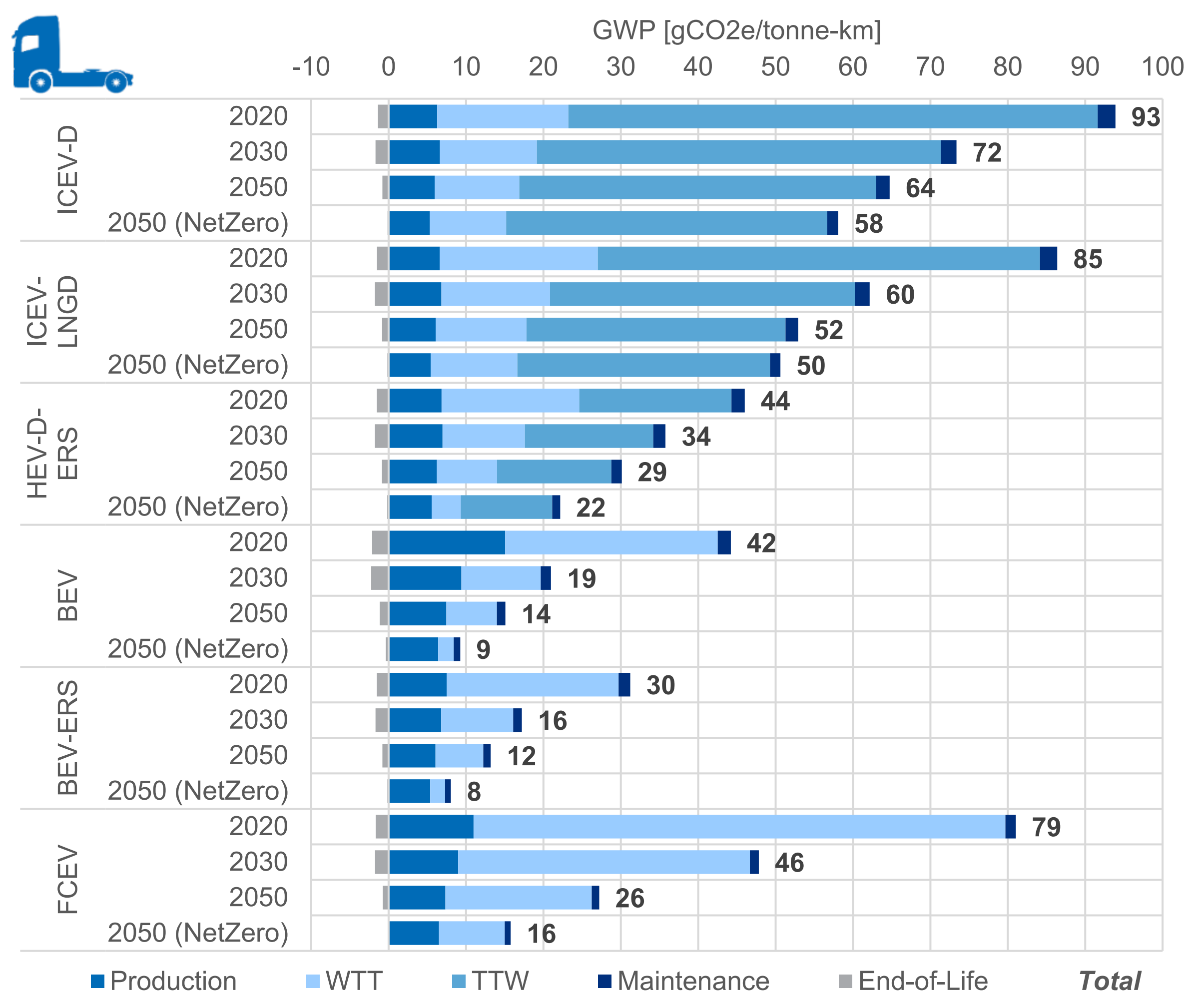


Notes: CED = cumulative energy demand. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix.

2.3 Articulated lorries

- ‘Zero Emission’ hydrogen and electric powertrains (xEVs) both offer potential for very significant lifecycle GHG emission reductions from articulated lorries due to their high lifetime activity.
  - Battery electric powertrains (both battery-only and catenary electric vehicles) offer the most significant lifecycle GHG reduction potential – around 74-78% for 2030, rising to 85-86% by 2050 (even including an estimate for reduced load capacity for these heavier vehicles).
  - Both hybrid diesel and battery electric catenary electric vehicles (operating on electric road systems – ERS) offer significant potential GHG savings compared to regular HEV and BEV.
  - Production emissions for BEVs are around 140% higher than diesel lorries in 2020 (mainly due to the batteries), but only account for up to 36% of total estimated lifecycle GHG emissions. This is because of the very high operational activity (and therefore impacts from energy use) of articulated lorries. By 2050 BEV production emissions could reach close to parity with those of conventional vehicles, due to battery manufacturing and technology improvements.
- Hydrogen fuel cell electric vehicles (FCEVs) also offer the opportunity to deliver large savings versus conventional vehicles. In 2030, the lifecycle GHG savings are estimated to save ~46% compared to a conventional diesel lorry, and by 2050, the GHG savings from a FCEV could increase to 73%.
- The analysis did not include biomass plus carbon capture and storage (CCS) directly for hydrogen, nor for electricity production, which could result in further significant reductions in emissions from FCEV or BEV (as this power combination delivers negative emissions).
- Impacts from building road-side infrastructure for ERS (electric road systems)/catenary electric vehicles (CEVs) are *not* included in the assessment. However, when spread over the vehicle fleet and considerable operational lifetime of the infrastructure, these are expected to be relatively small.
- A battery replacement would be expected to be needed for BEVs based on the current battery technology, the electric range/battery size for announced models and typical lifetime km activity. However, this may not to be necessary in the longer term, due to improvements in battery technology and higher capacity batteries (resulting in fewer full charge/discharge cycles).
- FCEV have a lower end-to-end energy chain efficiency compared to BEVs, with the cumulative energy consumption of hydrogen FCEVs being 2-3 times higher.
- Alternative and electric powertrains also provide significant reductions in direct air pollutant emissions - up to 100% for many pollutants for BEV and FCEV. This is particularly important to reduce human health impacts in urban environments. On a life-cycle basis impacts on human health are also expected to be significantly lower from alternative and electric powertrains, as emissions are lower, and occur further away from highly populated areas compared to conventional ICEVs.

Figure 2.6: Summary of breakdown of overall lifecycle greenhouse gas impacts for Articulated Lorries for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power scenario for 2050)



Notes: GWP = global warming potential for greenhouse gas emissions. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix.

Figure 2.7 provides a summary of the main results for the lifecycle greenhouse gas (GHG) emissions for a 40 tonne GVW articulated lorry operating in UK conditions[3] for a selection of key powertrain types, as well as a comparison of cumulative energy demand (CED) for BEV, BEV-ERS (i.e. battery catenary electric vehicle operating on an Electric Road System) and FCEV. (Further details for other powertrain types are provided in Appendix A2). *Note*: the results for 2020 are somewhat theoretical (i.e. represent technical potential) for many alternative powertrains, as real-world models are yet to be introduced.

The analysis for freight vehicles is presented in terms of impacts per tonne-km, and takes into account the lost freight carrying capacity of alternative fuel and electric powertrains due to their higher unladen mass (i.e. mainly due to gaseous fuel storage or traction batteries)[4]. (Electric range assumptions are provided in Appendix A1).

[3] The 40 tonne GVW vehicle is based on Ricardo's original study for DG CLIMA; in the UK slightly larger 44 tonne GVW articulated lorries are more commonly used.

[4] It is assumed that all vehicles operate the same number of vehicle-km over their lifetime, but that the useful tonne-km is based upon the same average % loading – so powertrains with greater unladen mass will deliver fewer tonne-km over their lifetime due to lower freight capacity. It does not take into account regulations for ZEVs which in some cases permit a higher permissible GVW due to the additional mass of energy storage.

Articulated lorries that typically operate on regional and long-haul operations require more significant range (and so more energy storage) compared to other vehicle types, and the efficiency benefits of electric powertrains are lower on longer distance higher speed driving profiles. Nevertheless, the lorries' much higher annual and lifetime activity also means that the benefits of reduced GHG from energy consumption are much more significant. Whilst vehicle production accounts for around 16% of total GHG emissions for conventionally fuelled passenger cars, it only accounts for around 7% of the total for articulated lorries. As a result, the analysis of lifecycle impacts shows similar trends in terms of the environmental benefits of alternatively fuelled and electric powertrains as for the other vehicle types.

Again, battery electric powertrains (i.e. BEV, BEV-ERS) show significantly greater lifecycle GHG and CED benefits than FCEV powertrains in all scenarios and periods, due to their higher efficiency leading to lower operational energy impacts (including also energy production chain efficiencies) and the very high lifetime km of articulated lorries. This differential also further increases in later years. The results for CED are particularly important in the context of potentially limited supplies of renewable electricity, as hydrogen FCEV require 2-3 times as much renewable electricity for their operation compared to battery electric alternatives. The performance of powertrains with hydrogen ICE is considerably worse (see Appendix A2), also in terms of GHG emissions, as these are significantly less efficient than FCEVs.

The results also show that catenary electric vehicles (i.e. HEV-D-ERS and BEV-ERS) show significant GHG benefits compared to similar non-catenary vehicles. For BEV-ERS powertrains, this is due to the lower battery size/mass versus a regular BEV, as well as lower losses from the catenary compared to battery charging. It should be noted that the impacts of the deployment of road-side catenary infrastructure systems are not included in the current analysis. However, based on Ricardo's recent analysis of the infrastructure requirements and costs for such vehicles (Ricardo Energy & Environment, 2019), the inclusion of such infrastructure impacts is not anticipated to significantly affect the outcome when spread over a reasonably sized catenary electric vehicle fleet.

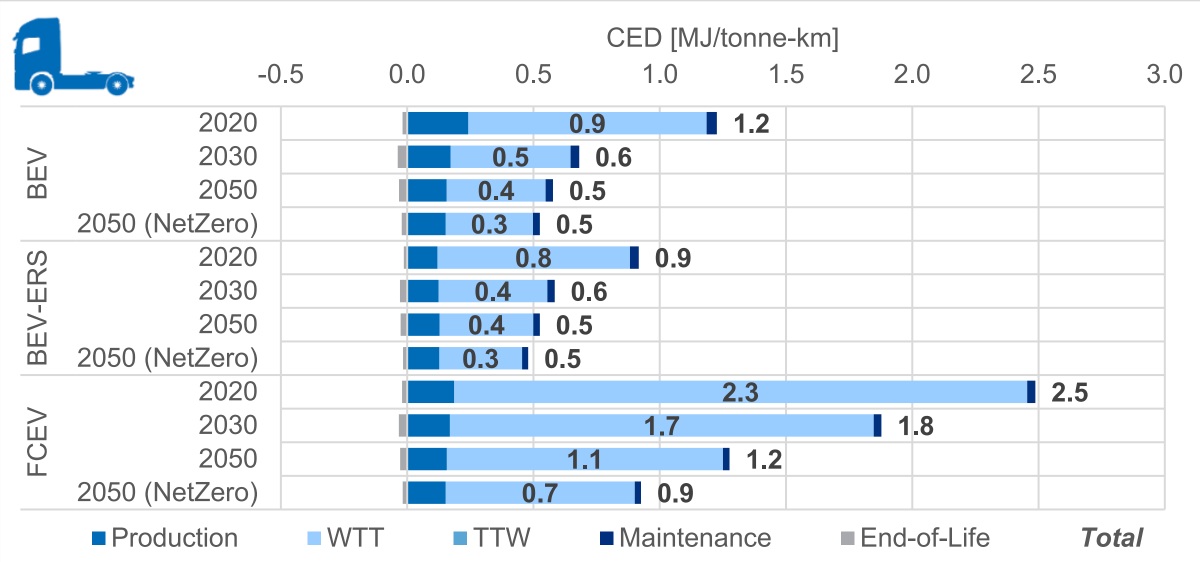
As for cars and buses, in future years the GHG emissions are projected to improve from all articulated lorry powertrain types, due to a combination of technical improvements to vehicle efficiency and xEV batteries, significant decarbonisation of UK electricity supply (and more modest decarbonisation of the conventional liquid fuel supply). As also noted for passenger cars earlier, BECCS (biomass energy plus carbon capture and storage) technologies, are not included in either the electricity mix, nor for hydrogen production in our analysis. These technologies offer the potential for significant net negative GHG emissions for the UK.

Vehicles fuelled by natural gas show modest improvements to lifecycle GHG emissions when operating on efficient LNG HPDI powertrains (which are significantly more efficient than conventional spark ignition LNG engines)[5]. More significant GHG reductions are also possible when operating on higher shares of liquified biomethane (LBM). Sensitivities on the comparative lifecycle performance of different powertrain types using 100% biofuels or synthetic e-fuels are provided in later Section 3.2.

The lifecycle air quality pollutant emissions from alternative fuel and electric powertrain vehicles were generally also found to be significantly lower than conventional diesel vehicles (see Appendix A2 for further details). Most (and in some cases) all of the air pollutant emissions occur in fuel (or vehicle production) for xEV powertrains in less populated areas (versus vehicle point-of-use emissions), and so the impacts on human health of these emissions are expected to be low. Lifecycle emissions of all vehicle powertrain types are reduced in future periods (due to improved operational efficiency and cleaner fuel and electricity production), so this is also likely to result in a reduction in associated human health impacts (depending on exposure/the locality of the emissions).

[5] Assumptions on the relative efficiency of LNG-fuelled SI and CI engines, and on the levels of methane slip, were based on Ricardo's experience with these technologies and also in particular UK testing results from (Cenex, 2019)

Figure 2.7: Summary of breakdown of overall lifecycle cumulative energy demand impacts for Articulated Lorries for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



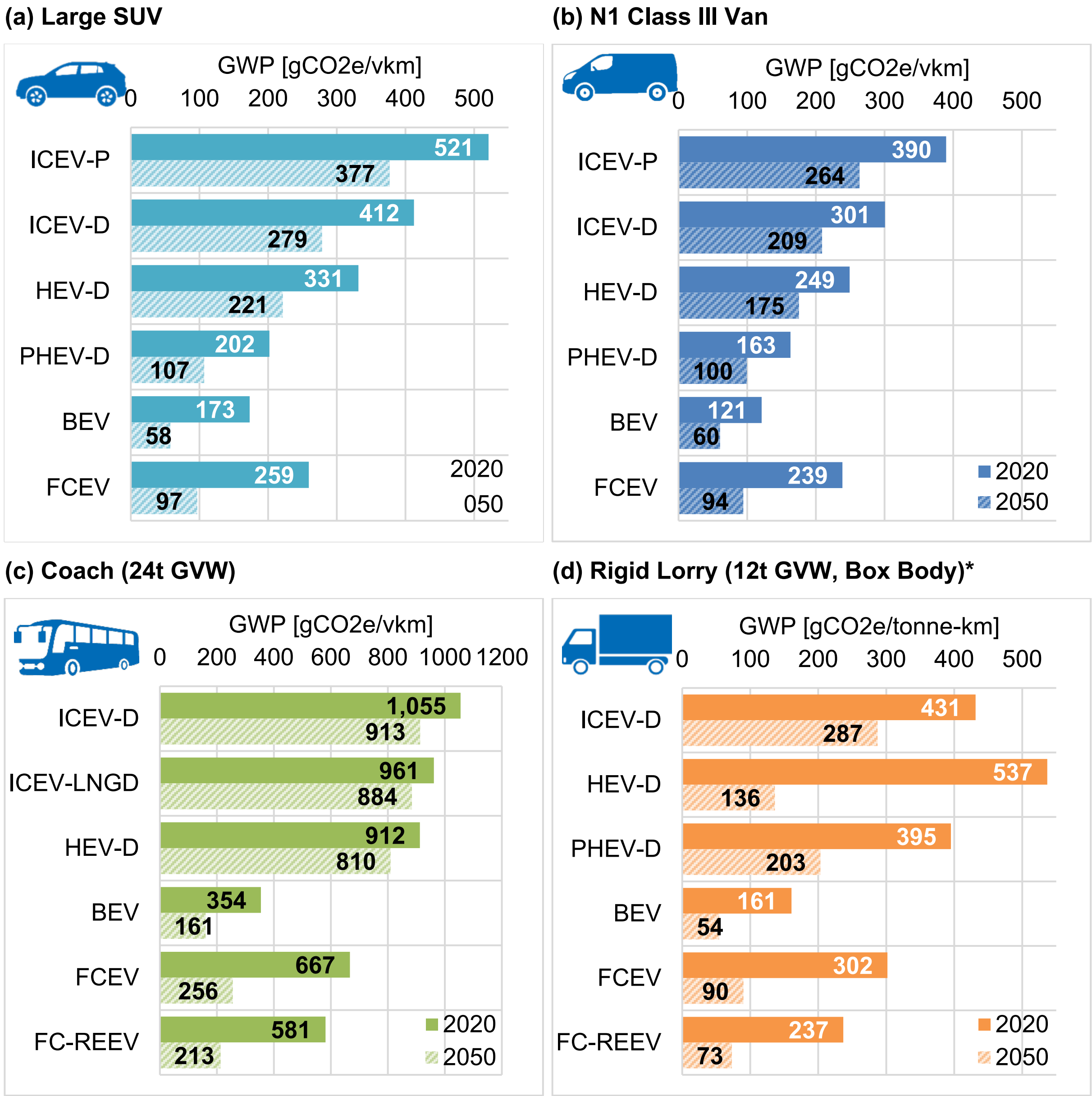
Notes: CED = cumulative energy demand. Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Results for '2050' are for the Baseline scenario conditions (e.g. improved energy mix, vehicle efficiency) and results for '2050 (NetZero)' present results for the Net Zero Power scenario with much more significant improvements in vehicle efficiency and energy mix. Analysis is based on an assumed 63% average loading factor, also used in the calculations for the 2021 UK Government's GHG conversion factors for company reporting (BEIS, 2021) and was calculated based on government freight statistics.

2.4 Other road vehicle types

- The LCA results for the other road vehicle types analysed show similar trends: electric powertrain vehicles (xEVs – including BEV, PHEV/REEV and FCEV) provide significant lifecycle greenhouse reductions compared to conventional petrol and diesel vehicles operating in UK conditions.
    - Battery electric vehicles (BEVs) provide GHG reductions ranging between 63% (for small 12t GVW rigid lorries) and 69% (for large Class III vans) in 2020. For the same vehicle types, these GHG savings could increase to 81% and 77% respectively by 2050.

The results of the LCA modelling calculations show similar trends as for the lower medium segment cars, urban buses and articulated lorries discussed in the previous sections of this report – i.e. with GHG reduction benefits (versus conventional vehicles) increasing with powertrain electrification level, and over time. The following Figure 2.8 provides a high-level illustration of these trends for total lifecycle GHG emissions for 2020 (Baseline) and 2050 (Net Zero Power scenario). For these other vehicle types, the relative benefits of electric vehicles are greatest for small rigid lorries, which frequently operate on urban delivery cycles, and least for intercity coaches with a high share of operation on higher-speed roads.

Figure 2.8: Summary of the overall lifecycle GHG impacts for other new 2020 and 2050 road vehicle types: (a) Large SUVs, (b) N1 Class III Vans, (c) Coaches (24t GVW), and (d) Rigid Lorries (12t GVW, Box Body)



Notes: GWP = global warming potential for greenhouse gas (GHG) emissions. *Analysis is based on an assumed 34% average loading factor, also used in the calculations for the 2021 UK Government's GHG conversion factors for company reporting (BEIS, 2021) and was calculated based on government freight statistics.

