An Environmental and Economic Assessment of Introducing Hydrogen to a Combined Heavy Duty/Off-Road Vehicle Fleet in the UK

Submitted in accordance with the requirements for the integrated degree of Doctor of Philosophy and Master of Science (Bioenergy)

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Believe & Achieve

Declaration of Authorship

The candidate confirms that the work submitted is their own, except where work which has formed part of jointly authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

Chapters based on work from jointly authored publications include:

- Chapters 3 and 4 (Baseline Conditions (3), and Economic Assessment of FCEVs (4)).

Publications which have been used:

- ***"A Comparative Total Cost of Ownership Analysis of Heavy Duty On-Road and Off-Road Vehicles Powered by Hydrogen, Electricity, and Diesel"***

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- Cameron Rout – Conceptualisation, data collection, analysis, writing, reviewing, editing.
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Abstract

The emissions from many industries have fallen over the past decade, however transport has failed to follow suit and has stayed consistently high, now being the largest source of CO_2 in the UK. Although the light duty sector is transitioning towards electrification, heavy-duty vehicles (HDVs) lack suitable technology and still rely heavily on diesel, with disproportionately high CO_2 emissions alongside criteria air pollutants. One potential solution for heavy duty transport is hydrogen fuel cell electric vehicles (FCEVs).

The aim of this project is to investigate whether hydrogen can be a suitable fuel for emissions reduction in the heavy-duty sector, whilst also remaining economical. This is achieved by first conducting an economic assessment using Total Cost of Ownership (TCO) analysis, which is then followed by an environmental investigation in the form of a Life Cycle Assessment (LCA) using SimaPro software with the widely recognised inventory database, Ecoinvent. Vehicle emissions software COPERT is also used to support this modelling further. Results compare and analyse the economics and life cycle emissions of a mixed fleet of FCEV heavy duty on-road and off-road vehicles to battery electric and diesel counterparts, and considers 6 vehicle types (cars, buses, trucks, tippers, refuse vehicles, and forklifts) and 14 fuel scenarios, offering a novel contribution to existing literature. In this work, results are generated from both a general perspective and a fleet-owner perspective using real mileage figures from UK council fleets. Results identify the cost components and life cycle stages with the greatest impact on FCEV competitiveness and a sensitivity analysis helps determine conditions under which hydrogen is most favourable, in addition to the prediction of future scenarios.

Results show that for most vehicles hydrogen is not cost-effective under base case conditions. Only hydrogen forklifts are cheaper than their diesel counterparts, whilst generally electric powertrains show the lowest costs overall. Despite this, BEVs may incur indirect costs from payload losses and efficiency drops in cold weather which could offset their savings, so should be considered before making final decisions. Further, the cost competitiveness of FCEVs can be improved if favourable policy and regulatory conditions are applied, like purchase grants and fuel price reductions. Hydrogen shows greater promise in terms of sustainability as several FCEV HDVs show lower life cycle emissions than diesel and electric counterparts. Similar to their costs, emissions can be reduced in the future by varying the modelling conditions, like the use of a decarbonised electricity grid, for example.

In general, hydrogen can significantly reduce the emissions from HDVs, but their costs are most likely going to restrict their uptake unless favourable conditions are implemented. If these conditions are not met, other technologies may help achieve net zero targets sooner.

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Abbreviations/Glossary:

BEV	Battery Electric Vehicle
BMS	Battery Management System
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRM	Critical Raw Material
CTG	Cradle-To-Grave
DOC	Diesel Oxidative Catalyst
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
EOL	End-Of-Life
FC	Fuel Consumption
FCEV	Fuel Cell Electric Vehicle
FOI	Freedom of Information
FS	Fossil Scarcity
GVW	Gross Vehicle Weight
GWP	Global Warming Potential
HBEFA	Handbook of Emission Factors (For Road Transport)
HC	Hydrocarbon
HDV	Heavy Duty Vehicle
ICEV	Internal Combustion Engine Vehicle
kW	Kilowatt
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LDV	Light Duty Vehicle
Li-ion	Lithium-Ion
LiFP	Lithium Iron Phosphate
LMO	Lithium Manganese Oxide
LNT	Lean NOx Trap
LT	Liquid Tanker
MEA	Membrane Electrode Assembly
MIR	Maximum Incremental Reactivity
NCA	Nickel Cobalt Aluminum
NEDC	New European Driving Cycle
NiMH	Nickel Metal Hydride
NMC	Nickel Manganese Cobalt
NMVOC	Non-Methane Volatile Organic Compound
NOx	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OFP	Ozone Formation Potential
OPEX	Operating Expenditure
PCU	Precooling Unit
PEMFC	Proton Exchange Membrane Fuel Cell
PEMS	Portable Emissions Measuring System
PHEM	Passenger Car and Heavy Duty Emissions Model
PM	Particulate Matter
RES	Renewable Energy Systems
RUL	Road User Levy
SA	Sensitivity Analysis
SCR	Selective Catalytic Reduction
SMR	Steam Methane Reforming
TCO	Total Cost Of Ownership

TEO	Total Emissions of Ownership
TT	Tube Trailer
VED	Vehicle Excise Duty
VOC	Volatile Organic Compound
WLTP	Worldwide Light Duty Test Procedure
WT	Wind Turbine
WTW	Well-To-Wheel
ZEV	Zero Emission Vehicle

1. Chapter 1 - Introduction

1.1. Current Reliance on Diesel Transport and its Impact on Global Warming:

Global warming is one of the biggest challenges facing humanity today and is evidenced by the continuous rise of global average temperatures, resulting in significant climate change over the past several decades. Allen *et al* [278] report that over the past half century, global temperatures have been consistently rising, but the most significant increases have been seen over the past decade; evidenced by data from Lindsey *et al* [277] which shows that 9 of the 10 warmest years on record were recorded over 2013-2021. These rising temperatures are a result of anthropogenic global warming from processes like industrialisation, transport, and fossil-based power generation.

Global warming is caused by the release of greenhouse gases (GHGs) which absorb heat and can remain in the atmosphere for long periods of time. The most common GHG is carbon dioxide (CO_2), although there are a range of others such as methane (CH_4) and nitrous oxide (N_2O) which have their own individual contribution to global warming over a specified period of time (typically 20 or 100 years), called 'global warming potential' (GWP), reported in units of CO_2-equivalent (CO_2e) [321]. Any quantity of GHG released can be reported in these units to highlight the amount of CO_2 that would have the equivalent global warming impact. For example, the 100-year GWP of CH_4 is ~25 which means 1 kg of CH_4 contributes 25 times more to global warming compared to 1 kg of CO2 [321]. CO_2e allows the GWP of multiple greenhouse gases to be combined to give one figure and enables different gases to be compared in terms of their global warming impact.

In more recent years, global warming has led to growing efforts to reduce carbon emissions, which is the primary focus of this work. The UK and many other countries have now set ambitious targets to limit global temperature rises to within 1.5°C of pre-industrial levels and to achieve net zero greenhouse gas emissions by 2050 [322]. These targets demand carbon reduction and promote the growth and use of clean energy from sources like wind and solar power. To achieve these ambitions, rapid decarbonisation is needed across all sectors, especially transport. Despite improvements in fuel efficiency, vehicle lightweighting, and exhaust aftertreatment technologies, Figure 1-1 shows transport has stayed consistently high and has been the largest emitter of greenhouse gas emissions since 2016, even overtaking the energy sector which saw positive transitions from coal to gas usage. As a result, this work focuses on addressing the carbon emissions from transport.

In 2020, transport was responsible for 24% of total CO_2e emissions with 91% attributed to road transport vehicles [280]. Even after the effects on Covid-19 this still remains the largest emitting sector in the UK in 2022 [280]. Of this 24% portion, the majority of emissions (52%) came from cars and taxis, whilst 19% came from heavy duty vehicles (HDVs). Although the portion of total emissions from HDVs is much lower, these vehicles account for a much smaller share of UK road transport compared to cars (6% vs 76%) and therefore contribute disproportionately, highlighting their high energy intensity as a transport mode [280].

