FINAL REPORT

Life Cycle CO_2e Assessment of Low Carbon Cars 2020 – 2030

For the

Low Carbon Vehicle Partnership

PE INTERNATIONAL
EXPERTS IN SUSTAINABILITY

LowCVP
Low Carbon Vehicle Partnership

On behalf of PE INTERNATIONAL AG and its subsidiaries

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

AHSS	Advanced High Strength Steel
ASR	Automotive Shredder Residue
BAT	Best Available Technology
BEV	Battery Electric Vehicle
CCS	Carbon Capture and Storage
CEWEP	Confederation of European Waste-to-Energy Plants
CML	Centre of Environmental Science at Leiden
DEFRA	Department for Environment, Food and Rural Affairs
EAA	European Aluminium Association
EC	European Commission
ECI	European Copper Institute
ELCD	European Life Cycle Database
E-motor	Electric motor
EoL	End-of-Life
EV	Electrified (drive train) Vehicle
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ILCD	International Life Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment

LowCVP	Low Carbon Vehicle Partnership
MSW	Municipal Solid Waste
NEDC	New European Driving Cycle
OEM	Original Equipment Manufacturer
PE	PE INTERNATIONAL
RED	Renewable Energy Directive
TTW	Tank-to-Wheel
US EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WTE	Waste-to-Energy
WTW	Well-to-Wheel

GLOSSARY (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva.

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems

Functional Unit

Quantified performance of a product system for use as a reference unit

Carbon dioxide equivalent (CO_2e)

Unit for comparing the radiative forcing of a greenhouse gas to carbon dioxide

Close loop & open loop

A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.

An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process (“gate of the factory”). It may also include transportation until use phase.

C-Segment vehicle

Car size classification referring the third-largest segment of passenger cars in the European market. C-Segment corresponds to “Small family car”, Compact car” or “Medium car”.

Glider

Refers to all parts of a vehicle except the engine, transmission and power train.

Global Warming Potential

Factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of CO_2 over a given period of time (taken to be 100 years in this study). Reported in units of tonnes of CO_2 equivalent (tonnes CO_2e).

Life cycle

A unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

Life Cycle Assessment - LCA

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle

Life Cycle Inventory - LCI

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact assessment - LCIA

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

EXECUTIVE SUMMARY

Background Introduction

This report, the “Life Cycle CO_2e Assessment of Low Carbon Cars 2020-2030”, is the outcome of a study commissioned by the LowCVP following on from previous report “Preparing for a Life Cycle CO_2 Measure” prepared for the LowCVP by Ricardo. Two of the main conclusions of the Ricardo study were that future CO_2e metrics for passenger cars need to go beyond the tail-pipe measures and take into account whole life cycle CO_2e emissions to more fully account for environmental impacts, especially when comparing different vehicle technologies. Additionally, embodied CO_2e emissions associated with vehicle production and disposal become a more significant part of the lifecycle as the use phase decarbonises. This study leads on from the Ricardo study to improve understanding of lifecycle CO_2e emissions of different vehicle technologies over the next two decades. The objectives of this study are:

- To estimate how total lifecycle CO_2e emissions will change for different vehicle technologies in the future;
- To estimate how the balance of CO_2e emissions associated with individual lifecycle stages will vary for different technologies in the future; and
- To assess the sensitivity of the study outputs to the choice of input assumptions and to determine those parameters having the most impact on the total lifecycle CO_2e emissions for each vehicle technology.

Discussion with the LowCVP steering group concluded that, among other considerations, efficiency improvements and biofuels availabilities for petrol are more certain in petrol than diesel in the 2030 timeframe. As such, the scope of this study is been limited to C-segment vehicles using petrol with a blend of bioethanol and/or electricity consumption, where applicable.

Methodology

This study is a “streamlined” LCA based largely on secondary data available from published literature. This study follows ISO 14040/44 and PAS 2050 guidelines but cannot be considered fully compliant with either standard/specification because this study is “single issue” i.e. focusing only on greenhouse gases, no critical review undertaken for comparative assertions (for ISO 1040/44 compliance) and no use of primary data (for PAS 2050 compliance). PE INTERNATIONAL has drawn heavily on our proprietary GaBi datasets for background data and relied on our internal expertise to make determine suitable estimates when data gaps were encountered.

This is a “cradle to grave” study covering:

- Extraction of raw materials, production of fuels & production of vehicle component parts;
- Assembly of vehicles;
- Use phase of vehicle over a defined lifetime (including replacement parts - i.e. lubricants, tyres etc.); and
- “Cut off” end of life of vehicle (considered to end just after vehicle shredding including limited disposal of wastes arising).

The vehicle technologies considered in this project are:

- Petrol internal combustion engine vehicle (ICEV) with petrol-biofuel blend;
- Hybrid electric vehicle (HEV) with petrol-biofuel blend;
- Plug-in hybrid electric vehicle (PHEV) with petrol-biofuel blend; and
- Battery Electric Vehicle (BEV).

The base case scenario for this study is 2012 and vehicle characteristics for this scenario are taken from the most current manufacturers' specifications for representative vehicles being assessed in this study. Future scenario cases considered are for the years 2020 and 2030. For each of the future scenarios "Typical case" and "Best case" scenarios are defined.

The "Typical case" represents the lower limits in the range of predictions on the improvements that can be made in the future for the drive train technologies considered while the "Best case" represents the upper limits of potential future improvements. Predicted conditions of vehicles under the future scenarios in this study are representative of possible Best Available Technology (BAT) conditions and will not necessarily be applicable to ALL relevant vehicles on the road in the UK at the time.

The scenarios that have been defined for this project are:

- Base Case 2012;
- Typical Case 2020;
- Best Case 2020;
- Typical Case 2030; and
- Best Case 2030 (which can be considered an "ambitious" low carbon scenario).

The "cut-off" end of life approach has been used to assess credits for recycling. This methodology favours the use of recycled content used during vehicle production (as scrap input is assumed to free of burdens) but, correspondingly, no credits are given for recycling at end of life. However, the effect of applying the "avoided burdens" approach (which gives credits for recycling at end of life, but also applies burdens for scrap input) is explored under a sensitivity analysis.

Summary of Main Assumptions

Vehicular lifetime mileage has been set to 150,000 km under conditions of the New European Driving Cycle (NEDC). Maintenance and replacements parts are considered over this lifetime of the vehicles.

All vehicles are based on the "average mid-sized petrol" car as detailed in the 2008 JRC IMPRO-car study. The vehicles are differentiated by adding or subtracting relevant components based on the drive train in question while all other common components (such as the vehicle glider) are assumed to remain the same.

Secondary data sets for raw materials extraction are taken from the GaBi database and represent real world sourcing conditions. Manufacture of vehicle components is assumed to be in Europe while vehicle assembly and use are assumed to be in the UK. Transportation of vehicle components has not been taken into account in this study.

It is expected that advancements in drive train technology coupled with light-weighting engineering over the entire vehicle will result in future reductions in energy consumption (of fuel and/or electricity) for all vehicles. Based on PE INTERNATIONAL's sector expertise and consultation with the LowCVP, conservative predictions of suitable potential reductions in fuel and electricity consumption have been applied across all vehicles for the future scenarios in this study.

The carbon intensities of the UK and European electricity grid mixes are expected to reduce in future with increasing amounts of renewables contributing to the grid, more nuclear power being adopted and the use of new technologies such as carbon capture and storage (CCS). Future grid mix intensities in this study have been estimated using information from EU statistics, the EC Roadmap, the UK Carbon Plan and the UK 2012 Draft Energy Bill. Electricity grid mix carbon intensities are assumed to be at the point of consumption.

The carbon intensity of gasoline is assumed to remain constant for all scenarios i.e. no change from the present situation.

No advanced/second generation biofuels have been considered.

The carbon intensities of ethanol derived from the feedstocks assessed in this study are adjusted for improved production efficiency assumed to come into effect in the future. All adjustments take into consideration the 60% GHG intensity savings threshold for biofuels in 2020 set by the EU Renewable Energy Directive (RED) as well as the 70% GHG intensity savings threshold for 2030.

CO_2 emissions from the combustion of bioethanol (being biotic emissions) are excluded from the carbon accounting in this study. CH_4 and NO_2 that may arise from the combustion of bioethanol are included in the carbon accounting as CO_2e but these only occur in very small quantities (the resulting tank-to-wheel emissions for bioethanol are virtually zero under this assumption). Therefore, by substituting petrol with bioethanol in an internal combustion engine (ICE) the effect is to reduce use phase CO_2e emissions.

End of life under the cut off approach adopted in this study ends just after the vehicle shredder. Significant components such as the lead acid battery, battery pack, catalytic converter, e-motor, power electronics, automotive glass and the tyres are separated from the car body (for potential recovery/recycling) prior to shredding. Liquids are assumed to be drained from the vehicle and incinerated prior to the vehicle shredding. Automotive shredder residue (ASR) remaining after materials recovery is assumed to be incinerated.

Indirect Land Use Change (ILUC) has not been considered for any aspects of this study.

Results

1. To estimate how total lifecycle CO_2e emissions might change for different vehicle technologies in the future.

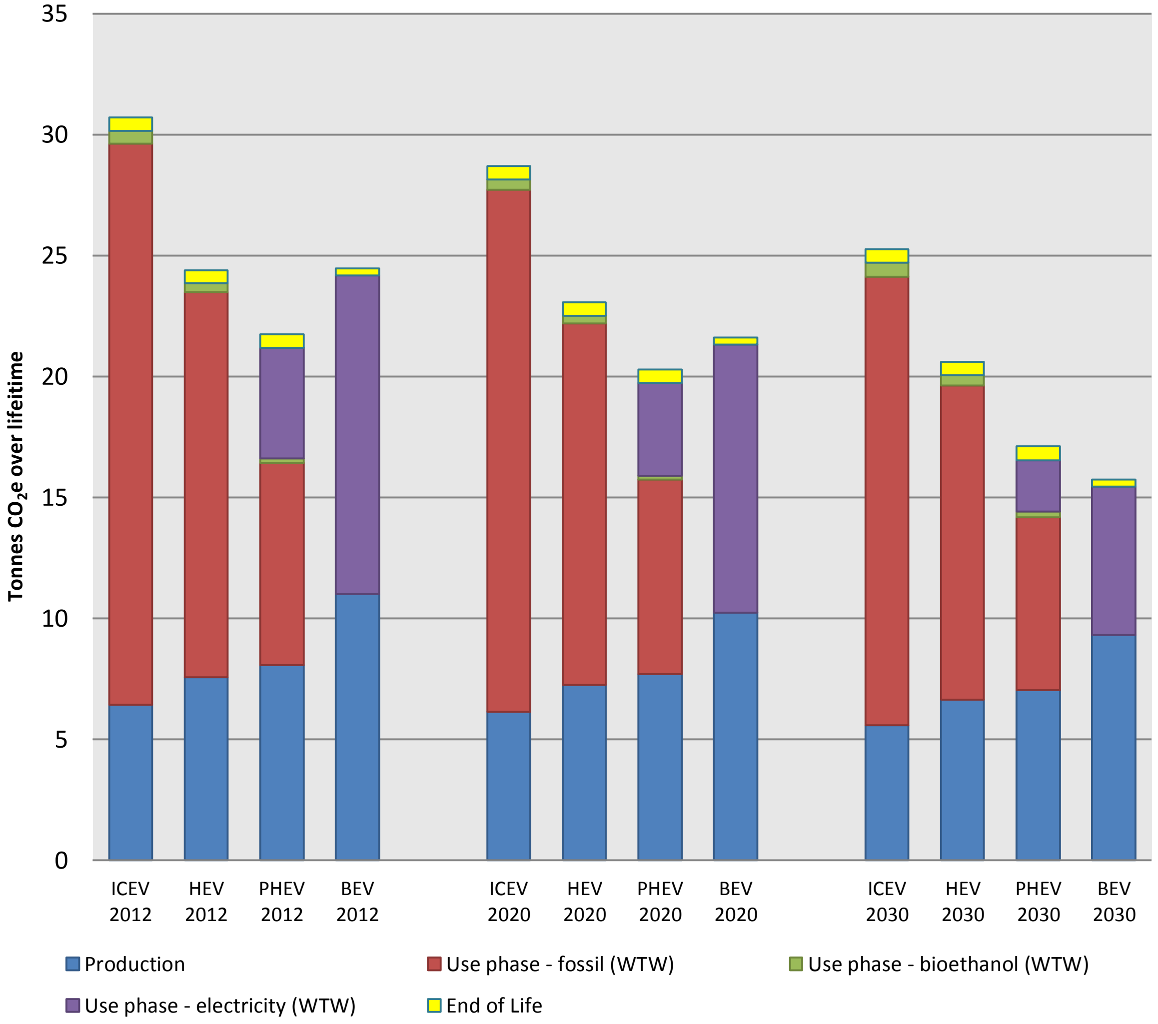

Figure 0-1: Life cycle CO_2e emissions, "Typical" scenarios for future cars 2020-2030

As seen in Figure 0-1, all technology options show reductions in life cycle impact in the period to 2030 compared to the 2012 situation.

For "Typical case 2020" scenarios, there is a 5-12 % range of savings in life cycle CO_2e impacts for all vehicles compared to the "Base 2012" scenarios. These savings mainly result from the expected reductions in the carbon intensity of the future grid mixes, fuel/electricity consumption savings from light-weighting and improved automotive technology as well as improvements in battery pack technology that are predicted to lead to lower embodied carbon impacts of this component.

For "Best case 2020" scenarios, the savings range from 9-24% for all vehicles compared to the "Base 2012" scenarios. These additional savings are from the additional reductions to fuel consumption, grid mix carbon intensity etc. that are modelled in the "Best case 2020" scenarios.

For “Typical case 2030” scenarios, there is an 18-36% range of savings in life cycle CO_2e impacts for all vehicles compared to the “Base 2012” scenarios. These savings are a result of further expected reductions in the carbon intensity of the future grid mixes, fuel/electricity consumption savings from light-weighting and automotive technology as well improvements in battery pack technology.

For “Best case 2030” scenarios, even further light-weighting, reductions in the carbon intensity of the future grid mixes etc are coupled with the use of 100% bioethanol in vehicles with internal combustion engines and a low carbon intensity electricity grid mix. This leads to a 55-70% range of savings in total life time CO_2e impacts for all vehicles when compared to the “Base 2012” scenarios.

2. **To estimate how the balance of CO_2e emissions associated with individual lifecycle stages might vary for different technologies in the future.**

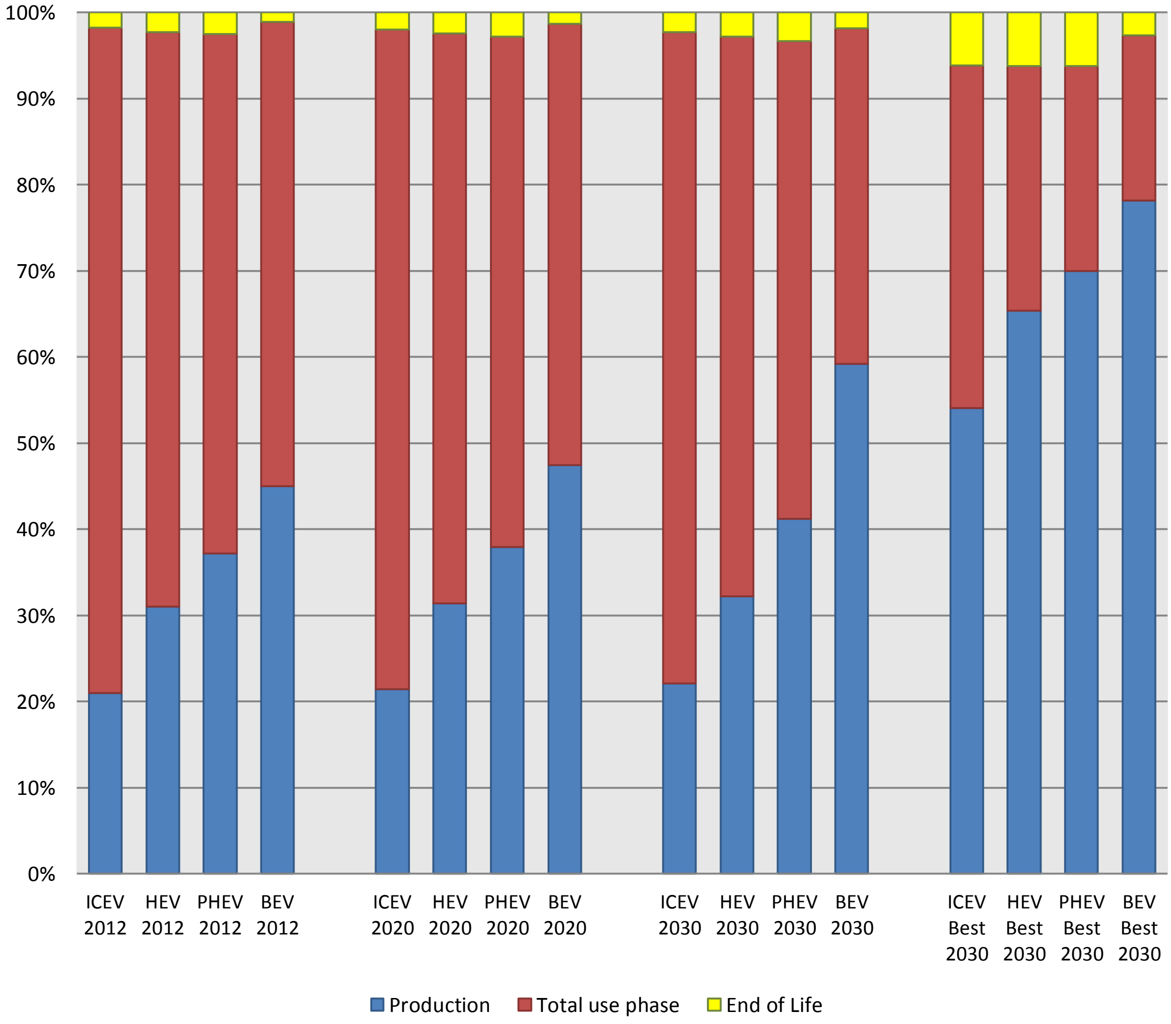

Figure 0-2: Proportion of lifecycle CO_2e emissions for future cars 2020-2030

Figure 0-2 shows that the “total use phase” (accounting for emissions from the production and combustion of petrol and bioethanol, from generation of electricity for battery powered vehicles) will be the dominant phase contributing to life cycle GHG emissions for at least the next decade. In the 2020 to 2030 timeframe, emissions from the production phase becomes steadily more important and dominates in some scenarios, particularly for increasing levels of vehicle electrification. In the most ambitious “Best Case 2030" scenario where 100% ethanol and electricity from a very low carbon intensive grid mix are factored in, there are savings of at least 55% in total life time CO_2e impacts for all vehicles when compared to the “Base 2012” scenario. However, for “Best Case 2030”, the production phase could account for up to 75% of the total impact (BEV 2030 Best). End of life remains a very small proportion of the impact with the assumptions used in this report. Vehicle production is dominated by raw material extraction and component manufacturing with vehicle assembly accounting for only 6-8% of lifetime CO_2e impacts for all vehicles over all scenarios.

3. **To understand how the sensitivity of the study outputs is influenced by the choice of input assumptions and which parameters have the most impact on the total lifecycle CO_2e emissions for each vehicle technology.**

The results of the lifetime sensitivity analysis show that emissions per km are reduced as vehicle lifetime mileage increases because the lower impacts from production and end of life outweigh the increased impacts from vehicle maintenance during use. However, because use phase impacts from fuel and energy use dominate the life cycle only a moderate reduction is seen overall.

With a lifetime of 300,000 km the use phase is generally the most significant contributor to lifetime impacts up until Typical Case 2030. Exceptions to this are the BEV for Best Case 2020 which has the use and production phases contributing almost equally to lifetime impacts and for Typical 2030, where the production phase impacts of the BEV account for 55%. For Best Case 2030 with the vehicular lifetime extended to 300,000 km, the production phase contributes the most to lifetime impacts for the HEV, the PHEV and the BEV. However, the ICEV still shows 52% of lifetime impacts coming from the use phase and only 42% attributed to the production phase.

The results of this analysis, which focuses on materials for light-weighting, show little sensitivity to the choice of materials used for light-weighting. A comparison of Typical Case 2030, with a default material light-weighting ratio of 2:8 aluminium to advanced high strength steel (AHSS) with a 2030 scenario where a material ratio of 8:2 aluminium to AHSS is used shows only a 5% increase in CO_2e impacts (for an ICEV) when more aluminium is used. There is a 6%, 7% and 8% increase in total impacts for the HEV, PHEV and BEV respectively when aluminium is the favoured material for light-weighting

On the whole, the choice of recycling methodology does not significantly affect the results. The overall impact profiles of the vehicles in scenarios where the use phase dominates are expected to follow similar patterns with either the avoided burdens or cut-off approaches to end of life. For scenarios where the production phase dominates, such as Best 2030, the “EoL sensitivity” indicates that the application of the avoided burdens approach may significantly alter the overall impact profiles of the vehicles in this scenario. Production impacts are expected to reduce for all vehicles but if significant recycling of the battery pack is achieved, then the BEV may no longer be an outlier in this scenario.

Conclusions

The findings of this study demonstrate the following:

- For the use phase, further work is required to understand the relationship between NEDC fuel consumption and real world consumption. The relative difference in these figures for each technology may provide further evidence for specific technology or policy direction;
- For future scenarios, reductions in the use phase impacts are extremely significant in the case of using 100% bioethanol in vehicles with ICEVs as well as with electric vehicles that run

on low carbon intensity grid mix electricity. This means that the current use of tailpipe CO_2 emissions as an established comparator for different vehicles will most certainly become less effective and almost irrelevant in terms of focusing on the true carbon profiles/carbon reduction potential for future vehicles. Development of a WTW approach is urgently needed to ensure focus remains on true carbon reduction in the use phase. Beyond 2020 a life cycle approach should also be considered as vehicle production impacts become more significant;

- As the contribution to lifecycle CO_2e impacts from the use phase decreases in future, so the embodied impacts of the vehicles themselves will become more of a focus for further decarbonisation;
- The vehicle assembly phase is an insignificant contributor to “embodied” lifetime CO_2e impacts so while technological advances here can aid decarbonisation there is much greater potential for decarbonisation through advances in vehicle component materials and production processes;
- EV battery pack production and recycling are increasingly critical. This is because the battery pack is the largest single element contributing to production phase impacts for the PHEV and BEV. Recycling/re-use of such high-impact vehicle components may have the potential to contribute significantly to decarbonisation efforts of the embodied impacts of future vehicles. There are little available data on this topic so further work with experts in battery chemistry/production and recycling should be undertaken in the medium term to better inform this aspect;
- When the choice of material used for light-weighting is between aluminium and AHSS, there is only a marginal difference in the overall embodied carbon of the vehicles assessed in this study. However, composite materials have not been assessed. As a key potential route to light-weighting, composites may become significant in passenger vehicles in the longer term. Further research is required into the GHG impact both in production and recycling phases;
- The EoL phase has a small contribution to the overall life cycle impacts. However data on the actual end of life fate of automotive vehicles is scarce; limiting our consideration to a cut off end of life approach. Further research into the actual end of life fate of automotive vehicles in general should be undertaken to better understand this lifecycle phase.