3 Sensitivity Scenarios

This section provides the analysis of four sensitivities on key parameters or assumptions for determining the LCA impacts of different vehicles, as outlined in Table 3.1. The results from this analysis are generally provided for GHG impacts of a passenger car, under the Net Zero Power scenario. In addition, a short summary of the conclusions from the sensitivity analysis for other vehicle types and periods is also provided where relevant.

Table 3.1: Summary of vehicle LCA modelling sensitivities

Sensitivity	Description	Variations	Area
UK Manufacturing	Comparison of the impacts of 100% UK manufacturing vs average import mix.	Default UK Import Mix / 100% UK production	Vehicle Production
Fuel selection	Comparison of impacts of the energy production chain/source on the overall environmental performance of vehicles	Baseline / Net Zero Power / Fossil / 100% Biofuel / e-Fuel	Vehicle Operation
PHEV range and use	Impact of different electric range and share of operation on electricity (e.g. due to use profile / charging behaviour)	Default / Low / High	Vehicle Operation
End-of-life	Sensitivity on vehicle and battery end-of-life assumptions – recycling recovery rates and second life for xEV batteries	Default / SVC* for battery and vehicle EoL / No recycling or 2nd life batteries.	Vehicle Production and End-of-Life

Notes: * Sustainable Value Chain = use of renewable energy for end-of-life recycling, improved recycling recovery rates versus baseline/default, and higher share of battery second life applications.

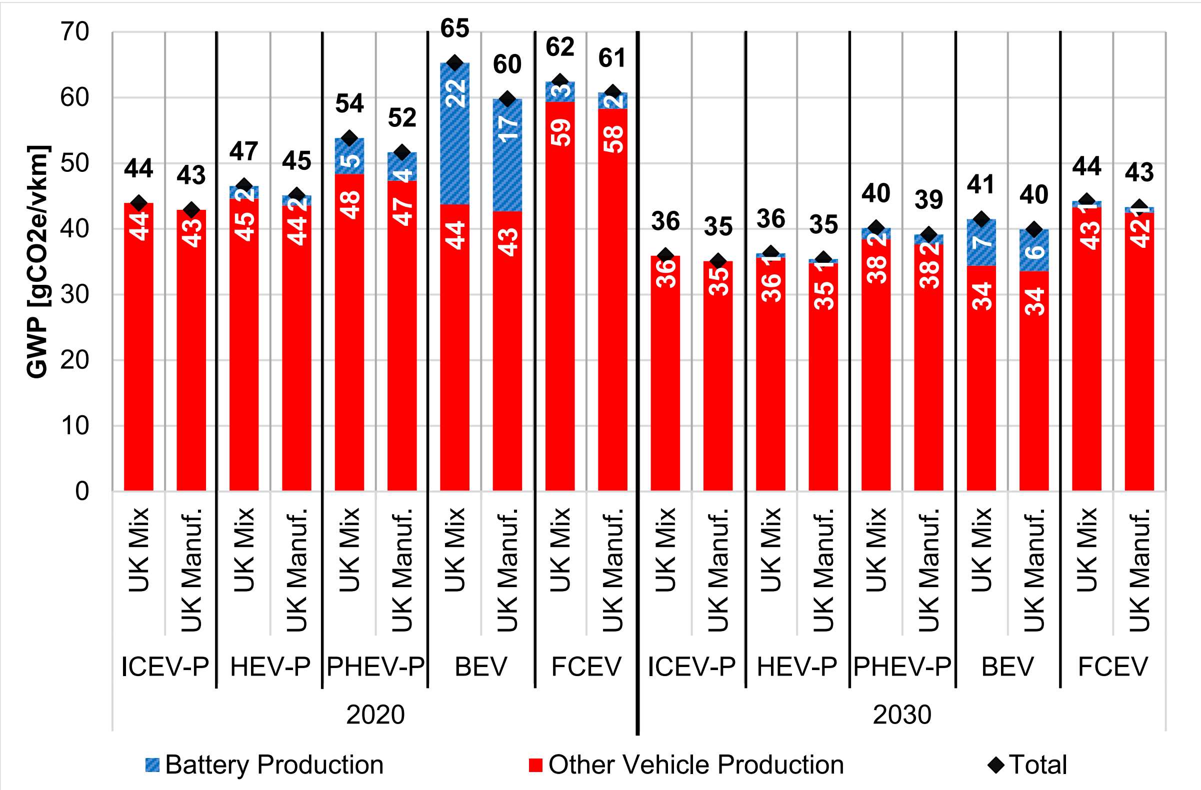
3.1 UK manufacturing

- GHG emission savings per vehicle-km can be achieved today by localising production of vehicles and batteries in the UK.
  - The benefits are more significant for xEV given that the manufacturing stage of these powertrains is responsible for a larger share of the total life cycle impacts: ~8% of the manufacturing GHG emissions can be saved by producing BEVs (including their battery) in the UK (for a lower medium car in 2020, compared to the current vehicle supply mix).
- Over time, the anticipated savings are expected to reduce due to the expected decarbonisation of electricity around the world, and the move to battery production in Europe from the rest of the world.
- The main contributing factor explored in this sensitivity consists of the differences in the carbon intensity of average electricity grid mixes in the key vehicle/battery production countries. Other factors (manufacturing techniques, efficiency, etc) have not been considered but could also affect the results and produce further benefits.

For vehicles used in the UK, this sensitivity explores the effects of an alternative scenario where all vehicle and battery manufacturing is located in the UK, compared to the current paradigm where only 9-10% of vehicle manufacturing and 0-9% battery production will take place in the UK (Figure A1 in Appendix A1.1).

Figure 3.1 shows that, for a lower medium car, the effects on the GHG impacts per vehicle-km (vkm) from the vehicle manufacturing stage are more significant for xEVs compared to the conventional powertrains but this effect is expected to diminish over time. Figure A23 in appendix provides the results of this sensitivity for the entire vehicle lifecycle.

Figure 3.1: Sensitivity on battery and vehicle production, Lower Medium Car, Net Zero Power Scenario - Vehicle manufacturing stage only



Notes: UK Manufacturing assumes 100% UK production of batteries and vehicles. UK mix is based on the average UK supply mix – see Appendix A1.1.

In 2020, the differences between the UK Mix (based on the average UK vehicle supply mix) and UK Manufacturing cases are larger for all powertrains, due to the lower carbon intensity of the electricity grid mix in the UK compared to other countries (e.g. EU27, Asia – see Figure A1 in appendix). These differences are more significant for xEVs and, in particular BEVs, given the higher use of electricity in the manufacturing of these powertrains and, in particular, the traction battery production.

Over time, the effects on the GHG impacts became smaller as a result of the widespread trend towards the decarbonisation of electricity across all key vehicle/battery production countries. For xEVs, the expected increase in the energy density of batteries is also expected to lead to lower impacts from the manufacturing stage and thus the effects become less significant.

This sensitivity has however only explored the effects of a more localised production based on the differences between the carbon intensity of electricity around the world. There are other important factors (e.g. manufacturing techniques, efficiency, etc) which have not been considered in this analysis but that could also affect the results.

3.2 Impacts of fuel selection – hypothetical scenarios on high levels of deployment of renewables, e-fuels and biofuels

- Significant greenhouse gas emission savings can be achieved when renewable electricity is used directly for BEVs (~78% reduced compared to the default 2020 petrol car; and a ~37% reduction compared to the same 2020 BEV car running on the average electricity grid mix over its lifetime).
- E-fuels produced with renewable electricity theoretically offer significant greenhouse gas emission savings versus ICEVs (~68% reduced compared to a petrol blend for a 2020 new vehicle). However, a BEV running on renewable electricity has lower GHG emissions than the equivalent ICEV using e-fuels in both light and heavy duty applications. A new BEV using renewables is estimated to save ~44% GHG emissions compared to an equivalent new ICE car

using e-fuels in 2030, and to save ~51% GHG emissions compared to an equivalent diesel articulated lorry using e-fuels in 2030.

- A hypothetical sensitivity test on an illustrative 100% biofuel blend for road transport suggests that conventional cars and lorries could theoretically reduce GHG emissions by ~70% compared to the equivalent car and ~52% reduction compared to the equivalent diesel articulated lorry*. However, a BEV running on renewable electricity has lower emissions (~44% compared to the equivalent petrol car using 100% biofuels and ~71% compared to an equivalent diesel articulated lorry on 100% biofuels for new vehicles in 2030).
- The use of e-fuels is also associated with much higher cumulative energy consumption over the vehicle's lifecycle compared to BEVs. In 2030, an articulated lorry running on e-fuels is estimated to use ~4.3 times more energy than the equivalent BEV running on renewable electricity. This will put significantly more pressure on the energy system at a time where it needs to achieve high levels of decarbonisation.
- The Net Zero Power scenario in 2050 in the sections above only assume a modest use of e-fuels or biofuels in road transport, as zero emission tailpipe technologies are assumed to be deployed, which can deliver larger CO_2 savings, conserving these fuels for difficult to decarbonise sectors.

Note: * The 100% biofuel blend would require the use of all potential biomass resources, irrespective of existing UK policies to limit the use of food and feed crops (for example), and with lower performing fuels negatively affecting the overall GHG savings, in particular for biodiesel produced from such feedstocks.

This sensitivity explores the effects of the energy production chain/source on the overall environmental performance of vehicles, using some hypothetical scenarios. As discussed above, the largest share of impacts for most powertrain types currently arises from the use stage and it is thus important to understand how these vehicles are affected by different choices in terms of energy chains.

Figure 3.2 provides an overview of the results of this analysis for two powertrains - conventional petrol ICEVs and BEVs:

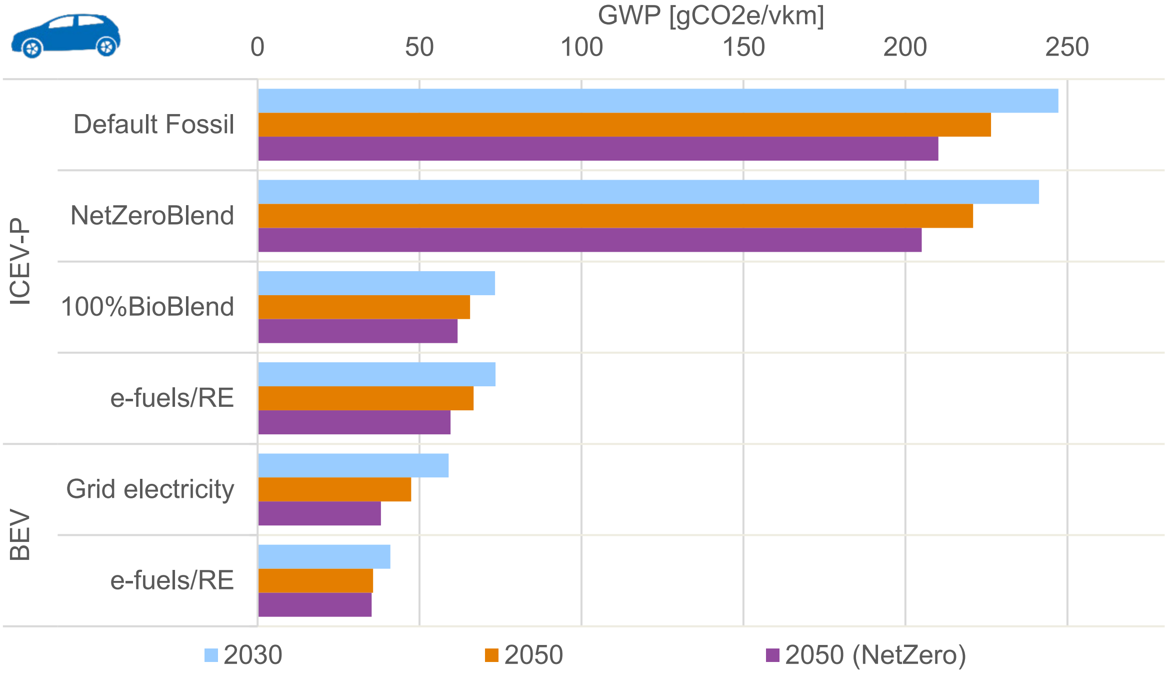
- In the case of BEVs, the main difference resides in the use of 100% renewable energy sources (in the e-fuels/RE option in the figure) compared to the use of average electricity grid mix.
- For ICEVs, different fuel blends are assumed – more details are provided in Appendix A1.2.

The assumptions behind these sensitivity tests have been quickly defined to highlight that it is likely that large scale deployment of e-fuels or biofuels in road transport will have higher emissions than a move to zero emission vehicles for road transport. The scenario for biofuels was developed by Ricardo and should not be seen as a projection of actual biofuel mix, but as one illustrative scenario. It does not necessarily reflect existing UK low carbon fuel policy and neither scenario is seen as a likely scenario for the deployment of these fuels in transport.

As expected, it shows that the GHG impacts are minimised when renewable electricity is used: directly for the BEV and in the form of e-fuels for the ICEV-P. Furthermore, the GHG impacts of the BEV in the best case are always lower than the ICEV-equivalent. In addition, the use of 100% biofuel blend (i.e. not including any e-fuels) in ICEV-P also results in significant reductions in GHG emissions.

Given the expected decarbonisation of electricity in the future, the overall GHG impacts from the BEV become lower and the net benefits of the BEV (in terms of lower impacts) increases compared to the ICEV-P.

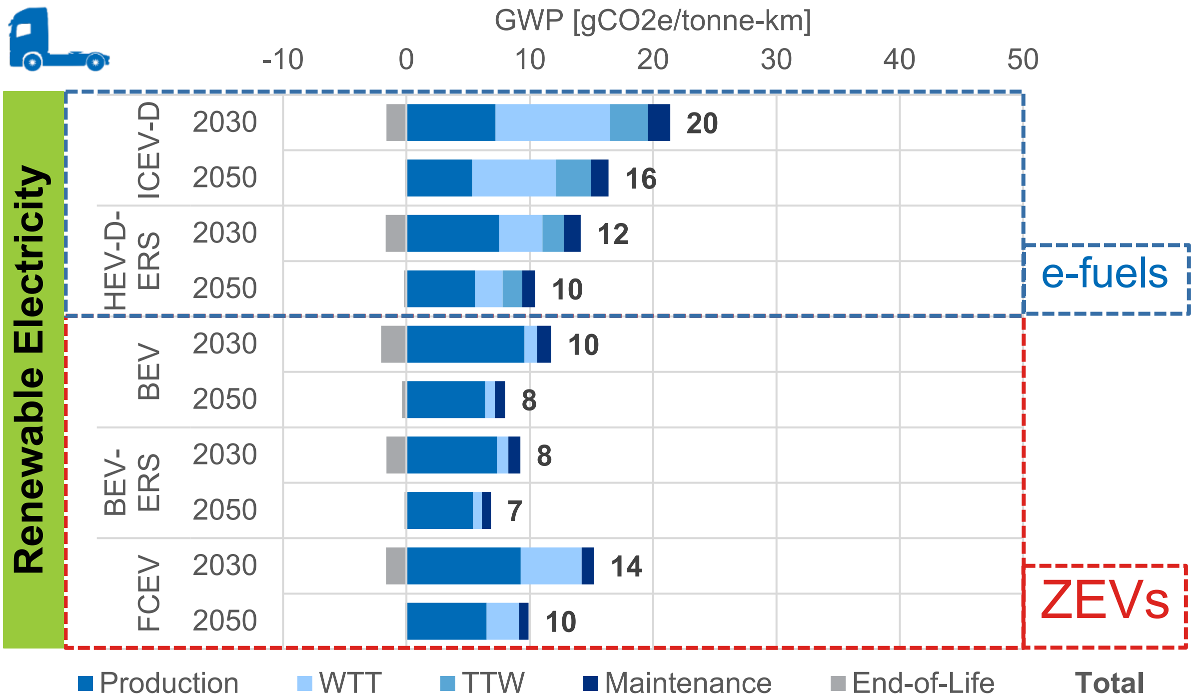
Figure 3.2: Summary of the influence of fuel/electricity chain assumptions on overall lifecycle GHG impacts for Lower Medium Cars for Gasoline ICEV and BEV powertrain types



Notes: Results are presented for operational energy consumption based on Baseline scenario for 2030 and 2050, and Net Zero Power scenario for 2050. Additional information on the fuel blends is presented in Appendix A1.2.

Similar trends are also seen for HDVs, particularly relevant given the challenges of electrifying heavier, long haul vehicles. However, the 100% biofuel GHG savings for biodiesel blends are lower as this scenario presumes that all available biomass resources (including those limited by current policies) are utilised, with fuels with a poorer GHG performance (e.g. biodiesel made from oil-producing crops) negatively affecting overall savings (see also Figure A26 in Appendix A2.5.2). In addition to the Figure 3.2 above for cars, Figure 3.3 presents the results for a range of powertrain options for an articulated lorry, in 2030 and 2050, running on renewable electricity (i.e. e-fuels in the case of ICEV and HEV powertrains and hydrogen produced via electrolysis for FCEV). It shows that the BEVs options tend to outperform the other powertrains even when these use low carbon fuels. The catenary electric vehicle option (BEV-ERS) has the lowest GHG impacts but these do not include any impacts from infrastructure. Furthermore, the potential performance of hybrid catenary electric vehicles (HEV-D-ERS) using e-fuels becomes slightly better than that of the FCEV using green hydrogen.