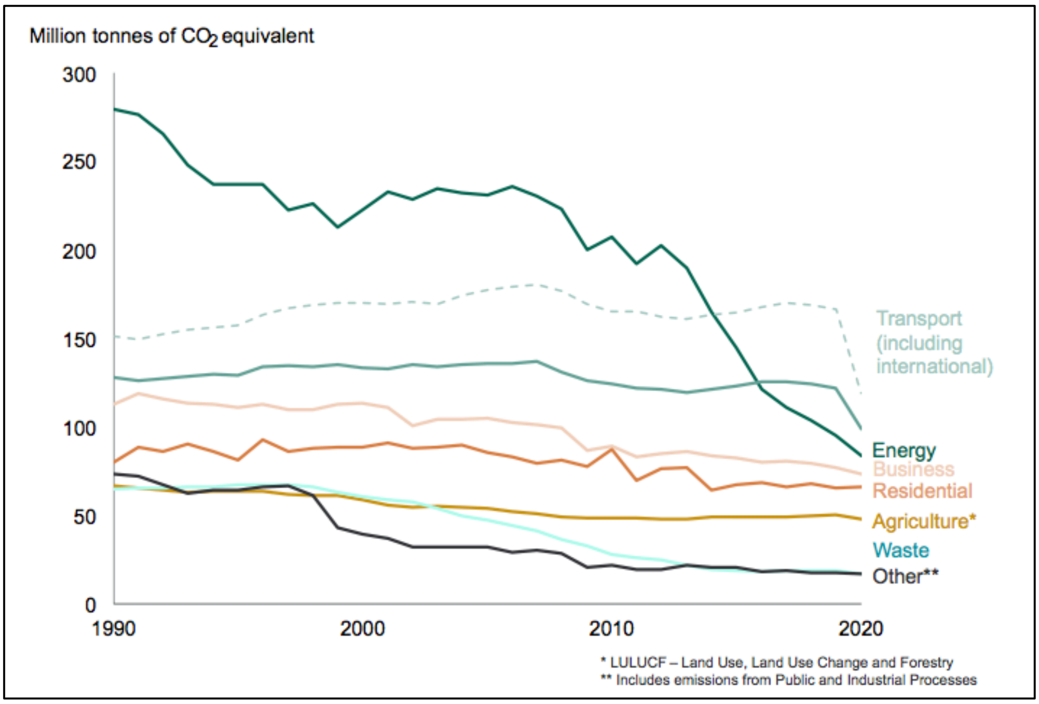


Figure 1-1 - UK CO_2e emissions by source (1990-2020). [280]

The vast majority of HDVs rely on diesel fuel [71]. Although more cars were powered by petrol compared to diesel on UK roads at the end of 2021 (18.7 vs 11.6m), diesels use dominates heavy duty transport as their engines offer high durability and reliability, high efficiency compared to petrol engines, and they have lower maintenance requirements [279]. These are some of the reasons why diesel engines are used so extensively in heavy duty applications, by vehicles characterised by intense duty cycles and high mileage requirements. Examples include on-road vehicles like buses, long haul trucks, and refuse collection vehicles, as well as off-road vehicles like trains, ships, and excavators. In the UK, the number of diesel vehicles tripled from 2001 to 2018, highlighting the scale of the demand for diesel which increased 17 out of the 19 years from 2000-2018 [217].

Despite the growth of diesel vehicles highlighted, it is widely understood that the technology can no longer be used as a long-term solution due to the emissions associated with their operation, making it highly unlikely that net zero targets are reached. This is because the use of these vehicles and the combustion of diesel fuel rarely takes place under ideal conditions. In an ideal combustion process, diesel generates CO_2 and water vapour as its only products. However, due to variable factors like engine temperature, fuel/air ratio, and ignition timing, the process is less efficient and generates other products like nitrogen oxides (NOx), carbon monoxide (CO), particulate matter (PM), volatile organic compounds (VOCs), and hydrocarbons (HC). These are explored further in Chapter 2, respectively.

1.2. Technologies for Significant Emission Reduction:

Despite improvements in powertrain efficiency, vehicle lightweighting, and optimisation of freight routes for diesel HDVs, the emission savings are not significant enough to achieve the climate targets set. Since these conventional fuels will no longer be suitable for use in the coming years, it is of great interest to researchers, policymakers, and fleet owners to explore alternative and low carbon fuels which are not only more sustainable, but which are also cost effective and provide a similar performance.

Ultra-low emission vehicles (ULEVs) are defined as those which emit 50g CO_2 per km or less from their exhaust. This limit was reduced from its previous value of 75 g/km to acknowledge the recent improvements in transport technology. Beyond this, zero emission vehicles (ZEVs) are those characterised by zero tailpipe emissions and include pure battery electric vehicles (BEVs) and hydrogen used in fuel cell electric vehicles (FCEVs). All of these solutions have the potential to significantly reduce carbon emissions and improve air quality, and if their fuels can be generated from renewable power, they can also lower the UK's dependence on fossil fuel imports; the impacts of which were seen throughout Russian/Ukrainian conflicts, highlighting the consequences on energy prices as a result of high reliance on other countries for energy and resources. As a result of these advantages, it is of great interest to increase the use of alternative fuels in vehicles today. Table 1-1 outlines some of the most popular and promising low carbon fuels available which could be used to reduce the emissions in the transport sector. A brief overview of the fuel is given, along with its pros, cons, and some case studies highlighting their use in real fleets.

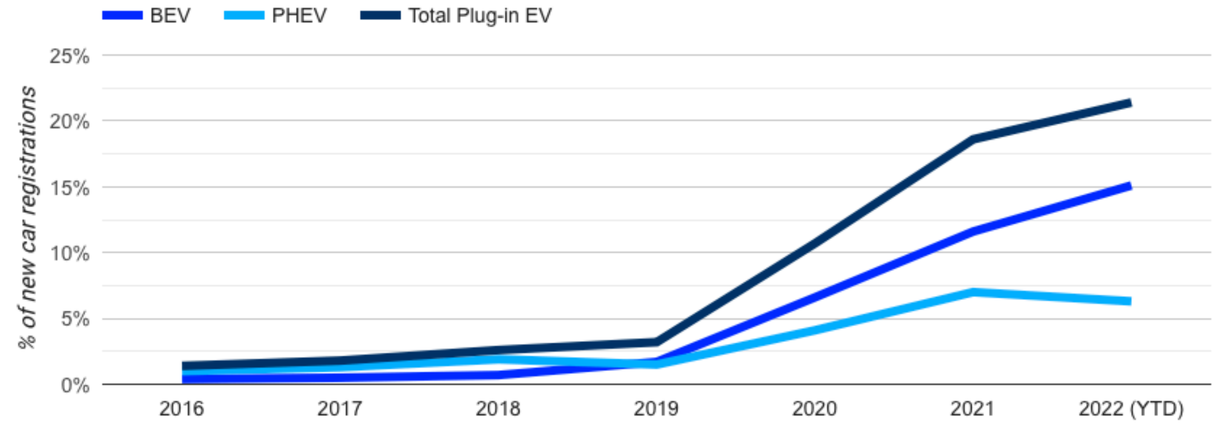
Table 1-1 - Overview of the most popular and promising alternative transport fuels available.