In summary, there appear to be clear possibilities for reducing the potential lifetime CO_2e emissions in the future for all vehicles considered. Greater reductions in lifetime CO_2e impacts can be achieved by adjusting a combination of factors from the production, use and end of life phases for the vehicles assessed in this study. Particular emphasis should be made on decarbonisation of the embodied impacts of the vehicles as well as factors that contribute to use phase impacts as these two phases drive overall lifetime impacts.

The findings presented in this report should be considered in the context of the limitations of the high level, streamlined nature of this study. These findings serve as an indicator of the potential lifetime CO_2e emissions of future C-segment ICEVs, HEVs, PHEVs and BEVs. The results from this study can also be used to highlight areas of further work or improvements in future studies of a similar nature.

1 INTRODUCTION

PE INTERNATIONAL has been commissioned by the Low Carbon Vehicle Partnership to undertake an assessment of the total lifecycle greenhouse gas emissions for four different vehicle technologies. PE INTERNATIONAL is an integrated sustainability solutions provider operating globally, providing consulting, software and content to clients across all industry sectors. PE INTERNATIONAL has extensive expertise with life cycle assessments in the automotive sector with the following organisations being PE clients: Audi, Daimler, Fiat, Ford, GM, Honda, Renault, Mitsubishi, Nissan, Toyota, VW, Volvo Bosch, Continental, Delphi, Siemens, Valeo and Anglo Platinum.

This report, the "Life Cycle CO_2e Assessment of Low Carbon Cars 2020-2030", is the outcome of a study commissioned by the LowCVP following on from previous report "Preparing for a Life Cycle CO_2 Measure" prepared for the LowCVP by Ricardo. Two of the main conclusions of the Ricardo study were that future CO_2e metrics for passenger cars need to go beyond the tail-pipe measures and take into account whole life cycle CO_2e emissions to more fully account for environmental impacts, especially when comparing different vehicle technologies. Additionally, embodied CO_2e emissions associated with vehicle production and disposal become a more significant part of the lifecycle as the use phase decarbonises. This study leads on from the Ricardo study to improve understanding of lifecycle CO_2e emissions of different vehicle technologies over the next two decades. A key underlying theme of the study is to look at how the life cycle impact will change in future with lower carbon energy sources that can reduce the environmental impact and change the emissions profile of vehicles over the next two decades.

The goals of the study are:

- To estimate how total lifecycle CO2e emissions will change for different vehicle technologies in the future;
- To estimate how the balance of CO2e emissions associated with individual lifecycle stages will vary for different technologies in the future; and
- To assess the sensitivity of the study outputs to the choice of input assumptions and to determine those parameters having the most impact on the total lifecycle CO2e emissions for each vehicle technology.

A model has been developed to assess where the impacts occur during the different stages of the life cycle and how these impacts may change in the future with scenarios for 2012, 2020 and 2030. Sensitivity analyses were conducted to assess the variable input choices and their associated impact on the outputs. Sensitivity analyses that have been carried out include:

- Vehicle lifetime mileage;
- End Of Life recovery/recycling of significant components; and
- Materials used for vehicle light-weighting.

The study is undertaken using a high level approach and is not designed to provide a very detailed assessment of each technology (the scope of work for a finely detailed assessment would be very extensive and would be a correspondingly costly exercise). This study is thus a modelling exercise to identify general trends and issues.

PE INTERNATIONAL worked closely with the LowCVP Steering Group (in a peer review stakeholder process) to define and finalise the scope of this study. The Steering Group has also provided commentary and feedback on the results/findings of this project which have been incorporated into this final report.

2 SCOPE OF THE STUDY

The following section describes the general scope of the project to achieve the stated goals. This includes the identification of specific vehicles to be assessed, the boundary of the study and description of the scenarios considered.

2.1 PROJECT OVERVIEW

The diagram below gives a top level summary of the approach taken by PE INTERNATIONAL to execute the project.

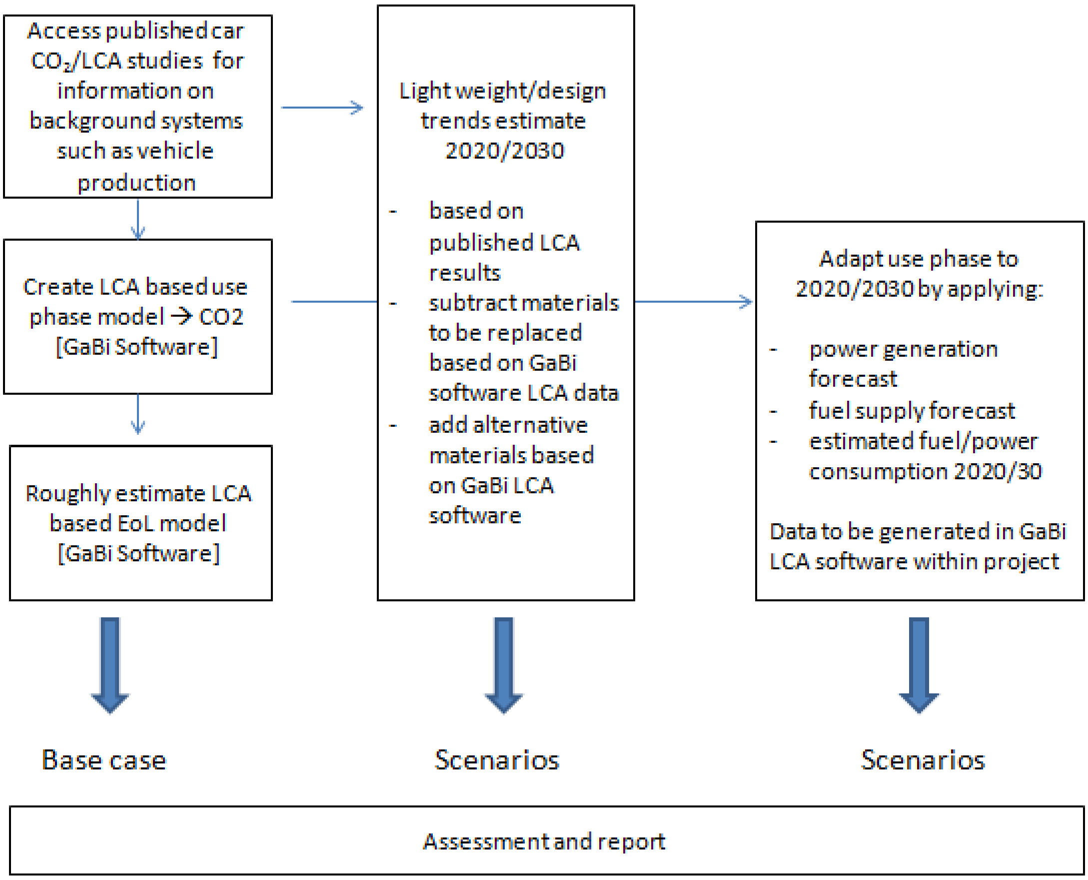

Figure 2-1: Top level summary of project approach

Figure 2-1 above describes a "Streamlined" LCA based on secondary data, available from published literature. This study follows ISO 14040/44 and PAS 2050 guidelines but cannot be considered fully compliant with either standard/specification because this study is "single issue" i.e. focusing only on greenhouse gases, there is no critical review for comparative assertions (for ISO 1040/44 compliance) and no use of primary data (for PAS 2050 compliance). Global warming potential (GWP) is the only environmental impact category that this study reports on.

2.2 FUNCTIONAL UNIT

The functional unit provides a common basis for comparing the different drive train technology options considered in this project. The functional unit selected for this study is defined as:

A C-Segment passenger vehicle travelling a distance of 150,000 km under NEDC conditions

The C-Segment is a European car size classification that corresponds to a "Small family car", "Compact car" or "Medium car". The vehicles in this study have been limited to C-Segment type only because this size of vehicle has come to dominate new car sales figures in Europe[19]. It is assumed that this trend will hold for the foreseeable future and, as such, an analysis limited to C-Segment vehicles is reasonable.

2.3 SYSTEM BOUNDARIES

This study considers impacts from "cradle to grave" and covers:

- Extraction of raw materials, production of fuels & production of vehicle component parts;
- Assembly of vehicles;
- Use phase of vehicle over a defined lifetime (including replacement parts - i.e. lubricants, tyres etc); and
- "Cut off" end of life of vehicle (considered to end just after vehicle shredding including limited disposal of wastes arising).

The vehicle technologies considered in this study are:

- Petrol internal combustion engine vehicle (ICEV) with petrol-biofuel blend;
- Hybrid electric vehicle (HEV) with petrol-biofuel blend;
- Plug-in hybrid electric vehicle (PHEV) with petrol-biofuel blend; and
- Battery Electric Vehicle (BEV).

The following sections describe the overall life cycle stages that constitute the system boundaries and the limits of the boundaries. Temporal, technological and geographical coverage are also described.

2.3.1 Overview of Life Cycle

Figure 2-2 below shows an overview of the life cycle of a vehicle and defines the boundaries of this study. Table 2-1 lists what is included within or excluded from the defined system boundaries.

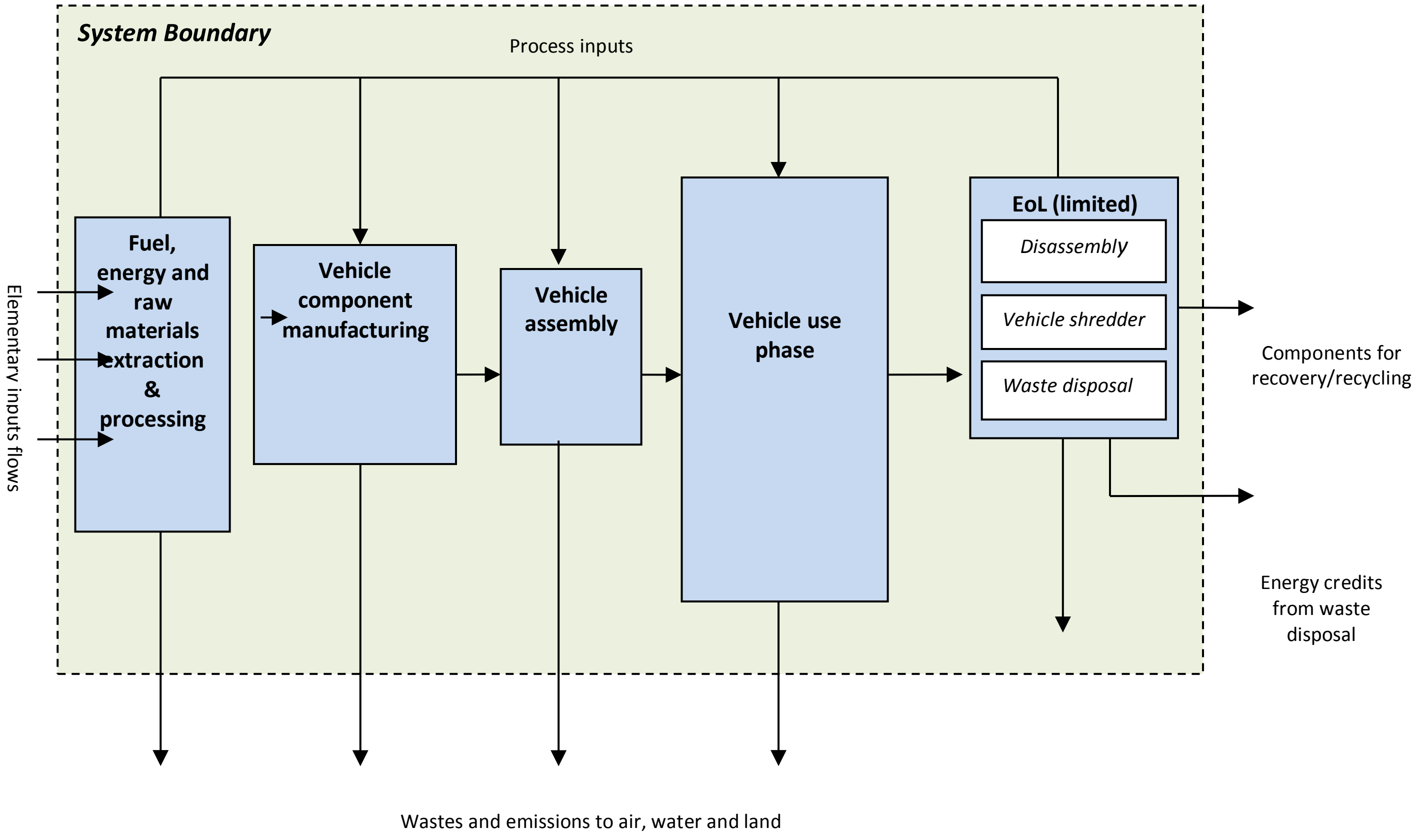

Figure 2-2: Product system assessed in this study indicating system boundary

Table 2-1: System Boundaries

Included	Excluded
× **Extraction/production of raw materials and fuels** × **Processing of raw materials and fuels** × **Vehicle component manufacture (limited)** × **Vehicle assembly power and energy inputs (limited)** × **Vehicle use phase fuel consumption** × **Maintenance and replacement parts in vehicle use phase** × **Preparation of components/material for recycling post recovery (limited)** × **Limited disposal of wastes left over during material recovery at EoL**	× Transport of vehicle components to assembly line × Transport of vehicle to end user × Transport of vehicle to EoL × Transport of workforce × Capital equipment × Disposal of wastes associated with vehicle component manufacturing, vehicle assembly , vehicle use phase or vehicle disassembly × Direct impacts of vehicle disassembly × Credits that may arise from recycling/reuse of recovered material/components and from WTE processes at EoL (limited recycling credits are only introduced for the case of the EoL sensitivity)

2.3.2 Temporal Coverage

The background data collected on raw materials extraction, production of the materials used, transportation mode(s) and end of life (EoL) processes are not older than 6 years and represent average technology. Exceptions are the datasets used for copper wire from the European Copper Institute (ECI, 2000) and aluminium recycling including scrap preparation from the European Aluminium Association (EAA, 2005). Despite their age, both of these datasets represent the best average data available and are provided by relevant trade associations.

2.3.3 Technological Coverage

The technology assessed for raw materials extraction, production of materials, transportation mode(s) and end of life processes are representative of the average technology that currently operates in UK, Europe and globally where appropriate.

For the base case vehicle characteristics, 2011-2012 publically available data from vehicle manufacturers (amongst others) are used.

2.3.4 Geographical Coverage

This study assumes:

- Global average data for raw materials that reflects real world sourcing situation;
- UK specific data for power grid mix for vehicle assembly and use phase etc., where applicable;
- European average data or closest fitting European national proxy data to fill in gaps where UK specific data is not available; and
- European average data for component manufacturing process proxies. This is because components may be sourced from several countries.

2.3.5 General Production Phase Considerations

The background system for the production phase considers vehicle component manufacture from raw material extraction through to production of the finished component including all intermediate processing steps. GaBi datasets have been used for most of the required background data – the exceptions to this are the case of biofuels (where data from the RED Annex V have been used) and the case of grid carbon intensity for the “Best 2030” scenario (where data from the 2011 UK Draft Energy Bill and 2009 EC EU energy trends to 2030 statistical data have been used).

2.3.6 General Use Phase Considerations

GHG emissions in the use phase derive from the production and combustion of petrol and bioethanol and from the generation of electricity for charging batteries.

Assumptions relating to vehicular lifetime and driving cycle have a significant influence on total use phase emissions.

Literature sources put the lifetime of a vehicle in Europe at between 12 and 15 years[2,12] and average total mileage varies from 150,000 – 300,000 km [2, 10 12, 15, 16]. Lifetime mileage for this study has been set to 150,000 km to align with previous studies carried out for the LowCVP. Hence, the functional unit specified in section 2.2 corresponds to the transport distance over a single vehicle life cycle.

Driving cycles are used to test the performance of a vehicle under set conditions and the choice of driving cycle directly affects the fuel consumption of a vehicle. In this study the use phase fuel consumption is based on the New European Driving Cycle (NEDC), which is widely used by OEMs and so provides standardisation in reporting. It is acknowledged that NEDC fuel consumption figures may differ from "real world" figures but a sensitivity assessment of the effect of other driving cycles is outside the scope of this study.

2.3.7 General Recycling/End of Life Considerations

The recycling methodology selected for this study is the "cut-off" approach, widely adopted by OEMs that carry out automotive LCAs (see Appendix 8.4 for details). Here, the EoL of the vehicle is assumed to end just after the shredder, with limited disposal of waste arising, so that:

- Burdens of vehicle shredding as well as the efforts needed to prepare materials for recovery/ recycling post shredder are assigned to the vehicle life cycle;
- Secondary material used in the production of the vehicle is assumed to be "burden free" but no credits are given for materials recovered post shredder or for any energy recovered from WTE processing of waste; and
- The quantity of recovered material corresponds to the requirements of the EU End of Life Vehicles Directive.

2.4 VEHICLE CHARACTERISTICS

This study has been limited to drive train technologies that run only on a blend of petrol/bioethanol fuel as well as BEV in the C-Segment vehicle class. Discussion with the LowCVP steering group concluded that, among other considerations, the efficiency improvements and advanced biofuels availabilities for petrol are more certain in petrol than diesel in the 2030 timeframe. Focusing on petrol is thus intended to facilitate the prediction of future scenarios for this study.

2.4.1 Base Vehicle Specifications

The GaBi LCA models developed for the material composition and assembly of the vehicles assessed are based on the "average mid-sized" European petrol passenger car as described by the 2008 JRC IMPRO-car study. This study is also used as a reference source of maintenance/replacement considerations for vehicle components subject to wear and tear or consumption over vehicular life time usage. Detailed material composition of this "Root vehicle" can be found in appendix 8.1. Assembly line data used in this study (sourced from the JRC IMPRO-car study) are also found in this appendix.

This root vehicle is adjusted to align with the four drive train technologies assessed in this study. The adjustment is based on published data and PE INTERNATIONAL's in-house expertise. Details of the LCA modelling approach used to adjust the JRC IMPRO-car root vehicle are given in section 3.

2.4.2 Internal Combustion Engine Vehicle (ICEV)

The characteristics for the ICEV used the base scenario in this study are as follows:

- Mid-size petrol, exemplified by. VW Golf , Ford Focus, Renault Mégane
- Vehicle mass = 1240 kg[2]
- Fuel blend = E10, 10% (vol.) ethanol, 90% (vol.) gasoline[12]
- Ethanol feed stock source = 75% sugar cane, 5% sugar beet, 20% wheat[13]
- Fuel consumption = 5.83 l/ 100 km (NEDC based average from Golf, Focus and Mégane 2011/2012)[18]

- Maintenance/replacement parts over vehicle life time = Battery (x 1); tyres (x 12); lubricants (47 litres); refrigerant (0.9 kg)[2,4]

2.4.3 Hybrid Electric Vehicle (HEV)

The characteristics for the HEV used the base scenario in this study are as follows:

- Mid size full hybrid, exemplified by Toyota Auris HEV
- Vehicle mass = 1420 kg[20,21]
- Fuel blend = E10, 10% (vol.) ethanol, 90% (vol.) gasoline[12]
- Ethanol feed stock source = 75% sugar cane, 5% sugar beet, 20% wheat[13]
- Battery pack type/size = NiMH battery pack, 1.3 kWh energy content[20,21]
- Electric motor rating = 60 kWh[22,23,24]
- Fuel consumption = 4.0 l/100 km (NEDC based)[20,21]
- Maintenance/replacement parts over vehicle life time = Battery (x1); tyres (x 12); lubricants (47 litres); refrigerant (0.9 kg)[2,4]

2.4.4 Plug-in Hybrid Electric Vehicle (PHEV)

The characteristics for the PHEV used the base scenario in this study are as follows:

- Mid-size plug-in hybrid, exemplified by Toyota Prius PHEV
- Vehicle mass = 1380 kg [22,23,24]
- Fuel blend = E10, 10% (vol.) ethanol, 90% (vol.) gasoline[12]
- Ethanol feed stock source = 75% sugar cane, 5% sugar beet, 20% wheat[13]
- Battery pack type/size = Li-Ion battery back, 4.4 kWh energy content[22,23,24]
- Electric motor rating = 60 kWh[22,23,24]
- Energy consumption, electrical = 5.2 kWh/ 100 km[28,29]
- Fuel consumption = 2.1 l/100 km (NEDC based, weighted, combined)[29]
- Maintenance/replacement parts over vehicle life time = Battery (x1); tyres (x 12); lubricants (47 litres); refrigerant (0.9 kg)[2,4]

2.4.5 Battery Electric Vehicle (BEV)

The characteristics for the BEV used for the base scenario in this study are as follows:

- Mid-size electric vehicle exemplified by Nissan Leaf
- Vehicle mass = 1530 kg[26]
- Battery pack type/size = Li-Ion battery pack, 24kWh energy content[25]
- Electric motor rating = 80 kWh[25]
- Energy consumption, electrical = 15.0 kWh/ 100 km[27]
- Maintenance/replacement parts over vehicle life time = Battery (x1); tyres (x 12); refrigerant (0.9 kg)[2,4]

2.5 SCENARIO DESCRIPTIONS

The base case scenario for this study is 2012. Future scenario cases considered are for the years 2020 and 2030. For each of the future scenarios, “Typical case” and the “Best case” scenarios are defined. The “Typical case” represents the lower limits in the range of predictions of the future improvements that can be made to the various drive train technologies, while the “Best case” represents the upper limits of potential future improvements.