Figure 3.3: Summary of the influence of renewable electricity chain assumptions on overall lifecycle GHG impacts for Articulated Lorry, Net Zero Power Scenario

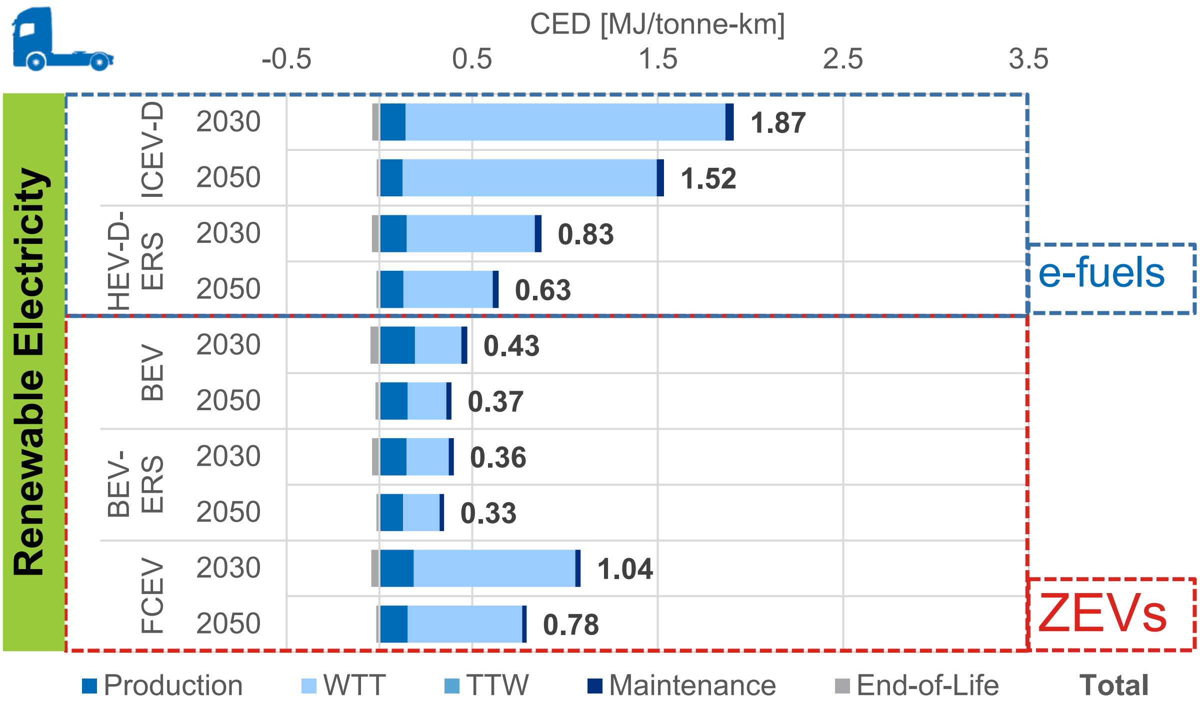


Notes: Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** (Well-to-Tank) = fuel/electricity production cycle; **TTW** (Tank-to-Wheel) = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

However, GHG emission performance is not the only important consideration, as the availability of renewable electricity is limited. Figure 3.4 provides the same analysis for cumulative energy consumption (CED) impacts. It shows that the cumulative energy demand across the lifecycle for use of e-fuels is significantly higher compared to electric and hydrogen fuel cell electric vehicles. Among the ZEVs, the FCEV requires significantly more energy than BEV (and BEV-ERS) over its lifecycle. An illustration of the cumulative losses across the energy chain and vehicle operation is provided also in Notes: Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** (Well-to-Tank) = fuel/electricity production cycle; **TTW** (Tank-to-Wheel) = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

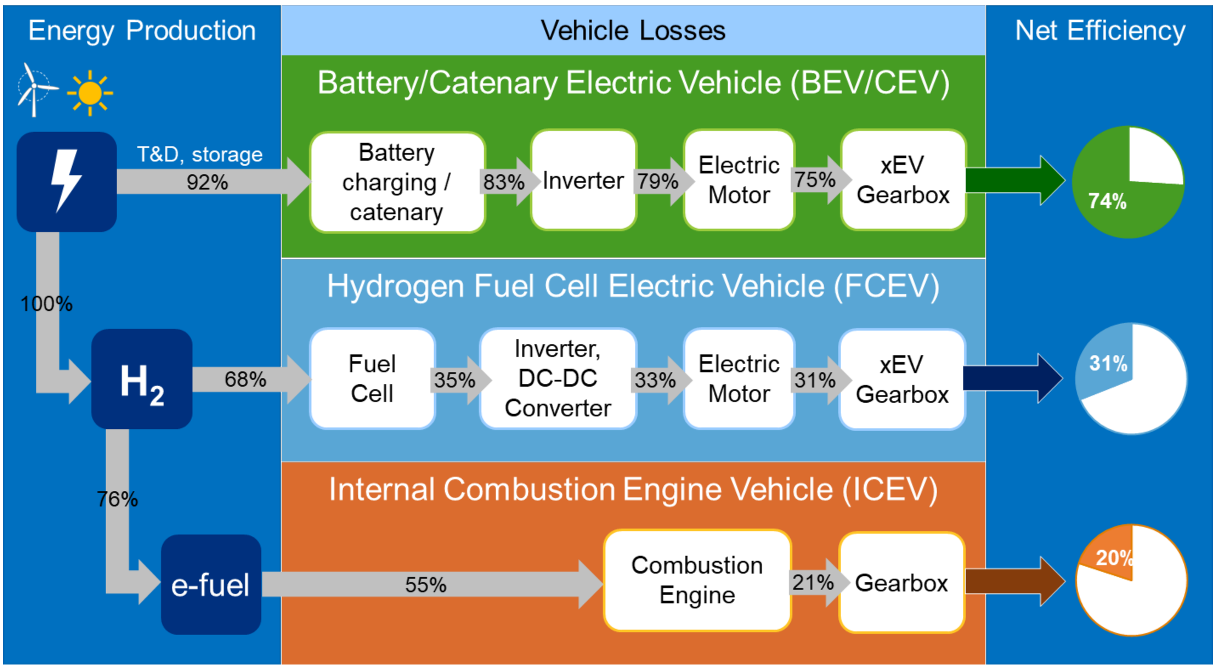
Figure 3.5 below.

Figure 3.4: Summary of the influence of renewable electricity chain assumptions on overall lifecycle CED impacts for Articulated Lorry, Net Zero Power Scenario



Notes: Key for lifecycle stages: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** (Well-to-Tank) = fuel/electricity production cycle; **TTW** (Tank-to-Wheel) = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

Figure 3.5: Illustration of the cumulative efficiency losses associated with converting electricity into motive energy for BEVs, FEVs and ICEVs



Notes: Illustrative schematic view based on typical conversion efficiencies, produced by Ricardo. e-fuels are produced by 'power-to-liquids' (PtL) process using hydrogen produced from electrolysis of water, captured CO_2 (from the air or other sources) and Fischer-Tropsch synthesis.

3.3 PHEV electric range and use

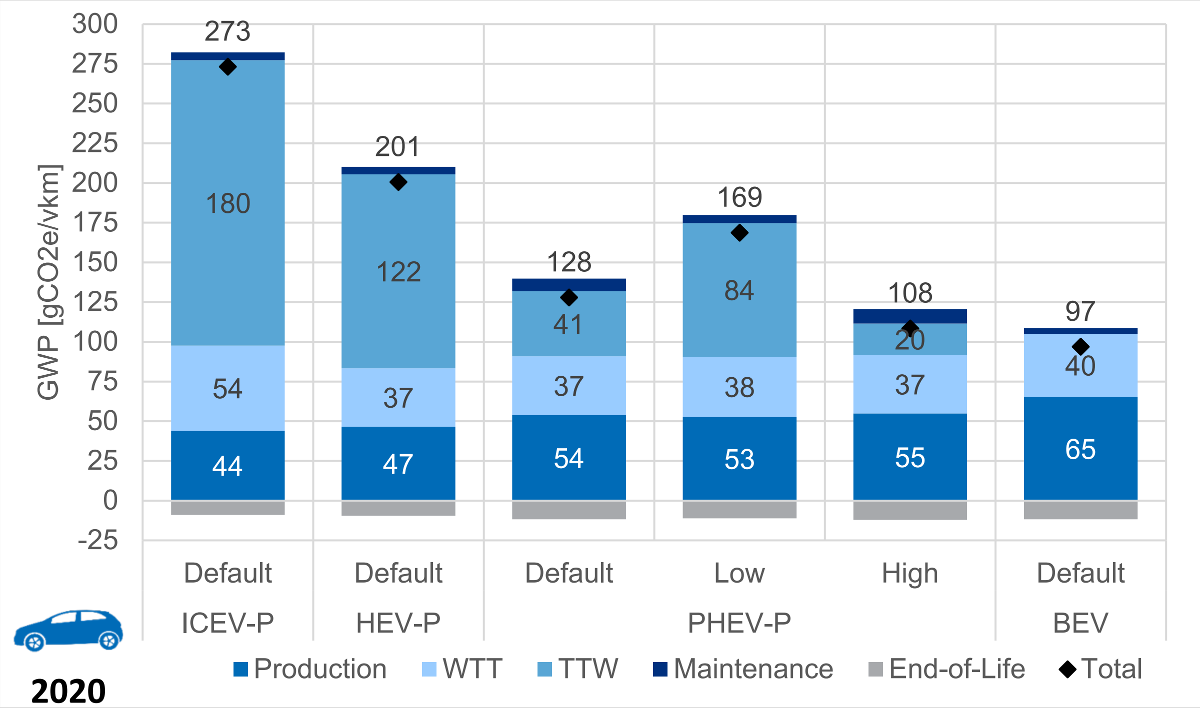
- The net GHG emission reducing benefits of PHEVs (compared to conventional vehicles) increase with the share of electric driving. This share depends on the available real world electric range of these vehicles as well as their use profiles and charging behaviour:
    - A PHEV with a higher electric range and higher share of electric driving could reduce emissions by 15% for a lower medium car in 2020 compared to the base assumptions.
    - However, a PHEV with a lower electric range and lower share of electric driving could increase emissions by 32% for a lower medium car in 2020 compared to the base assumptions.
- This analysis does not account for the full range of uncertainty on PHEV usage. For instance, if drivers do not charge PHEVs at all (i.e. effectively operating only as a full hybrid) then emissions can be over 57% higher than the default case – i.e. higher even than a petrol hybrid equivalent.
- The effect of the share of electric operation becomes more significant over time due to the expected decarbonisation of electricity which increases the net benefits of electric driving.

This sensitivity explores variations in the electric range and the electric driving share of plug-in hybrid electric vehicles (PHEVs), compared to the default assumptions in this study:

- Alternative assumptions for the electric range of PHEVs (low, high) are assessed to account for the uncertainty of real world electric ranges. This assumption in turn affects the share of electric driving of PHEVs. Figure A8 in Appendix A1.3 shows the variation in the assumptions on electric range modelled in this sensitivity analysis for different time periods. For 2020, the default regulatory electric range for a PHEV Lower Medium Car was assumed to be 50 km, with a low/high range sensitivity at 40 km / 60 km respectively.
- Variations in the use profiles and charging behaviour of PHEVs are also assessed. For cars and vans, this sensitivity is based on the WLTP Light Duty Vehicle utility function (UF) represented in Figure A9 in Appendix A1.3, but applied to the calculated real-world range (accounting for higher real-world consumption). It explores an optimistic and pessimistic case compared to the default utility function assumed which determines the share of electric driving.

As expected, higher overall GHG impacts are observed for the case with a lower share of electric driving (Figure 3.6 for a car in 2020). The effects of this sensitivity on the PHEV-P are also more significant for the low case (i.e. low electric range and low electric driving share). This reflects the larger difference in the assumptions on electric driving share between this case and the default case. The cases of HEV and BEV are also included for comparison. Their overall impacts are similar to those expected from the PHEV-P assuming 0% or 100% electric driving, respectively.

Figure 3.6: Sensitivity on PHEV electric range and use, Lower Medium Car, Net Zero Power Scenario, 2020



Notes: Lifecycle stages as per Figure 2.2. PHEV default elec. range = 50 km; low/high sensitivity = 40 km/60 km. Calculated real-world electric driving shares for PHEVs for default/low/high electric range *and* user charging behaviour = 69%/ 35%/ 85% of total km. See Figure A8 and Figure A9 in Appendix A1.3 for further information.

This sensitivity illustrates that the available electric range as well as the use and charging behaviour of these vehicles are very important factors to determine their overall net benefits. A low share of operation on electricity due to low range or use profile / charging behaviour significantly reduces the potential GHG savings these vehicle powertrains can offer.

Considering that these vehicles are expected to support the transition to a zero emission vehicle fleet, it will be important to ensure that their potential net benefits are maximised. For example, setting minimum (real world) electric range requirements or making EV charging options more widely available would provide incentives for the higher use of these vehicles on electric mode.

In the future, these effects are expected to become even more pronounced as the differences between the low case and default case increase. This is due to the increasing benefits from electric driving associated to the future decarbonisation of electricity.

3.4 End-of-Life (EoL) assumptions

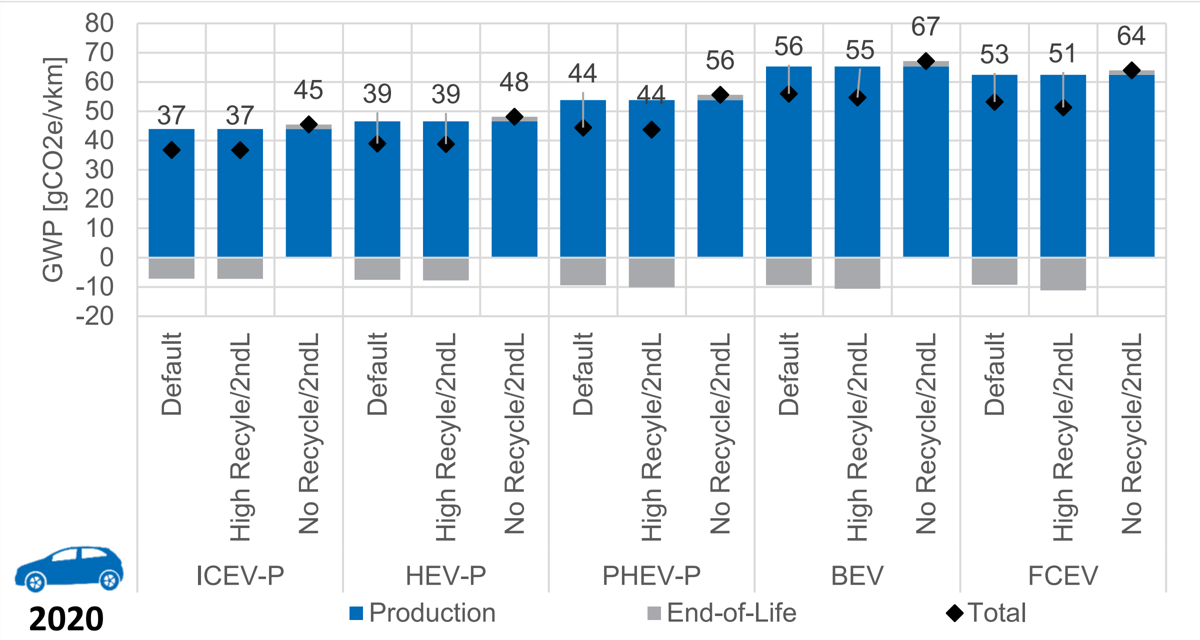
- End-of-life recycling and energy recovery is estimated to reduce the net greenhouse gas (GHG) impacts resulting from vehicle production and end-of-life disposal by up to 18%.
- The absolute GHG reduction benefits resulting from a higher level of recycling and higher share of battery re-purposing/second life are greater for xEVs compared to petrol/diesel vehicles.
- In 2030, higher xEV battery recycling and re-purposing is expected to have a diminishing effect on GHG as batteries which are replaced will have had a lower impact associated with their manufacture and the grid electricity assumed in the default case also decarbonises.
    - However, recovery of scarce critical materials will also be important at a system-level to help ensure sufficient future supply for the production of new vehicles/batteries.

This sensitivity assesses the effects of varying assumptions on the share of vehicle and battery recycling and the share of xEV batteries going to second life applications. It is intended to account for the uncertainty around these processes. In particular, the re-purposing of batteries is still at early stages and is modelled in this study as a credit for the avoided use of an equivalent new battery. Two different cases were assessed in comparison to the default case:

- **High recycling and high share of battery re-purposing**: assumes higher recycling rates, more sustainable end-of-life processes (i.e., lower carbon-intensive electricity) and a slightly higher share of battery repurposing (see Figure A10 in Appendix A1.4) compared to the default case.
- **No recycling and no battery re-purposing:** assumes materials in vehicles and batteries are not recycled, and that batteries are not used in second life applications.

Figure 3.7 below shows that the effects on GHG impacts per km, focusing on the production and end-of-life stages only (i.e. vehicle embedded emissions), can be significant for a lower medium car in 2020. As expected, the high recycling and battery re-purposing case leads to lower impacts, in particular for xEVs compared to conventional powertrains. A similar figure presenting the results on Abiotic Resource Depletion of Minerals and Metals (ARD_MM) is also presented in Figure A27 in Appendix A2.5 to show how these assumptions affect the recovery of key materials.

Figure 3.7: Sensitivity on end-of-life assumptions, Lower Medium Car, Net Zero Power Scenario, 2020 – Vehicle embedded GHG emissions only



Notes: Lifecycle stages as per Figure 2.2.

For a 2030 car, the effects are expected to become smaller due to two factors: improvements in battery production over time mean that the batteries to be replaced in the future had a lower manufacturing impact and thus the credit obtained from their re-use is smaller; in addition, the expected decarbonisation of electricity in the future in the default case reduces the net benefits from the more sustainable end-of-life processes.

This sensitivity shows the importance of recycling and battery re-purposing, especially for the xEV powertrains entering the fleet today. In addition, at the system/fleet level, recycling of critical materials will also be important to ensure sufficient supply for the production of new vehicles/batteries.

4 References

BEIS. (2020). *Updated energy and emissions projections 2019; Main report and Annex O - Net Zero and the power sector scenarios.* Retrieved from .GOV: https://www.gov.uk/government/publications/updated-energy-and-emissions-projections-2019

BEIS. (2021). *2021 Government Greenhouse Gas Conversion Factors for Company Reporting: Methodology Paper for Conversion Factors.* A report by Ricardo Energy & Environment for the UK Department for Business, Energy and Industrial Strategy (BEIS). Retrieved from https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

BEIS. (2021a). *Impact Assessment for the sixth carbon budget.* Retrieved from legislation.gov.uk: https://www.legislation.gov.uk/ukia/2021/18/pdfs/ukia_20210018_en.pdf

Bui, M., Zhang, D., Fajardy, M., & Mac Dowell, N. (2021). Delivering carbon negative electricity, heat and hydrogen with BECCS – Comparing the options. *International Journal of Hydrogen Energy, Volume 46*(Issue 29), Pages 15298-15321. doi:https://doi.org/10.1016/j.ijhydene.2021.02.042

CE Delft et al. (2017). *Assessment of the Modalities for LDV CO2 Regulations beyond 2020.* A report by CE Delft, TNO, TM Leuven and Cambridge Econometrics for the European Commission, DG Climate Action. Retrieved from https://ec.europa.eu/clima/sites/clima/files/transport/vehicles/docs/ldv_co2_modalities_for_regulations_beyond_2020_en.pdf

Cenex. (2019). *Dedicated to Gas - An Innovate UK Research Project to Assess the Viability of Gas Vehicles.* Innovate UK. Retrieved from https://www.cenex.co.uk/app/uploads/2019/11/Dedicated-to-Gas-Assessing-the-Viability-of-Gas-Vehicles.pdf

EUROBAT. (2021). *Avicenne study: "EU battery demand and supply (2019-2030) in a global context" shows that in the next decade lead and lithium batteries are critical to clean energy transition.* Retrieved from EUROBAT: https://www.eurobat.org/news-publications/press-releases/492-avicenne-study-eu-battery-demand-and-supply-2019-2030-in-a-global-context-shows-that-in-the-next-decade-lead-and-lithium-batteries-are-critical-to-clean-energy-transition

European Commission. (2018). *A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy.* European Commission, IN-DEPTH ANALYSIS IN SUPPORT OF THE COMMISSION COMMUNICATION COM(2018) 773. Retrieved from https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

ifeu. (2020). *Climate-friendly road freight transport – putting catenary trucking in context.* Retrieved from The Centre for Sustainable Road Freight: http://www.csrf.ac.uk/wp-content/uploads/2020/10/2.-2020-09-10-ifeu-Putting-ERS-into-context-V2-clean.pdf

NikkeiAsia. (2020). *Toray boosts carbon fiber output for fuel cell vehicles by 50%*. Retrieved from NikkeiAsia: https://asia.nikkei.com/Business/Materials/Toray-boosts-carbon-fiber-output-for-fuel-cell-vehicles-by-50

Ricardo. (2018). *Understanding the life cycle GHG emissions for different vehicle types and powertrain technologies.* Final Report for LowCVP (Low Carbon Vehicle Partnership). Retrieved from https://www.lowcvp.org.uk/assets/reports/LowCVP-LCA_Study-Final_Report.pdf

Ricardo Energy & Environment. (2019). *Zero Emission HGV Infrastructure Requirement.* A report by Ricardo Energy & Environment for the Committee on Climate Change. Retrieved from https://www.theccc.org.uk/publication/zero-emission-hgv-infrastructure-requirements/

Ricardo Energy & Environment et al. (2015). *Light weighting as a means of improving Heavy Duty Vehicles' energy efficiency and overall CO2 emissions.* A report by Ricardo Energy & Environment, Ricardo UK, TEPR, Millbrook and TRT for the European Commission, DG Climate Action. Service Request 2 under the HDV framework contract ref.