Fuel:	Overview:	Advantages:	Disadvantages:	Case Studies:
Compressed Natural Gas (CNG)	Natural gas can either be compressed in gaseous (CNG) form or liquefied (LNG). Proven technology with many countries using it. Can reduce exhaust emissions but its use can lead to fossil-fuel lock in.	Avoids the boil-off losses that are associated with LNG. CNG is cheaper to produce and store compared to LNG. Rapid dispersion in air due to its lower density is a safety advantage. Studies have shown an average of 80% fewer ozone-forming emissions are generated compared to petrol fuel.	Requires additional storage space on board the vehicle (due to its low energy density). CNG infrastructure is currently limited and requires expansion. Higher purchase costs of NG vehicles partly due to the additional tanks required. Despite lower exhaust emissions, it still locks in fossil fuel use which net zero is trying to minimise in the future.	Roughly 18m vehicles run on CNG worldwide with many fleets switching to it from diesel [286]. CNG has seen rapid growth in China and India especially. Hermes operate a large fleet of 160 CNG delivery vehicles in the UK which they state will reduce their carbon footprint by 24,000 tCO_2/year.
Liquefied Natural Gas (LNG)		Has already been used as a transport fuel for decades.	Can suffer from losses due to boil off associated with temperature gradients.	LNG has been used for several years and many studies have outlined its

		High specific density compared with diesel (more energy per unit mass). This gives it a longer driving range. More efficient engine operation than diesel. Studies show LNG is cheaper than diesel. Much lower exhaust emissions (Volvo study suggests LNG trucks give 20% lower CO_2 than diesels).	Highly insulated tanks required. Studies have suggested air pollution is worsened with the use of LNG. Higher NOx emissions. Higher purchase costs of LNG vehicles due to the tanks required and high fuel cost due to liquefaction required. More refuelling stations required if LNG is to be used extensively. Current infrastructure is low.	advantages and potential as an alternative fuel. Paris shopping chain Castorama redesigned its logistics by replacing diesel lorries with LNG. Not only was the plan successful but they managed to cut the number of lorries required (from 7 to 6) to achieve the same output.
Biodiesel	Derived from biological sources like vegetable oils and animal fats.	Completely free of fossil fuel dependence, though can be blended with regular diesel in any percentage. Fuel production emissions are very low. Improves air quality.	High demand for biofuels could lead to competition for land use, potentially reducing crop growth. High blends of biodiesel may not perform well under cold temperatures as it contains compounds which can crystallise.	The 'Powered by Biodiesel' project included the use of biodiesel for city buses in Portugal and aimed to quickly reduce their emissions. Regular diesel was replaced with no changes to the buses themselves and no additional costs, and results showed an 84% reduction in GHGs. No changes were seen to bus performance and no additional maintenance was required [272].
Hydrogen	Typically used in gaseous form at 350 or 700 bar pressure. Production route used highly impacts its sustainability. Can offer a truly zero-carbon solution to the transport sector.	No exhaust emissions. High energy density (more energy per unit mass). Can be produced in several ways, some of which do not rely on fossil fuels. Long range similar to existing diesel vehicles. Fast refuelling which avoids productivity losses.	Most common production route (SMR) currently uses fossil resources. Hydrogen produced from renewable power is currently expensive. Large infrastructure network must be built to facilitate FCEV use. Public perception of hydrogen safety remains uncertain. Its supply chain can be energy intensive as it requires a lot of processing stages.	Many countries now have extensive hydrogen fleets already in operation. Aberdeen has one of the largest FCEV fleets in the world with several buses, cars, and refuse vehicles. California operates a number of FCEV buses and has several refuelling stations available. Other countries with FCEV fleets include China, Japan, Germany, and Australia.

Electricity	Currently the most popular alternative fuel to diesel available. Overall emissions are highly impacted by grid mix used. Can offer a truly zero-carbon solution to the transport sector.	Very efficient operation. No exhaust emissions. An extension and rapidly growing infrastructure of chargers available. Many options available on the market to choose from.	Battery constraints currently limit its suitability in HDV applications. Supply chain associated with battery materials is energy intensive. Long recharging times which can affect productivity. Only as clean as the electricity it relies on. If using grid mix with fossil fuels, emissions are high.	BEVs are used globally and an extensive infrastructure of chargers are available from your home to your supermarket. Most BEVs are passenger cars, but other vehicles like buses and forklifts are also used around the world. Prototypes for BEV trucks are in operation with companies like Tesla planning to bring these to market in the next couple of years.

BEVs and FCEVs powered by renewable energy are the only truly zero carbon solutions that have no exhaust emissions. It is for this reason that these powertrains are considered in this work. Their operation has the potential to significantly improve both global warming and air quality. By the end of November 2022 there were ~620,000 battery electric cars in the UK (and ~440,000 plug-in hybrid electric vehicles (PHEVs)) which was the largest annual increase in registrations with roughly 395,000, equivalent to a 92% rise from 2020 figures [281]. As for FCEVs, there were no new registrations in the second quarter of 2022. Based on these figures and the data in Figure 1-2, BEVs have a clear head start which suggests their uptake is more likely to dominate the passenger car sector. However, for HDVs with greater duty cycles, current battery technology lacks suitability for these applications, which is one of their biggest downfalls. In contrast, hydrogen offers a potential solution for the decarbonisation of the HDV sector and is therefore the main focus of this study.



Source: SMMT, November 2022

Figure 1-2 - New car registrations from 2016-2022.

The lack of literature considering both the economic and environmental position of ZEVs in HDV transport was highlighted by Gray *et al* [282] and presents an area demanding further investigation, also discussed further in Chapter 2. Currently, the majority of studies assessing the suitability of BEVs and FCEVs focus only on one vehicle type and fail to consider multiple fuels and powertrains. Often in these works upcoming low and zero emission powertrains are compared to conventional ones to highlight their advantages and assess their potential as a solution to carbon intense transport [282]. At the time of writing this work, the literature has very few studies which focus on a direct comparison of two zero emission solutions. Due to the rapidly evolving nature of the technology however, these studies have started growing in number leading to growing markets and an increased push towards low carbon fuels by government. However, a lot of work still focuses on the light duty sector since these are often the first to transition and the most commonly used vehicle types responsible for the majority of transport emissions.

This work is of high importance and is needed in the context of transport because both its slow rate of decarbonisation over the past several decades and the net zero target are now calling for new low carbon fuels to be introduced in replace of conventional ones. This is especially important for the HDV sector which currently operates almost exclusively with diesel fuel and does not show suitability with battery technology today, making it an area of particular concern. As a result, not only is it vital that studies are conducted to assess the effectiveness of solutions like hydrogen in reducing emissions, but they also need to be economically feasible otherwise they are unlikely to be adopted in time. To the authors knowledge, the comparison and analysis of the economics and life cycle emissions of both on-road and off-road vehicles, 6 vehicle types, 3 powertrains, and 14 fuel scenarios in this project offers a unique and novel contribution to the existing literature.

1.3. Thesis Structure:

The structure of this thesis is shown in Figure 1-3 and consists of 9 main chapters with 3 supporting appendix chapters. The first chapter presented an introduction to global warming and climate change with an overview of the UK's net zero commitments. This was followed by the current reliance on diesel fuel and the impacts this has on both global warming and air quality, before providing an introduction into some alternative fuels.

Chapter 2 highlights the major air pollutants from the transport sector and then introduces hydrogen as the focus of the study, starting with its production routes and the operating principles of both fuel cells and electrolysers. It then reviews the current FCEV market before moving on to the most relevant and recent literature studies focusing on FCEV economics and emissions in transport, inclusive of BEVs and/or ICEVs for comparison. The chapter aims to identify gaps in the research which can be filled by this work. By the end of this chapter the reader should have an improved understanding of FCEV suitability and their current economic and environmental positions. Using this information, the key research questions which this thesis aims to answer and the objectives in place to help achieve this are given.