It is worth noting here that the predicted conditions of vehicles under the future scenarios in this study will not necessarily be applicable to ALL relevant vehicles on the road in the UK at the time. Rather, the vehicles in the future scenarios are more representative of possible Best Available Technology (BAT) of the type of vehicles under consideration in this study.

Thus, the list of scenarios in the analysis is:

- Base scenario 2012
- Typical case scenario 2020
- Best case scenario 2020
- Typical case scenario 2030
- Best case scenario 2030

This section provides an overview of the assumptions used. A detailed description of these scenarios can be found in Appendix 8.2. The assumptions that apply across all scenarios are:

- Vehicle lifetime of 150,000km; including relevant maintenance considerations such as oil changes, tyre replacements, etc.

- Vehicle component production is assumed to be in the EU with materials sourced globally; vehicle assembly and use are assumed to be in the UK

- Light-weighting of vehicles is modelled for future scenarios by substituting mild steel with aluminium and advanced high strength steel (AHSS) in a ratio of 2:8

- EoL for vehicle follows the “cut-off” approach as detailed in section 2.3.6 above.

The table below provides a summary of the scenario descriptions found in Appendix 8.2

Table 2-2: Summary of scenario descriptions

ICEV		
	Typical Case	Best Case
2012	Fuel consumption = 5.83 l/100km E10 petrol blend utilised	NA
2020	7% improvement in fuel consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 5.42 l/100km E10 petrol blend utilised Ethanol used in E10 petrol blend meets the 60% GHG intensity savings threshold	11% improvement in fuel consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 5.19 l/100km E15 petrol blend utilised Ethanol used in E15 petrol blend meets the 60% GHG intensity savings threshold

	stipulated by the RED 2009 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively.	stipulated by the RED 2009 14% & 34% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively.
2030	9% improvement in fuel consumption from typical 2020 due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 4.93 l/100km E15 petrol blend utilised Ethanol used in E15 petrol blend meets the 70% GHG intensity savings threshold stipulated by the RED 2009 28% & 51% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively.	13% improvement in fuel consumption from typical 2020 due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 4.72 l/100km 100% bioethanol utilised Ethanol used meets the 70% GHG intensity savings threshold stipulated by the RED 2009 60% & 83% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively.
HEV		
	Typical Case	Best Case
2012	Fuel consumption = 4.00 l/100km E10 petrol blend utilised	NA
2020	6% improvement in fuel consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 3.76 l/100km. E10 petrol blend utilised. Ethanol used in E10 petrol blend meets the 60% GHG intensity savings threshold stipulated by the RED 2009 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts of battery pack assumed due to potential advancements in the technology.	9% improvement in fuel consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 3.64 l/100km. E15 petrol blend utilised. Ethanol used in E15 petrol blend meets the 60% GHG intensity savings threshold stipulated by the RED 2009 14% & 34% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon impacts of battery pack assumed due to potential advancements in the technology.
2030	8% improvement in fuel consumption from typical 2020 due to light-weighting and	11% improvement in fuel consumption from typical 2020 due to light-weighting

	assumed advancement in technology. Resulting fuel consumption = 3.46 l/100km. E15 petrol blend utilised. Ethanol used in E15 petrol blend meets the 70% GHG intensity savings threshold stipulated by the RED 2009 28% & 51% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts of battery pack from typical 2020 assumed due to potential advancements in the technology.	and assumed advancement in technology. Resulting fuel consumption = 3.35 l/100km. 100% bioethanol utilised. Ethanol used meets the 70% GHG intensity savings threshold stipulated by the RED 2009 60% & 83% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon impacts of battery pack from typical 2020 assumed due to potential advancements in the technology.
PHEV		
	Typical Case	Best Case
2012	Fuel consumption = 2.10 l/100km Electricity consumption = 5.20 kWh/100km E10 petrol blend utilised	NA
2020	4% improvement in fuel/electricity consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 2.01 l/100km; resulting electricity consumption = 5.09 kWh/100km E10 petrol blend utilised Ethanol used in E10 petrol blend meets the 60% GHG intensity savings threshold stipulated by the RED 2009 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts of battery pack assumed due to potential	6% improvement in fuel/electricity consumption due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 1.97 l/100km; resulting electricity consumption = 5.04 kWh/100km E15 petrol blend utilised Ethanol used in E15 petrol blend meets the 60% GHG intensity savings threshold stipulated by the RED 2009 14% & 34% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon impacts of battery pack assumed due to

	advancements in the technology.	potential advancements in the technology.
2030	6% improvement in fuel/electricity consumption from typical 2020 due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 1.89 l/100km; resulting electricity consumption = 4.94 kWh/100km. E15 petrol blend utilised. Ethanol used in E15 petrol blend meets the 70% GHG intensity savings threshold stipulated by the RED 2009 28% & 51% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts of battery pack from typical 2020 assumed due to potential advancements in the technology.	8% improvement in fuel consumption from typical 2020 due to light-weighting and assumed advancement in technology. Resulting fuel consumption = 1.85 l/100km; resulting electricity consumption = 4.89 kWh/100km. 100% bioethanol utilised. Ethanol used meets the 70% GHG intensity savings threshold stipulated by the RED 2009 60% & 83% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon impacts of battery pack from typical 2020 assumed due to potential advancements in the technology.
BEV		
	Typical Case	Best Case
2012	Electricity consumption = 15.0 kWh/100km	NA
2020	2% improvement in electricity consumption assumed due to light-weighting. Resulting electricity consumption = 14.7 kWh/100km. 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts of battery pack assumed due to potential advancements in the technology.	2% improvement in electricity consumption assumed due to light-weighting. Resulting electricity consumption = 14.6 kWh/100km. 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon impacts of battery pack assumed due to potential advancements in the technology.
2030	3% improvement in electricity consumption from typical 2020 assumed due to light-weighting. Resulting electricity consumption = 14.3 kWh/100km 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 10% reductions in embodied carbon impacts	4% improvement in electricity consumption from typical 2020 assumed due to light-weighting. Resulting electricity consumption = 14.1 kWh/100km 7% & 17% reductions in carbon intensities of EU & UK electricity grid mixes (from 2012 figures) respectively. 15% reductions in embodied carbon

	of battery pack from typical 2020 assumed due to potential advancements in the technology.	impacts of battery pack from typical 2020 assumed due to potential advancements in the technology.

All scenarios and applied assumptions were developed in conjunction with the LowCVP Steering Group.

2.6 SELECTION OF LCIA METHODOLOGY AND TYPES OF IMPACTS

As mentioned in section 2.1 above, this streamlined LCA focuses only on the Global Warming Potential (GWP) indicator with a time horizon of 100 years. The CML impact assessment methodology framework was selected for this assessment based on the most recent update (November 2010), as described in Table 2-3. The CML characterization factors are applicable to the European context and are widely used and respected within the LCA community.

Global Warming Potential was chosen because of its direct relevance to climate change in which there are high levels of high public and institutional interest and is widely deemed to be the most pressing environmental issue of our times.

In this study, biogenic CO_2 has been excluded from the GWP impact assessment. This is because in a relatively short time frame (much less than 100 years) the amount of CO_2 released from the combustion of biotic material is assumed to be equal to the amount of CO_2 that the plants/crops have taken in from the atmosphere over their growth – essentially a “net zero effect”.

Table 2-3: Impact Assessment Category Descriptions

Impact Category	Indicator	Description	Unit	Reference
Climate Change	Global Warming Potential (GWP)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	tonnes CO_{2e}	[GUINÉE 2001]

It shall be noted that the GWP impact category represents an impact *potential*, i.e., it is an approximation of the environmental impact that could occur if the emitted molecules would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so.

GWP results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

2.7 SOFTWARE AND DATABASES

The LCA model was created using the GaBi 5 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. GaBi software and databases are widely used by OEMs in the automotive sectors who engage in LCA activities.

The GaBi 5 2011 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system. Documentation for all non-project-specific datasets can be found at www.gabi-software.com/support/gabi/gabi-lci-documentation.

As mentioned in section 2.1, no primary data were collected for this study. Additional data for background and foreground systems have been taken from publically available literature. Such sources include vehicle manufacturers' promotional material/websites and publicly available literature on automotive LCA studies.

3 LCA MODELLING APPROACH

This section describes the approach taken to develop the LCA models for this study. It also lists the assumptions made during model development.

3.1 OVERVIEW OF MODELLING APPROACH

To achieve the goals of this study, we have:

- Built flexible/parameterised models in GaBi of the four vehicles based on material compositions sourced from literature. These models also cover the production of vehicle components using “generic” manufacturing processes. The models include replacement materials necessary for vehicle maintenance during the lifecycle.
- Built a flexible/parameterised model in GaBi for the vehicle assembly phase, with the assumption that requirements for assembly will not vary greatly for the four vehicles. Hence these models are essentially the same for all vehicles.
- Built flexible/parameterised models in GaBi for the use phase of the four vehicle types. Use phase model will be tailored to the specific technologies, i.e.
  - use phase for HEVs and ICE accounts for fuel production and combustion;
  - use phase for PHEV accounts for fuel production and combustion plus electricity consumption for EV travel mode;
  - use phase for BEV accounts for electricity consumption for EV travel mode.
- Built an end of life model to account for recovery and recycling of battery/battery pack components, neodymium magnets and precious metals in catalytic converter for the specific end of life sensitivity assessment. The end of life model also accounts for the vehicle shredding process.

The models have been adjusted to assess the required scenarios for 2020 and 2030 as follows:

- Light-weighting of vehicles by replacing materials i.e. increasing the amounts of advanced high strength steel and aluminium in the car body and reducing mild steel amounts present accordingly;
- Change in the bioethanol feedstock source split;
- Change in the bioethanol – gasoline volumetric blend;
- Change in the carbon intensities of power grid mix;
- Improvements in ICE technology leading to better fuel economy/performance.

Fuels saving predictions from light-weighting are modelled along the guidelines finalised in consultation with the LowCVP Steering Group members.

3.2 OVERVIEW OF MODELLING ASSUMPTIONS

The following assumptions were made when developing the LCA models.

3.2.1 Vehicle component manufacture assumptions

Generic GaBi 5 datasets have been used to account for component manufacturing processes such as stamping and bending metal sheets; casting and machining metal parts; injection moulding plastic parts, etc. For simplicity, in this high level streamlined study, it has been assumed that component manufacture is in Europe under prevailing fuel and electricity grid mix conditions.

No attempt has been made to predict future changes in the carbon intensities of raw materials used in component manufacture. However, the carbon intensity of electricity used in component manufacture is varied for future scenarios.

3.2.2 Vehicle assembly assumptions

A lack of publically available data on vehicle assembly operations has meant that data from the 2008 JRC IMPRO-car study has been applied to the assembly of all the vehicles considered in this study.

In reality the exact requirements for vehicle assembly may vary for the four drive train technologies considered in this study. However, this study applies the same data for vehicle assembly across all the technologies. Past studies show that vehicle assembly is a very minor contributor to overall life cycle CO_2e impacts. In addition, assembly line technologies are expected to be quite similar across all the drive trains considered so using the same data for all drive train technologies in this study should not impact greatly on the results.

The carbon intensity of electricity used in vehicle assembly is varied for future scenarios.

3.2.3 Vehicle composition assumptions

All vehicles are based on the “average mid-sized petrol” car as detailed in the 2008 JRC IMPRO-car study (which corresponds to the C-Segment focus of this project). The vehicles are differentiated by adding or subtracting relevant components based on the drive train in question with all other common components (such as the vehicle glider) assumed to remain the same e.g. the BEV has no ICE and no catalytic converter but will include an appropriately sized e-motor, power electronics and battery pack. Alternatively, the petrol ICEV will have a catalytic converter, engine oil/lubricants but no e-motor or battery pack.

For light-weighting, the only materials considered are aluminium and AHSS. The use of composites and other alternative materials for light-weighting have not been included in this streamlined LCA study. Light-weighting in this study is only considered for non-drive chain components i.e. the vehicle glider.

Where it has not been possible to exactly match the material composition of vehicle components, the best available GaBi datasets have been used as proxies. The choice of proxies/estimation has been based on PE INTERNATIONAL’s professional experience and judgment.

3.2.4 Logistics assumptions

The nature of this study means that it has not been feasible to look for publically available information on raw material or component transportation. As such, no transports of materials, vehicle components or even delivery of assembled vehicles to their end users have been included in this study.

3.2.5 Fuel/Electricity assumptions

The carbon intensity of gasoline is assumed to remain constant for all scenarios, i.e. no change from the present situation.

No considerations of advanced/second generation biofuels have been taken into account for this study due to lack of data and high uncertainties surrounding the future of biofuels.

All values used in this study for bioethanol GHG intensities are the “Typical values” given in Annex 5 of the EC Renewable Energy Directive (RED), Annex 5, 2009.

The carbon intensity of bioethanol is varied for future scenarios in two ways:

1. By adjusting the proportion sourced from different feedstocks over time; and
2. By assuming the individual carbon intensities for the production (WTT) of ethanol from sugar cane, wheat and sugar beet also reduce in future.

Adjustments are made from the current situation based on expert opinion via consultation with the LowCVP Steering Group and using figures from the EC Renewable Energy Directive, Annex 5. All adjustments take into consideration the 60% GHG intensity savings threshold for biofuels in 2020 set by the Renewable Energy Directive as well as the 70% GHG intensity savings threshold for 2030. As a result, bioethanol from sugar beet is excluded from the feedstock source mix in 2030. This is because there are no foreseeable improvements to the production technology that would drop the WTT GHG intensity of sugar beet bioethanol below the 70% threshold stipulated by the Renewable Energy Directive [13]. Detailed assumptions on proportion of ethanol sourced from different feedstocks as well as reductions in WTT carbon intensities of ethanol sourced from different feedstocks used for the scenarios in this study can be found in appendix 8.2 of this report.

The carbon intensity of the grid mix changes for future scenarios. For 2020, grid mix carbon intensities are based on EC statistical predictions. For the UK grid mix in 2030, carbon intensities are assumptions based on information from the UK Carbon Plan and the 2012 UK Draft Energy Bill. For the EU grid mix in 2030, carbon intensities are assumption based on information the EC “Roadmap for moving to a low-carbon economy in 2050” and “Power perspectives 2030: on the road to a decarbonised power sector”. Detailed assumptions on the carbon intensities of future grid mixes used for the scenarios in this study can be found in appendix 8.2 of this report.

Electricity grid mix carbon intensities are assumed to be at the point of consumption i.e. at the end user’s power outlet and thus include transmission losses and other associated factors.

3.2.6 Use phase assumptions

The rate of wear and tear/maintenance detailed under vehicle characteristics in section 2.4 of this report is assumed to be the same for all vehicles assessed. This is again taken from the 2008 JRC IMPRO-car study as the best publically available average data. The fact that different drive trains require different materials for maintenance/normal running is taken into account.

Replacement of the battery pack of advance drive chain technologies is not considered under wear and tear/maintenance. This is because for electrified vehicles, manufacturers currently provide a typical warranty on battery packs for up to 160,000km (or 8 years). As vehicular lifetime in this study is set to 150,000km, it is assumed that the original battery pack suffices for the full life cycle.

It has been assumed that the NEDC fuel consumption applies to all vehicles considered in this study.

CO_2 emissions from the combustion of bioethanol (being biotic emissions) are excluded from carbon accounting as this is assumed to be equivalent to the CO_2 uptake during biomass production. CH_4 and NO_2 that may arise from the combustion of bioethanol are included in the carbon accounting as CO_2e but these only occur in very small quantities. Under this assumption, the TTW carbon intensity of bioethanol is 0.0008 kg CO_2e/MJ. Therefore, by substituting petrol with bioethanol in an ICE the effect is to reduce use phase CO_2e emissions.

3.2.7 End of life assumptions

Liquids are assumed to be drained from the vehicle and incinerated prior to shredding.

Automotive shredder residue (ASR) remaining after materials recovery is assumed to be incinerated using an "Incineration of mixed municipal solid waste (MSW)" dataset as best available proxy data.

Significant components such as the lead acid battery, battery pack, catalytic converter, e-motor, power electronics, automotive glass and the tyres are separated from the car body (for potential recovery/recycling) prior to shredding.

The EoL sensitivity analysis only focuses on the recovery/recycling of the major differentiating components outlined in section 2.3.6. The introduction of "avoided burden credits" from recycling /recovery to the product system is only intended as a very top level indicator of the potential benefits of recycling. The recovery rate of materials has been set to 90% to take potential material losses into account. No impacts from the recycling process have been accounted for with the exception of the battery pack of the electrified drive train. In this case very little detailed data are publically available so it is assumed that 50-75% of the production impacts of the battery pack could be credited to the system on recycling this component as a conservative estimation.

Waste material arising after recovery and recycling is assumed to be incinerated. Datasets used for these incineration operations are closely matched to the materials in question and include "waste incineration of plastics (PE, PP, PS, PB)", "waste incineration of glass/inert material", "hazardous waste incineration (non specific, worst case)", "waste incineration of plastics (rigid PVC)" and "waste incineration of plastics (unspecified) fraction in MSW".

3.2.8 General assumptions

Assessment of Indirect Land Use Change (ILUC) has not been considered for any aspects of this study.

3.3 SENSITIVITY ANALYSES

Sensitivity analyses are vital for this study to help understand the influence on the results of the many variables and the uncertainties in model assumptions. Consultation with the LowCVP and the Steering Group has focused on the following sensitivity analyses:

- Vehicle lifetime mileage;
- EoL recovery/recycling of selected components; and
- Materials for vehicle light-weighting.

3.3.1 Vehicle lifetime mileage

Current literature puts the lifetime of ICEV between 150,000 km and 300,000 km. Future vehicles are expected to compete with their predecessors and so exploring the upper limit of lifetime mileage is of relevance to this study. The vehicle lifetime sensitivity will explore the effects of increasing vehicle lifetime mileage to from 150,000 km to 300,000 km, taking into account additional maintenance/replacement parts that will be required for this extended lifetime.

3.3.2 End of life following avoided burdens approach

The embodied carbon of the battery pack and certain components of electrified drive chains are known to be significant differentiators between the drive chain technologies being considered and make noticeable contributions to the overall lifetime CO_2e impacts of these vehicles. However, it is argued that with potential recovery and recycling of such components, these impacts could be significantly reduced.

As the “cut off” recycling methodology at EoL applied to this study does not give credits for recycling at end of life, elements of the “avoided burdens” approach are introduced ***in isolation*** in this sensitivity test (see Appendix 8.4 for details of this methodology). Under the avoided burdens approach, as applied in this sensitivity analysis, recycling credits show up as “negative burdens” associated with EoL that have the effect of reducing net burdens of the product system under analysis.

A comprehensive EoL sensitivity analysis following the avoided burdens approach is limited by data constraints for this study. However, the inclusion of such a test is considered adequate to provide an indication of the benefits of recycling certain components that are themselves expected to have high embodied carbon or comprised of materials with high carbon intensities. Thus, EoL under the avoided burdens approach will include:

- Recovery and recycling of the battery pack;
- Recovery and recycling of the lead acid battery;
- Recovery and recycling of neodymium magnets used in the electric motor; and
- Recovery and recycling of precious metals used in catalytic converter.

3.3.3 Materials for light-weighting

The default state of the models assumes a 2:8 split between aluminium and advanced high strength steel to substitute for mild steel to achieve vehicle light-weighting. However, this leads to a more “steel-centric” vehicle with inherently lower embedded CO_2e (see Appendix 8.3 for carbon intensities of steel versus aluminium).

Aluminium can also be used extensively in car bodies (usually in the case of premium vehicle brands) so skewing the ratio of aluminium to AHSS used in light-weighting to favour an “Aluminium-centric” to 8:2 aluminium to AHSS is presented as the final sensitivity test.

4 LIFE CYCLE IMPACT ASSESSMENT (LCIA) RESULTS

In this section, the results of the cycle CO_2e impact assessments are presented and discussed. Results are presented with tables and charts at a "top level" and also at a "detailed level".

4.1 TOP LEVEL IMPACT ASSESSMENT RESULTS

The top level results of the study are presented in Table 4-1.

Table 4-1: Top level results showing CO_2e emissions associated with the various drive train technologies and scenarios

	Base 2012	Typical 2020	Best 2020	Typical 2030	Best 2030
Vehicle	t CO_2e	t CO_2e	t CO_2e	t CO_2e	t CO_2e
ICEV	30.70	28.70	27.51	25.27	9.35
HEV	24.40	23.07	22.29	20.62	9.27
PHEV	21.74	20.30	18.87	17.11	9.21
BEV	24.46	21.60	18.49	15.74	11.06

The top level results show that if current trends in the automotive industry continue in future then the potential life cycle CO_2e impacts associated with the every vehicle technology considered in this study progressively reduce over time. That said, the significant carbon reductions shown in the "Best case 2030" scenario can only be achieved with aggressive decarbonisation measures.

With reference to Base Case 2012;

- For the ICEV, there is a 7% reduction in total potential lifetime CO_2e impacts for Typical Case 2020, a 10% reduction for Best case 2020, an 18% reduction for Typical Case 2030 and a 70% reduction for Best Case 2030;
- For the HEV, there is a 5% reduction in total potential lifetime CO_2e impacts for Typical Case 2020, a 9% reduction for Best case 2020, a 15% reduction for Typical Case 2030 and a 62% reduction for Best Case 2030;
- For the PHEV, there is a 7% reduction in total potential lifetime CO_2e impacts for Typical Case 2020, a 13% reduction for Best case 2020, a 21% reduction for Typical Case 2030 and a 58% reduction for Best Case 2030; and
- For the BEV, there is a 12% reduction in total potential lifetime CO_2e impacts for Typical Case 2020, a 24% reduction for Best case 2020, a 36% reduction for Typical Case 2030 and a 55% reduction for Best Case 2030.

The following section looks at each scenario presented in the results above in more detail to provide a better understanding of the main aspects contributing to the CO_2e emissions in significant phases of a vehicle's life cycle.