CLIMA.C.2/FRA/2013/0007. Retrieved from http://ec.europa.eu/clima/policies/transport/vehicles/heavy/docs/hdv_lightweighting_en.pdf

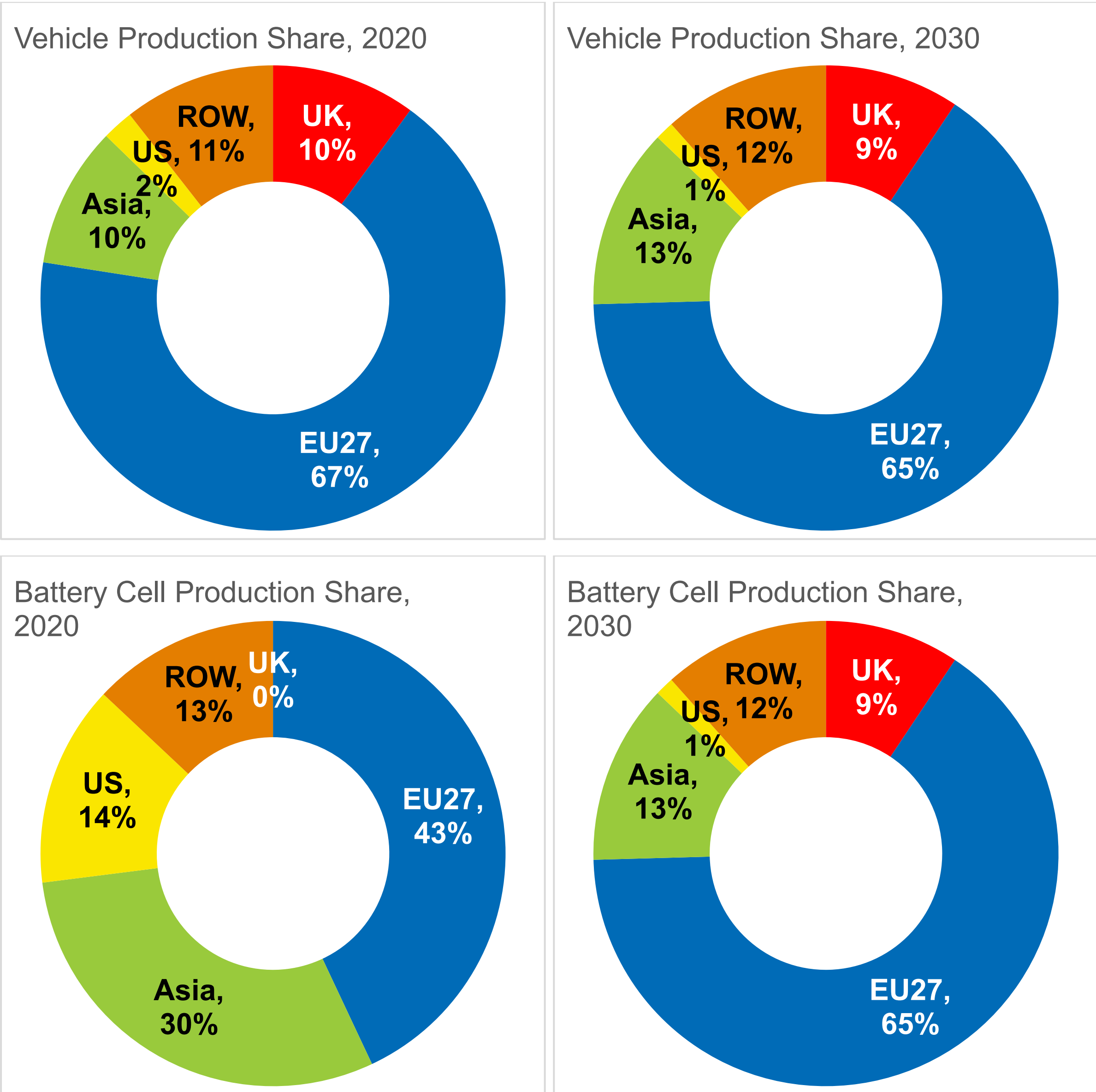
Ricardo et al. (2020). *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA.* A report by Ricardo, ifeu and E4tech for the European Commission, DG Climate Action. Retrieved from https://ec.europa.eu/clima/policies/transport/vehicles_en#tab-0-1

T&E. (2020). *Electrofuels? Yes, we can … if we're efficient.* Retrieved from Transport & Environment: https://www.transportenvironment.org/sites/te/files/publications/2020_12_Briefing_feasibility_study_renewables_decarbonisation.pdf

A1 Appendix 1: Selected key input assumptions used in the lifecycle assessment calculations

A1.1 Manufacturing

Figure A1: Shares of vehicle and battery production as a % of total vehicles registered in the UK

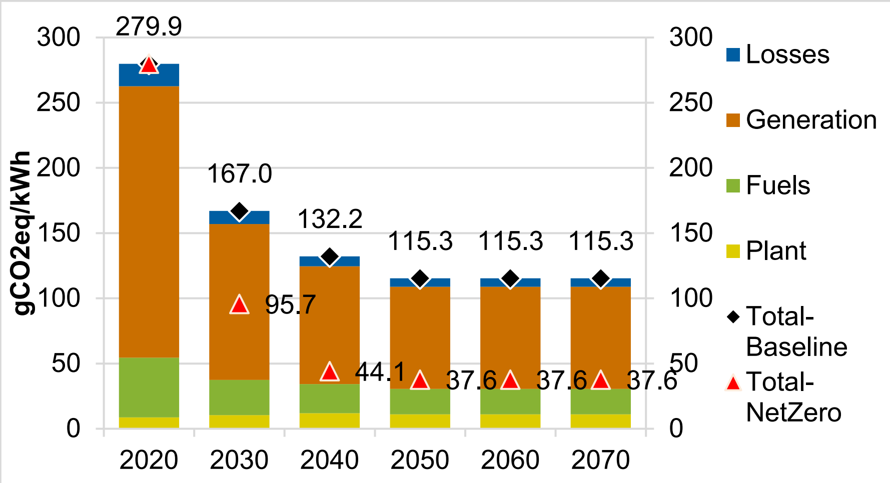


Notes: Manufacturing shares for Asia and for the EU27 are broken down into further detail in the LCA modelling based on confidential data provided by DfT, which cannot be presented here. Based on analysis of the planed/projected European battery production capacity, it is expected that Europe will be self-sufficient in battery manufacturing for automotive applications before 2030, e.g. (EUROBAT, 2021).

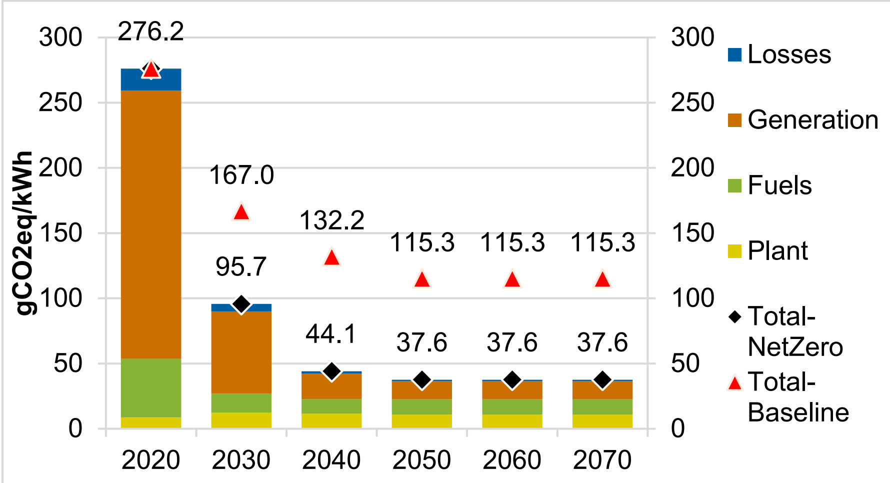
A1.2 Fuels and Electricity

Figure A2: Greenhouse gas impacts calculated from the UK average electricity generation mix, used in the overall Vehicle LCA modelling

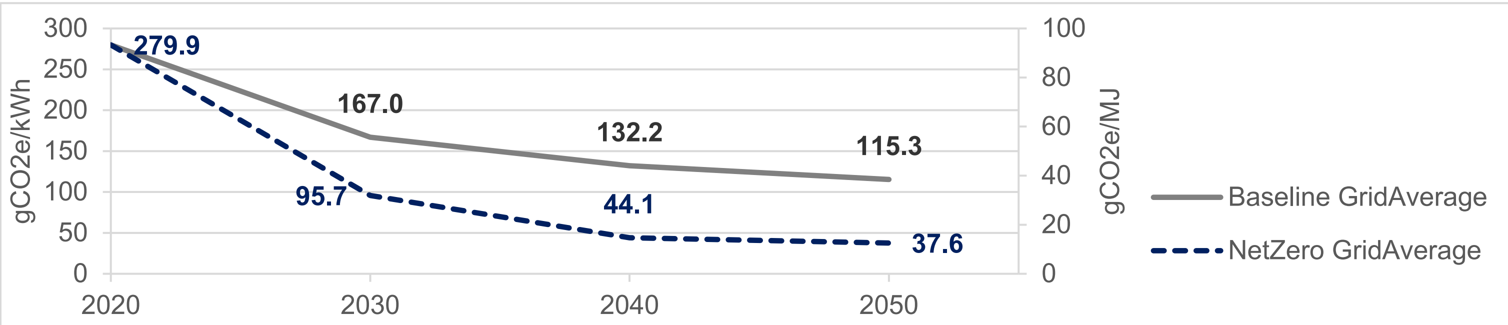
UK Electricity generation GHG impacts, Baseline Scenario



UK Electricity generation GHG impacts, Net Zero Power Scenario

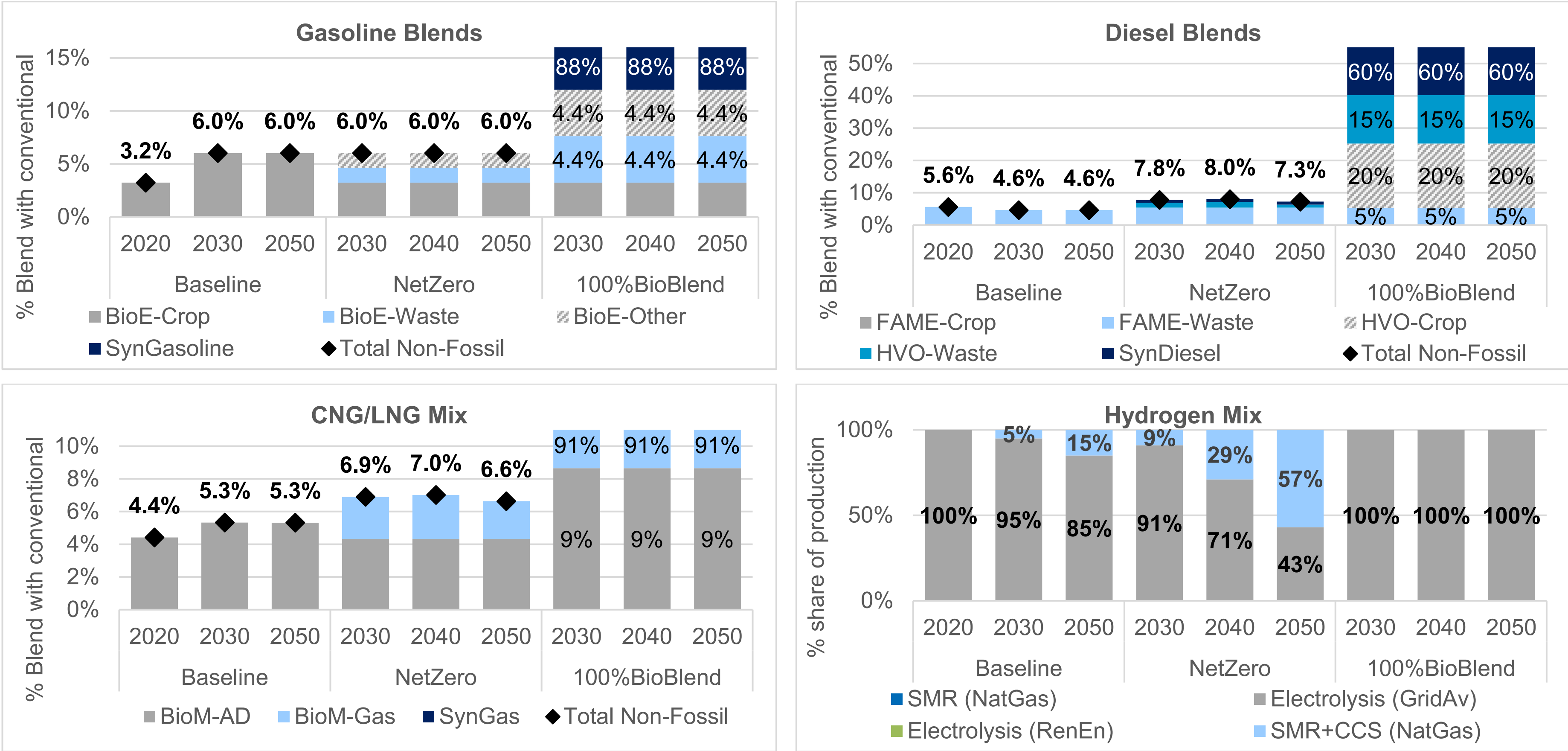


UK Electricity generation grid average GHG impacts, Baseline and Net Zero Power Scenarios



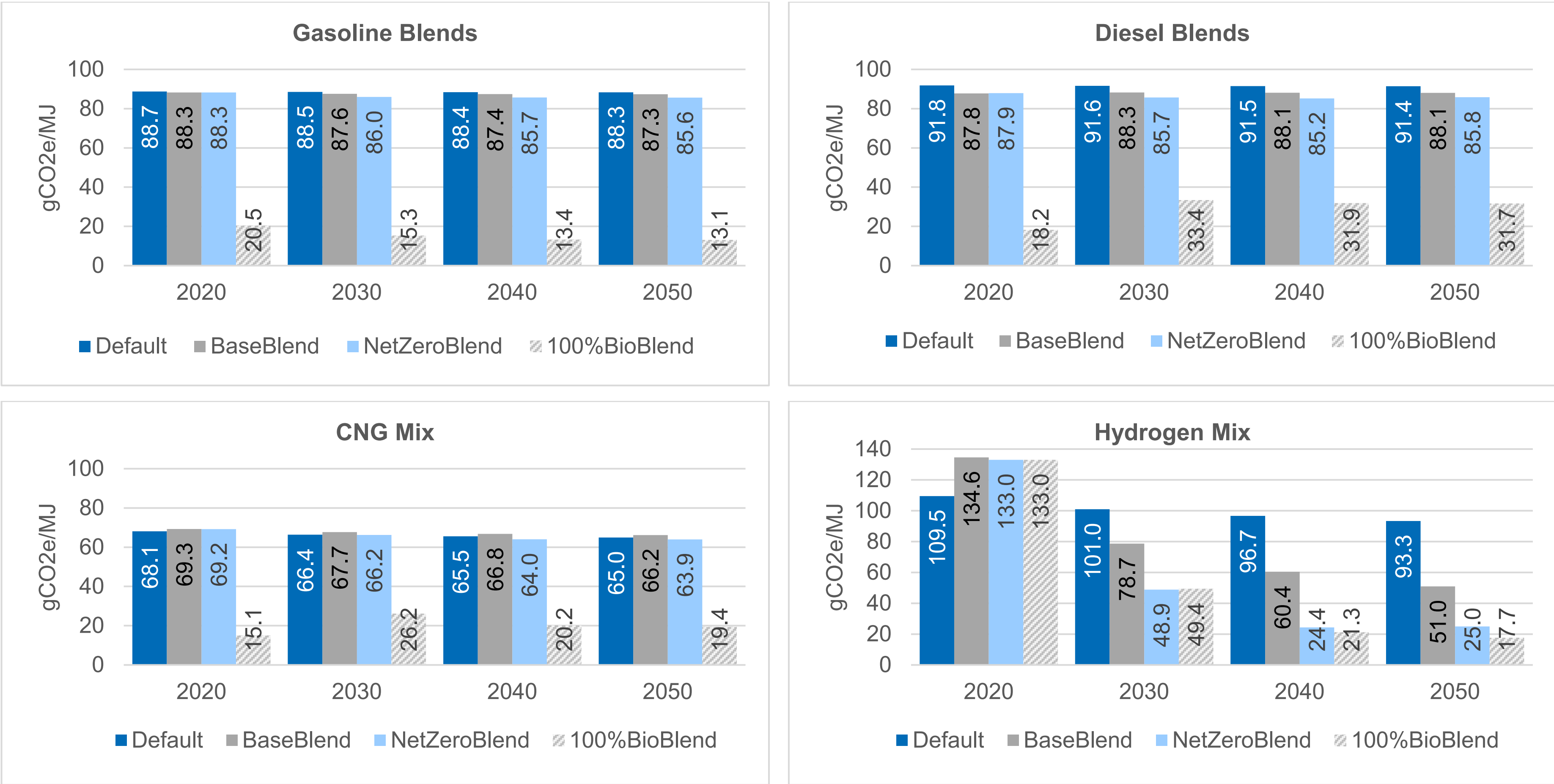
Notes: The mix of electricity power generation is based on BEIS illustrative baseline and net zero electricity demand and generation scenarios provided by UK BEIS (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/947439/energy-emissions-projections-2019-annex-o-net-zero-power-sector-scenarios.pdf). The data are based on their scenario modelling from (BEIS, 2020), with our Net Zero Power scenario based on an average of the BEIS low and high Net Zero scenarios. Emissions from each power generation source, and net GHG impacts were calculated for this project using Ricardo's electricity LCA model. Therefore, estimates of emissions will differ from BEIS estimates.

Figure A3: UK fuel blend/production mix assumptions used in the overall Vehicle LCA modelling, as a percentage of the total including conventional fossil fuels



Notes: The diesel and gasoline blends were provided by DfT, for a baseline and Net Zero Power scenario. These do not reflect the latest policy development and analysis changes to the RTFO. The hydrogen mix came from analysis supporting the BEIS sixth carbon budget Impact Assessment (BEIS, 2021a), with the option of biomass gasification and CCS removed, and hydrogen reallocated to electrolysis or SMR + CCS. The baseline hydrogen uptake scenario was developed by Ricardo-EE assuming that only low levels of SMR+CCS was available (which is consistent with assumptions on the electricity grid), and selecting electrolysis using grid average emissions above SMR, due to the lower emissions. The blend/mix of fuel production chains assumed are only indicative as these were limited by the subset of the currently available fuels that have been modelled as part of this project. BioE = bioethanol, BioM-AD = biomethane from anaerobic digestion process chains, BioM-Gas = biomethane from gasification process chains, SynGasoline / SynDiesel includes biomass-to-liquid (BtL) chains. No e-fuel / PtX chains are included in these scenarios, however a separate sensitivity on 100% e-fuels was also conducted. As noted elsewhere including biomass gasification and CCS could significantly reduce emissions from hydrogen and electric vehicles (as this technology has negative emissions).

Figure A4: Summary of GHG impacts resulting from the UK average fuel blend/production mix assumptions used in the overall Vehicle LCA modelling



Notes: The blend/mix of fuel production chains assumed are only indicative as these were limited by the subset of the currently available fuels that have been modelled as part of this project. Default values are for 100% fossil diesel, gasoline or natural gas and in the case of hydrogen SMR reforming of natural gas; BaseBlend is the blend assumed under the baseline scenario and NetZeroBlend is the blend assumed under the Net Zero Power Scenario. The 100% BioBlend scenario represents a sensitivity whereby an illustrative 100% biofuel substitution is achieved for all liquid and gaseous fuel types from 2030 onwards, as defined by Ricardo. No e-fuel / PtX chains are included in these fuel mix scenarios, however a separate sensitivity on 100% e-fuels was also conducted.