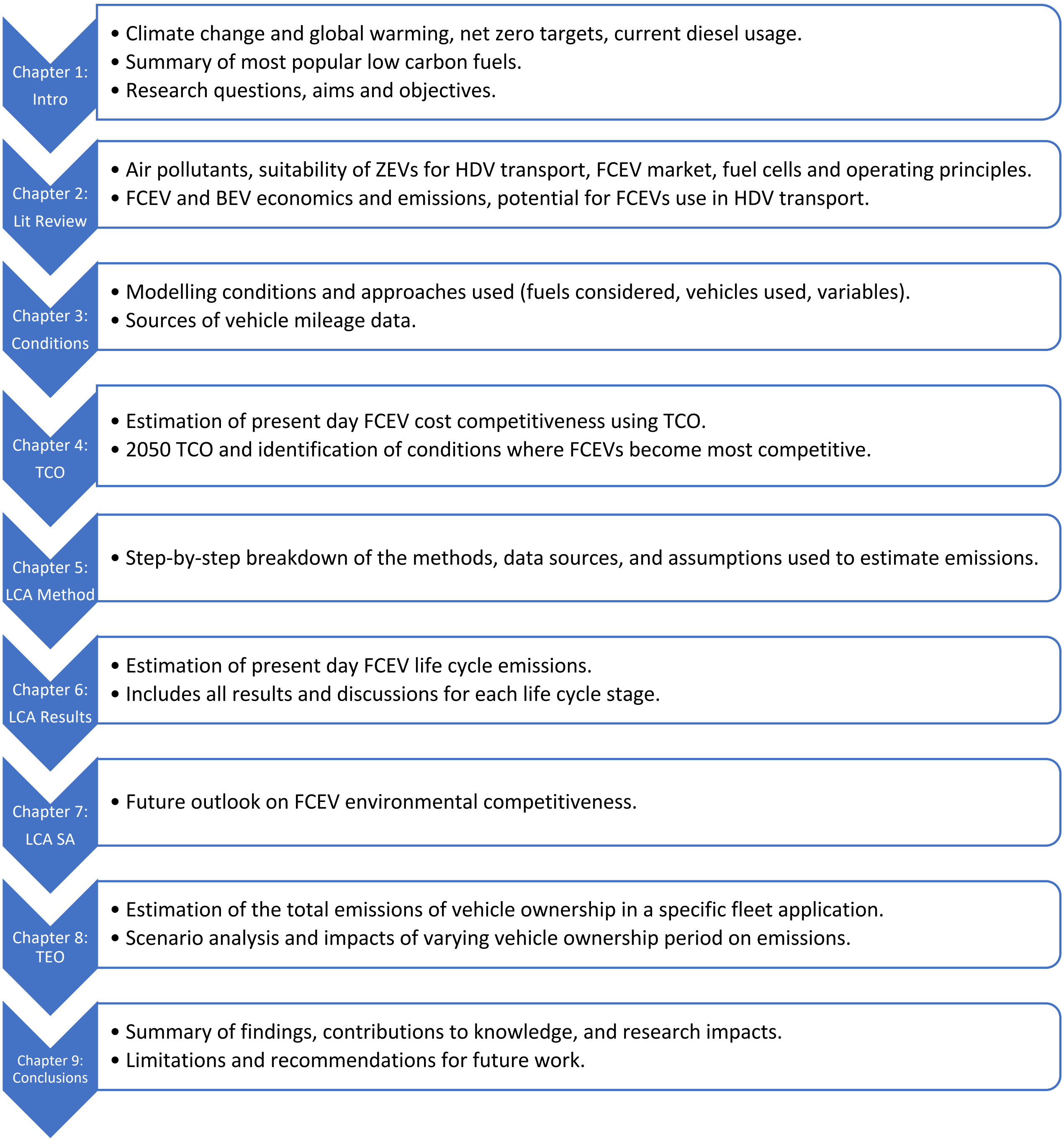
Chapter 3 gives an overview of the more general conditions and key assumptions used to generate results in the study. It provides a technical summary of the reference vehicles used, their operating characteristics, and the study boundaries, as well as an introduction to the fuel scenarios considered. This chapter provides initial foundations which will be built upon further in later chapters.

Chapter 4 provides an economic assessment of FCEVs from the perspective of a fleet owner using TCO analysis and compares these to BEV and ICEV equivalents. It also identifies specific conditions under which FCEVs becomes most cost competitive. A future outlook to 2050 is also presented taking into account likely changes in TCO due to variable parameters such as electricity price and vehicle purchase price.

An environmental assessment across the entire life cycle of the vehicles follows and is presented in 3-part series over Chapters 5-7. This aims to highlight the energy intensity of FCEVs from vehicle and fuel production (cradle) to end-of-life stages (grave) from a general perspective. Similar to the TCO analysis, these emissions are compared to BEVs and ICEVs and environmental hotspots are identified. Chapter 5 first outlines the methodology for this assessment and includes a step-by-step breakdown for each life cycle stage, including all assumptions and data sources respectively, before results are presented and discussed in Chapter 6. The impact of a decarbonised electricity grid (among other variables) on the life cycle emissions is then examined in a sensitivity analysis in Chapter 7. Similar to Chapters 5-7, Chapter 8 examines the environmental impacts of FCEVs this time from the perspective of a fleet owner and considers two vehicle ownership scenarios.

Finally, Chapter 9 will summarise key research findings, outline the contributions to knowledge and research impacts, and highlight limitations and areas for future work.

Chapters 10-12 are supplementary and include additional material supporting Chapters 3-9.



Chapter 1: Intro
- Climate change and global warming, net zero targets, current diesel usage.
- Summary of most popular low carbon fuels.
- Research questions, aims and objectives.

Chapter 2: Lit Review
- Air pollutants, suitability of ZEVs for HDV transport, FCEV market, fuel cells and operating principles.
- FCEV and BEV economics and emissions, potential for FCEVs use in HDV transport.

Chapter 3: Conditions
- Modelling conditions and approaches used (fuels considered, vehicles used, variables).
- Sources of vehicle mileage data.

Chapter 4: TCO
- Estimation of present day FCEV cost competitiveness using TCO.
- 2050 TCO and identification of conditions where FCEVs become most competitive.

Chapter 5: LCA Method
- Step-by-step breakdown of the methods, data sources, and assumptions used to estimate emissions.

Chapter 6: LCA Results
- Estimation of present day FCEV life cycle emissions.
- Includes all results and discussions for each life cycle stage.

Chapter 7: LCA SA
- Future outlook on FCEV environmental competitiveness.

Chapter 8: TEO
- Estimation of the total emissions of vehicle ownership in a specific fleet application.
- Scenario analysis and impacts of varying vehicle ownership period on emissions.

Chapter 9: Conclusions
- Summary of findings, contributions to knowledge, and research impacts.
- Limitations and recommendations for future work.

Figure 1-3 - Thesis structure and focus points of each chapter.

2. Chapter 2 - Theoretical Background and Literature Review

This chapter first provides an overview of the major air pollutants generated from road transport and follows with an introduction to hydrogen as a low carbon transport fuel. This was achieved by outlining the current technologies used for hydrogen production and reviewing the range of fuel cells available and their operating principles. Then, an overview of the current FCEV market is given, along with some of the major factors influencing the suitability of ZEVs in HDV applications. This is followed by a review of recent literature on the economics and environmental status of hydrogen as a transport fuel which is used to identify research gaps.

2.1. Air Quality and Pollutants:

2.1.1. Air Quality in the UK and EU:

Alongside the global warming concerns highlighted in Chapter 1, growing concerns also surround air quality as the transport sector is responsible for significant quantities of air pollutants harmful to human health. Air pollution is a major cause of premature death and disease and reported as the "single largest environmental health risk in Europe", responsible for roughly 400,000 premature deaths per year in the EU [216]. Diesel vehicles in particular are especially harmful to the surrounding air quality due to their fuel combustion inefficiencies. As a result, it is more greatly affected in areas with a high concentration of diesel vehicles, such as cities where buses and cars operate in close proximity to pedestrians and travel at slow speeds. Both short and long-term exposure to these air pollutants can not only cause respiratory problems, but studies have highlighted growing evidence of its links to other health issues such as type 2 diabetes, obesity, Alzheimer's, and dementia [216]. For these reasons, the use of hydrogen in FCEVs can greatly improve air quality as it has zero tailpipe emissions.

2.1.2. Particulate Matter:

Particulate matter (PM) emissions from transport are significant and accounted for 14% of the UK's total emissions in 2020 [280]. PM is responsible for a high number of deaths in the EU as its inhalation can lead to heart disease and strokes, along with various respiratory issues. PM from transport can be either primary (a direct emission to the atmosphere) or secondary (formed by reactions of other air pollutants) and is generated both as exhaust PM during diesel combustion as well as non-exhaust PM from brake, road, and tyre wear respectively. In the combustion process, PM can be formed from the agglomeration of minute particles of unburnt fuel along with other sources. As a result, it is largely a product of incomplete combustion and is influenced by parameters like combustion temperature and fuel quality. Here, the majority of the PM is soot, whilst the remainder is from soluble organic fraction and inorganic fraction. Secondary PM also includes sulphates and nitrates formed from SOx and NOx which contribute towards acidification and eutrophication.