4.2 DETAILED IMPACT ASSESSMENT RESULTS

This section provides charts that show the contributions to the total lifecycle GHG emissions from significant phases in the vehicle life cycle. For the detailed results, the impacts have been grouped as follows:

- Production - this grouping includes the embodied impacts of the vehicle as well as impacts associated with component manufacture and vehicle assembly;
- Use phase fossil (WTW) - this grouping covers the production of gasoline as well as the tailpipe emissions from combustion of the fuel from use in the vehicle;
- Use phase bioethanol (WTW) - this grouping includes the production of bioethanol as well as tailpipe emissions from use in the vehicle;
- Use phase electricity (WTW) - this grouping covers the production and transmission of electricity to the point of consumption by the end user; and
- End of life - this grouping includes the impacts of shredding the vehicle, preparing materials for recovery/recycling and disposal of wastes arising from shredding and disassembly.

The same groupings are applied throughout this report wherever charts showing detailed results are presented.

4.2.1 Base case scenario 2012

Figure 4-2 below shows the detailed results for the "Base case 2012" scenario.

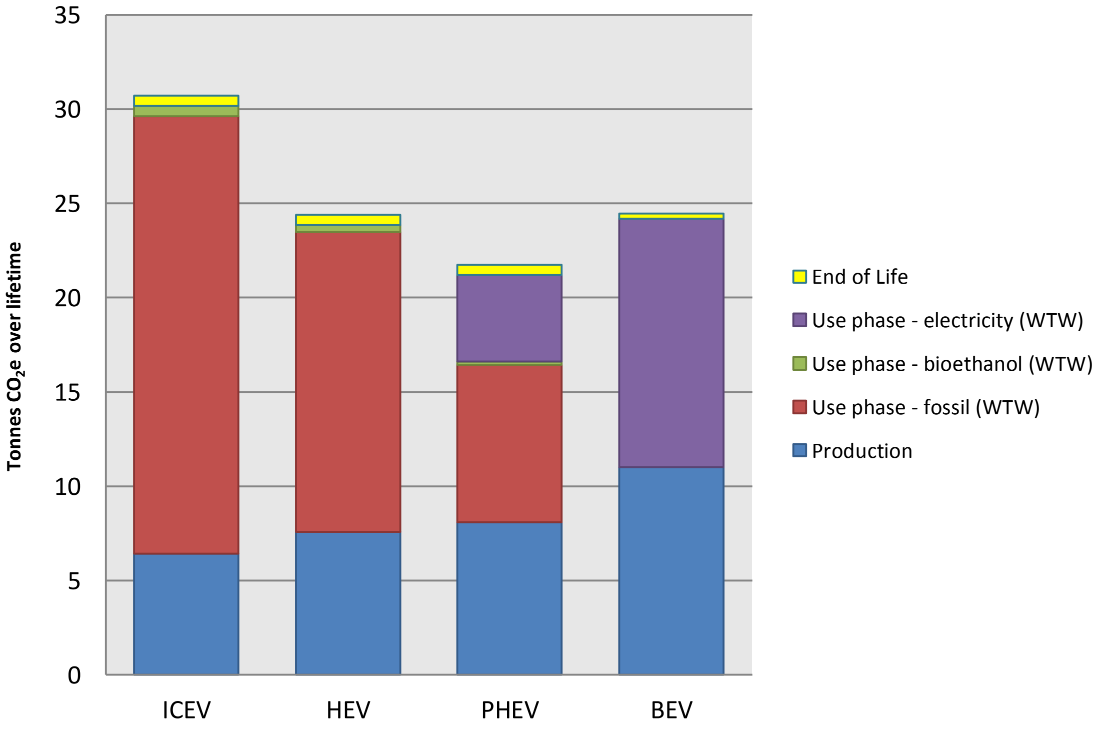

Figure 4-1: Detailed results for "Base case 2012"

The Base Case 2012 shows that under the prevailing assumptions (see section 2.4) the use phase dominates the potential lifetime CO$_2$e impacts for all the vehicles. For the ICEV, the use phase accounts for about 80% of the impacts, for the HEV it is close to 70%, for the PHEV it is about 60% while for the BEV it is close to 55%.

The differences in the use phase CO_2e impacts between the ICEV and the HEV are due to the higher fuel consumption of the ICEV. The PHEV has even lower fuel consumption than the HEV but consumes additional grid electricity as is seen in the chart above. The BEV's use phase is totally reliant on grid electricity.

Another significant contributor to potential lifetime CO_2e impacts is the production phase. For the ICEV, the production phase accounts for about 21% of the impacts, for the HEV it is close to 33%, for the PHEV it is about 37% while for the BEV it is close to 45%. Production phase impacts for all vehicles are driven by the embodied CO_2e of components with vehicle assembly only accounting for 5-6% of total impacts.

The increase in the production phase impacts can be explained by the additional components required by the advanced drive train technologies such as electric motors, power electronics and battery packs.

For all vehicles the end of life phase contributes only 1-3% of potential lifetime CO_2e impacts. End of life as defined in this study only accounts for impacts from shredding vehicles after specified components have been separated for potential recovery/recycling as well as disposal of wastes arising during separation/shredding. Thus, these low figures are in line with our expectations. The same explanation holds for all following scenarios in this section of the report.

Close scrutiny of figure 4-2 indicates that end of life impacts for the BEV appear to be marginally lower than for other vehicles. This is because, without an engine, the mass of the BEV sent on to the shredder after specified components have been separated is lower than those of the other vehicles. Thus, less effort is required to shred the stripped BEV and this is reflected in the results. The same explanation holds for all following scenarios in this section of the report.

4.2.2 Typical case scenario 2020

Figure 4-3 below shows the detailed results for the "Typical case 2020" scenario.

For Typical Case 2020, we see a similar trend as for Base Case 2012 with the use phase still responsible for the majority of potential lifetime CO_2e impacts followed by impacts from the production phase. For the ICEV, the use phase accounts for about 77% of the impacts, for the HEV it is close to 66%, for the PHEV it is about 59% while for the BEV it is close to 51%.

For the ICEV, the production phase accounts for about 21% of the impacts, for the HEV it is close to 31%, for the PHEV it is about 38% while for the BEV it is close to 48%. Production phase impacts for all vehicles are driven by the embodied CO_2e of components with vehicle assembly only accounting for 4-6% of total impacts.

The end of life phase contributes 1-3% of potential lifetime CO_2e impacts across the vehicles considered.

However, the prevailing assumptions for this scenario (see section 2.4) lead to a general reduction in the potential lifetime CO_2e for all vehicle types as compared to Base Case 2012 figures.

For the ICEV, there is a 4% reduction in the production impacts from Base Case 2012 levels and a 7% reduction in the use phase-fossil WTW impacts.

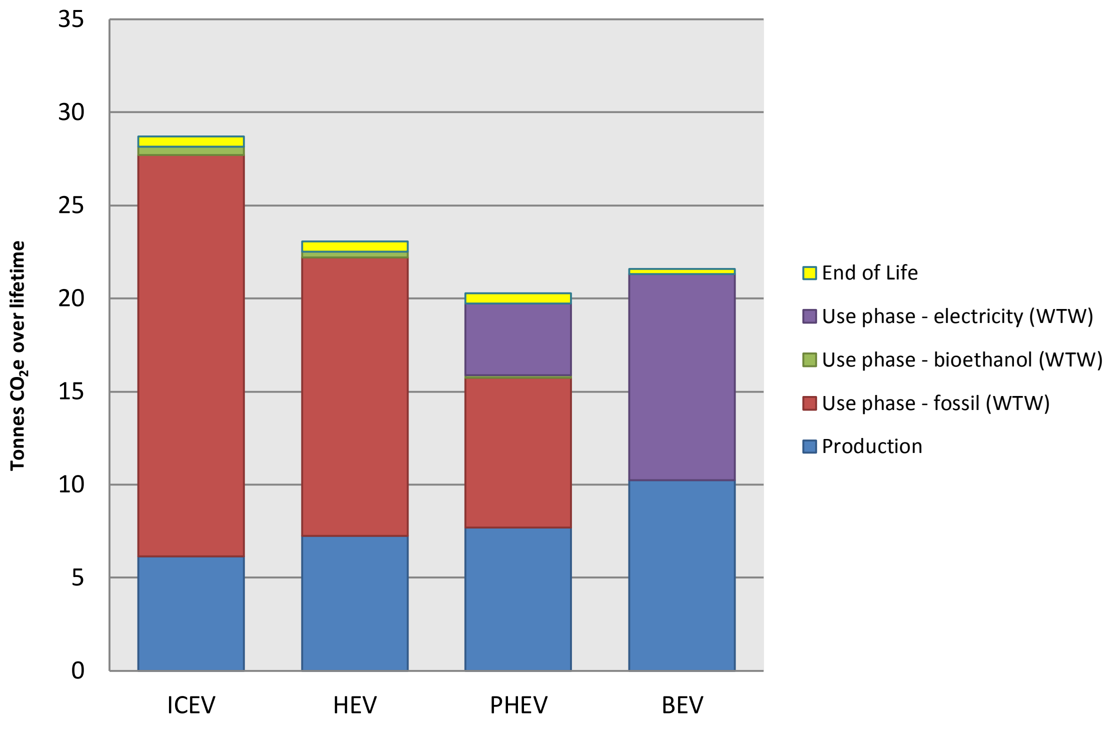

Figure 4-2: Detailed results for “Typical case 2020”

For the HEV, there is a 3% reduction in the production impacts from Base Case 2012 levels and a 6% reduction in the use phase-fossil WTW impacts.

For the PHEV, there is a 4% reduction in the production impacts from Base Case 2012 levels, a 4% reduction in the use phase-fossil WTW impacts and a 16% reduction in use phase-electricity WTW impacts.

For the BEV, there is a 6% reduction in the production impacts from Base Case 2012 levels and a 16% reduction in the use phase-electricity WTW impacts.

4.2.3 Best case scenario 2020

Figure 4-4 below shows the detailed results for the “Best case 2020” scenario.

For Best Case 2020, we see the use phase still clearly dominating the potential lifetime CO_2e impacts for the ICEV at about 77%, approximately 66% for the HEV and about 58% for the PHEV. However, the use phase only accounts for about 46% of lifetime CO_2e impacts for the BEV.

The impacts from the production phase are about 21%, 31%, 39% and 53% for the ICEV, HEV, PHEV and BEV respectively. Production phase impacts for all vehicles are driven by the embodied CO2e of components with vehicle assembly only accounting for 4-8% of total impacts.

The end of life phase contributes 1-3% of potential lifetime CO_2e impacts across the vehicles considered.

The prevailing assumptions for this scenario (see Appendix 8.2 for details) lead to an even greater reduction in the potential lifetime CO_2e for all vehicle types as compared to Base Case 2012 figures.

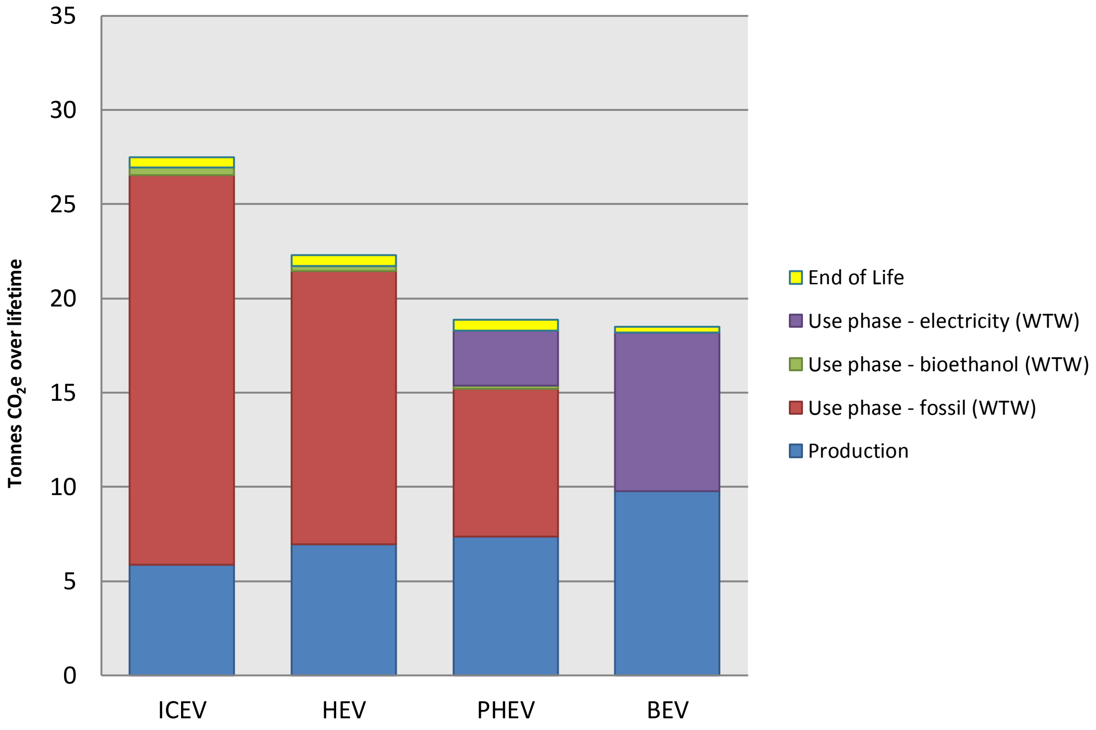

Figure 4-3: Detailed results for "Best case 2020"

However, comparing the results for Typical Case 2020 and Best Case 2020, it can be seen that the PHEV and the BEV are more similar for Best Case 2020 than for Typical Case 2020. This is explained by the significant reduction in the carbon intensity of the electricity grid mix for Best Case 2020 as compared to Typical Case 2020 under the prevailing assumptions for both scenarios. This is seen in the reduction of the use-phase electricity impacts when comparing figures 4-3 and 4-4 above.

An increase in the amount of bioethanol in the gasoline blend used in vehicles with ICEs can now just be seen in the chart above. This contributes to fewer impacts from use phase-fossil WTW impacts.

For the ICEV, there is a 9% reduction in the production impacts from Base Case 2012 levels and an 11% reduction in the use phase-fossil WTW impacts.

For the HEV, there is a 7% reduction in the production impacts from Base Case 2012 levels and a 9% reduction in the use phase-fossil WTW impacts.

For the PHEV, there is an 8% reduction in the production impacts from Base Case 2012 levels, a 6% reduction in the use phase-fossil WTW impacts and a 36% reduction in use phase-electricity WTW impacts.

For the BEV, there is an 11% reduction in the production impacts from Base Case 2012 levels and a 36% reduction in the use phase-electricity WTW impacts.

4.2.4 Typical case scenario 2030

Figure 4-5 below shows the detailed results for the “Typical case 2030” scenario.

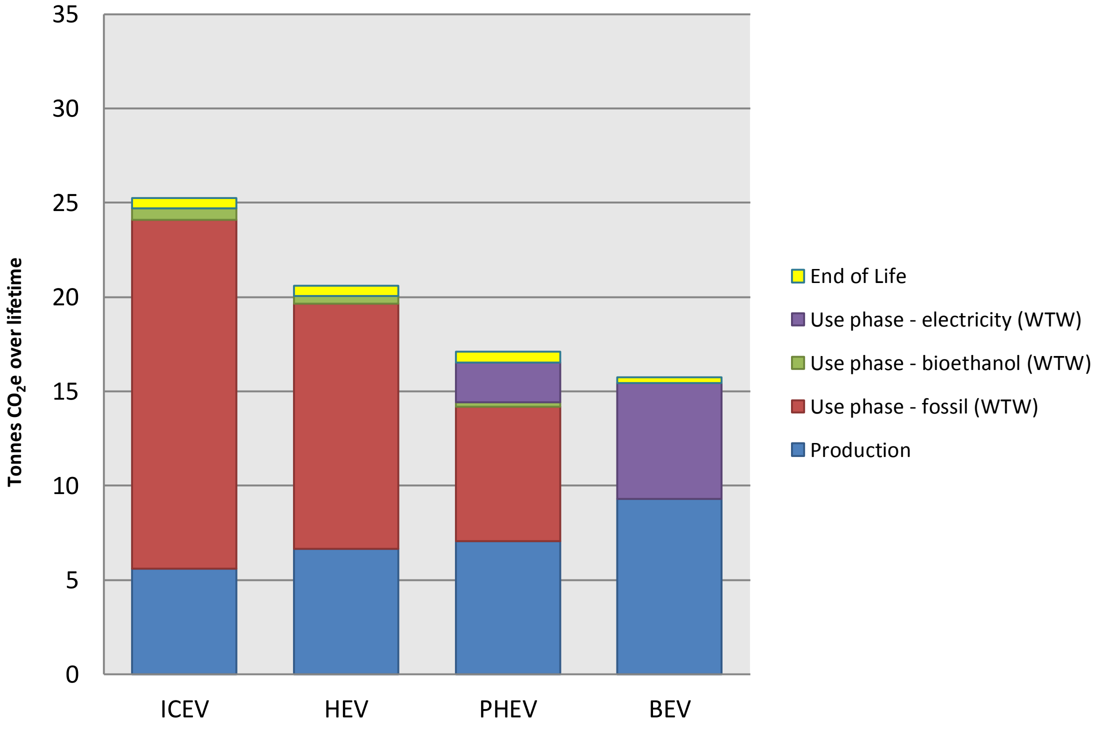

Figure 4-4: Detailed results for “Typical case 2030”

In Typical Case 2030, the use phase now accounts for approximately 76%, 65%, 56% and 39% of the overall CO_2e impacts for the ICEV, the HEV, the PHEV and the BEV respectively.

The production phase is now responsible for about 22%, 32%, 41%, and 59% of the overall CO_2e impacts for the ICEV, the HEV, the PHEV and the BEV respectively. Production phase impacts for all vehicles are driven by the embodied CO_2e of components with vehicle assembly only accounting for 4-6% of total impacts.

The end of life phase contributes 2-3% of potential lifetime CO_2e impacts across the vehicles considered.

Under the prevailing assumptions for this scenario (see section 2.4), a significant reduction in the potential lifetime CO_2e for all vehicle types can be seen compared to Base Case 2012 figures.

An increase in the amount of bioethanol in the gasoline blend used in vehicles with ICEs again contributes to fewer impacts from use phase-fossil WTW impacts. Further significant reduction in the carbon intensity of the electricity grid mix drives marginal reductions in the production phase and clear reductions in the use phase of the vehicles that consume electricity.

For the ICEV, there is a 13% reduction in the production impacts from Base Case 2012 levels, a 20% reduction in the use phase fossil WTW impacts but an 11% increase in the use phase bioethanol WTW impacts.

For the HEV, there is a 12% reduction in the production impacts from Base Case 2012 levels, an 18% reduction in the use phase-fossil WTW impacts but a 14% increase in the use phase-bioethanol WTW impacts.

For the PHEV, there is a 12% reduction in the production impacts from Base Case 2012 levels, a 15% reduction in the use phase-fossil WTW impacts, a 53% reduction in use phase-electricity WTW impacts but a 19% increase in the use phase-bioethanol WTW impacts.

For the BEV, there is a 15% reduction in the production impacts from Base Case 2012 levels and a 53% reduction in the use phase-electricity WTW impacts.

4.2.5 Best case scenario 2030

Figure 4-6 below shows the detailed results for the "Best case 2030" scenario.

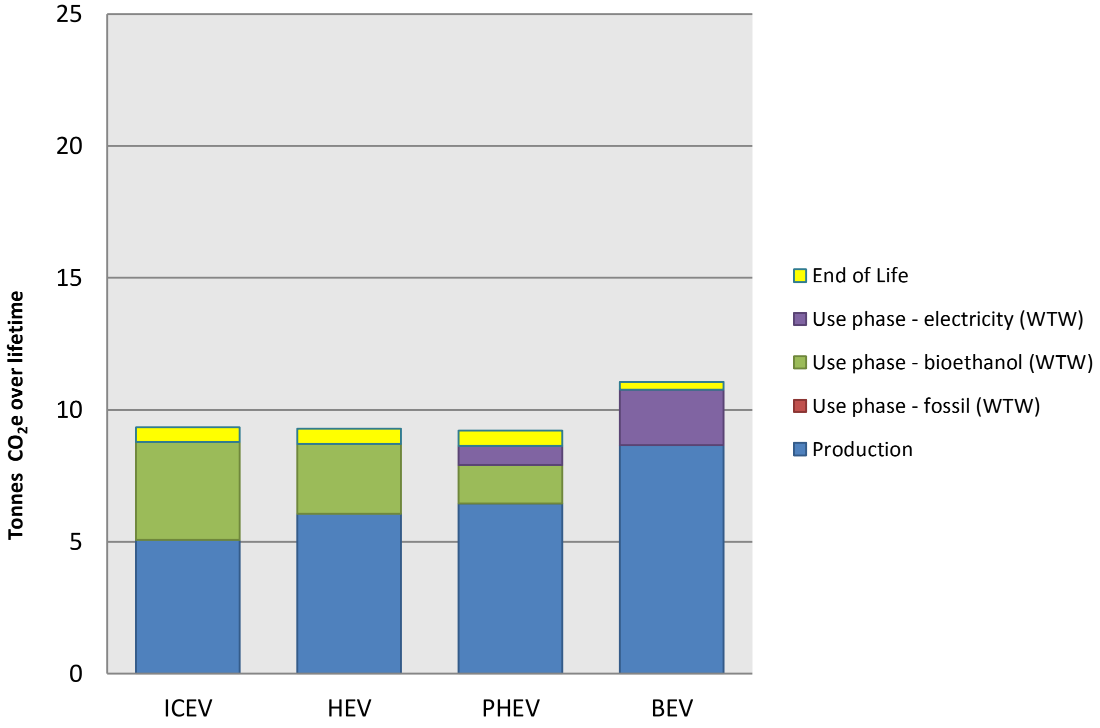

Figure 4-5: Detailed results for "Best case 2030"

Best Case 2030 can be regarded as an "ambitious" scenario (see section 2.4). The most significant assumptions in the prevailing conditions of this scenario are that:

- The carbon intensity of the electricity grid mix is greatly reduced by 83% for the UK (based on the UK Draft Energy Bill, 2012) and by 60% for the EU (based on EC "Roadmap for moving to a competitive low-carbon economy in 2050", 2011) as compared to Base 2012 figures. These numbers are driven by ambitious targets set by the UK and the EC for a low carbon future (the UK figure is derived from a draft energy bill and so therefore may be subject to change while EU figure may also change with cutbacks to planned installation of new nuclear power plants following the Japanese nuclear disaster, amongst other considerations); and

- Vehicles with ICEs run on 100% bioethanol (this assumption may not be applicable to all ICEVs on the road in 2030 but represents a potential BAT for ICEVs at this point in time).