A1.3 Vehicle operation

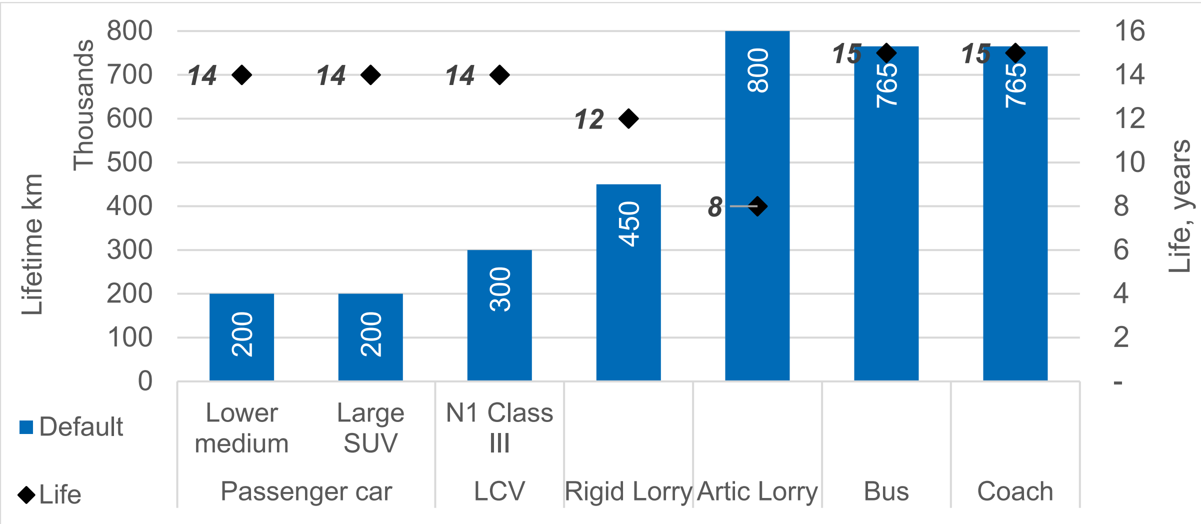
Table A1: Reference vehicle and powertrain characteristics used in the analysis

Vehicle Type	Powertrain Reference	Cycle	Energy, MJ/km	Mass, kg	GVW, kg	Power, kW	Average Load, %	Capacity, kg
Car Lower Medium	ICEV-P	WLTP	2.15	1,325	2,500	96	N/A	N/A
Car Large SUV	ICEV-D	WLTP	3.07	2,149	3,500	182	N/A	N/A
Van N1 Class III	ICEV-D	WLTP	2.72	2,217	3,500	106	41%	1,208
Rigid Lorry 12t GVW Box	ICEV-D	Urban Delivery	10.10	6,130	12,000	175	34%	5,795
Artic Lorry 40t GVW Box	ICEV-D	Long Haul	12.95	14,377	40,000	325	63%	25,548
Bus 12m Single Deck (SD)	ICEV-D	Urban Bus	12.60	12,008	18,000	175	20%	5,917
Coach 24t GVW SD	ICEV-D	Coach	9.36	13,335	24,000	350	30%	10,590

Source: Based on market average data for LDVs (cars and vans), and default values/results from VECTO simulation of generic vehicle types for HDVs.

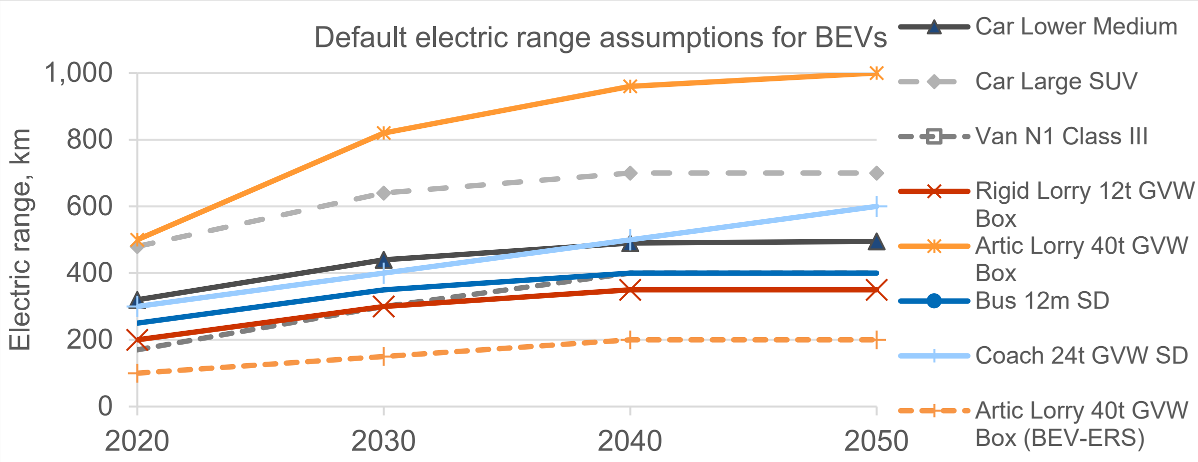
Notes: Energy consumption, vehicle unladen mass and total payload capacity are calculated within the LCA model for the other different powertrain types. Mass and capacity parameters are calculated based on the scaling parameters for different system components and other factors, such as the electric range (which affects the size/mass of the required battery).

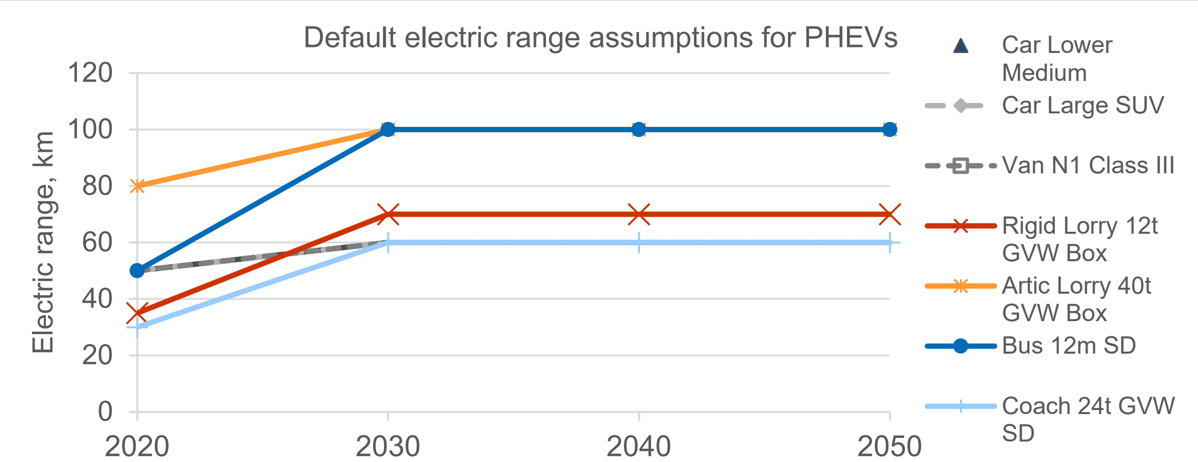
Figure A5: Summary of the default assumptions on lifetime kilometre activity and life in years



Source: Default assumptions provided by DfT, based on analysis of UK vehicle licensing statistics.

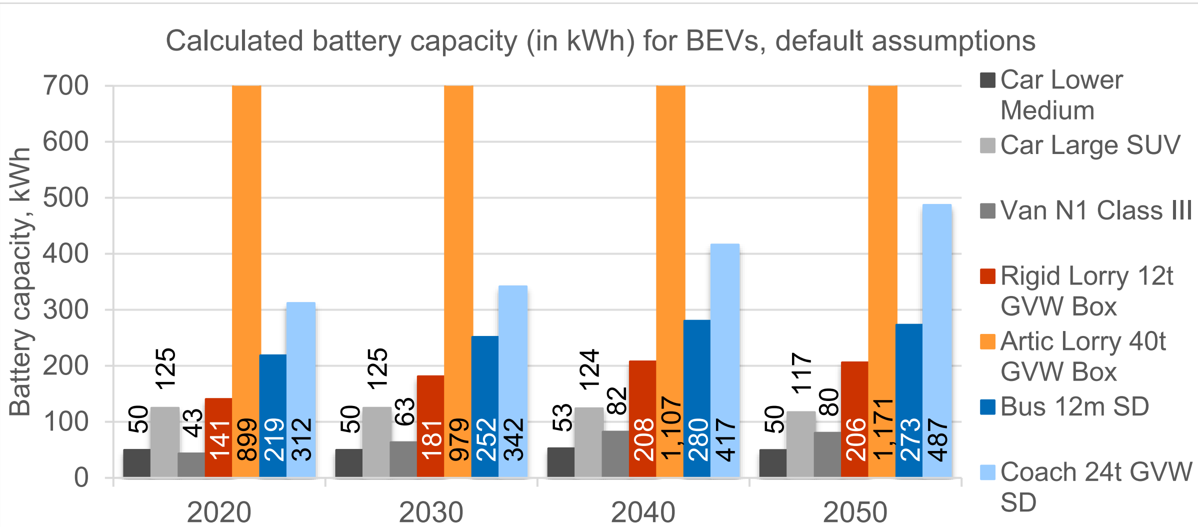
Figure A6: BEV and PHEV electric range default assumptions by vehicle type





Notes: Electric range defined based on standard test cycle, which is WLTP for LDVs. For HDVs the following base VECTO cycles are assumed: Rigid = Urban Delivery, Artic = Long haul, Bus = City urban bus, Coach = Coach. Study assumptions for electric range based on a market analysis by Ricardo for available and proposed models, and future expectations based on mass deployment and battery technology improvements and cost reduction.

Figure A7: BEV battery capacities by vehicle type, calculated based on the study methodology using default electric range and baseline vehicle energy consumption projections



Notes: Future battery capacities are lower in the Net Zero Power scenario as this assumes greater future improvements in overall vehicle efficiency, therefore requiring smaller batteries to achieve the same overall electric range. Calculated battery capacities for BEV-ERS Articulated Lorries are 169 kWh in 2020, and reach 217 kWh by 2040.

Figure A8: Assumptions on WLTP electric range for Lower Medium Car PHEVs and the high/low sensitivities on this

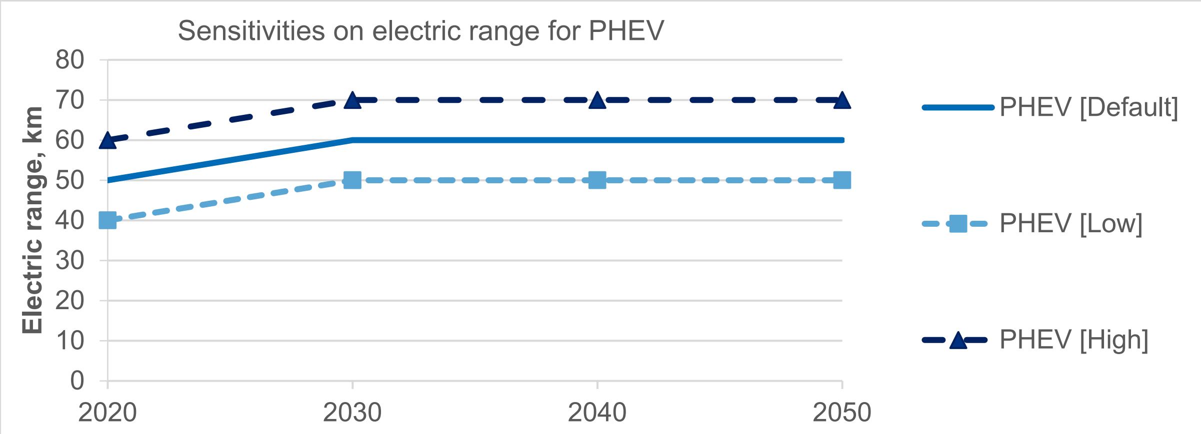
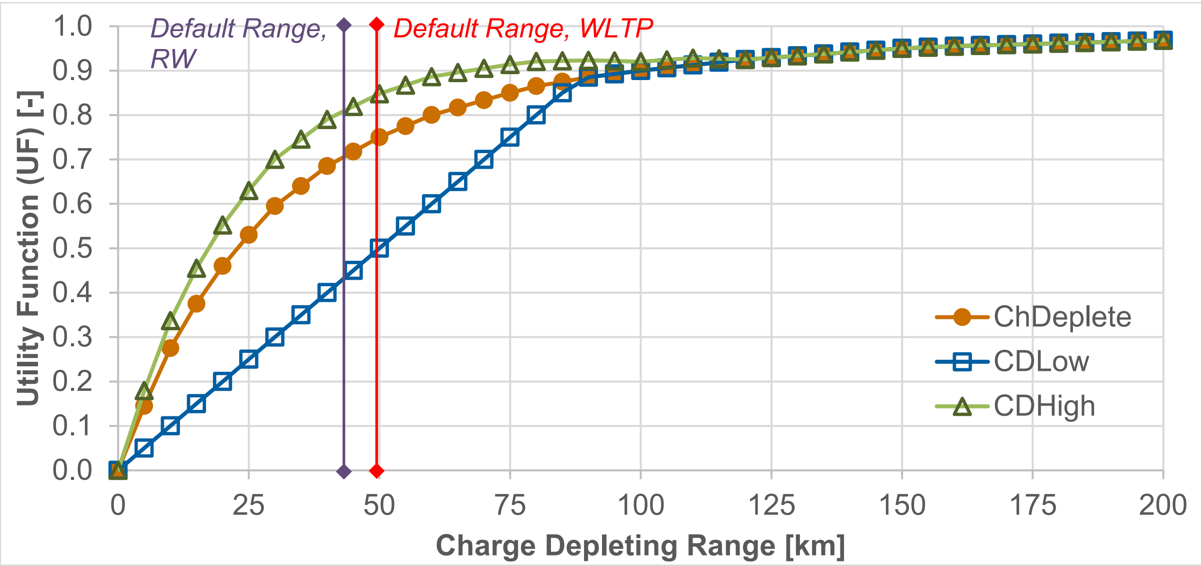


Figure A9: WLTP light duty vehicle utility function (UF), used to estimate share of operation in electric mode given the vehicle electric range, plus high/low sensitivities used in the analysis

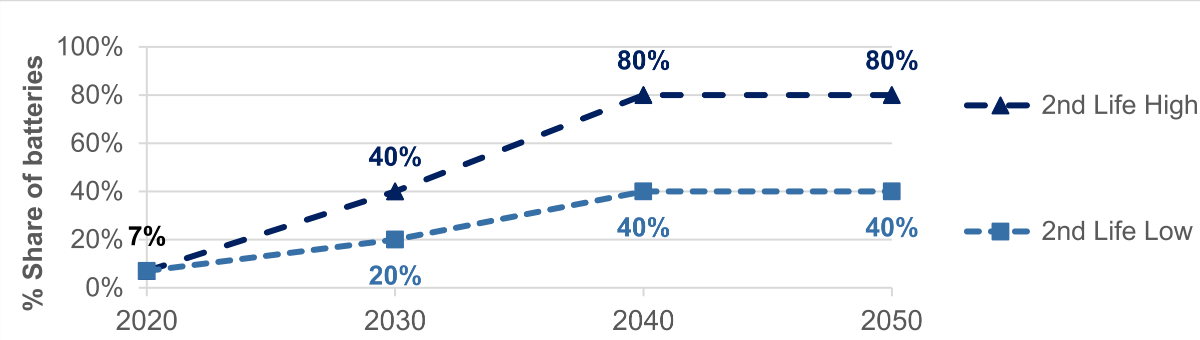


Notes: RW = real-world operation; WLTP = the regulatory testing protocol used for light duty vehicle type approval.

A1.4 End-of-Life

The end-of-life recycling/material recovery rates used in the analysis are the same as those utilised in Ricardo's previous analysis for EC DG CLIMA, as reported in Appendix A4.3 of that report (Ricardo et al., 2020). Additional assumptions used in the end-of-life sensitivity for this study are presented below.

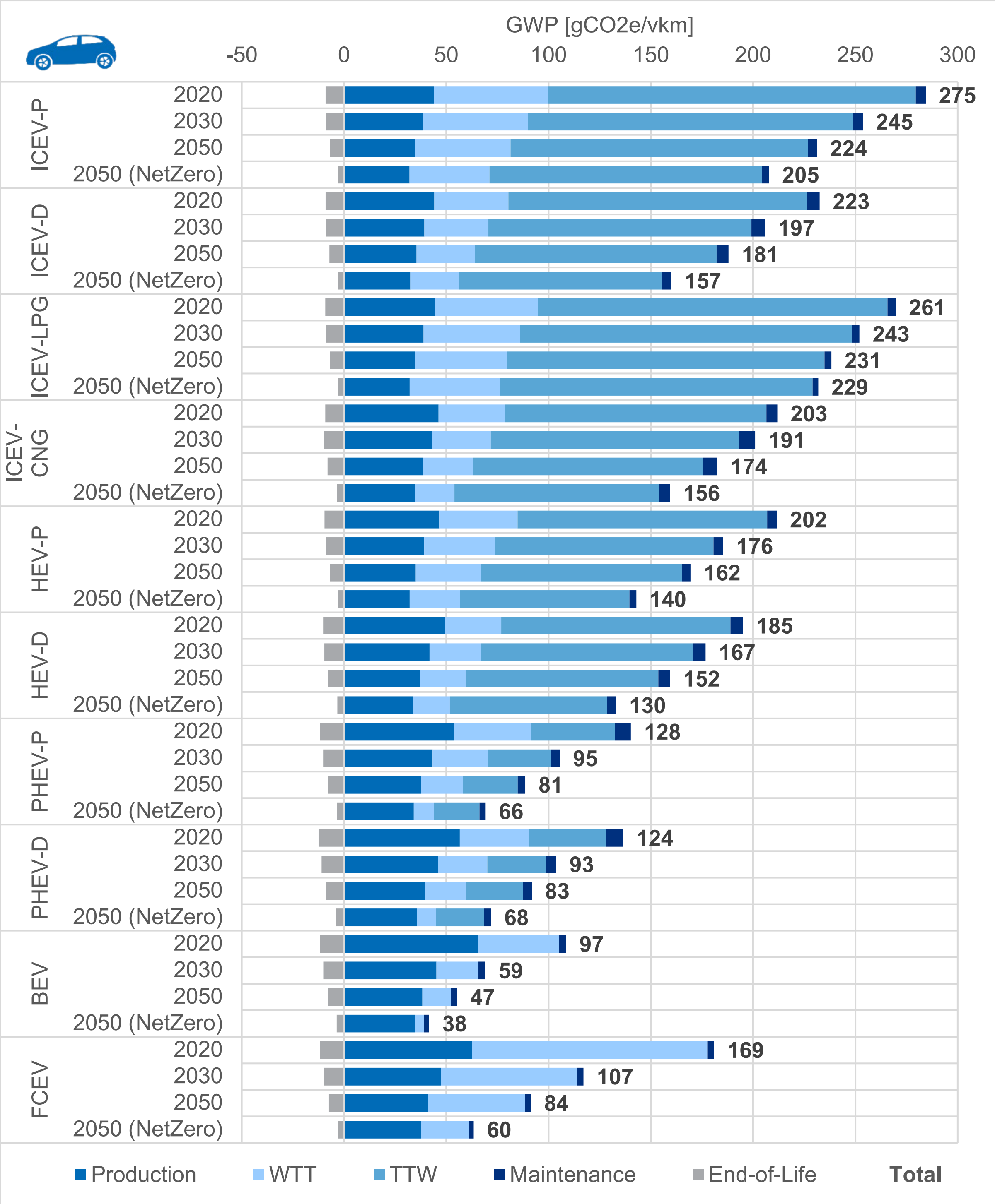
Figure A10: Assumed shares of battery repurposing for second-life