2.1.3. Nitrogen Oxides:

Road transport is the biggest source of NOx emissions worldwide and contributes between 40-70% [229]. NOx consists of both NO and NO_2 and is emitted from diesel combustion at high temperatures. The vast majority (85-

95%) of NOx emissions arise in the combustion chamber in the form of NO, where N2 is oxidised to NO at temperatures over 1600°C and under high oxygen concentration and residence time. However, emissions of NO_2 are also released which are influenced by the exhaust temperature and aftertreatment technology used. This NO emitted into the air is also gradually converted into NO_2 and can react with other compounds in the atmosphere to cause damage to both people and the environment.

In 2019 prior to Covid-19, road transport generated approximately 31% of UK NOx with passenger cars making up the majority whilst off-road transport accounted for 16% respectively [71]. Despite these figures falling compared to previous years due to the replacement of older vehicles and the introduction of stricter emission limits, improvements are needed. This is supported by Defra [284] who highlight the number of regional zones in the UK exceeding the annual average NO_2 limits. Here, only 10 zones complied with these limits, whilst 33 failed with emissions greater than the 40 $\mu g/m^3$ limit. Not only are NOx emissions a precursor to acid rain and a contributor of human lung disease, but they can also react with volatile organic compounds (VOCs) in the presence of sunlight which leads to tropospheric ozone formation.

2.1.4. Volatile Organic Compounds:

VOCs are chemicals containing carbon and hydrogen with boiling points between 50°C and 260°C. They can be divided further into very-VOCs (VVOCs) and semi-VOCs (SVOCs) and originate from both anthropogenic and natural sources. The two anthropogenic sources of VOC with the largest impact on atmospheric emissions are transport and industrial processes. Deng *et al* [285] highlight that due to many industries moving away from urban areas and due to the rapid growth of vehicle numbers in cities, transport exhausts now account for approximately half of all VOC emissions from urban area pollution. VOCs are precursors to the formation of tropospheric ozone, with each individual VOC compound having its own ozone formation potential. In addition, VOCs can also cause cancer and other diseases in both humans and animals, so its formation should be minimised where possible.

2.1.5. Carbon Monoxide:

Carbon monoxide (CO) is another air pollutant caused by incomplete combustion which can negatively impact human health. Exposure to and inhalation of CO can lead to asphyxiation since it binds itself to haemoglobin and restricts its ability to transport oxygen around the body. Its formation is greatly influenced in transport by parameters such as the air/fuel ratio, with concentrations of CO increasing under fuel-rich mixtures with low air content, since there is not enough oxygen available to convert all the carbon in the diesel fuel to CO_2. As a result, its formation is greatest under cold starts or aggressive acceleration, though it still occurs in lean fuel mix conditions as a result of chemical kinetics effects [229]. CO formation in diesel engines is relatively low due to the high air/fuel ratios they employ, which enables most of the fuel to be converted to CO_2, unless the fuel droplets are too large or conditions in the combustion chamber include insufficient turbulence, for example.

2.1.6. Hydrocarbons:

Hydrocarbon (HC) emissions from vehicles can react with other compounds to form ozone, as well as contributing to respiratory illnesses and causing cancer. These emissions consist mainly of unburnt fuels which pass into the exhaust and are a result of low combustion temperatures. In diesel engines, HC formation is low but can be encouraged at light loads and slow speeds where the temperatures are lower. Other parameters also influencing HC formation include instantaneous engine power demand as well as its design.

2.1.7. Addressing the Impacts of Air Pollutants:

As a result of their high contribution to global warming and poor air quality, the UK introduced a ban on the sale of new petrol and diesel cars from 2035, which has since been brought forward to 2030, with predictions for this ban to be extended to HDVs from 2040 [41]. This ban, along with stricter emissions limits, is now forcing automakers to consider more low carbon fuels for transport.

2.2. Common Technologies for Hydrogen Production:

There are 3 common routes to produce hydrogen, with a host of others available which are lower in maturity and in the development phase, having not yet reached large scale operation. This section introduces these 3 popular routes, each of which produces a different hydrogen variation on its colour-spectrum, which is now used as an indicator of its production route, the sources of energy used, and its carbon intensity. These are:

1. Steam Methane Reforming (grey hydrogen)
2. Steam Methane Reforming with Carbon Capture and Storage (CCS) (blue hydrogen)
3. Renewable Electrolysis (green hydrogen)

2.2.1. Steam Methane Reforming:

Steam methane reforming (SMR) is the most common production method and is responsible for roughly 50% of the world's hydrogen [273]. It is popular because of its low cost and high efficiency which produces high purity grey hydrogen in large volumes for use in petroleum refining, as well as heating and transport. The process uses natural gas which is desulfurized by passing it over a chemical adsorbent before reacting it with steam at high temperatures of 800-900°C and medium/high pressures (30-40 bar) in the presence of a nickel-based catalyst, producing carbon monoxide and hydrogen (Equation 1). The reaction temperatures are achieved by combusting a certain quantity of the desulfurized natural gas in a furnace which encloses the reformer tubes. The CO by-product of Equation 1 is then reacted further with steam in a water gas shift reactor downstream of the reformer and at lower temperatures, to increase the yield of hydrogen, producing carbon dioxide as a by-product in the process (see Equation 2). Once hydrogen is produced, it is purified. This is achieved most commonly in a pressure swing absorption (PSA) unit which operates over a cycle of several flow and pressure steps to give a hydrogen product of purity high enough for use in the desired application. If for example this application is transport, the hydrogen must be at least 99.999 vol% pure in order to avoid degradation to fuel cell components. As a result, in the PSA unit, the pressurisation sees impurities bind to an adsorbent whilst hydrogen passes through leaving pure hydrogen at the outlet. Once the impurities have accumulated, the pressure is reduced, the adsorbent bed is purged and repressurised with some of the product hydrogen and impurities are fully removed.

$$\mathrm{CH_4 + H_2O \rightarrow 3H_2 + CO}$$ Equation 1

$$\mathrm{CO + H_2O \rightarrow H_2 + CO_2}$$ Equation 2

Despite its high efficiency and low costs, SMR is an energy intensive and polluting process that relies on fossil fuels, largely from the heat demand at the reformer tubes, which is met by the furnace. As a result, many industry experts oppose the use of SMR technology and view it as a way to lock in the continued use of fossil fuels in the future. Furthermore, considering the growth of the hydrogen industry, the use of SMR alone is unlikely to produce the quantities of hydrogen required for future demands predicted. As a result, the continued use of SMR is uncertain as growing pressure is being placed on industry to transition away from these sources and utilise more renewable practices that generate cleaner, greener and more sustainable hydrogen that can support net zero targets. As an alternative to grey, many people believe that blue hydrogen can offer fewer emissions, whilst also being a more economical option to green hydrogen, which can have high costs.

2.2.2. Reforming with Carbon Capture:

SMR with carbon capture and storage (CCS) is a production route which has gained notoriety in the past few years due to its lower costs compared to green hydrogen and its lower carbon emissions compared with grey hydrogen. Other blue reforming technologies of fossil fuels with CCS, such as autothermal reforming (ATR), are also expected to gain interest in the future. However currently, there are around 50 blue hydrogen CCS projects under development globally, with this number expected to increase tenfold by 2030 [287]. SMR with CCS technology produces hydrogen using SMR but captures the CO_2 using a variety of techniques; the most common industry standard being capture from the shifted syngas using absorbents such as monoethanolamine. Other methods are available which give CCS technology a CO_2 capture rate in the range of 56-90% respectively [193]. Once the CO_2 is captured it is transported by pipeline and injected into underground geological stores such as salt caverns or depleted oil and gas fields where it remains stored for very long periods of time.