In Best Case 2030, the use phase now accounts for approximately 40%, 28%, 24% and 19% of the overall CO_2e impacts for the ICEV, the HEV, the PHEV and the BEV respectively.

The production phase dominates in this scenario and is now responsible for about 54%, 65%, 70%, and 78% of the overall CO2e impacts for the ICEV, the HEV, the PHEV and the BEV respectively. Production phase impacts for all vehicles are driven by the embodied CO_2e of components with vehicle assembly only accounting for 6-8% of total impacts.

The end of life phase contributes 3-6% of potential lifetime CO_2e impacts across the vehicles considered.

It can be seen from figure 4-6 that the potential lifetime CO_2e impacts associated with the use phase are dramatically reduced in this scenario. For the ICEV, the HEV, and the PHEV there are no longer any impacts from the use of fossil fuels. Use phase bioethanol emissions have increased for these three vehicles but this is mostly accounted for by the production of the bioethanol and not from direct use phase emissions (see section 3.2.5 for details).

The reduction of the carbon intensities of the UK grid mix to 0.100 kg CO_2e/kWh and that of the EU grid mix to 0.196 kg CO_2e/kWh drive further reductions in the production phase impacts significant impacts in the use phase of the vehicles that consume electricity.

For the ICEV, there is a 21% reduction in the production impacts from Base Case 2012 levels, no impacts at all from the use phase-fossil WTW but a 610% increase in the use phase-bioethanol WTW impacts. This increase is largely associated with bioethanol production and the same explanation applies to the increases in use-phase bioethanol WTW impacts described below for other technologies.

For the HEV, there is a 19% reduction in the production impacts from Base Case 2012 levels, no impacts at all from the use phase-fossil WTW but a 633% increase in the use phase-bioethanol WTW impacts.

For the PHEV, there is a 19% reduction in the production impacts from Base Case 2012 levels, no impacts at all from the use phase-fossil WTW, an 84% reduction in use phase-electricity WTW impacts but a 672% increase in the use phase-bioethanol WTW impacts.

For the BEV, there is a 21% reduction in the production impacts from Base Case 2012 levels and an 84% reduction in the use phase-electricity WTW impacts.

4.3 EMBODIED CO_2E COMPARISON

This section highlights the differences between the potential embodied CO_2e of the vehicles considered in this study. A distinction between contributing components or groups of components can be seen in the charts below. “Best case” scenarios have not been presented in this section.

4.3.1 Base case scenario 2012

Figure 4-7 shows the embodied CO_2e impacts for each vehicle type considered in Base Case 2012.

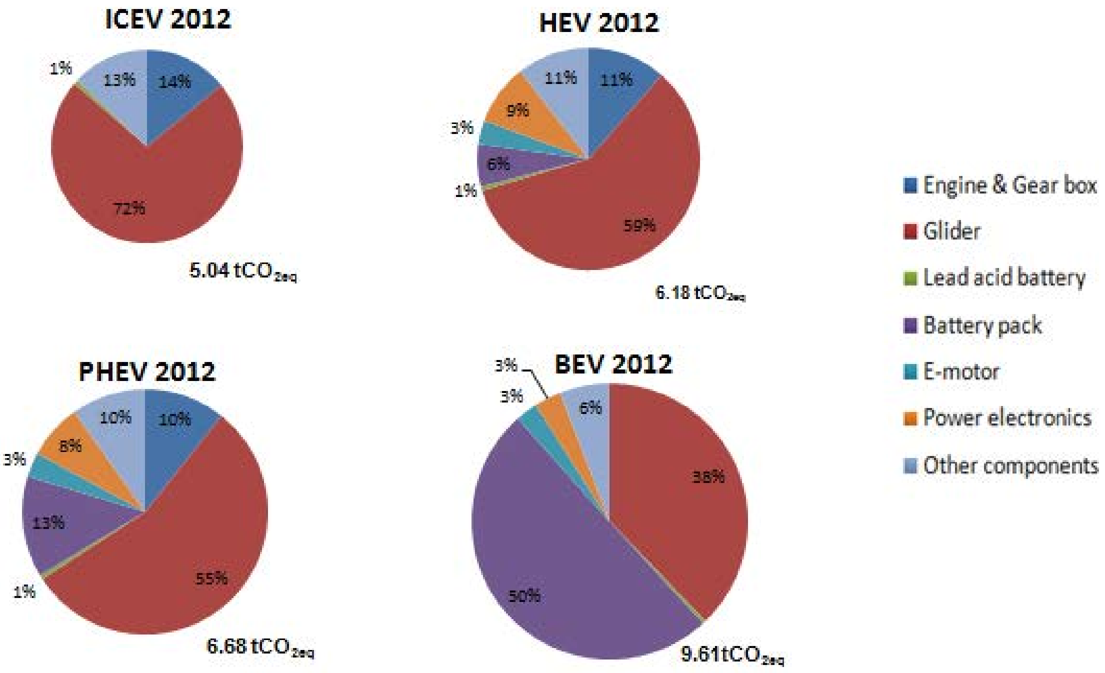

Figure 4-6: Embodied CO_2e comparison for considered vehicles “Base 2012”

The BEV has the largest embodied CO_2e impacts for Base Case 2012. The battery back contributes about 50% of these impacts, the glider another 38% with the rest of the impacts distributed across the electric motor, power electronics and other components.

The HEV and PHEV are similar in terms of embodied CO_2e impacts with gliders accounting for about 55-60% of the impacts. The battery pack for the PHEV is larger than that of the HEV and so accounts for more embodied impacts. The engine & gear box, power electronics, electric motor, lead acid battery, battery pack and other components have similar contributions to embodied CO_2e impacts.

The ICEV has the lowest embodied impacts for this scenario. The glider dominates the contribution with 72% of the impacts, the engine & gear box contribute 14% of embodied impacts, “other components” account for 13% of impacts while the lead acid battery contributes about 1%.

4.3.2 Typical case scenario 2020

Figure 4-8 shows the embodied CO_2e impacts for each vehicle type considered in Typical Case 2020.

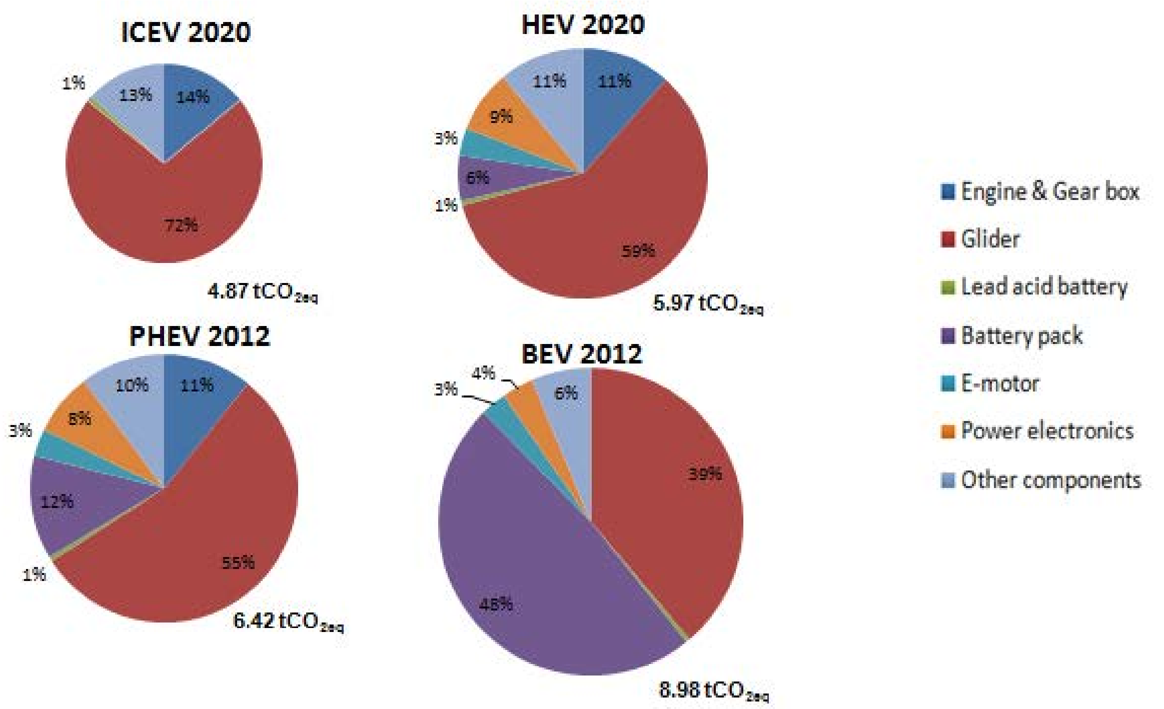

Figure 4-7: Embodied CO_2e comparison for considered vehicles "Typical 2020"

The prevailing conditions of Typical Case 2020 (light-weighting of the vehicles and reduction in the carbon intensities of the grid mix used for component manufacture), lead to a decrease in the overall embodied CO_2e impacts associated with all vehicles. Compared to Base Case 2012 there is a 3% reduction in embodied impacts for the ICEV, a 3% reduction for the HEV, a 4% reduction for the PHEV and a 7% reduction for the BEV in this scenario.

However, the contributions to embodied CO_2e impacts trends from different vehicle components are broadly the same as for the Base Case 2012 scenario.

4.3.3 Typical case scenario 2030

Figure 4-9 shows the embodied CO_2e impacts for each vehicle type considered in Typical Case 2030.

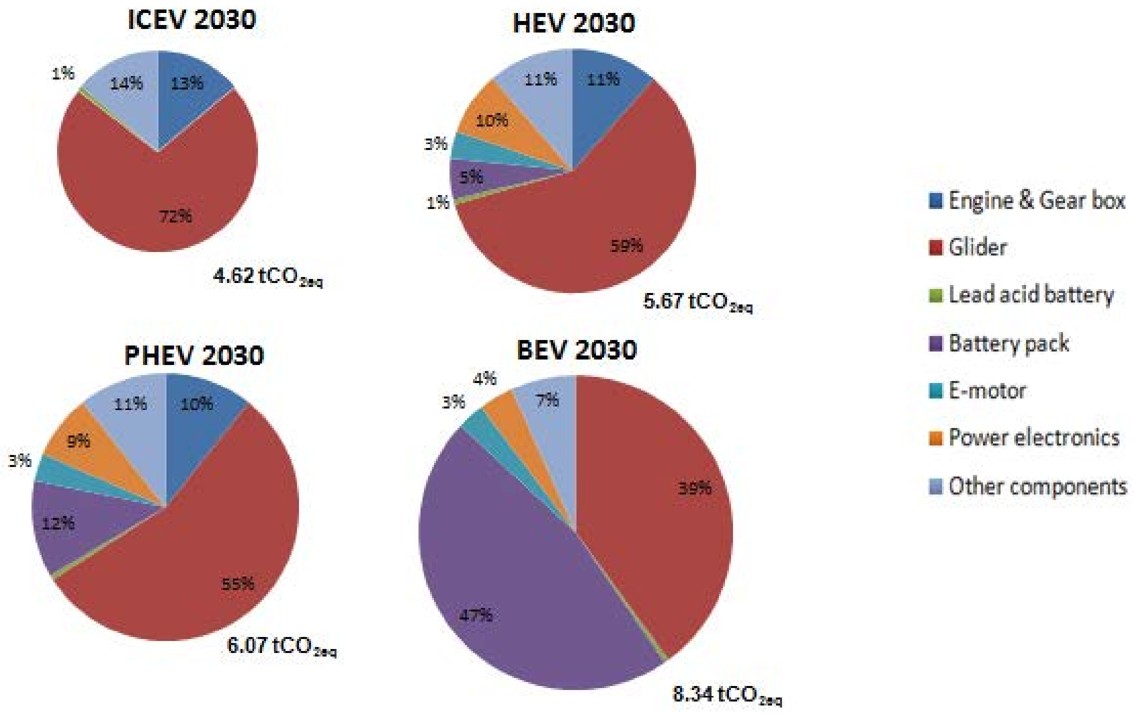

Figure 4-8: Embodied CO_2e comparison for considered vehicles "Typical 2030"

The prevailing conditions of Typical Case 2030 (further light-weighting of the vehicles and further reduction in the carbon intensities of the grid mix used for component manufacture), lead to a continuing decrease in the embodied CO_2e impacts associated with all vehicles. Compared to Base Case 2012 there is an 8% reduction in embodied impacts for the ICEV, an 8% reduction for the HEV, a 9% reduction for the PHEV and a 13% reduction for the BEV in this scenario.

However, the contributions to embodied CO_2e impacts trends from different vehicle components remain broadly the same as for the Base Case 2012 scenario.

5 SENSITIVITY ANALYSIS RESULTS

This section discusses the sensitivity analyses that were performed to test the robustness of the results towards uncertainty and the main assumptions.

5.1 VEHICLE LIFETIME MILEAGE

As mentioned in section 3.3.1, this sensitivity analysis examines the effects of extending the assumed vehicle lifetime mileage to the upper limit of the range quoted in literature.

The results displayed in this section for the lifetime sensitivity test are those particular to "Typical 2030" scenario obtained by extending vehicle lifetime mileage from 150,000 km to 300,000 km and are intended to serve as an indicator of trends for the other scenarios. Parts/materials for maintenance were doubled from the base scenario and include tyres, lubricants (where applicable), lead acid battery (where applicable) and refrigerants.

For electrified vehicles, manufacturers currently provide a typical warranty on battery packs for up to 160,000 km (or 8 years). On the basis of this information, two separate battery pack replacement sensitivities are considered:

- Vehicle lifetime mileage of 300,000 km with 0.5 battery pack replacement (i.e. 1.5 battery packs used over lifetime); and
- Vehicle lifetime mileage of 300,000 km with 1 battery pack replacement (i.e. 2 battery packs used over lifetime).

No replacement of internal combustion engines, power electronics and electric motors was assumed over the extended vehicle lifetime (where applicable).

5.1.1 Vehicle lifetime sensitivity results

Figure 5-1 shows that, as expected, extending the lifetime of a vehicle directly increases the potential lifetime CO_2e impacts. Figure 5-2 shows that this is largely driven by use phase impacts which proportionally increase with the extended lifetime for Typical Case 2030. There is some increase in production impacts across all vehicles and this can be explained by the additional maintenance requirements over the extended lifetime (i.e. more component/materials are needed and these increase the embodied impacts of the vehicle).

For drive train technologies with battery packs, the increase in the production phase impacts is clearer to see. For the HEV and PHEV, the difference production phase impacts does not appear to be that great if the battery pack is either entirely replaced or half replaced over the extended lifetime. The difference in the BEV in production phase impacts for an extended lifetime using an entire replacement battery pack or half a replacement battery pack is more marked. This can be explained by the large size of the BEV battery pack and its associated embodied impacts (see section 4.3 above for more details).

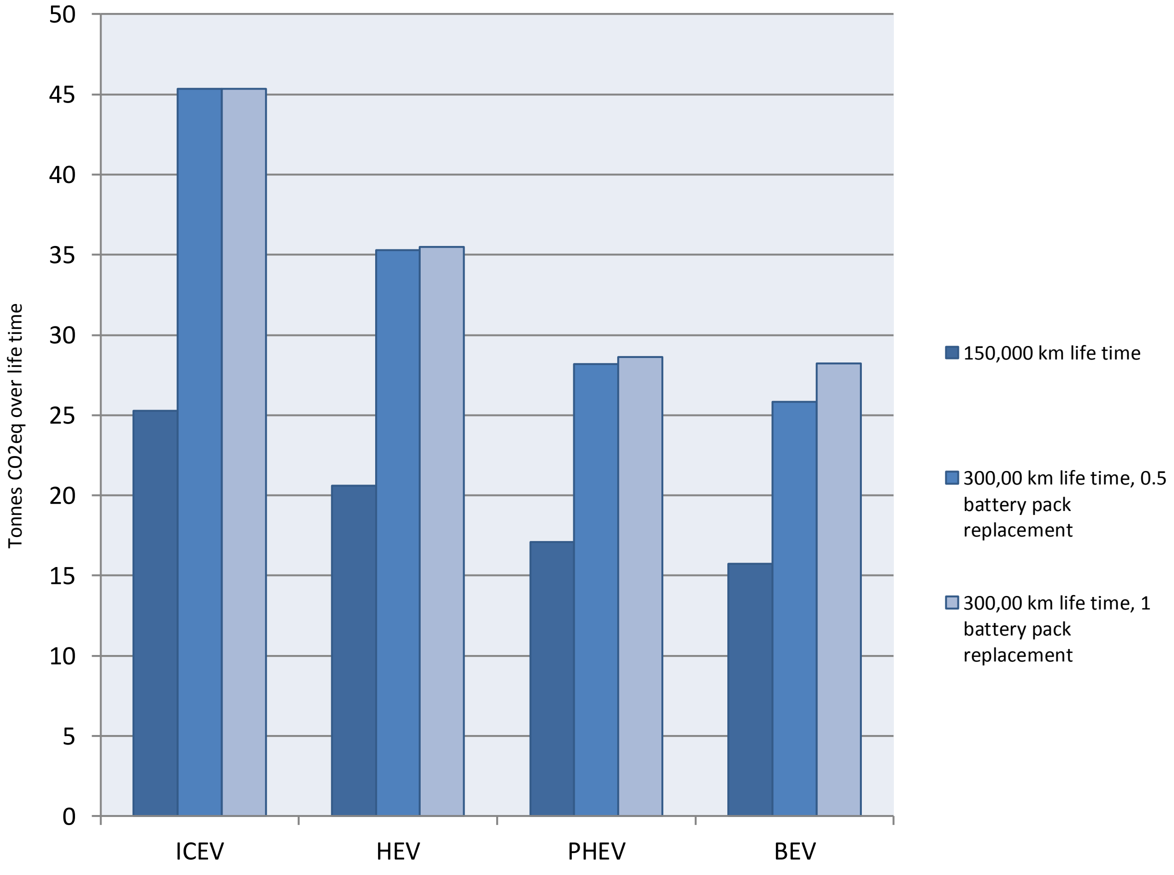

Figure 5-1: Impacts over 1 vehicle life cycle for lifetime sensitivity "Typical 2030"- Overview

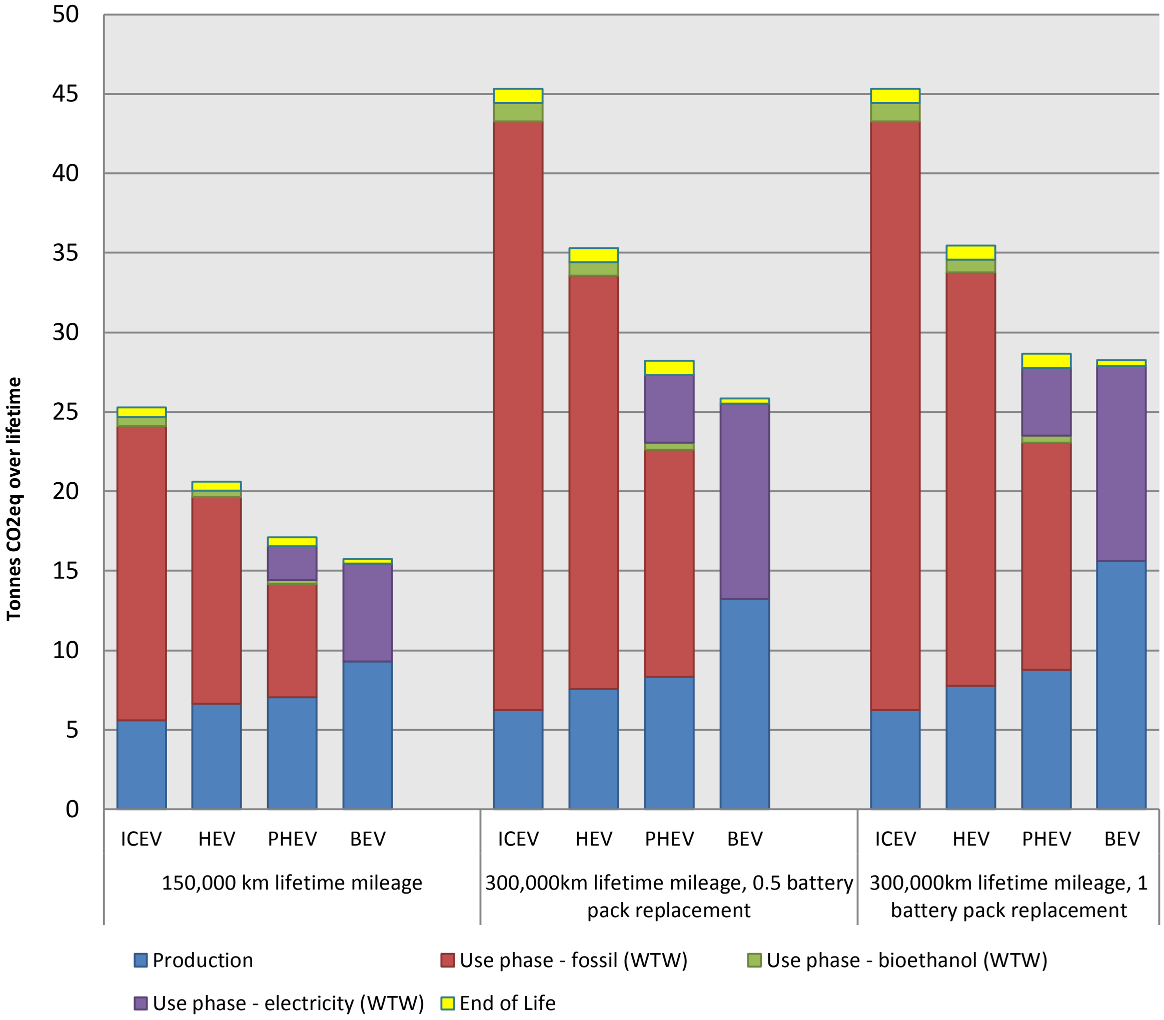

Figure 5-2: Impacts over 1 vehicle life cycle for Lifetime sensitivity "Typical 2030" – Detailed view

However, it should be noted that the results presented in Figures 5-1 and 5-2 are for the *whole life cycle of the cars*. As such, the vehicles with the extended lifetime mileage of 300,000 km are not being compared according to the functional unit defined in section 2.2. Accordingly, this comparison is not comparing like with like. A fairer comparison to understand the relative impacts of the different vehicles will be to assess them both over the same distance travelled.