A2 Appendix 2: Further detail on vehicle LCA results

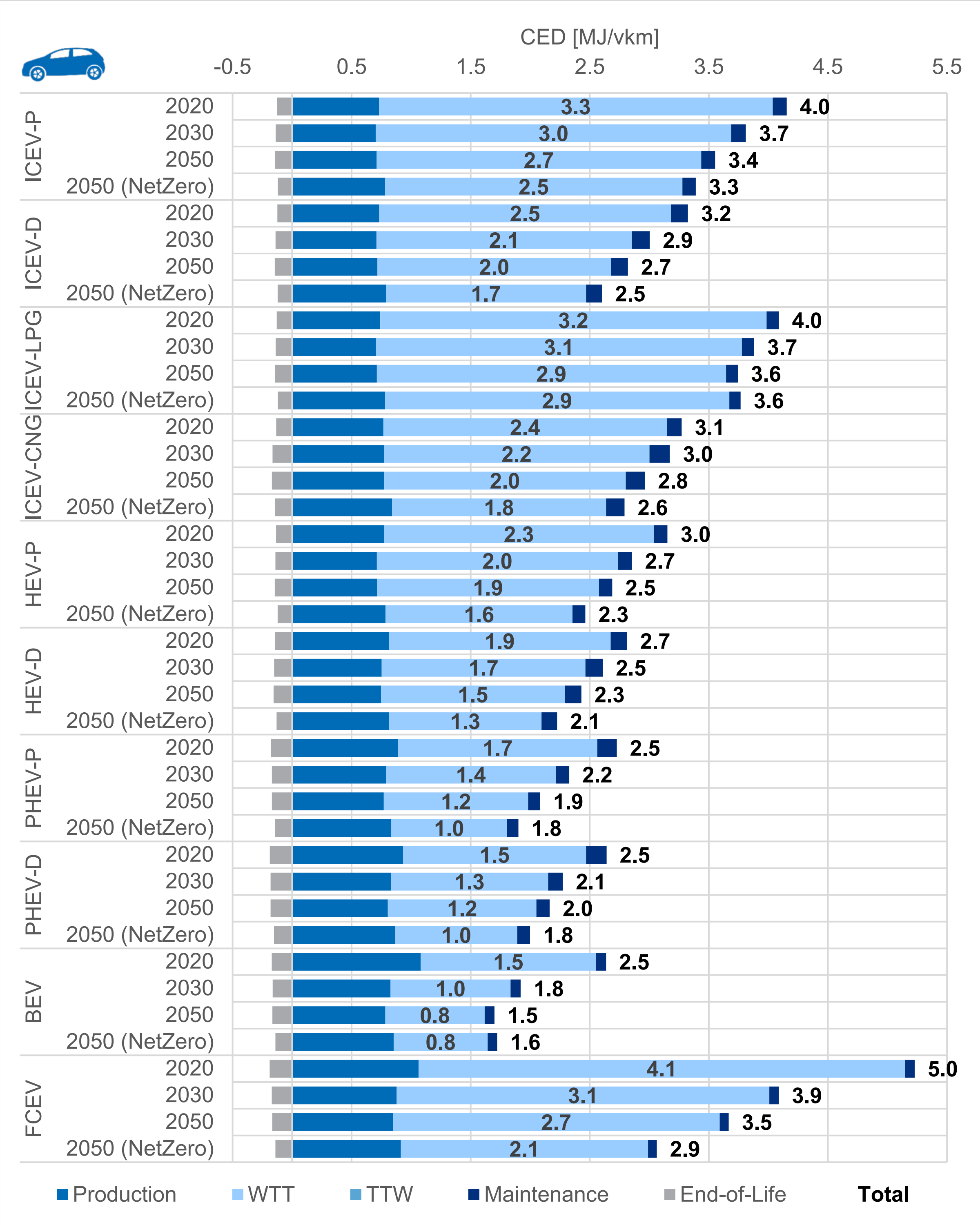
A2.1 Passenger cars – main results

Figure A11: Summary of breakdown of overall lifecycle GHG impacts (as GWP) for Lower Medium Cars for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power for 2050)



Notes: GWP = global warming potential for greenhouse gas emissions. **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

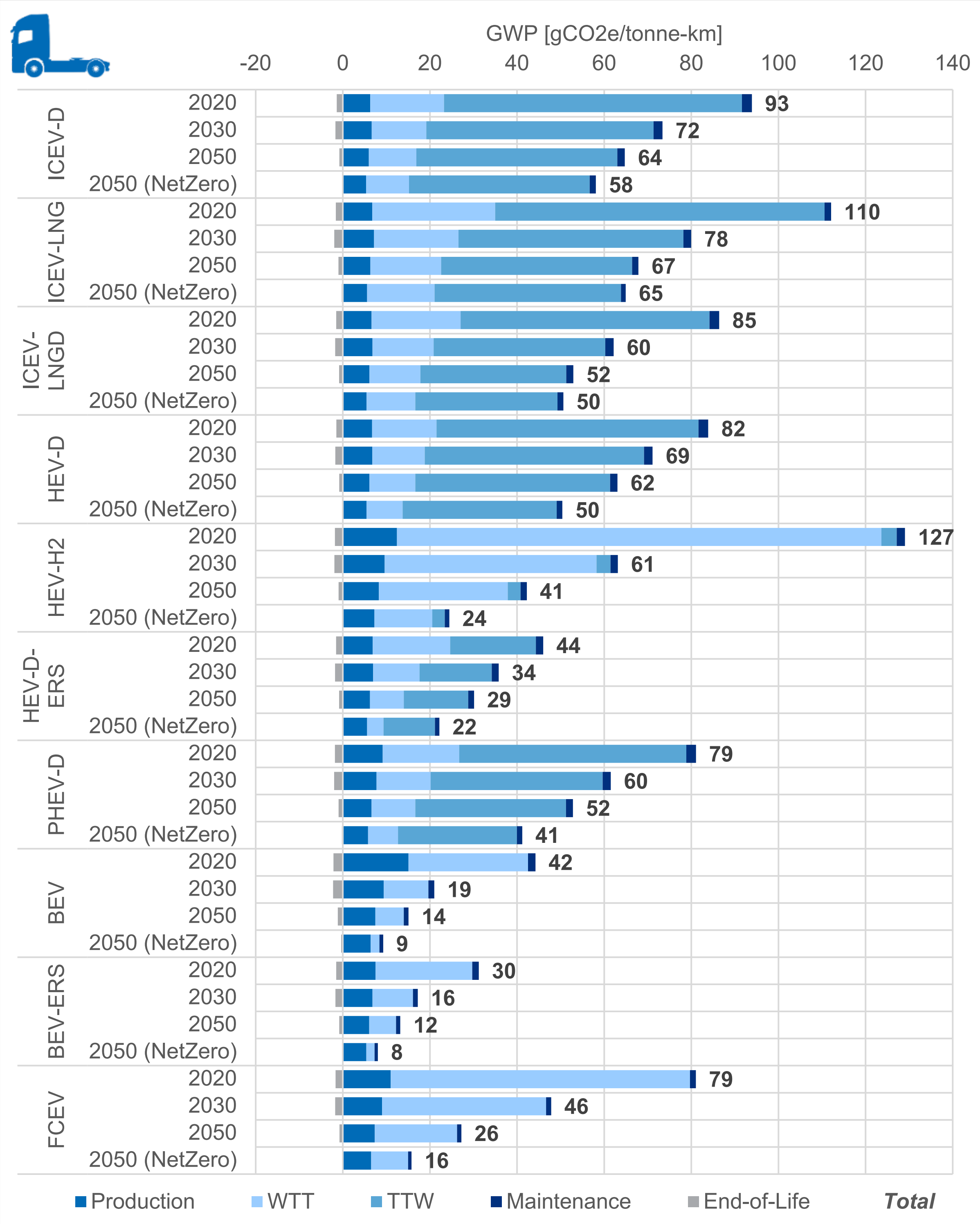
Figure A12: Summary of breakdown of overall lifecycle CED impacts for Lower Medium Cars for selected powertrain types (Baseline scenario for 2020, 2030 and 2050, Net Zero Power for 2050)



Notes: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

A2.2 Articulated lorries – main results

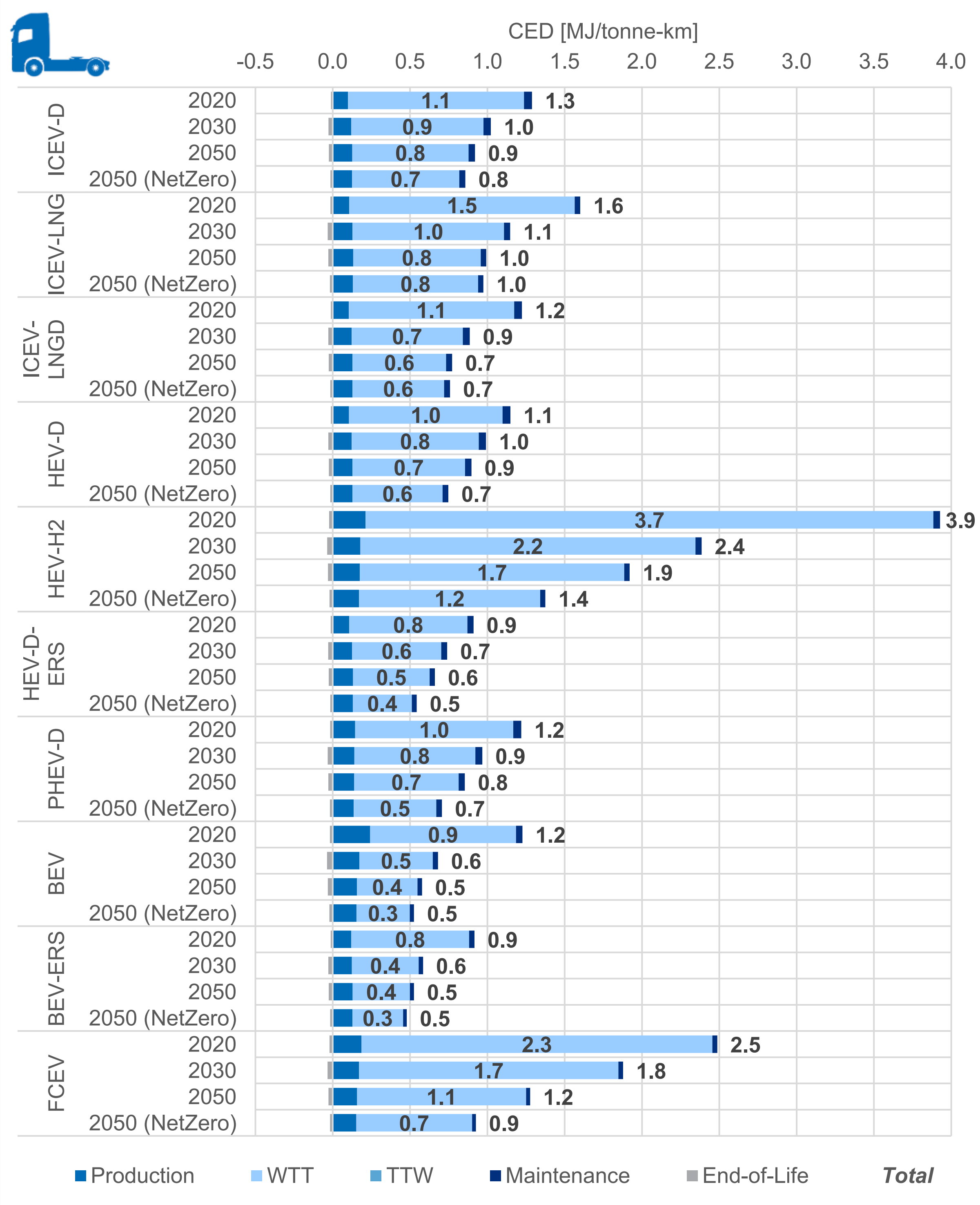
Figure A13: Summary of breakdown of overall lifecycle GHG impacts for Articulated Lorries (40t GVW, Box Body) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types affects freight capacity, influencing the results.

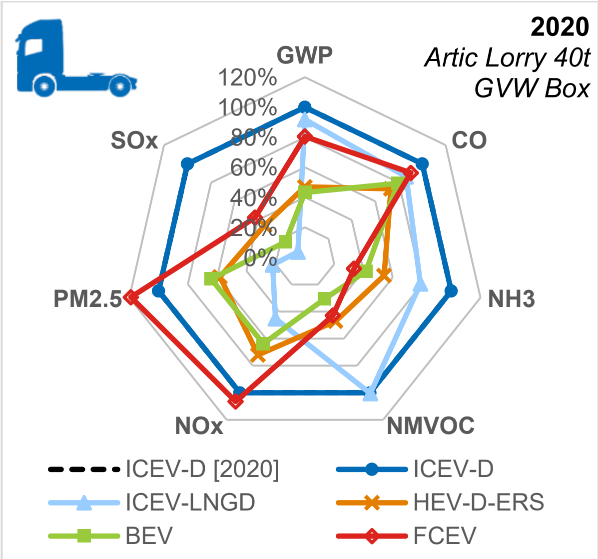
2020	ICEV-D	ICEV-LNG	ICEV-LNGD	HEV-D	HEV-H2	HEV-D-ERS	PHEV-D	BEV	BEV-ERS	FCEV
Unladen mass, kg	14,469	14,602	14,842	14,906	16,601	15,103	16,664	19,302	14,675	15,953
% ICEV-D	*100%*	*101%*	*103%*	*103%*	*115%*	*104%*	*115%*	*133%*	*101%*	*110%*
Lifetime tkm (thousands)	12,830	12,763	12,642	12,609	11,756	12,510	11,723	10,394	12,726	12,082
% ICEV-D	*100%*	*99%*	*99%*	*98%*	*92%*	*98%*	*91%*	*81%*	*99%*	*94%*

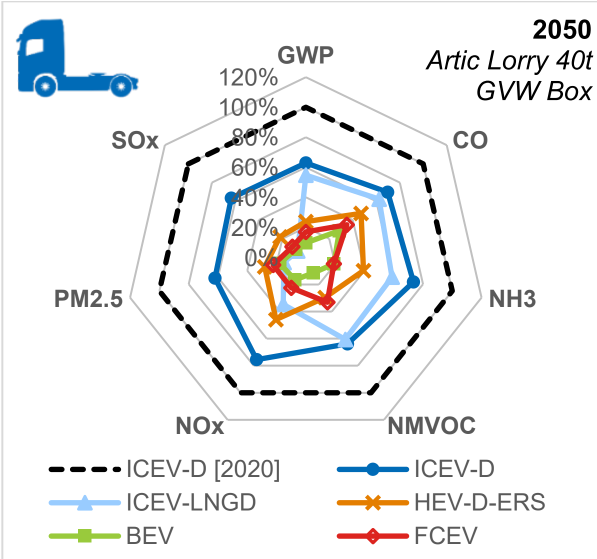
Figure A14: Summary of breakdown of overall lifecycle CED impacts for Articulated Lorries (40t GVW, Box Body) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types affects freight capacity, influencing the results.

Figure A15: Summary of the relative impacts for Articulated Lorries (40t GVW) for GHG (GWP) and air quality pollutant emissions (CO, NH_3, NMVOC, NOx, $PM_{2.5}$, SOx) for 2020 and 2050 powertrains (Net Zero Power scenario).



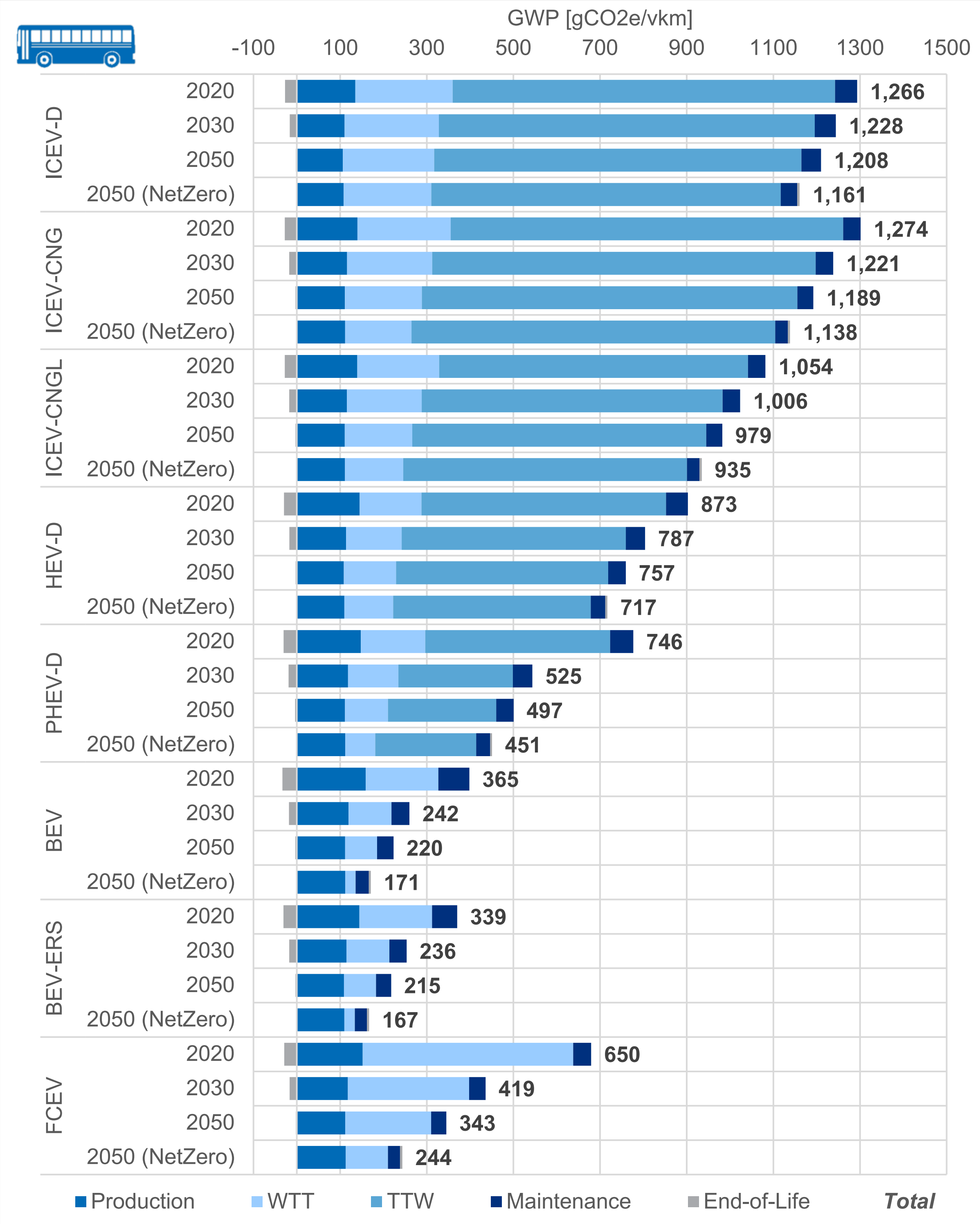


Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. Exhaust (TTW) air pollutant emissions are based on the version of COPERT current at the time this report was prepared, and assuming new vehicles meet the most stringent Euro VI emission standards in place.

Whilst electric vehicles don't have exhaust emissions when operating on electricity (or hydrogen), there are still non-exhaust particulate emissions (from tyre and brake wear) and emissions associated with the vehicle manufacturing and electricity (or hydrogen) production. The non-exhaust emissions of xEVs are assumed to be similar to other vehicle types as there are currently no robust datasets available on their emissions versus conventional vehicles. Tyre wear emissions from xEVs are likely to be higher due to their higher weight, but brake wear emissions are likely to be lower due to regenerative braking.