CCS adapted to reforming technologies has been described by some industry experts as an intermediate route that can be used instead of SMR and as a low carbon bridging option towards green hydrogen until its costs fall to a competitive price. However, despite the reduced emissions from CCS, this route also faces scrutiny over its place in the hydrogen mix since it has yet to be proven on the large scale with very few plants currently in use. Other opponents argue that CCS still releases carbon emissions even under a high capture rate of 90%, and the CCS plants built now will likely still be in operation in 20 years, close to when net zero targets are due, effectively locking-in the reliance on natural gas and fossil fuels. There is also uncertainty regarding the security of carbon sequestration as some experts predict the CO_2 may leak from these geological stores. Furthermore, one study by [288] highlights that emissions from CCS technology can actually surpass those from burning natural gas on its own, due to the additional fossil energy requirements associated with operating the carbon capture equipment itself. Other drawbacks include methane emissions which can originate from the production of natural gas, which have a much greater contribution to global warming compared to carbon dioxide. As a result, it has been suggested that SMR with CCS is unlikely to be used for new plants in the coming years as other emerging technologies show better efficiency and economics.

2.2.3. Electrolysis:

Water electrolysis is the most sustainable production route available to produce hydrogen, provided the electricity used to power it is entirely generated using renewables [274]. This hydrogen is labelled green and uses electricity to split water into hydrogen and oxygen in an electrolyser at efficiencies of around 65%. Current hydrogen production using electrolysis is generally not as mature or cost competitive as grey or blue hydrogen, primarily due to the high cost of renewable power and so only 4% of global hydrogen production comes from electrolysis. Based on the current figures, several studies predict the production of green hydrogen will not be enough to provide for the future demand, with supplies expecting to be limited over the next several decades [288]. However, despite these shortcomings, costs are falling rapidly as renewable generation capacity and electrolyser efficiency both increase. Green hydrogen also allows countries to be self-sufficient with their energy generation, reducing reliability on imports for fossil fuels.

There are four main electrolysers used for water electrolysis. These are polymer electrolyte membrane (PEM), alkaline, solid oxide, and microbial electrolysis cells respectively. PEM electrolysis is one of the most favourable methods due to its high efficiency, high purity product, compact design, and low temperature operation. However, due to its catalyst materials which include platinum, it can be more expensive. The electrolysis process uses electricity to break down water into hydrogen, which is used as a fuel, and oxygen which can be either released into the atmosphere or stored and used for industrial processes. In a PEM electrolyser, water is pumped in at the anode where it is split into oxygen, protons (H^+), and electrons (e^-). The protons are transported across the membrane to the cathode whilst the electrons pass from the anode through an external circuit to the cathode, providing electrical energy for the reaction before they react with the protons to form hydrogen, according to the reactions below. This is also shown in Figure 2-1.

$$4\mathrm{H}^+ + 4\mathrm{e}^- \rightarrow 2{\mathrm{H}_2}^+ \qquad \text{Equation 3 (Cathode)}$$

$$2\mathrm{H}_2\mathrm{O} \rightarrow \mathrm{O}_2 + 4\mathrm{H}^- + 4\mathrm{e}^- \qquad \text{Equation 4 (Anode)}$$

$$2\mathrm{H}_2\mathrm{O} \rightarrow \mathrm{O}_2 + 2\mathrm{H}_2 \qquad \text{Equation 5 (Overall)}$$

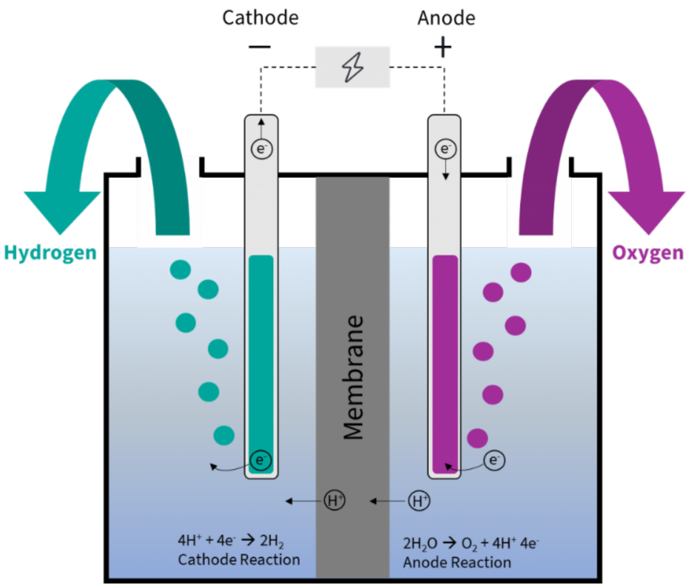


Figure 2-1 - Operation of a PEM electrolyser.

2.3. Fuel Cells and Operating Principles:

In the opposite way to electrolysers, fuel cells are devices used to generate electricity through an electrochemical reaction using hydrogen as the input fuel. It efficiently and reliably converts the chemical energy of hydrogen into electrical energy with the only outputs being heat and water. A fuel cell also does not require recharging like a battery; provided there is a hydrogen supply available, electricity can be generated. Individual fuel cells can be layered together in stacks using bipolar plates and can be easily scaled to provide the power demands required by the specific application using them, hence they offer flexibility in their applications.

The operation of PEM fuel cells is highlighted by the reactions in Equation 6-Equation 8. These are the most commonly used fuel cells for transport applications largely due to their high energy density, compactness, and rapid response times. All fuel cells consist of a membrane electrode assembly (MEA) and includes a membrane that separates two electrodes (anode and cathode) and acts as a barrier for reactant gases. The anode and cathode catalyst layers are typically made from platinum and account for a large portion of the fuel cells production emissions and costs. As a result, to avoid degradation they require hydrogen at very high purity (99.999%).

PEM fuel cells are simple in their operating principle, quiet, and efficient, and are summarised in Figure 2-2. Hydrogen enters at the negative electrode (anode) whilst oxygen from the air enters at the positive electrode (cathode). At the anode, the catalyst dissociates hydrogen into its protons and electrons via Equation 6 where the electrons flow around an external circuit to generate electricity whilst the protons pass through the permeable electrolyte membrane to the cathode. At the cathode, these protons react with the oxygen and the electrons which have passed through the circuit in Equation 7 to produce water as the only product. The overall process is summarised in Equation 8.

$$H_2 \rightarrow 2H^+ + 2e^-$$ Equation 6 (Anode)

$$\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$$ Equation 7 (Cathode)

$$2H_2 + O_2 \rightarrow 2H_2O$$ Equation 8 (Overall)

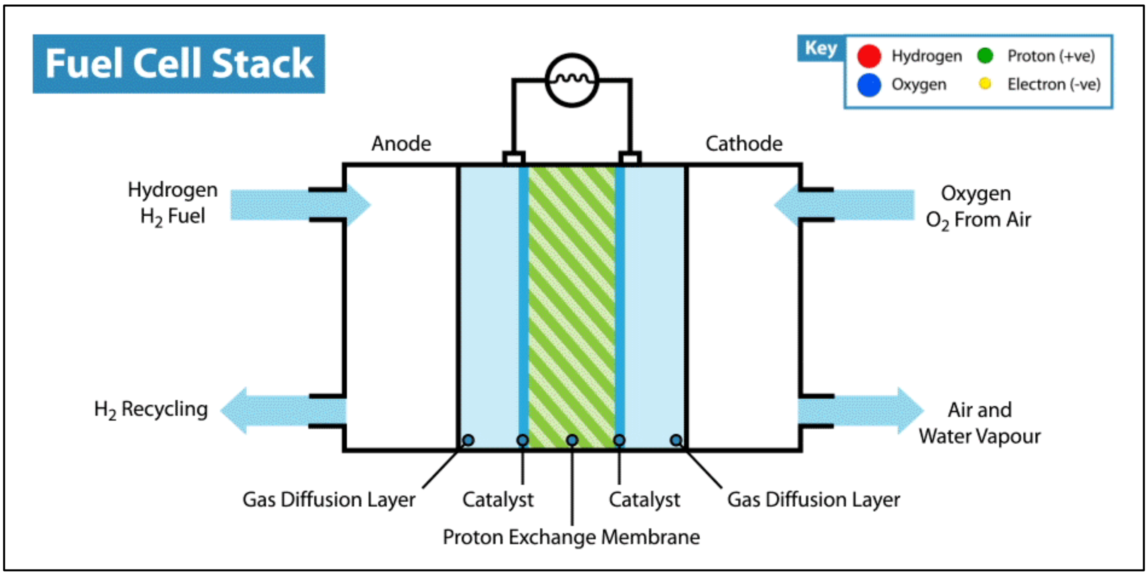


Figure 2-2 - Basic operation of a fuel cell.