To show this clearly in this sensitivity analysis we propose a new functional unit as follows:

A C-Segment passenger vehicle travelling a distance of 300,000 km under NEDC conditions

It is clear from this functional unit that two conventional vehicles with a lifetime mileage of 150,000 km are required to provide the same function as one vehicle with a lifetime mileage of 300,000 km.

Figure 5-3 presents the top level results when this functional unit is applied to all vehicles.

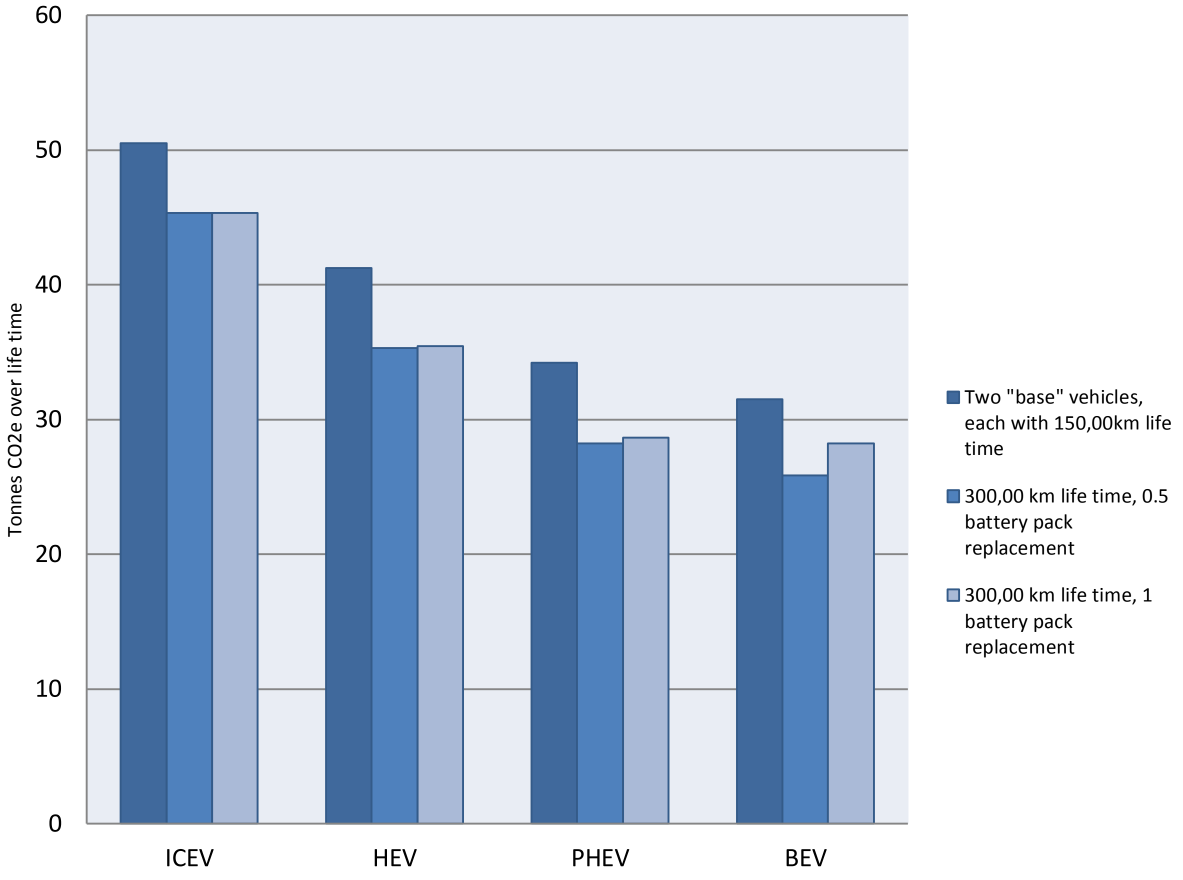

Figure 5-3: Functional unit-based lifetime sensitivity "Typical 2030" – Overview

The ICEV shows a reduction of about 10% when comparing the Typical 2030 baseline against an extended use phase scenario, while for the HEV reductions of about 14% are observed. For the PHEV, the effects of extending the lifetime in comparison to the baseline equivalent are reductions ranging from 16-18% (depending on the level of battery pack replacement). For the BEV, reductions range from 10-18% (again depending on the level of battery pack replacement) when comparing the Typical 2030 baseline against an extended use phase situation.

Focusing on the situations where the use phase driving distance is now 300,000 km, the effects of extending the lifetime mileage of a vehicle vary for the different scenarios considered in this study. For Base Case 2012, the use phase impacts are the most significant for all vehicles. This remains the same for Typical Case 2020.

For Best Case 2020 the use phase remains the most significant contributor to lifetime impacts for the ICEV, the HEV and the PHEV (ranging from 68-84%). However, for the BEV there is only a marginal difference between contributions from the use phase impacts (about 50%) and the production phase impacts (about 48%).

For Typical Case 2030, the use phase is the most relevant contributor to lifetime CO_2e impacts for the ICEV, the HEV and the PHEV (ranging from 66-84%). For the BEV in this scenario, production phase impacts account for about 55% of impacts while the use phase now accounts for 43%.

For Best Case 2030, the production phase now is the most significant contributor to lifetime impacts for the HEV, the PHEV and the BEV (ranging from 54-75%). For the ICEV, the use phase impacts now contribute to about 52% of overall impacts with 40% being attributed to production phase impacts.

In summary, the use phase is the most significant contributor to lifetime impacts for all scenarios except Best Case 2030. The only exceptions to this are the BEV for Best Case 2020 (where the use and production phases contributing almost equally to lifetime impacts) and for Typical 2030 where the production phase impacts of the BEV account for 55% of lifetime impacts.

For Best Case 2030, the production phase contributes the most to lifetime impacts for the HEV, the PHEV and the BEV. For the ICEV the use phase impacts remain the most important with 52% of lifetime impacts and 42% now coming from the production phase.

It is worth noting for the cases of the ICEV, HEV & PHEV that production phase impacts are not significantly affected by the level of battery pack replacement. However, for the BEV (having a larger battery pack) production phase impacts are more noticeable with an 8% increase in overall lifetime impacts from 0.5 battery pack replacement to 1 replacement over the extended life time.

From the above, it can be seen that doubling the vehicle lifetime does yield reductions in GHG emissions when comparing vehicles over equivalent transport distances as impacts from vehicle production and disposal are greatly reduced (although impacts from vehicle maintenance are increased). However, these reductions are only moderate in extent because the use phase is still responsible for the majority of the impacts in the life cycle for most scenarios.

5.2 END OF LIFE UNDER AVOIDED BURDENS APPROACH

As mentioned in section 3.3.2 above, this section explores the effects of applying a limited avoided burdens approach to an isolated scenario to provide an indication of the benefits that could be gained from recycling.

The results displayed in this section for the lifetime sensitivity test are those particular to the “Typical 2030” scenario and are intended to serve as an indicator of trends for the other scenarios. Materials/components liable for receiving credits from end of life recovery/recycling are lead acid battery, battery pack, neodymium magnet from e-motor and precious metals from catalytic converters. Credits have not been applied to other vehicle components (such as the glider) that are common to all drive chain options – although large proportions of these components would be eligible for credits if this methodology was applied to the whole vehicle.

The recovery rate of all of the materials in the above components, with the exception of the battery pack, is set to 90% to account for losses and impacts from the recovery/recycling processes themselves.

As the EV battery pack technology is still in its early stages, specific data on the potential recycling gains achievable with battery packs are not available. The paper “Electric Vehicles: A Synthesis of the Current Literature with a Focus on Economic and Environmental Viability” (LCA works, Imperial College 2012) cites a possible 50% credit on recycling a battery pack but given the uncertainty associated with this relatively new technology, PE has chosen to include an additional scenario where a 75% credit is possible as a “best case” in this sensitivity analysis.

Hence, two separate sensitivities are considered for the recovery/recycling of the battery pack

- Recovery/recycling leading to a 50% crediting against the original impacts associated with battery pack production; and
- Recovery/recycling leading to a 75% crediting against the original impacts associated with battery pack production.

5.2.1 End of life sensitivity results

Figure 5-4 below gives an overview of the results when the avoided burdens approach is applied to the specific materials/components discussed in the sensitivity analysis description given above. The chart describes the net results obtained from considering recycling credits over vehicular lifetime.

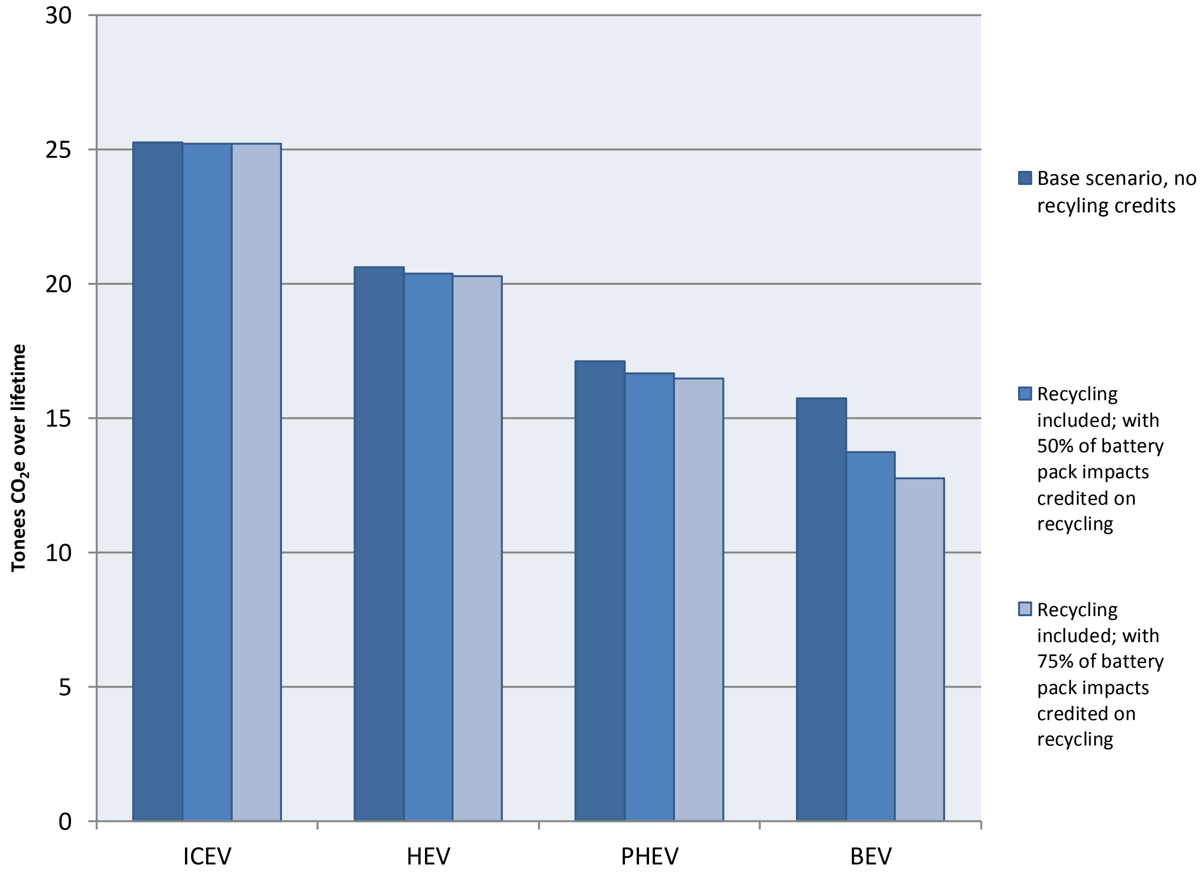

Figure 5-4: End of life sensitivity “Typical 2030” – Overview

Figure 5-5 below displays the detailed results when the avoided burdens approach is applied. By avoiding the requirement to produce primary material recycling results in credits at end of life representing these avoided CO_2e emissions. Where recycling credits are greater than EoL processing impacts these credits appear in the negative section of the y axis in the following chart.

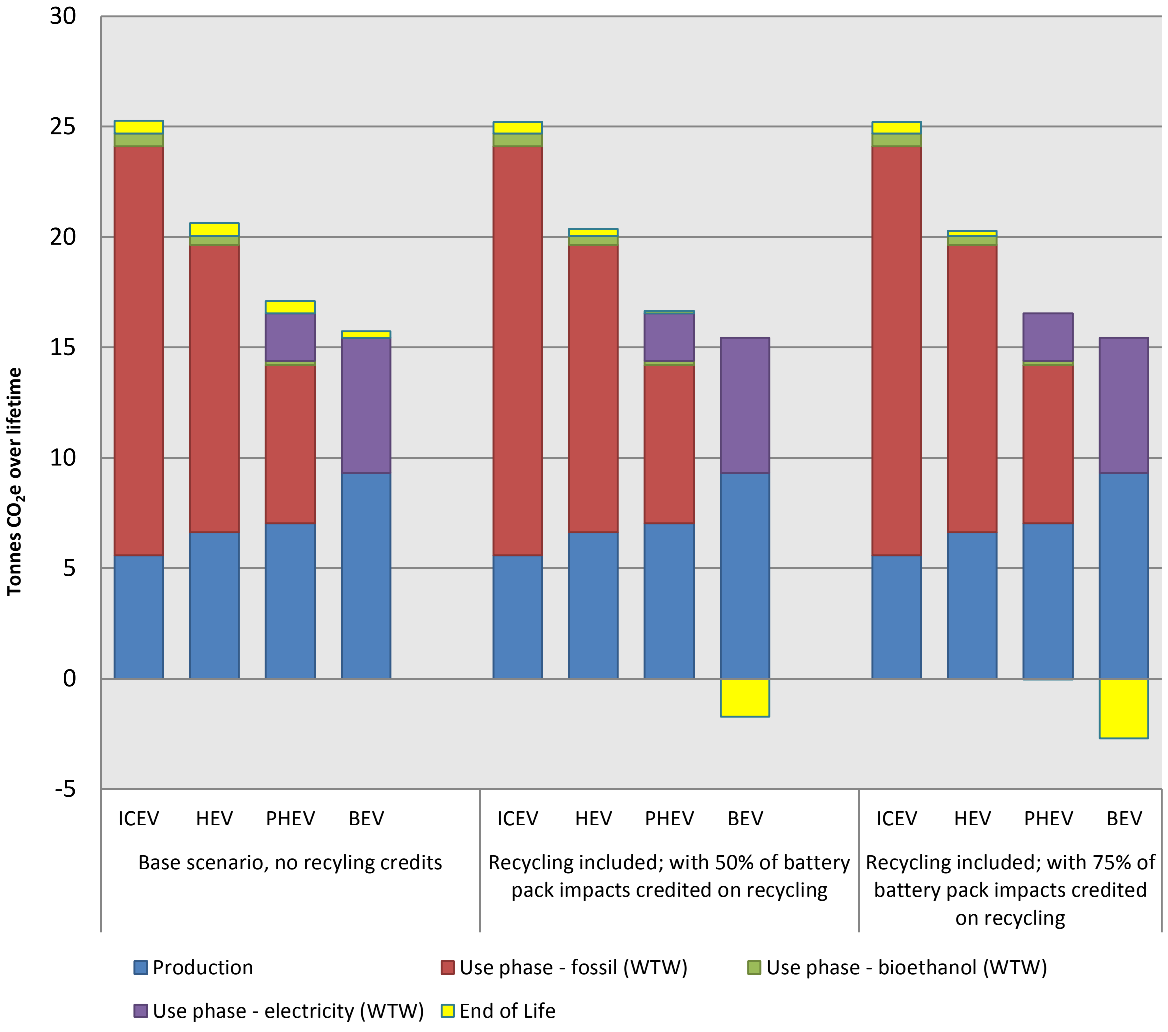

Figure 5-5: End of life sensitivity "Typical 2030"– Detailed view

The ICEV appears to show no significant reductions when recycling is considered. This is because the amounts of materials that are recovered and recycled (from the catalytic converter and the lead acid battery) are very small. Thus, the recycling credits from avoided burdens are correspondingly small and do not make a discernible difference to the over impacts.

There is a marginal difference between the HEV for the recycling scenarios. The reduction in impacts is driven largely by the savings made from recycling the battery pack.

The PHEV shows a relatively larger degree of reduction and this can be directly linked to the larger battery pack for which more recycling credits are accrued.

With the largest battery pack of the electrified vehicles, the BEV displays the clearest reduction in over all impacts due to battery pack recycling. Figure 5-5 indicates significant savings when the battery pack of the BEV is recycled.

Under the defined conditions of the EoL sensitivity, the overall lifetime CO$_2$e impacts of the ICEV, the HEV and the HEV display negligible sensitivity to the choice of recycling methodology. For the BEV however, at 50% recycling of the battery pack, there is a 10% reduction in overall impacts as compared to the cut-off methodology. At 75% recycling of the battery back, there is a reduction of about 13%. Similar trends hold for all other scenarios in this study with the exception of “Best Case 2030” where recycling of the battery pack could have proportionally greater reduction effects on overall impacts. .

5.3 MATERIALS FOR VEHICLE LIGHT-WEIGHTING

As mentioned in section 3.3.3 above, the default state of the models assumes a 2:8 split between aluminium and advanced high strength steel for substitution for mild steel in vehicle light-weighting. This section compares the results of the base light-weighting assumption with those of a more “Aluminium-centric” light-weighting with 8:2 aluminium to AHSS split.

The results displayed in this section for the lifetime sensitivity test are those particular to “Typical 2030” scenario and intended to serve as an indicator of trends for the other scenarios.

The Base 2012 scenario is included in figures 5-6 and 5-7 to illustrate overall CO_2e reductions as compared to baseline conditions (although vehicle light-weighting is only one of several contributing factors leading to this reduction).

5.3.1 Light weighting materials sensitivity results

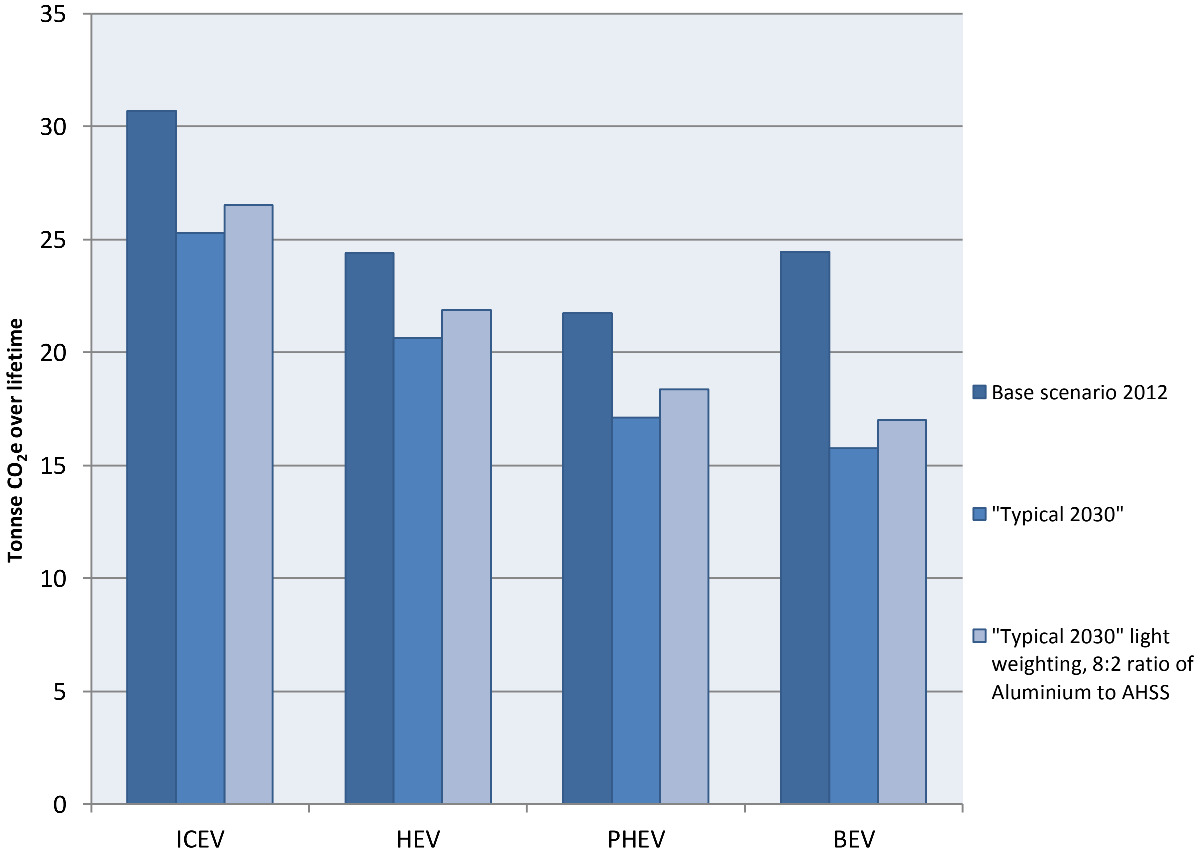

Figure 5-6: Light-weighting sensitivity “Typical 2030” - Overview

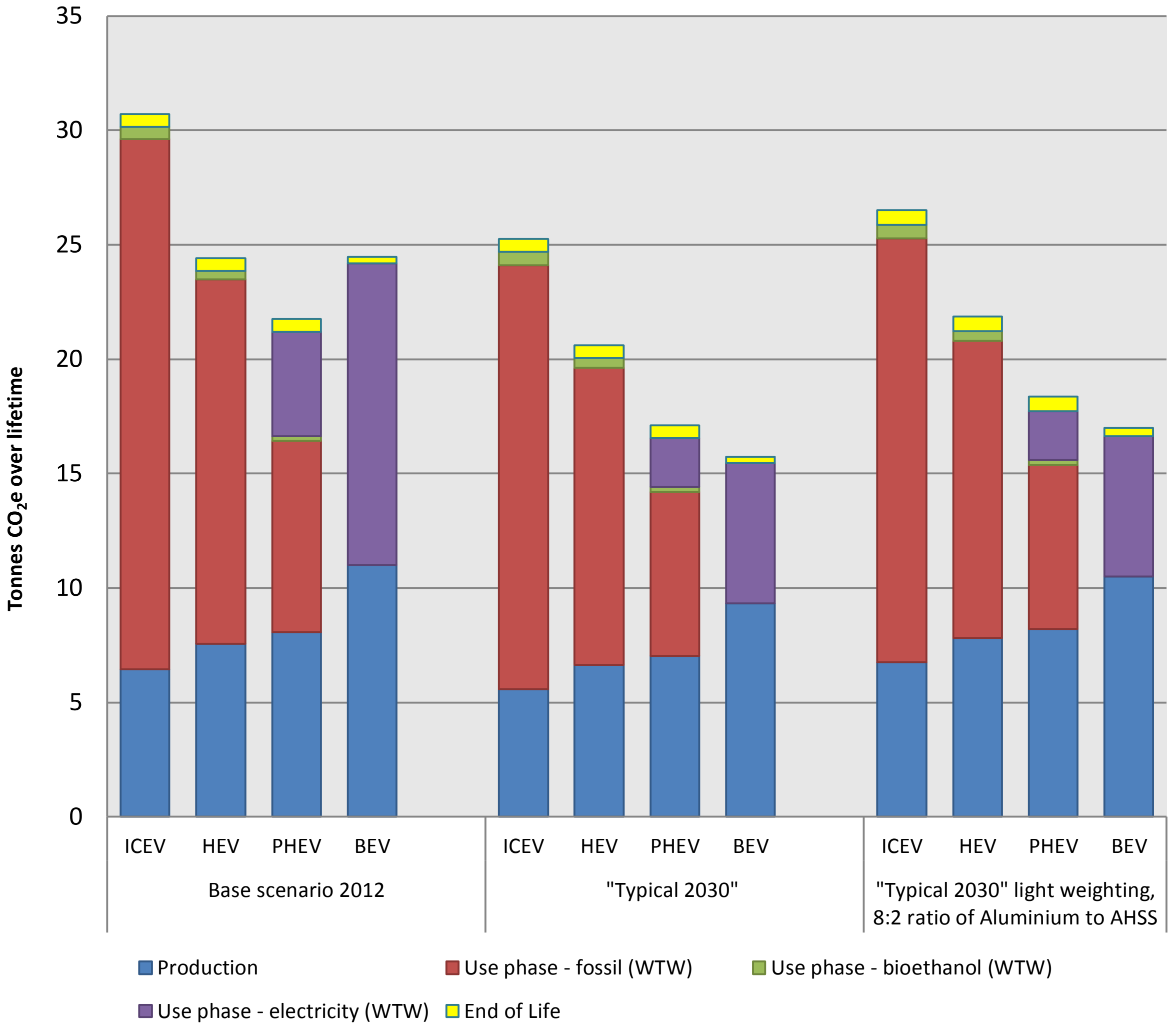

Figure 5-7: Light-weighting sensitivity "Typical 2030" – Detailed view

Figure 5-7 shows an increase in the production phase of the vehicles when aluminium is used extensively for light-weighting in Typical 2030. This is because aluminium has significantly higher carbon intensity per kg than steel.