A2.3 Urban buses – main results

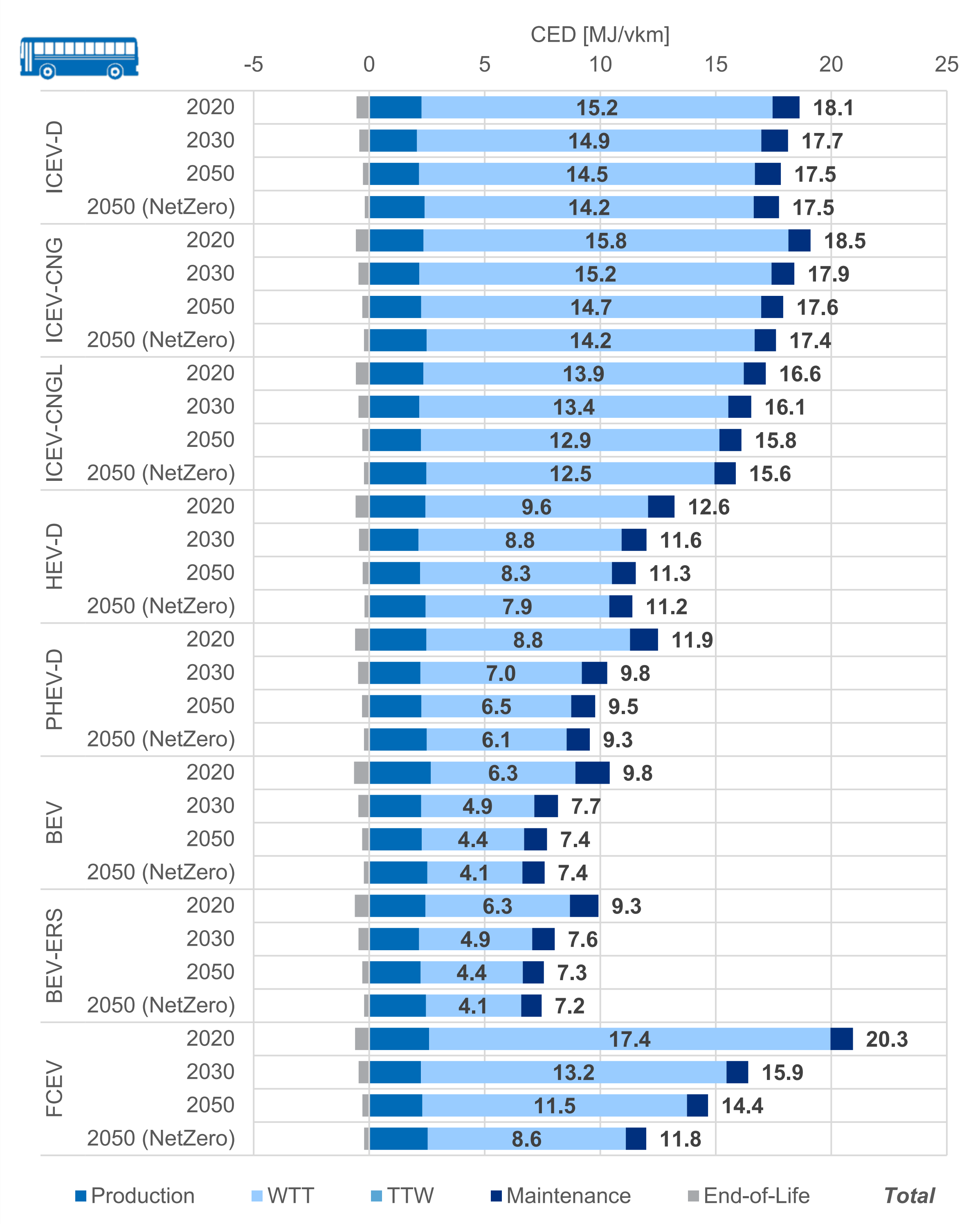
Figure A16: Summary of breakdown of overall lifecycle GHG impacts for urban buses (12m single deck) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types also influences the overall results. CNGL = CNG lean-burn engine, based on Ricardo testing and simulation work; technology is not yet available in the marketplace.

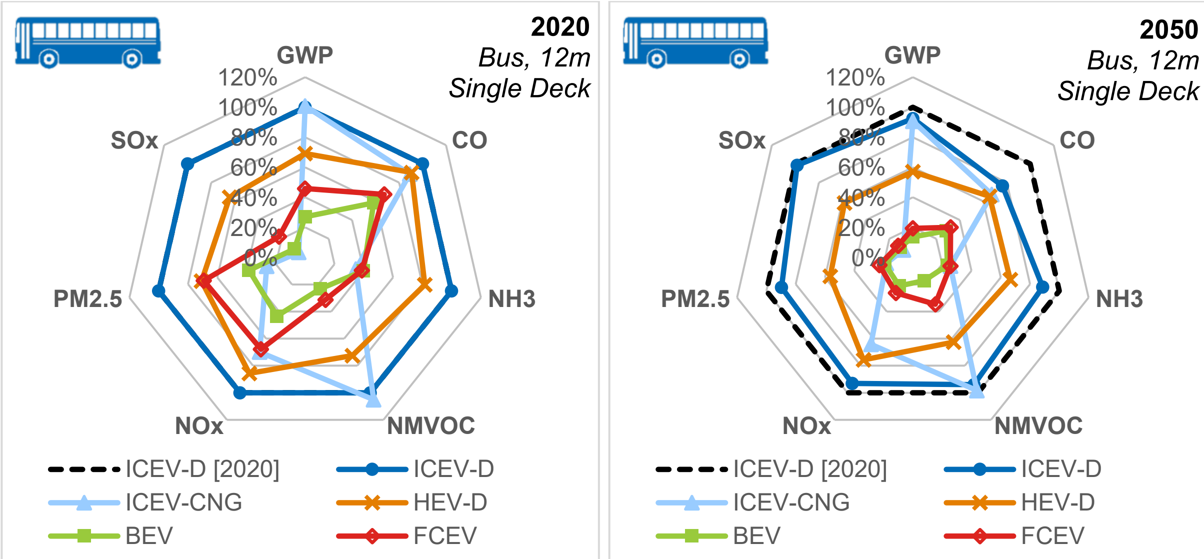
2020	ICEV-D	ICEV-CNG	ICEV-CNGL	HEV-D	PHEV-D	BEV	BEV-ERS	FCEV
Unladen mass, kg	11,944	12,174	12,108	12,552	12,717	12,709	11,978	12,026
% ICEV-D	*100%*	*102%*	*101%*	*105%*	*106%*	*106%*	*100%*	*101%*
Lifetime vkm (thousands)	765	765	765	765	765	765	765	765
% ICEV-D	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*	*100%*

Figure A17: Summary of breakdown of overall lifecycle CED impacts for urban buses (12m single deck) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: The calculated unladen mass of the different vehicle types also influences the overall results.

Figure A18: Summary of the relative impacts for urban buses (single deck) for GHG (GWP) and air quality pollutant emissions (CO, NH_3, NMVOC, NOx, $PM_{2.5}$, SOx) for 2020 and 2050 powertrains (Net Zero Power scenario).

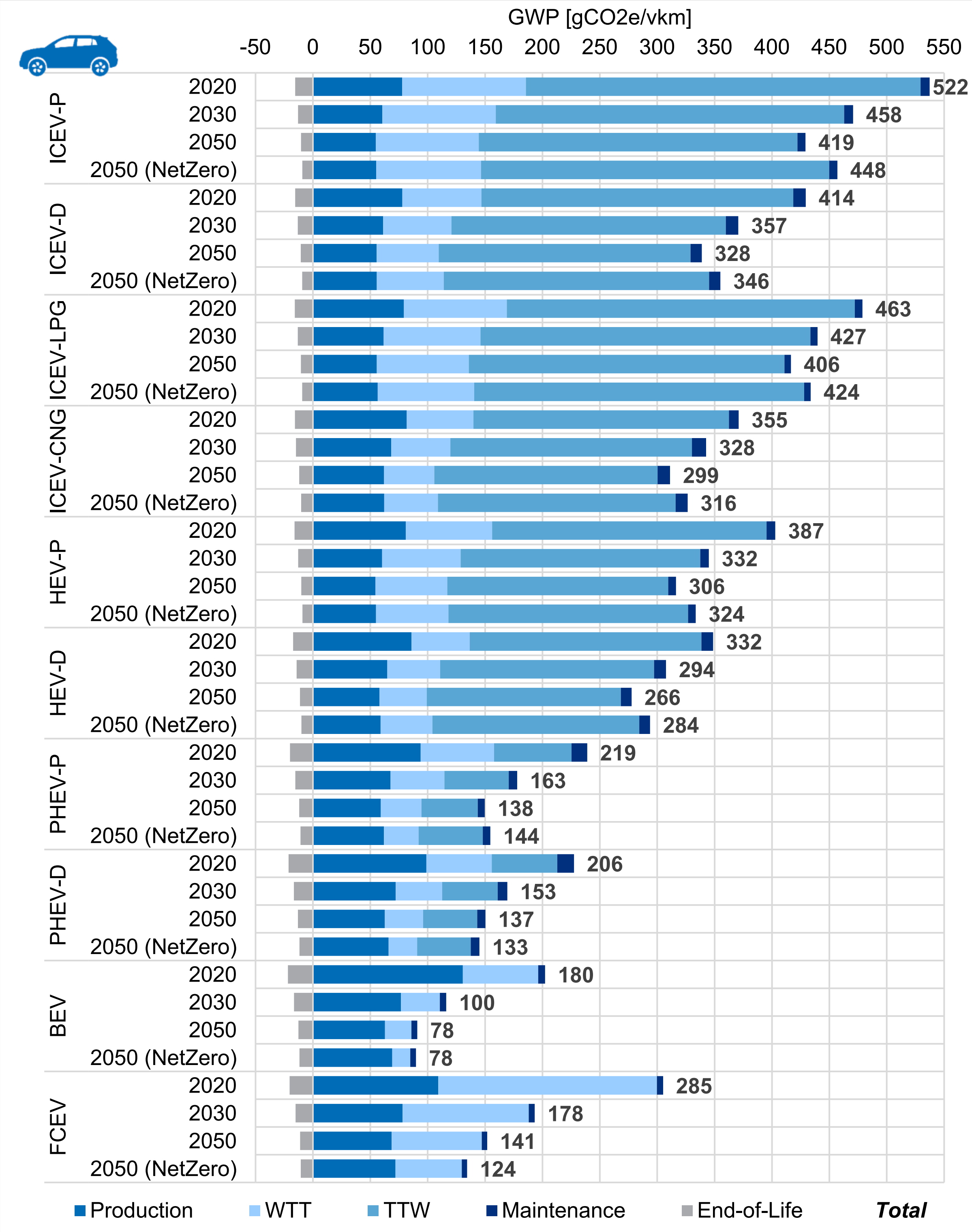


Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%. Exhaust (TTW) air pollutant emissions are based on the version of COPERT current at the time this report was prepared, and assuming new vehicles meet the most stringent Euro VI emission standards in place.

Whilst electric vehicles don't have exhaust emissions when operating on electricity (or hydrogen), there are still non-exhaust particulate emissions (from tyre and brake wear) and emissions associated with the vehicle manufacturing and electricity (or hydrogen) production. The non-exhaust emissions of xEVs are assumed to be similar to other vehicle types as there are currently no robust datasets available on their emissions versus conventional vehicles. Tyre wear emissions from xEVs are likely to be higher due to their higher weight, but brake wear emissions are likely to be lower due to regenerative braking.

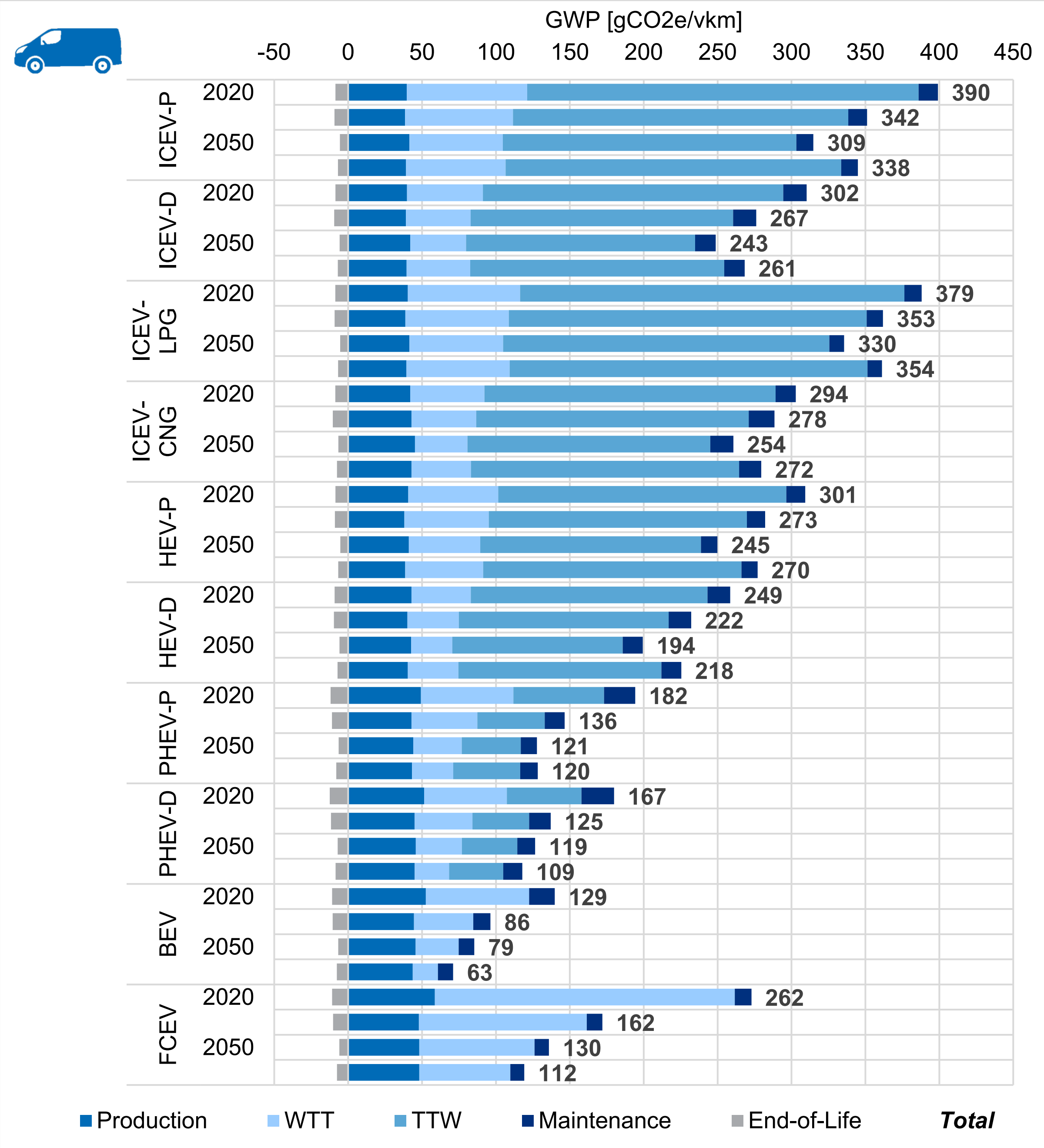
A2.4 Other vehicle types – main results

Figure A19: Summary of breakdown of overall lifecycle GHG impacts for Large SUVs for different powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



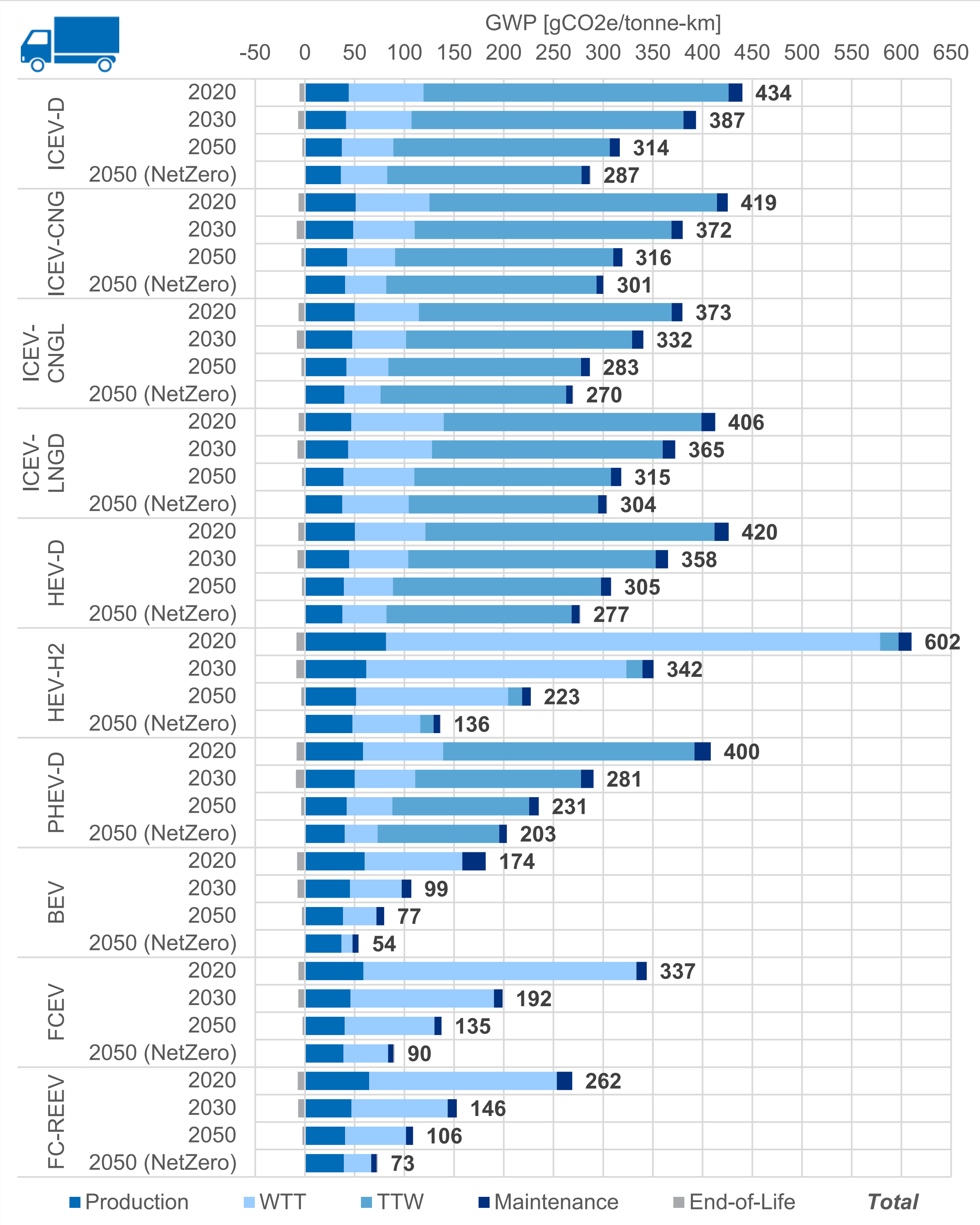
Notes: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

Figure A20: Summary of breakdown of overall lifecycle GHG impacts for N1 Class III Vans for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

Figure A21: Summary of breakdown of overall lifecycle GHG impacts for Rigid Lorries (12t GVW, box body) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)