Despite PEM fuel cells currently being the most commonly used in transport, there are a range of fuel cell chemistries available, a few of the most common are shown in Table 2-1. Typically, fuel cells are classified based on their electrolytes which impacts the operating characteristics and the applications they are best suited for. In the table, each fuel cell type is briefly outlined with some of their pros and cons.

Table 2-1 - Summary of some common fuel cell types.

Type:	Applications:	Electrical Efficiency:	Pros:	Cons:
Polymer Electrolyte Membrane	Backup Power, Portable Electronics, and Transport	60%	• High power density offers light weight and small size. • Robust construction. • Easily scaled up so has potential to be used in a range of applications. • High efficiency and low temperature. • Fast and dynamic response well suited for transport. • Low corrosion due to solid electrolyte.	• Platinum supply chains are energy intensive. • Expensive due to the precious materials used (catalyst). • Durability issues.
Solid Oxide	Heat and Power, Distributed Generation	60%	• High efficiency. • Flexible with regards to fuel type.	• High temperatures can lead to corrosion and component deterioration. • Long start up times.
Alkaline	Transport, Backup Power, Space	60%	• Wide range of stable materials allows low costs to be achieved. • Low operating temperatures. • Fast start up times without pre-heating.	• Uses a liquid electrolyte which requires more attention. • Sensitive to CO_2 in fuel and air so requires pure reactants. • Purification processes add additional costs.
Phosphoric Acid	Utilities, Distributed Generation	40%	• Suitable for CHP. • Higher resistance to fuel impurities. • Stable and mature technology.	• Lower efficiency. • Expensive catalysts. • Long start up times. • Less powerful than other options.
Molten Carbonate	Utilities, Distributed Generation	50%	• Flexible fuels. • Suitable for CHP. • Efficient solution.	• Highly corrosive. • Slow response time. • Low power density.

The major fuel cell components are covered in detail later in Chapter 5.

2.4. FCEV Market Overview:

Globally in 2020, FCEVs made up a minute share of the total vehicle stock (<0.01%), and only 0.3% of the total electric vehicle stock. However, despite this, FCEVs showed record year-on-year increases in sales of 82% sparked by technology developments in regions like Asia and the US and by substantial financial discounts and government support [289]. By the end of 2020, FCEV numbers worldwide reached roughly 35,000 with the majority in Asia (65%), 27% in the US, and only 8% in Europe [290]. However, when considering BEVs and plug-in hybrid EVs which sold 4.6m and 1.9m in the same year, these FCEV sales figures are less than impressive [63]. In terms of the vehicle mix making up FCEV sales, light duty passenger cars dominated and accounted for approximately 75%, whilst HDVs like buses and trucks made up only 16% and 9% respectively [290].

From Figure 2-3, by June 2021 the largest users of FCEVs were Korea, the US, and China, with Europe having a small portion of ~4,000 FCEVs on the roads. The small market size of FCEVs is seen even more clearly in the UK which offers only two FCEV car models and 14 refuelling stations, failing to offer consumers much variety when purchasing a new vehicle and failing to instil confidence in the refuelling availability for drivers carrying out longer journeys. Although there are a number of FCEV prototypes in development targeting HDV applications and a number of FCEV fleets already in operation, numbers are significantly lower than their BEV equivalents. This is supported by the fact that the vast majority of FCEVs currently in use are in LDV applications and only a small fraction are used for HDVs, which is where the majority of their advantages are seen. Recent market data could not be sourced for the UK but in California where there is a more established FCEV market, approximately 13,500 FCEV cars were sold or leased by April 2022 and only 66 FCEV buses were in operation with 76 more in development [291]. There were also only 3 FCEV truck refuelling stations in operation which highlights the current size of the FCEV HDV market, which is predicted by many to be the most suitable application for this technology in the transport sector, discussed in the next section respectively [291].

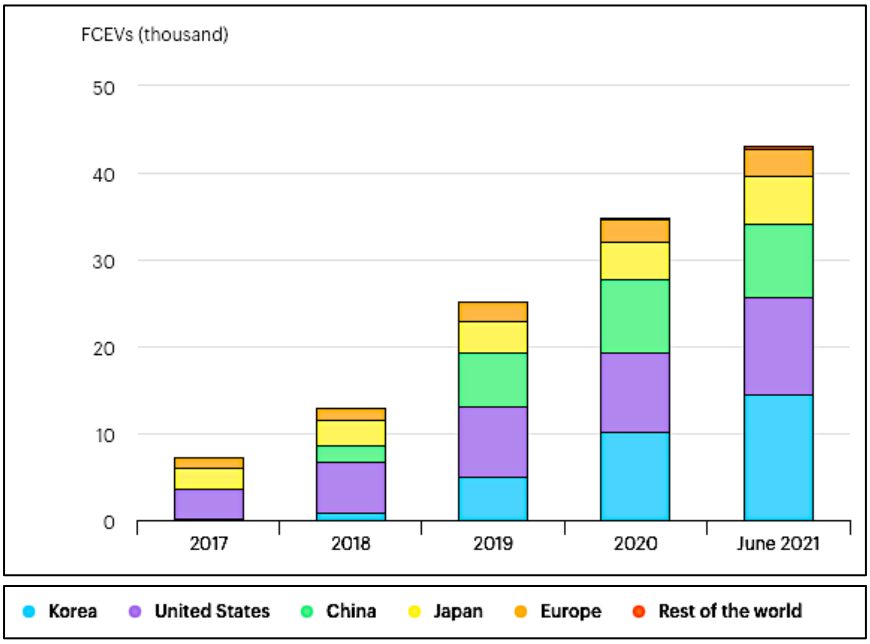


Figure 2-3 - FCEV stock by region (2017- June 2021) [289]

Despite the current lack of FCEVs in LDV and specifically HDV applications, increased fuel cell production volumes and falling hydrogen production costs are expected to support the increase in their numbers on the market. In addition, the stringent emissions regulations as a result of net zero and the upcoming ban on new petrol and diesel vehicles will also likely play a contributing role. Both governments and private sectors are investing heavily in fuel cell technology, introducing more prototypes and transitioning fleets to hydrogen, and as markets grow, their supply chains will also develop further. In Figure 2-4 the total global fleet of ZEVs is shown and was roughly 600,000 in 2015 increasing rapidly to 8.5m by mid-2021 with expectations to increase exponentially. For the FCEV market, in 2021 it was valued at $4.98bn and forecasts now predict this to grow to $35.6bn by 2030 [292].

The number of HDVs using hydrogen is also predicted to surge as these are the applications which battery technology currently fails to deliver on [323]. For example, the market for HDVs in the UK is approximately 50,000 per year which is predicted to increase 10% by 2030. In the EU, this number is 320,000 and roughly 45% is attributed to long haul trucks which have high range demands and are currently unsuitable for battery use. In addition, the National Composites Centre [293] suggest battery technology alone is not enough to achieve the net zero targets on time and other zero carbon technologies are needed, especially in the case of high duty-cycle HDVs which are disproportionately high in their emissions. They also forecast the FCEV market share to be around 15% of the total HDV market by 2030 in the EU, equivalent to 60,000 vehicles each year. However, this is not without restraints as the expensive and currently limited infrastructure requires more funding support, public acceptance remains uncertain with many still viewing hydrogen as a dangerous fuel, and the existence of a booming and ever-improving BEV industry is a direct competitor to the success of FCEVs.