Total lifecycle increases in CO_2e impacts of 5%, 6%, 7% and 8% are seen for the ICEV, HEV, PHEV and BEV respectively when more aluminium is used for light-weighting compared to the Typical 2030 scenario.

It is concluded that the results of this study show a small degree of sensitivity to the choice of materials used for light-weighting.

6 Discussion & Conclusions

This section of the report summarises the overall results of the project considering the project goals, discusses the observable trends, presents conclusions and provides recommendations for further work.

6.1 CO_2E Emissions for Different Vehicle Technologies and Time Periods

Table 6-1 provides a view of the top level results from this study presented as a heat map, to give an overall impression of the relative performance of the different technologies and timescales.

Table 6-1: Heat map of top level lifetime CO_2e emissions (green = low emissions, red = high emissions)

	Base 2012 (t CO_2e)	Typical 2020 (t CO_2e)	Best 2020 (t CO_2e)	Typical 2030 (t CO_2e)	Best 2030 (t CO_2e)
ICEV	30.7	28.7	27.5	25.3	9.35
HEV	24.4	23.1	22.3	20.6	9.27
PHEV	21.7	20.3	18.9	17.1	9.21
BEV	24.5	21.6	18.5	15.7	11.1

An overview of the results in section 4 of this report shows that for the “Base 2012” scenario, the ICEV has the highest lifetime CO_2e impacts. The HEV and the BEV show similar lifetime impacts in this scenario while the PHEV has the lowest lifetime CO_2e impacts.

Moving on to the “Typical 2020” scenario, there is a reduction in lifetime CO_2e impacts across all vehicles but the ICEV still has the highest impacts. The HEV comes next and there is now a noticeable difference with the BEV coming third in terms of highest impacts. The PHEV remains the drive train technology with the lowest impacts in this scenario.

In the “Best 2020” scenarios, there is further reduction in lifetime CO_2e impacts for all vehicles. The ICEV again has the highest impacts, the HEV has the next highest but now there is only a marginal difference between the PHEV and the BEV in terms of which vehicle has the lowest impacts. The BEV now has the lowest lifetime CO_2e impacts in this scenario.

For the “Typical 2030” scenario, further reductions in lifetime CO_2e impacts are seen across all vehicles. The ICEV remains the vehicle with the highest impacts, followed by the HEV but now there is a clearer distinction between the PHEV and BEV. The BEV remains the vehicle with the lowest lifetime CO_2e impacts.

Looking at the results for “Best 2030”, there is a drastic reduction in lifetime CO_2e impacts for all the vehicle types considered in this study. In this scenario, the ICEV, the HEV and the PHEV all have similar impacts, with the BEV now showing the highest lifetime CO_2e impacts. This shows the potential carbon savings that can be achieved by adopting high blend bioethanol and a highly decarbonised grid. However as demonstrated from the finding of the "End of life" sensitivity analysis in section 5.2 of this report, the application of a uniform avoided burdens approach where credits are allocated for recycling of components (in particular EV battery packs) may result in a situation where embodied CO_2e impacts of the BEV are significantly reduced and all vehicles would have more or less equivalent impacts in this scenario.

Under the prevailing scenario conditions of this study, we can conclude that total lifecycle CO_2e emissions will decrease over the next two decades for vehicles using all technology types. With reference to Base Case 2012 scenario:

- For the ICEV, there is a range of 7-70% reduction in total potential lifetime CO_2e impacts from Typical Case 2020 to Best Case 2030;
- For the HEV, there is a range of 5-62% reduction in total potential lifetime CO_2e impacts from Typical Case 2020 to Best Case 2030;
- For the PHEV, there is a range of 7-58% reduction in total potential lifetime CO_2e impacts from Typical Case 2020 to Best Case 2030; and
- For the BEV, there is a range of 12-55% reduction in total potential lifetime CO_2e impacts from Typical Case 2020 to Best Case 2030.

6.2 GHG PROFILE OF DIFFERENT TECHNOLOGIES AND TIME PERIODS

In summary, the results comparing the GHG profiles of different technologies and time periods show that:

- For Base Case 2012 and Typical Case 2020, the use phase is the most significant contributor to lifecycle CO_2e impacts;
- For Best Case 2020, the ICEV, the HEV and the PHEV still show the use phase contributing the most to lifecycle CO_2e impacts. However for the BEV, the production phase now becomes the most significant;
- For Typical Case 2030, the results are similar to those described for Best Case 2020 above; and
- For Best Case 2030, the production phase for all vehicles now is the most significant contributor to lifecycle CO_2e impacts with use phase impacts ranging from about 19 to 40% of the total.

The choice of fuel used in vehicles with ICEs appears to be very significant in terms of overall potential lifetime CO_2e emissions arising from the total use phase of such vehicles. This is particularly apparent in the Best Case 2030 scenario where 100% bioethanol is used. Here for the ICEV, total use phase impacts are reduced by 84% in comparison to those of Base Case 2012 using a high petrol blend fuel. For the HEV, there is also an 84% reduction in use phase impacts while for the PHEV, the use phase impacts are reduced by 83%.

The carbon intensity of the grid mix has a marked effect on the lifetime CO_2e impacts associated with some drive chain options. Drive chains that rely more on battery power are particularly sensitive to the effect of the carbon intensity of the electricity grid mix and this is effectively the most important factor in the CO_2e impact of such cars. As the carbon intensity of the electricity grid mix is projected to reduce significantly, these cars will have a "built in" reduction potential in the lifetime CO_2e impact for the years to 2030.

With regards to embodied impacts, across all scenarios:

- The BEV has the highest impacts with up to 50% coming from the battery pack and 40% from the vehicle glider;
- The PHEV follows with up to 13% coming from the battery pack and 55% from the vehicle glider;
- The HEV is next in line with up to 6% coming from the battery pack and 60% from the vehicle glider; and
- The ICEV has the lowest embodied impacts of all vehicles considered in this study. But here, the vehicle glider accounts for about 72% of embodied impacts.

The vehicle assembly and end life phases do not contribute significantly to overall lifetime CO_2e impacts, each only accounting for up to 8% of these impacts across all scenarios.

6.3 SENSITIVITY ANALYSES

The results of the lifetime sensitivity analysis show that emissions per km are reduced as vehicle lifetime mileage increases. This is because the lower impacts from production and end of life outweigh the increased impacts from vehicle maintenance during use. However, because use phase impacts from fuel and energy use dominate the life cycle only a moderate reduction is seen overall.

With a lifetime of 300,000 km the use phase generally is the most significant contributor to lifetime impacts up until Typical Case 2030. Exceptions to this are the BEV for Best Case 2020 which has the use and production phases contributing almost equally to lifetime impacts and for Typical 2030, the production phase impacts of the BEV account for 55%. For Best Case 2030 with the vehicular lifetime extended to 300,000km, the production phase contributes the most to lifetime impacts for the HEV, the PHEV and the BEV. However, the ICEV still shows the use phase as being the most important with 52% of lifetime impacts and 42% attributed to the production phase.

From the results of the end of life sensitivity analysis it is concluded that ICEV, the HEV and the PHEV are not particularly sensitive to the choice of recycling methodology. For the BEV however, the use of the avoided burdens methodology can have a noticeable effect on lifetime CO_2e impacts compared to the cut-off methodology with reductions ranging of 10% and 13% when the battery back is recycled at a rate of 50% and 75% respectively.

On the whole, the choice of recycling methodology does not significantly affect the results stated in sections 6.1 and 6.2 above. The overall impact profiles of the vehicles in scenarios where the use phase dominates are expected to follow similar patterns with either the avoided burdens or cut-off approaches to end of life. For scenarios where the production phase dominates, such as Best 2030, the “EoL sensitivity” indicates that the application of the avoided burdens approach may significantly alter the overall impact profiles of the vehicles in this scenario. Production impacts are expected to reduce for all vehicles but if significant recycling of the battery pack is achieved, then the BEV may no longer be an outlier in this scenario.

The sensitivity analysis focusing on light-weighting indicates that while the choice of material used to achieve light-weighting can affect the degree of lifetime CO_2e savings, the overall results are not so sensitive to this assumption. The results stated in the discussion above hold true even when more aluminium is used for light-weighting than AHSS.

6.4 CONCLUSIONS

The results of this study indicate that as the contribution to lifecycle CO_2e impacts from the use phase decreases in future, so the embodied impacts of the vehicles themselves will become more of a focus for further decarbonisation. The vehicle assembly phase is an insignificant contributor to “embodied” lifetime CO_2e impacts so while technological advances here can aid decarbonisation there is much greater potential for decarbonisation through advances in vehicle component materials and production processes. Reductions in the use phase impacts are extremely significant in the case of using 100% bioethanol in vehicles with ICEVs as well as with electric vehicles that run on low carbon intensity grid mix electricity. This trend means the use of tailpipe CO_2 emissions as an established comparator for different vehicles will most certainly become less effective and almost irrelevant in terms of focusing on the true carbon profiles/carbon reduction potential for future vehicles.

In summary, there appear to be clear possibilities for reducing the potential lifetime CO_2e emissions in the future for all vehicles considered. Reductions in lifetime CO_2e impacts can be achieved by adjusting a combination of factors from the production phase, use phases and end of life phase. Particular emphasis should be made on decarbonisation of the embodied impacts of the vehicles as well as factors that contribute to use phase impacts as these two phases both drive lifetime impacts. Recycling/re-use of high-impact vehicle components such as electric vehicle battery packs may have the potential to contribute significantly to decarbonisation efforts of the embodied impacts of future vehicles.

The findings presented in this report should be considered in the context of the limitations of the high level, streamlined nature of this study. These findings serve as an indicator of the potential lifetime CO_2e emissions of future C-segment ICEVs, HEVs, PHEVs and BEVs. The results from this study can also be used to highlight areas of further work or improvements in future studies of a similar nature.

6.5 LIMITATIONS & RECOMMENDATIONS

This study is a high level, streamlined LCA that is completely based on publically available secondary data. The product systems being assessed are very complex and many technologies are commercially sensitive. As such, it has not been possible, in a number of cases, to find detailed secondary data for relevant foreground and background systems. Best available/proxy data have been used to fill any gaps, very often at a high level. This may result in a lack of specificity and a certain degree of uncertainty in the results.

Limitations to the study are presented in below in bold text, followed by a brief discussion and recommendations for improving similar studies as this one in the future.

Limitation: Lack of detailed material composition of the representative drive train vehicles. The effect of this lack of data means that the results for the embodied impacts of the vehicles are rather generic. We recommend partnering with manufacturers of representative vehicles to obtain detailed materials composition of these vehicles as well as data on their assembly. Such an association may well also lead to better data regarding the replacement parts and consumables in relation to vehicle lifetime mileage.

Limitation: Lack of precise data on material composition and manufacturing data for the battery pack for electrified vehicles. The effect of this lack of data means that there is a high degree of uncertainty in results that are driven by the battery pack. We would recommend partnering with a manufacturer of EV battery packs to get a better understanding of life cycle impacts associated with the production of these components.

Limitation: Lack of precise data on battery pack lifetime and performance. The effect of this lack of data adds additional uncertainty to results that are directly linked to battery pack replacement. More work is required to understand factors that could influence battery pack lifetime and performance such different driving and environmental conditions that could potentially lead to battery pack degradation.

Limitation: Lack of precise data on transport of vehicle components. From a life cycle perspective, logistics does not normally have a significant effect on the overall results for automotive assessments. However in the case of complex supply chains such as those for automobile manufacture, further research of logistics and the application of such data to future studies would provide a more complete assessment.

Limitation: Lack of certainty regarding data on future carbon intensities of UK and EU electricity grid mixes. The effect of this lack of data means that there is a significant degree of uncertainty in use phase results for future cars that rely on grid electricity consumption for their use phase. In this study the use of different scenarios for typical and best cases helps to identify the possible range of results due to this uncertainty. Similar issues apply to vehicles with ICEs in regards to future carbon intensities of gasoline and bioethanol. We recommend further research into how the carbon intensities of electricity grid mixes and fuels may change in the future. In addition, further work could explore the impact of base and marginal load electricity grid carbon intensities, showing potential diurnal effects of vehicle charging.

Limitation: Lack of precise data on future advancements in the drive train as well as glider technologies considered and their effects on fuel/electricity consumption as well as embodied impacts. The lack of data here may have significant effects on use phase impacts of future vehicle. We would recommend partnering with manufacturers of representative vehicles to get first hand information of potential advancements in technologies for the drive-trains in question. Such a partnership may also lead to better information on the use of alternative materials (composites etc) that could be of crucial use for the light weighting of future vehicles. Further research will be needed to get a better understanding of the life cycle impacts associated with the production of such materials.

Limitation: Application of "theoretical" driving cycle to represent use phase. We have chosen to model use phase fuel consumption based on the NEDC because this is the closest to a "standard" within the automotive industry. However, there are arguments that the NEDC may differ greatly from real world driving conditions. We thus recommend further research into the relationship between NEDC fuel consumption and real world consumption as a relevant expansion of scope in future studies similar in nature to this one.

Limitation: Lack of precise data on end of life fate of general automotive components & end of life recovery/recycling of battery packs for electric vehicles. The effect of this lack of data means that there is a high degree of uncertainty in results that are driven by credits from the battery pack recycling, amongst others. As a recommendation, more research into the actual end of life fate of automobiles is needed (in particular to the EoL fate and recycling options applicable to EV battery packs). This would allow for the application of the avoided burdens approach as an alternative to the cut off approach for end of life which is currently the norm for the automotive sector LCAs. Agreeing an industry wide approach to applying the avoided burdens approach could have a material effect in assessing the overall lifecycle environmental impact of the vehicles and could play a role in driving end of life practices.

Limitation: Single focus study, looking only at CO_2e impacts. One environmental indicator is not sufficient to draw definitive conclusions about the environmental performance of complex products such as automotive vehicles. We recommend that other LCA impact categories should be included in similar assessments in the future. Knowledge of potential CO_2e impacts alone cannot paint a complete picture of the environmental performance of automobiles. Additional indicators that may be of interest include abiotic resource depletion potential, acidification potential, eutrophication potential, photochemical ozone creation potential, eco-toxicity potential and water consumption.

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8 APPENDICES

8.1 ROOT VEHICLE CHARACTERISTICS

Tables 8-1 and 8-2 provide details of the composition and assembly line production for the root vehicle.

Table 8-1: "Root vehicle" materials composition

Materials	(kg)	% of total
Total content of ferrous and non-ferrous metals	*819*	*66.05%*
Steel BOF	500	40.32%
Steel EAF	242	19.52%
Total content of iron and steel	*742*	*59.84%*
Aluminium primary	42	3.39%
Aluminium secondary	26	2.10%
Total content of aluminium	*68*	*5.48%*
Cu	9	0.73%
Mg	0.5	0.04%
Pt	0.001	0.00%
Pl	0.0003	0.00%
Rh	0.0002	0.00%
Glass	40	3.23%
Paint	36	2.90%
Plastics		
PP	114	9.19%
PE	37	2.98%
PU	30	2.42%
ABS	9	0.73%
PA	6	0.48%
PET	4	0.32%
Other	27	2.18%
Miscellaneous (textile, etc.)	23	1.85%
Tyres		
Rubber	4	0.32%
Carbon black	2	0.16%
Steel	1	0.08%
Textiles	0.4	0.03%
Zinc oxide	0.1	0.01%
Sulphur	0.1	0.01%
Additives	1	0.08%
Sub-total (4 units)	*31*	2.50%
Battery		
Lead	9	0.73%
PP	0.7	0.06%
Sulphuric acid	4	0.32%

Materials	**(kg)**	**% of total**
PVC	0.3	0.02%
Sub-total	*14*	*1.13%*
Fluids		
Transmission fluid	7	0.56%
Engine coolant	12	0.97%
Engine oil	3	0.24%
Petrol	23	1.85%
Brake fluid	1	0.08%
Refrigerant	0.9	0.07%
Water	2	0.16%
Windscreen cleaning agent	0.5	0.04%
Sub-total	*50*	4.03%
Total weight	***1240***	***100.00%***

Table 8-2: Assembly line energy consumption for "average" EU petrol car

Assembly line energy consumption[1]				
Year: 2004	5.093.000 cars produced			
	MWh	GJ	MJ/car	kWh/car
Gas and coal	5 680 000	20 448 000	4 015	1 115
Electricity	7 210 000	25 956 000	5 096	1 416
District heating	3 020 000	10 872 000	2 135	593
Total	***15 910 000***	***57 276 000***	***11 246***	***3 124***

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[1] Though 2004 data appears to be quite old, impacts from vehicle assembly line have been shown to account for an insignificant fraction of total CO_{2e} emissions associated with a vehicle over its life time[29]. Moreover, as such data is extremely rare in the public domain and as this study assumes the same assembly data across all technologies, using 2004 verified data provided by VW is deemed the best approach to apply here.

8.2 DESCRIPTION OF SCENARIOS

This section provides a list of the assumptions behind the scenarios modelled for this study.