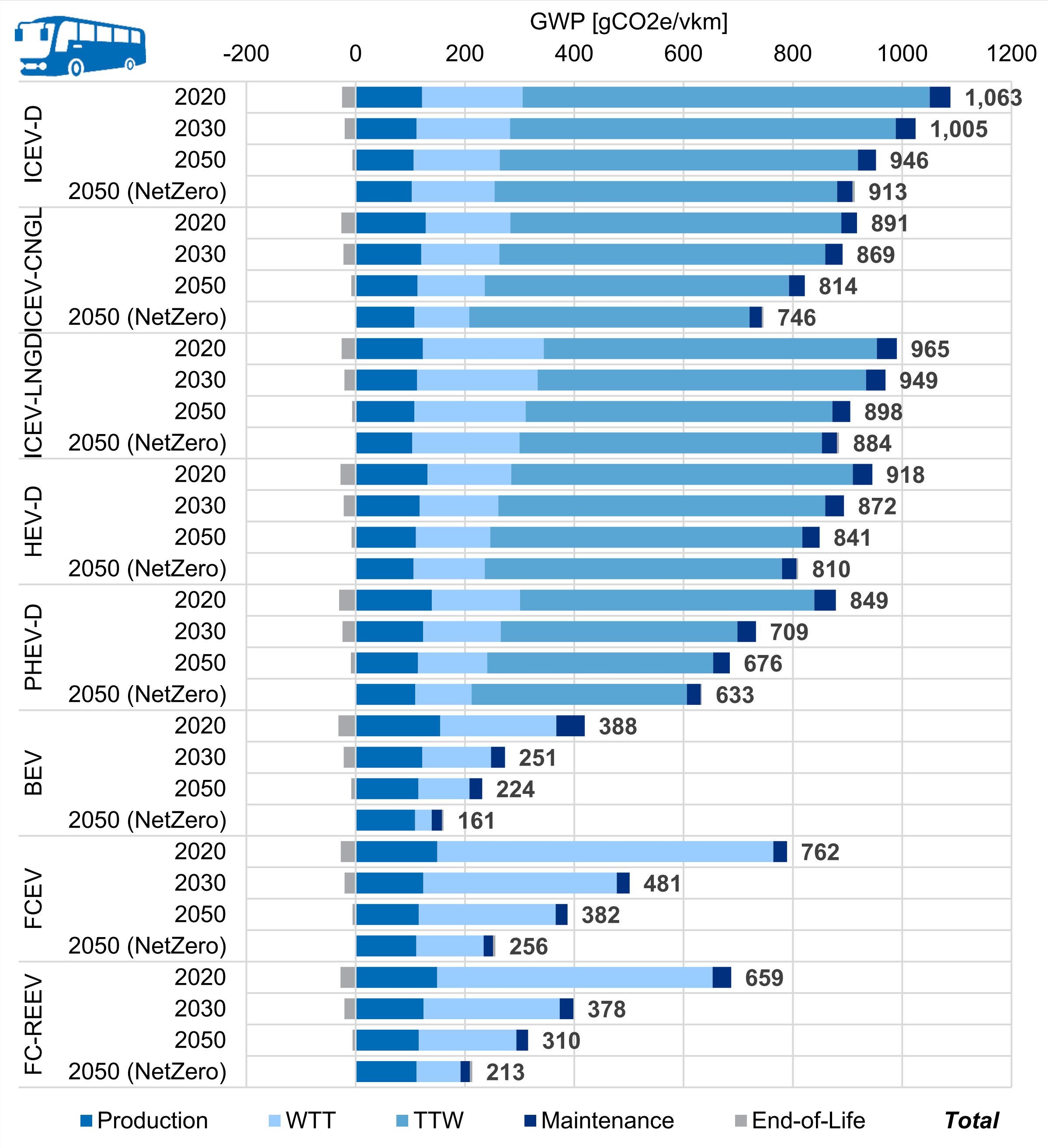


Notes: The calculated unladen mass of the different vehicle types also influences the overall results.

2020	ICEV-D	ICEV-CNG	ICEV-CNGL	ICEV-LNGD	HEV-D	HEV-H2	PHEV-D	BEV	FCEV	FC-REEV
Unladen mass, kg	6,146	6,444	6,378	6,319	6,482	6,948	6,797	6,494	6,285	6,500
% ICEV-D	*100%*	*105%*	*104%*	*103%*	*105%*	*113%*	*111%*	*106%*	*102%*	*106%*
Lifetime tkm (thousands)	884	839	849	858	833	761	785	831	863	830

2020	ICEV-D	ICEV-CNG	ICEV-CNGL	ICEV-LNGD	HEV-D	HEV-H2	PHEV-D	BEV	FCEV	FC-REEV
% ICEV-D	*100%*	*95%*	*96%*	*97%*	*94%*	*86%*	*89%*	*94%*	*98%*	*94%*

Figure A22: Summary of breakdown of overall lifecycle GHG impacts for Coaches (24t GVW) for selected powertrain types (Baseline scenario for 2020 and 2030, Net Zero Power scenario for 2050)



Notes: **Production** = production of raw materials, manufacturing of components and vehicle assembly; **WTT** = fuel/electricity production cycle; **TTW** = impacts due to emissions from the vehicle during operational use; **Maintenance** = impacts from replacement parts and consumables; **End-of-Life** = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries.

A2.5 Sensitivities

A2.5.1 UK manufacturing

Figure A23: Sensitivity on battery and vehicle production, Lower Medium Car, Net Zero Power Scenario - Total vehicle lifecycle GWP impacts [in gCO2e/vkm (lifetime)]

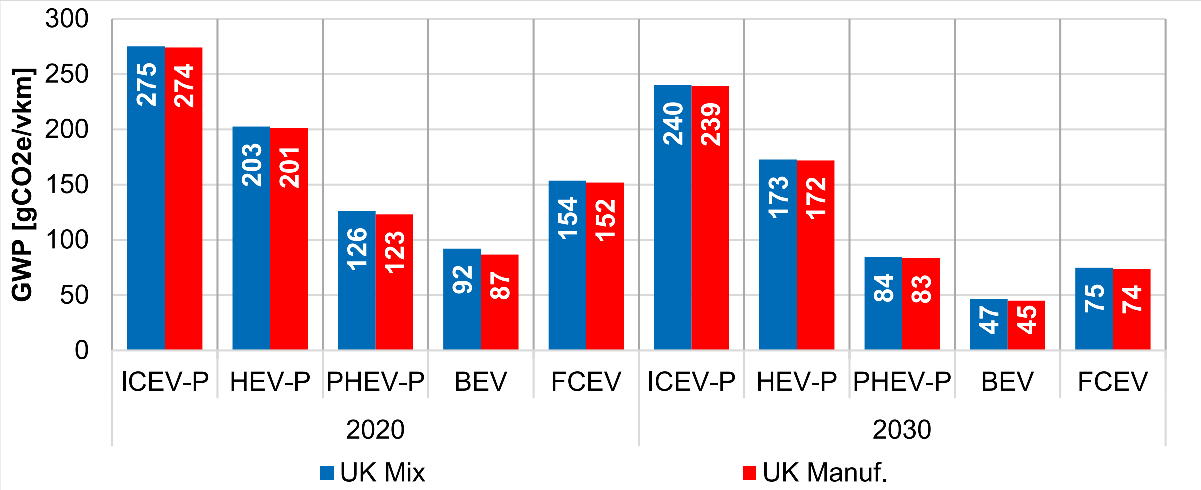


Figure A24: Sensitivity on battery and vehicle production, Lower Medium Car, Net Zero Power Scenario – Battery manufacturing (only) GWP impacts [in kgCO2e/kWh (battery)] and battery pack energy density [in Wh/kg]

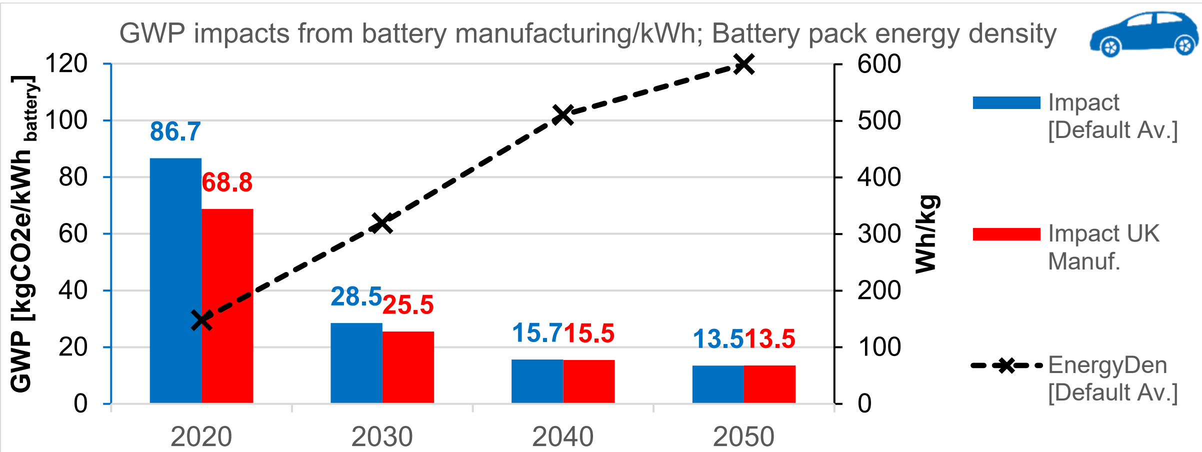
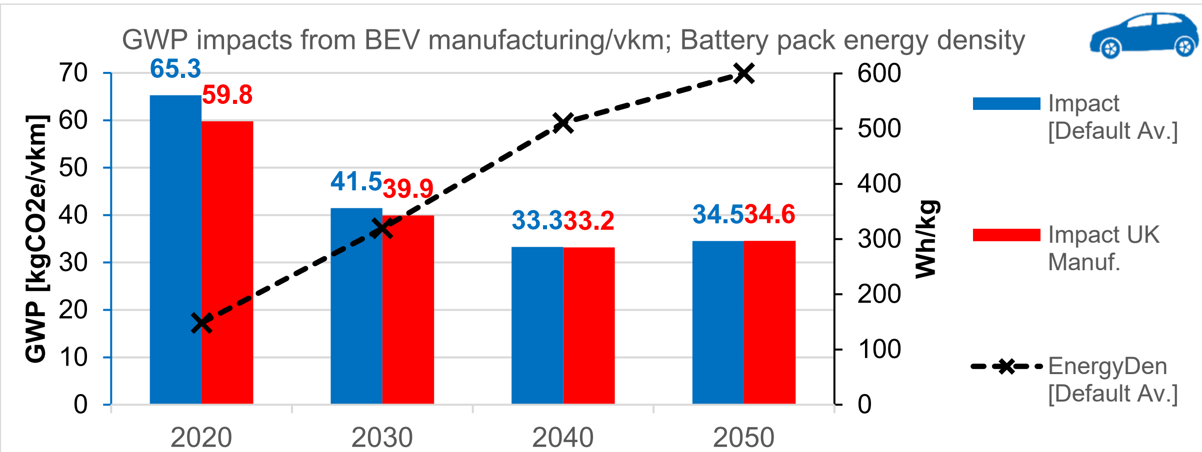
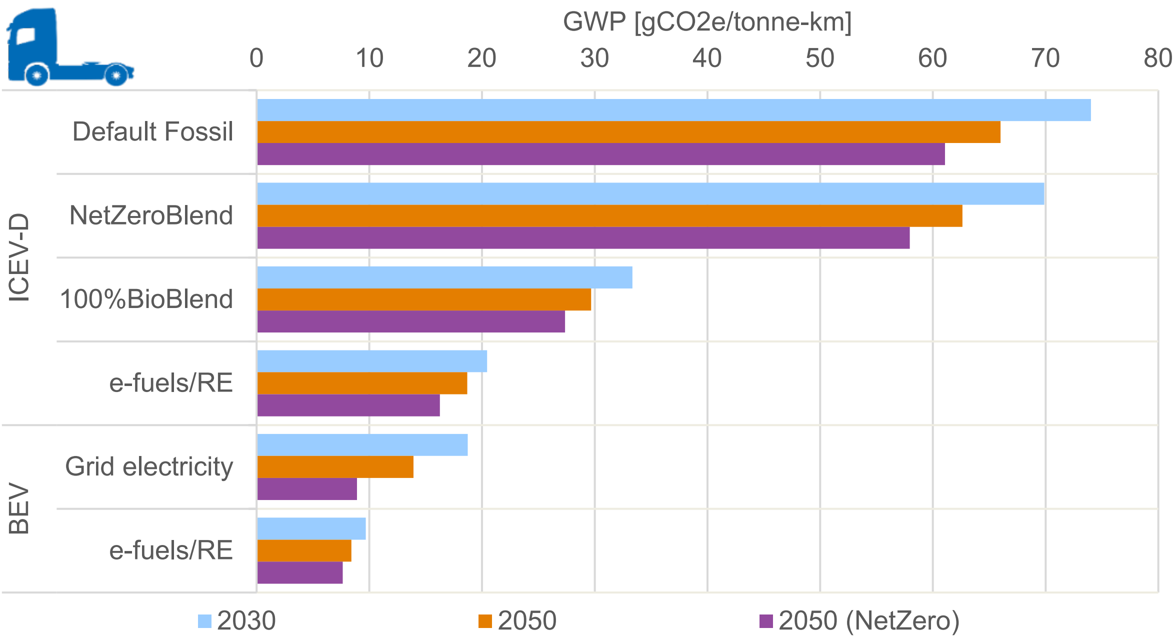


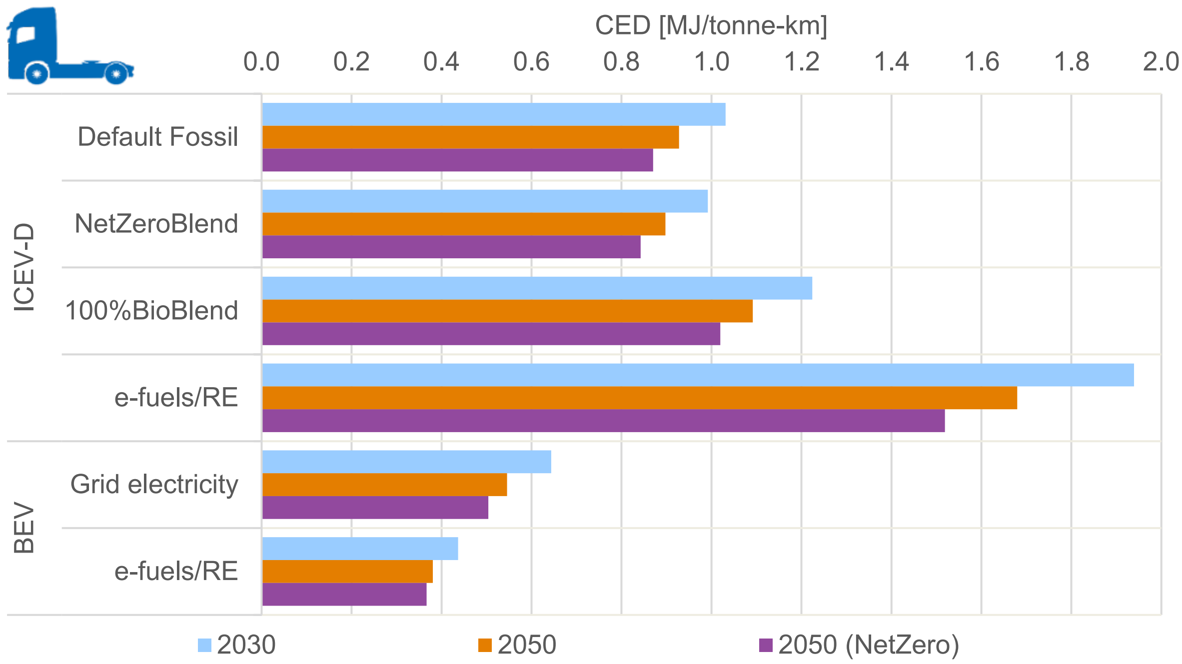
Figure A25: Sensitivity on battery and vehicle production, Lower Medium Car, Net Zero Power Scenario – BEV manufacturing (total) GWP impacts [in kgCO2e/vkm (lifetime)] and battery energy density [in Wh/kg]



A2.5.2 Impacts of fuel selection – hypothetical scenarios on high levels of deployment of renewables, e-fuels and biofuels

Figure A26: Summary of the influence of fuel/electricity chain assumptions on overall lifecycle greenhouse gas (GWP) and cumulative energy demand (CED) impacts for Articulated Lorries (40t GVW) for Diesel ICEV and BEV powertrain types

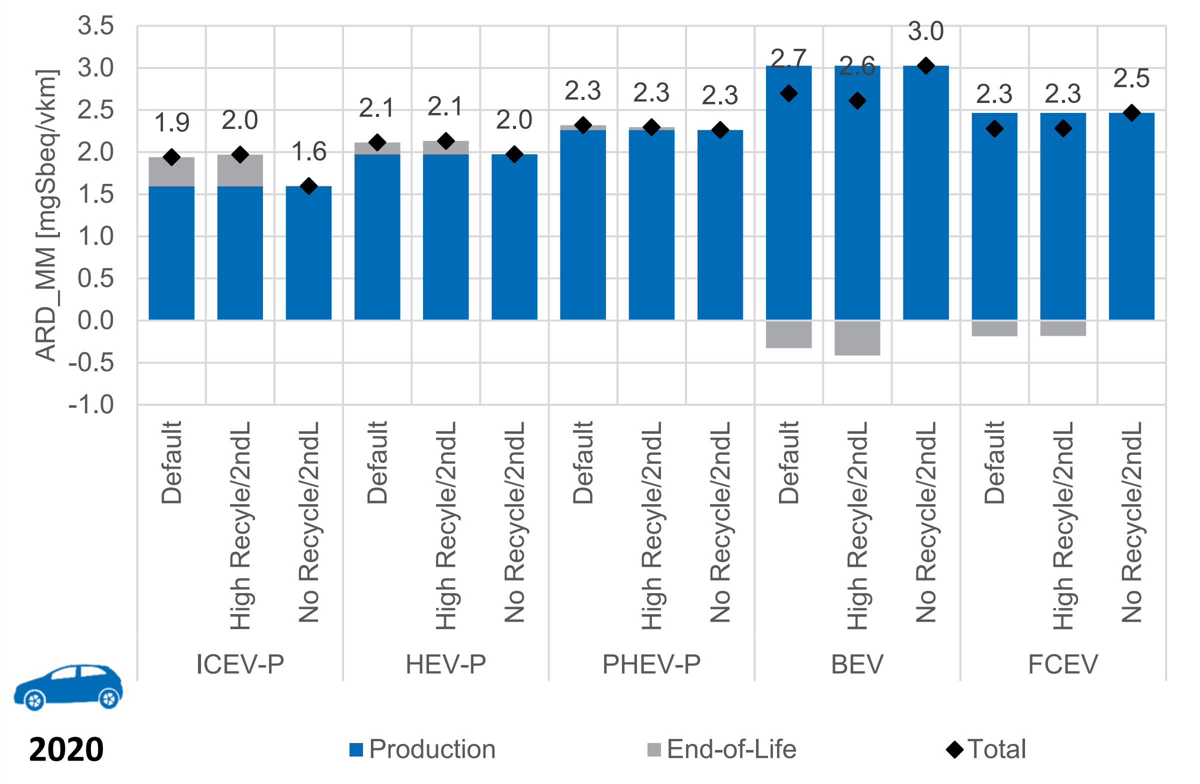




Notes: Results are presented for operational energy consumption based on Baseline scenario for 2030 and 2050, and Net Zero Power scenario for 2050. Additional information on the fuel blends is presented in Appendix A1.2.

A2.5.3 End-of-Life (EoL) assumptions

Figure A27: Sensitivity on end-of-life assumptions, Lower Medium Car, Net Zero Power Scenario, 2020 – Vehicle embedded emissions only, for ARD_MM (Abiotic Resource Depletion, Minerals & Metals) indicator



Notes: ARD_MM impacts are in units of mgSb eq/vkm = milligrams of Sb (antimony) equivalent per vehicle-km

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