8.2.1 Petrol ICEV with Biofuel blend

Typical 2012
- Same as base vehicle specification in section 2.4 of this report

Typical 2020	Best 2020
- Vehicle with “stop – start” system as standard - 10% vehicle light-weighting[1,7,11] leading to 3% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 4% fuel saving after light-weighting[13] - Resulting fuel consumption = 5.42 l/100km - Share of bioethanol in gasoline remains at 10% as standard based on information from 3, 8, 13 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 3% reduction in the 2009 RED WTT GHG intensity factors for sugar cane and sugar beet ethanol, with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol, 32 g CO_{2e}/MJ for sugar beet bioethanol and 23.9 g CO_{2e} for wheat bioethanol. - Carbon intensity of electricity grid mix in the UK drops to 0.502 kg CO_2e/kWh (17% reduction from 2012 figures), while that of the EU drops to 0.454 kg CO_2e/kWh (7% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	- Vehicle with “stop – start” system as standard - 15% vehicle light-weighting[1,7,11] leading to 5% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 6% fuel saving after light-weighting[13]. - Resulting fuel consumption = 5.19 l/100km - Share of bioethanol in gasoline increase to 15% as standard based on information from 3,8, 13 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 5% reduction in the 2009 RED WTT GHG intensity factors for sugar cane and sugar beet ethanol, with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 228 g CO_{2e}/MJ for sugar cane bioethanol, 31.4 g CO_{2e}/MJ for sugar beet bioethanol and 23.4 g CO_{2e} for wheat bioethanol. - Carbon intensity of electricity grid mix in the UK drops to 0.387 kg CO_2e/kWh (34% reduction from 2012 figures), while that of the EU drops to 0.421 kg CO_2e/kWh (14% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

Typical 2030	Best 2030
- Vehicle with “stop – start” system as standard - 10% vehicle light-weighting[1,7,11] from “Typical 2020” leading to a further 4% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] , leading to an additional 5% fuel savings after light weighting[13] - Resulting fuel consumption = 4.93 l/100km - Share of bioethanol in gasoline increase to 15% as standard based on information from 3,8, 13 - Feed stock source split for bioethanol changes to 45% sugar cane and 50% wheat.[13] - 3% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol and 23.9 g CO_{2e}/MJ for wheat bioethanol - Carbon intensity of electricity grid mix in the UK drops to 0.287 kg CO_2e/kWh (51% reduction from 2012 figures), while that of the EU drops to 0.352 kg CO_2e/kWh (28% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	- Vehicle with “stop – start” system as standard - 15% vehicle light-weighting[1,7,11] from “Typical 2020” leading to a further 6% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] , ,leading to an additional 7% fuel savings after light weighting[13] - Resulting fuel consumption = 5.19 l/100km - ICE using 100% bioethanol [13] - Feed stock source split for bioethanol changes to 45% sugar cane and 55% wheat[13] - 5% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 22.8 g CO_{2e}/MJ for sugar cane bioethanol and 23.4 g CO_{2e}/MJ for wheat bioethanol - Carbon intensity of electricity grid mix in the UK drops to 0.1 kg CO_2e/kWh (83% reduction from 2012 figures), while that of the EU drops to 0.196 kg CO_2e/kWh (60% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

8.2.2 HEV

Typical 2012
- Same as base vehicle specification in section 2.4 of this report

Typical 2020	Best 2020
- 10% vehicle light-weighting[1,7,11] leading to 2% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] ,	- 15% vehicle light-weighting[1,7,11] leading to 3% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] ,

leading to an additional 4% fuel saving[13] - Resulting fuel consumption = 3.76 l/100km - Share of bioethanol in gasoline remains at 10% as standard based on information from 3, 8, 28 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 3% reduction in the 2009 RED WTT GHG intensity factors for sugar cane and sugar beet ethanol, with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2012 figures[b] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol, 32 g CO_{2e}/MJ for sugar beet bioethanol and 23.9 g CO_{2e} for wheat bioethanol - Carbon intensity of electricity grid mix in the UK drops to 0.502 kg CO_2e/kWh (17% reduction from 2012 figures), while that of the EU drops to 0.454 kg CO_2e/kWh (7% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	leading to an additional 6% fuel saving[13] - Resulting fuel consumption = 3.64 l/100km - Share of bioethanol in gasoline increase to 15 % as standard based on information from 3,8, 28 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 5% reduction in the 2009 RED WTT GHG intensity factors for sugar cane and sugar beet ethanol, with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2012 figures. - Resulting WTT GHG intensity factors are 22.8 g CO_{2e}/MJ for sugar cane bioethanol, 31.4 g CO_{2e}/MJ for sugar beet bioethanol and 23.4 g CO_{2e} for wheat bioethanol - Carbon intensity of electricity grid mix in the UK drops to 0.387 kg CO_2e/kWh (34% reduction from 2012 figures), while that of the EU drops to 0.421 kg CO_2e/kWh (14% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

Typical 2030	**Best 2030**
- 10% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 3% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 5% fuel saving	- 15% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 4% fuel saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 7% fuel savings

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[b] The range of an electric vehicle is subject to many variables such as driving styles, use of auxiliaries, ambient temperatures etc. and is not a standalone limiter to EV performance. Battery technology on the other hand is arguably the most significant limiter of the performance of electrified vehicles and so this has been chosen as the main technological focus for the future scenarios of electrified drive trains.

from best 2020 figures[13] - Resulting fuel consumption = 3.46 l/100km - Share of bioethanol in gasoline increase to 15 % as standard based on information from 3,8, 28 - Feed stock source split for bioethanol changes to 45% sugar cane and 55% wheat[13] - 3% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol and 23.9 g CO_{2e}/MJ for wheat bioethanol - Improved battery tech (e.g. higher energy density of cells)[4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.287 kg CO_2e/kWh (51% reduction from 2012 figures), while that of the EU drops to 0.352 kg CO_2e/kWh (28% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	from best 2020 figures[13]. - Resulting fuel consumption = 3.35 l/100km - ICE using 100% bioethanol [13] - Feed stock source split for bioethanol changes to 40% sugar cane and 50% wheat[13] - 5% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 22.8 g CO_{2e}/MJ for sugar cane bioethanol and 23.4 g CO_{2e}/MJ for wheat bioethanol - Improved battery tech (e.g. higher energy density of cells)[4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.1 kg CO_2e/kWh (83% reduction from 2012 figures), while that of the EU drops to 0.196 kg CO_2e/kWh (60% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

8.2.3 PHEV

Typical 2012
- Same as base vehicle specification in section 2.4 of this report

Typical 2020	Best 2020
- 10% vehicle light-weighting[1,7,11] leading to 2%energy consumption saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] , leading to an additional 2% fuel saving[13] - Resulting fuel consumption = 2.0 l/100km; resulting electricity consumption = 5.09 kWh/100km - Share of bioethanol in gasoline remains	- 15% vehicle light-weighting[1,7,11] leading to 3% energy consumption saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6] ,leading to an additional 3% fuel saving[13] - Resulting fuel consumption = 1.97 l/100km; resulting electricity consumption = 5.04 kWh/100km - Share of bioethanol in gasoline increase

at 10% as standard based on information from 3, 8, 28 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 3% reduction in the 2009 RED WTT GHG intensity factors for sugar cane and sugar beet ethanol, with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol, 32 g CO_{2e}/MJ for sugar beet bioethanol and 23.9 g CO_{2e} for wheat bioethanol. - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2012 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.502 kg CO_2e/kWh (17% reduction from 2012 figures), while that of the EU drops to 0.454 kg CO_2e/kWh (7% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	to 15 % as standard based on information from 3,8, 28 - Feed stock source split for bioethanol changes to 52% sugar cane, 8% sugar beet, 40% wheat[13] - 5% reduction in the 2009 WTT RED GHG intensity factors for sugar cane and sugar beet ethanol, with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 22.8 g CO_{2e}/MJ for sugar cane bioethanol, 31.4 g CO_{2e}/MJ for sugar beet bioethanol and 23.4 g CO_{2e} for wheat bioethanol. - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2012 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.387 kg CO_2e/kWh (34% reduction from 2012 figures), while that of the EU drops to 0.421 kg CO_2e/kWh (14% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

Typical 2030	**Best 2030**
- 10% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 3% energy consumption saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 3% fuel saving from best 2020 figures[13]. - Resulting fuel consumption = 1.89 l/100km; resulting electricity consumption = 4.94 kWh/100km - Share of bioethanol in gasoline increase to 15 % as standard estimation based on information from 3,8, 28 - Feed stock source split for bioethanol	- 15% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 4% energy consumption saving[13] - Improved technology in ICE leading to better fuel economy e.g. adapting ICE to cope with higher octane number fuels[6], leading to an additional 4% fuel saving from best 2020 figures[13]. - Resulting fuel consumption = 1.85 l/100km; resulting electricity consumption = 4.89 kWh/100km - ICE using 100% bioethanol [13] - Feed stock source split for bioethanol changes to 45% sugar cane and 50% wheat[13]

changes to 45% sugar cane and 50% wheat[13] - 3% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 8% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 23.3 g CO_{2e}/MJ for sugar cane bioethanol and 23.9 g CO_{2e}/MJ for wheat bioethanol - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.287 kg CO_2e/kWh (51% reduction from 2012 figures), while that of the EU drops to 0.352 kg CO_2e/kWh (28% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	- 5% reduction in the 2009 RED WTT GHG intensity factor for sugar cane ethanol with a 10% reduction in the GHG intensity factor for wheat ethanol; reductions to account for future improvements in technology and efficiencies[13] - Resulting WTT GHG intensity factors are 22.8 g CO_{2e}/MJ for sugar cane bioethanol and 23.4 g CO_{2e}/MJ for wheat bioethanol - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.1 kg CO_2e/kWh (83% reduction from 2012 figures), while that of the EU drops to 0.196 kg CO_2e/kWh (60% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

8.2.4 BEV

Typical 2012
- Same as base vehicle specification in section 2.4 of this report

Typical 2020	**Best 2020**
- 10% vehicle light-weighting[1,7,11] leading to 2% energy consumption saving[13] - Resulting electricity consumption = 14.7 kWh/100km - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2012 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.502 kg CO_2e/kWh (17% reduction from 2012 figures), while that of the EU drops to 0.454 kg CO_2e/kWh (7% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	- 15% vehicle light-weighting[1,7,11] leading to 3% energy consumption saving[13] - Resulting electricity consumption = 14.6 kWh/100km - Improved battery tech (e.g. higher energy density of cells) [4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2012 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.387 kg CO_2e/kWh (34% reduction from 2012 figures), while that of the EU drops to 0.421 kg CO_2e/kWh (14% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

Typical 2030	Best 2030
- 10% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 3% energy consumption saving[13] - Resulting electricity consumption = 14.3 kWh/100km - Improved battery tech (e.g. higher energy density of cells)[4] leading to smaller batteries and a saving of 10% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.287 kg CO_2e/kWh (51% reduction from 2012 figures), while that of the EU drops to 0.352 kg CO_2e/kWh (28% reduction from 2012 figures) estimation based on information from 9,14,17,31,32	- 15% vehicle light-weighting[1,7,11] from "Typical 2020" leading to a further 4% energy consumption saving[13] - Resulting electricity consumption = 14.1 kWh/100km - Improved battery tech (e.g. higher energy density of cells)[4] leading to smaller batteries and a saving of 15% of embodied impacts of battery pack production from 2020 figures. - Carbon intensity of electricity grid mix in the UK drops to 0.1 kg CO_2e/kWh (83% reduction from 2012 figures), while that of the EU drops to 0.196 kg CO_2e/kWh (60% reduction from 2012 figures) estimation based on information from 9,14,17,31,32

8.3 DATA FOR LCI

This appendix provides the data (and sources) used to build up the LCI for this study. Data is presented according to the main vehicular lifecycle stages described in section 2 of this report.

8.3.1 Vehicle component manufacture – Background Data

Table 8-3: Datasets used in inventory analysis for vehicle components

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO_2e
Steel hot dip galvanized (BOF route)	worldsteel	2007	RER	1 kg	2.56
Aluminium ingot mix (primary)	PE	2010	RER	1 kg	9.90
Aluminium ingot mix (secondary)	PE	2010	DE	1 kg	4.51
Acrylonitrile-butadiene-styrene granulate (ABS)	PE	2010	RER	1 kg	3.83
Polypropylene granulate (PP)	PE	2010	RER	1 kg	1.99
Polyethylene terephthalate granulate (PET)	PE	2010	RER	1 kg	3.33
Polyamide 6.6 (PA 6.6) fabric	PE	2010	RER	1 kg	14.66
Cotton fabric	PE	2010	RER	1 kg	2.30
Glass fibres	PE	2010	DE	1 kg	3.48
Magnesium	PE	2010	CN	1 kg	31.29
Platinum mix	PE	2010	GLO	1 kg	18540.53
Natural rubber (NR)	PE	2010	DE	1 kg	1.57
SBR-butadiene-rubber (SBR)	PE	2010	DE	1 kg	3.70
Lubricants at refinery	PE	2008	EU-27	1 kg	1.04
Neodymium magnets	PE	2010	DE	1 kg	29.13
Lead (99.99%)	PE	2010	DE	1 kg	1.74
Sulphuric acid (96%)	PE	2010	RER	1 kg	0.256
Polyvinyl chloride granulate	PE	2010	DE	1 kg	2.23
Cast iron part	PE	2010	DE	1 kg	0.69
Ethylene glycol	PE	2010	DE	1 kg	1.12

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO_2e
Power Supply Unit (power electronics estimation)	PE	2010	GLO	1 kg	30.8
Ring core coil (with housing)	PE	2010	GLO	1 kg	9.27
Aluminium extrusion profile	PE	2010	RER	1 kg	0.741
Capacitor Al-capacitor radial THT	PE	2010	GLO	1 kg	9.48
Copper wire	ELCD/ECI	2000	EU-15	1 kg	0.79
Brass component	PE	2010	RER	1 kg	1.37
Fixing material screws stainless	PE	2010	DE	1 kg	7.20
Steel cold rolled coil	worldsteel	2007	RER	1kg	2.26
Lubricant (aqueous)	PE	2010	GLO	1kg	1.20
Silica sand (flour)	PE	2010	US	1 kg	0.31
Aluminium sheet	EAA	2010	RER	1 kg	10.10
Polyester fabric	PE	2010	RER	1 kg	6.95
Viscose fabric	PE	2010	RER	1 kg	6.56
Polyamide 6.6 fabric	PE	2010	RER	1 kg	14.60
Base coat solvent-based (metallic)	PE	2010	DE	1 kg	3.90
Clear coat solvent-based (2K)	PE	2010	DE	1 kg	4.93
Ethanol (via hydrogenation with nitric acid)	PE	2010	DE	1 kg	2.40
Steel rebar	worldsteel	2007	GLO	1 kg	1.27
Float flat glass	PE	2010	EU-27	1 kg	1.07
Polyethylene high density granulate	PE	2010	DE	1 kg	1.65
Polyurethane rigid foam	PE	2010	DE	1 kg	6.06
Rhodium mix	PE	2010	GLO	1 kg	38302.18
Palladium mix	PE	2010	GLO	1 kg	17484.59
Li-Ion battery pack	LCAworks	2012	GLO	1 kWh	200.00
NiMH battery back	Oeko	2010	GLO	1 kWh	289.00
Freon (Tetrafluoroethane R134 a)	PE	2010	DE	1 kg	12.20

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO$_2$e
Thermal energy from natural gas	PE	2008	EU-27	1 MJ	0.07
Electricity grid mix (at point of consumption)	PE	2009	EU-27	1 kWh	0.49
Electricity grid mix (typical case, at point of consumption)	PE	2020	EU-27	1 kWh	0.45
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32,36	2020	EU-27	1 kWh	0.42
Electricity grid mix (typical case, at point of consumption)	estimated from 9,14,17,31,32,36	2030	EU-27	1 kWh	0.352
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32,36	2030	EU-27	1 kWh	0.196

8.3.2 Vehicle assembly– Background Data

Table 8-4: Datasets used in inventory analysis for vehicle assembly

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO$_2$e
Thermal energy from hard coal	PE	2008	GB	1 MJ	0.11
Thermal energy from natural gas	PE	2008	GB	1 MJ	0.06
Electricity grid mix (at point of consumption)	PE	2009	GB	1 kWh	0.59
Electricity grid mix (typical case, at point of consumption)	PE	2020	GB	1 kWh	0.50
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32,36	2020	GB	1 kWh	0.39
Electricity grid mix (typical case, at point of consumption)	estimated from 9,14,17,31,32,36	2030	GB	1 kWh	0.29
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32,36	2030	GB	1 kWh	0.1

8.3.3 Use phase – Foreground Data

Table 8-5: Datasets used in inventory analysis for vehicle use phase

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO_2e
Bioethanol (from wheat, straw/CHP) WTT	RED	2009	EU	1 MJ	0.026
Bioethanol (from wheat, NG/CHP) WTT	RED	2009	EU	1 MJ	0.039
Bioethanol (from sugar cane) WTT	RED	2009	EU	1 MJ	0.024
Bioethanol (from sugar beet) WTT	RED	2009	EU	1 MJ	0.033
Petrol mix (regular) at refinery WTT	PE	2008	EU-27	1 MJ	0.014
Bioethanol 100%, TTW	US EPA	2010	_	1 l	0.02
Petrol 100%, TTW	DEFRA	2011	_	1 l	2.31
Lubricants at refinery	PE	2008	EU-27	1 kg	1.04
Electricity grid mix (at point of consumption)	PE	2009	GB	1 kWh	0.59
Electricity grid mix (typical case, at point of consumption)	PE	2020	GB	1 kWh	0.50
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32	2020	GB	1 kWh	0.39
Electricity grid mix (typical case, at point of consumption)	estimated from 9,14,17,31,32	2030	GB	1 kWh	0.29
Electricity grid mix (best case, at point of consumption)	estimated from 9,14,17,31,32	2030	GB	1 kWh	0.1

8.3.4 End of life – Background Data

Table 8-6: Datasets used in inventory analysis for vehicle end of life

Dataset name	Source	Year	Geography	Ref. unit	GHG intensity, kg CO_2e
Preparation of aluminium scrap for recycling	PE	2005	RER	1 kg	0.52
Waste incineration of plastics (PE, PP, PS, PB)	ELCD/ CEWEP	2006	EU-27	1 kg	1.09
Waste incineration of plastics (Nylon 6,Nylon 66, PAN)	ELCD/ CEWEP	2006	EU-27	1 kg	1.01
Used oil treatment (worst case scenario)	PE	2012	GLO	1 kg	2.98
Waste incineration of glass/inert material	ELCD/ CEWEP	2006	EU-27	1kg	0.123
Waste incineration of plastics (rigid PVC)	ELCD/ CEWEP	2006	EU-27	1 kg	1.68
Hazardous waste incineration (non specific, worst case scenario)	PE	2010	GLO	1 kg	2.97
Waste incineration of plastics (unspecified) fraction in MSW	ELCD/ CEWEP	2006	EU-27	1 kg	0.69
Waste incineration of MSW	ELCD/ CEWEP	2012	EU-27	1 kg	0.33
Car shredder	PE	2012	DE	1 kg	0.04

8.4 EOL RECYCLING METHODOLOGIES

This appendix describes two common recycling methodologies in LCA that are referred to in this study.

8.4.1 Cut-Off Approach

The cut off approach (also called the recycled content approach or 100:0 approach) allocates the recycling process emissions and removals to the life cycle that uses the recycled material. No burdens are received for using scrap as an input material to a recycling process, and no credits are received for scrap that is available to recycle at end of life.

This approach has the effect of promoting the use of recycled content, as recycling processes generally have much lower impacts than primary production processes. In contrast, there is very little incentive to recycle at end of life (except that impacts associated with alternative end of life options are avoided).

The *GHG Protocol: Product Life Cycle Accounting and Reporting Standard* advises that the recycled content approach should be used when:

- The product contains recycled input, but no recycling occurs downstream;
- The market for the recycled material is saturated (e.g., not all material that is recovered is used as a recycled input, supply exceeds demand) and therefore the creation of recycled material may not displace the extraction of virgin material;
- The content of recycled material in the product is directly affected by the company's activities alone, and therefore the company has control over how much recycled material input to procure (which could potentially be used as a reduction mechanism); or
- The time period of the product's use stage is long and/or highly uncertain and therefore the amount of material recycled at the end-of-life is also highly uncertain.

8.4.2 Avoided Burdens Approach

The avoided burdens approach (also called the end of life recycling approach, the closed loop approximation method or the 0:100 approach) accounts for the impact that end-of-life recycling has on the net virgin acquisition of a material. Under this method, scrap available for recycling at end of life is assumed to offset demand for primary material resulting in a credit to the product system.

This approach has the effect of promoting recycling at end of life as the more that is recycled the greater the credit that is received. In contrast, there is no incentive to increase recycled content as this uses scrap that would otherwise offset primary production (i.e. recycled content has the same impacts as primary material).

The *GHG Protocol: Product Life Cycle Accounting and Reporting Standard* advises that the end of life recycling approach should be used when:

- When the recycled content of the product is unknown because recycled material is indistinguishable from virgin material in the market;
- When the market for the recycled material is not saturated (e.g., all material that is recovered is used as a recycled input, demand exceeds supply) and therefore creating more recycled material is likely to increase the amount of recycled material used; or
- When the time period of the product's use stage is short and/or well known.

It should also be noted that the end of life recycling approach is only valid if the recycled material directly offsets the use of primary material. If the recycled material is of lower quality than the primary material then it cannot directly substitute for it and the full credit should not be claimed. In these cases alternative approaches, such as “value-corrected substitution”, may be applied where the credit is based on the relative value of the recycled and primary materials.

8.5 RESULTS

This appendix presents the results data used to generate the charts displayed in the main body of this report.

8.5.1 Top Level Results

Table 8-7: Top level results for vehicles across all scenarios

	Base 2012	Typical 2020	Best 2020	Typical 2030	Best 2030
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	30.70	28.70	27.51	25.27	9.35
HEV	24.40	23.07	22.29	20.62	9.27
PHEV	21.74	20.30	18.87	17.11	9.21
BEV	24.46	21.60	18.49	15.74	11.06

8.5.2 Detailed Results

Table 8-8: Detailed results for “Base case 2012” scenario

	Component production	Vehicle assembly	Bioethanol production, WTT	Gasoline production, WTT	Electricity production, WTW	Use phase, gasoline TTW	Use phase, bioethanol TTW	End of life
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	5.04	1.40	0.51	5.01	0	18.18	0.02	0.55
HEV	6.11	1.40	0.35	3.44	0	12.47	0.01	0.55
PHEV	6.61	1.40	0.18	1.81	4.57	6.55	0.01	0.55
BEV	9.56	1.40	0	0	13.19	0	0	0.27

Table 8-9: Detailed results for “Typical case 2020” scenario

	Components production	Vehicle assembly	Bioethanol production, WTT	Gasoline production, WTT	Electricity production, WTW	Use phase, gasoline TTW	Use phase, bioethanol TTW	End of life
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	4.87	1.28	0.42	4.66	0	16.90	0.01	0.56
HEV	5.97	1.28	0.29	3.23	0.00	11.73	0.01	0.56
PHEV	6.42	1.28	0.16	1.74	3.84	6.30	0.01	0.56
BEV	8.98	1.28	0	0	11.07	0	0	0.28

Table 8-10: Detailed results for “Best case 2020” scenario

	Components production	Vehicle assembly	Bioethanol production, WTT	Gasoline production, WTT	Electricity production, WTW	Use phase, gasoline TTW	Use phase, bioethanol TTW	End of life
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	4.76	1.11	0.40	4.46	0.00	16.19	0.01	0.57
HEV	5.84	1.11	0.28	3.13	0.00	11.35	0.01	0.57
PHEV	6.27	1.11	0.15	1.69	2.93	6.14	0.01	0.57
BEV	8.65	1.11	0	0	8.45	0	0	0.29

Table 8-11: Detailed results for “Typical case 2030” scenario

	Component production	Vehicle assembly	Bioethanol production , WTT	Gasoline production , WTT	Electricity production , WTW	Use phase, gasoline TTW	Use phase, bioethanol TTW	End of life
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	4.62	0.97	0.56	4.00	0	14.52	0.02	0.57
HEV	5.67	0.97	0.39	2.81	0.00	10.19	0.01	0.57
PHEV	6.07	0.97	0.22	1.54	2.13	5.60	0.01	0.57
BEV	8.34	0.97	0	0	6.14	0	0	0.29

Table 8-12: Detailed results for “Best case 2030” scenario

	Component production	Vehicle assembly	Bioethanol production, WTT	Gasoline production, WTT	Electricity production, WTW	Use phase, gasoline TTW	Use phase, bioethanol TTW	End of life
Vehicle	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*	*t CO2e*
ICEV	4.35	0.71	3.59	0	0	0	0.13	0.58
HEV	5.36	0.71	2.54	0	0	0	0.09	0.58
PHEV	5.74	0.71	1.41	0	0.73	0	0.05	0.58
BEV	7.94	0.71	0.00	0	2.12	0	0.00	0.29