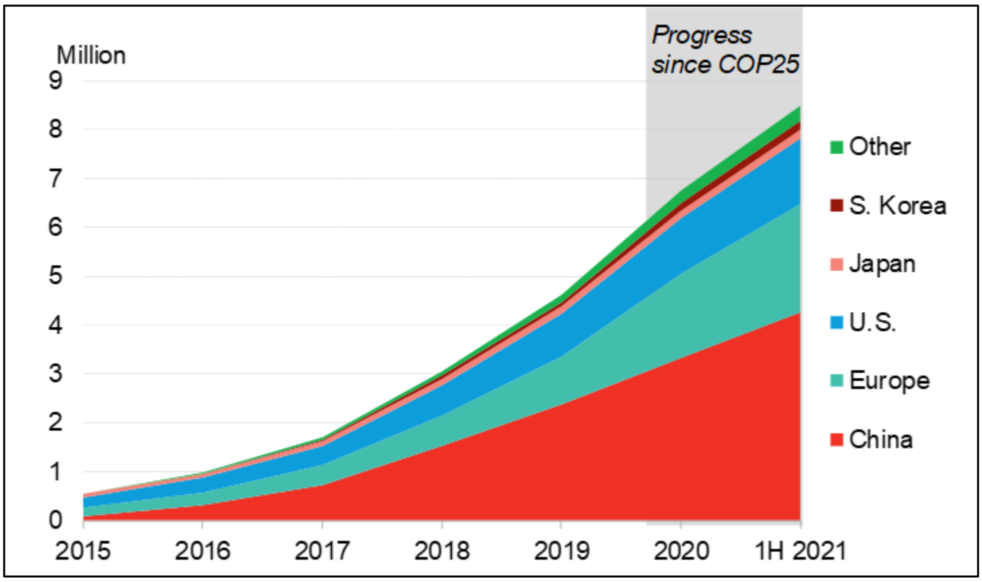


Figure 2-4 - Global fleet of ZEVs (pure BEVs and FCEVs) from 2015-2021.

2.5. Zero Emission Vehicles for Heavy Duty Applications:

The number of BEV sales far exceeds those of FCEVs due to the time that BEVs have been on the market, giving them a head start and leading to a more extensive and developed infrastructure. As of 2022 the UK has approximately 14 hydrogen refuelling stations compared to an extensive network of electric chargers scattered around the country, making it much easier for these vehicles to operate and minimising the range anxiety experienced by drivers during earlier uptake periods. This is something that some current FCEV drivers still experience which negatively impacts sales. However, although electrification currently dominates the ZEV market and provides an effective means of decarbonising the light duty vehicle (LDV) sector, which is characterised by low range demands and small battery requirements, Yan *et al.* [168] highlights that this solution still lacks the technological advancements needed for the high load capacities and long range demands of HDVs.

The issues limiting widespread BEV use in HDV applications include weight compounding and material shortages. Li *et al.* [4] highlighted some of the advantages of FCEVs over BEVs with regards to HDVs; namely fast refuelling, a range similar to ICEVs, and sustained operation under extreme weather conditions without losses in efficiency. Despite their extensive charging network, Gray *et al.* [282] highlight that many of these chargers have relatively low power as they are made primarily for light duty passenger car use with small battery packs. The use of these chargers by HDVs with larger batteries could lead to increased downtime which may show negative impacts on fleet provision and productivity, and it could put pressure on local electrical grids, rendering upgrades. This can potentially lead to more vehicles being needed to fulfil the same duty, which ultimately increases emissions and costs further and offsets any savings from using them in the first place. Other approaches have been proposed for the electrification of HDVs, such as electric road systems in which batteries are charged during vehicle operation. However, these technologies are much less mature with low commercial readiness levels.

Considering Tesla's best battery packs with an energy density of 260 Wh/kg, the weight of the battery for the high duty cycles of HDVs is too great [5]. For example, some heavy duty electric trucks by Daimler weigh ~1400-1800 kg more than their conventional diesel equivalents, which is attributed largely to their batteries [37]. As weight increases to provide a range competitive with diesel, so does the weight for extra structural support, leading to compounding making them unsuitable for HDVs. As shown by Gray *et al.* [282], this increased weight can reduce the available payload capacity of the vehicle meaning it cannot perform the same functions as one powered by diesel or hydrogen, for example. This is less of an issue in LDVs which have lower range demands, but no issue for FCEVs using compressed hydrogen with a high energy density. For FCEVs, increases in range can be easily compensated by basic vehicle adaptations, though they still rely on critical materials like platinum for fuel cell electrodes. BEVs also rely on costly materials like lithium and scarce ones like cobalt (which are listed on the 2020 EU Critical Raw Materials List) for their manufacture. The European Commission [38] also highlight that in order to supply the EU economy in 2030 for BEVs and energy storage, approximately 18 times more lithium and 5 times more cobalt is needed. Since ~64% of the world's cobalt is currently sourced from the Democratic Republic of Congo using unsustainable practices, this could potentially cause supply chain issues in the future.

Despite the downsides of BEVs mentioned, there are other areas for debate surrounding hydrogen use, such as its limited availability due to a current lack of refuelling infrastructure, which is a big obstacle for its uptake in automotive applications and one of the reasons why there are so few FCEVs on the current market. In the LDV sector there are only two FCEVs available on the market: the Toyota Mirai and the Hyundai ix35. Even in the HDV sector where hydrogen is more suitable there are still very limited fuel cell vehicles available to purchase. However, prototypes are in development including a refuse collection vehicle by Ballard and the GenH2 long haul truck by Daimler which aim to be on the market very soon. To accelerate the development of FCEV HDVs, the government has also launched a number of schemes and competitions aimed to help promote the roll out. One of these was the FCEV Fleet Support Scheme which included a £2m fund aimed to encourage fleets to transition to FCEVs by covering up to 75% of the purchase cost of a new vehicle.

Since refuelling accessibility is one of the major barriers in the early uptake stages, back-to-base (B2B) applications can ensure a consistent hydrogen demand is maintained. B2B and HDV fleet applications appear at the moment to be the most suitable applications for FCEVs. Examples of these fleets include StreetDeck FCEV buses which operate around the cities of Aberdeen, London, and Birmingham and refuel at a designated filling station close to their base. Other examples of B2B fleets are those transporting passengers and goods at airports, such as shuttle buses, for example. These fleets offer a simple solution to this refuelling infrastructure problem experienced in the LDV and public sectors.

2.6. Economics of Hydrogen Transport:

In addition to environmental benefits, the introduction of low carbon fuels in heavy duty transport also needs to consider the economics of a transition. Total cost of ownership (TCO) is one of the most useful pieces of information required by fleet owners and operators which can greatly influence their decision to switch from conventional fuels like diesel to more low carbon alternatives. In order for these solutions to be considered, they must offer costs that are at least consistent with current technologies. Currently, the biggest roadblocks in the way of these transitions are associated with the higher purchase costs of zero emission vehicles (ZEVs) and their associated infrastructure. As a result, it is of great importance that economic models and accurate cost estimations are made and reviewed to gain a better understanding of their potential as a transport fuel for HDVs.

Since FCEVs are still relatively under-developed in the transport sector and numbers remain low due to high costs, limited infrastructure, and technology lock-in, it is important that actions are taken in the early adoption stages to make hydrogen cost effective and affordable for fleet owners and private users. A lack of literature investigating the costs of low-carbon powered HDVs is outlined by Alonso-Villar *et al.* [294], in contrast to a wide coverage of alternatively fuelled LDVs. Recommendations are made for more attention to be placed on assessing the performance of HDVs in terms of all costs, emissions, and efficiency. Demeulenaere *et al.* [7] investigated the potential of fleet environments to support the diffusion of these alternative fuel vehicles and outlined these are often chosen as early adopters because they give quick insights into their operation and barriers to their implementation. Often these vehicles are characterised by high mileage, central or back-to-base refuelling, and predictable duty cycles. Taking this into account, increased FCEV deployment could be achieved through the conversion of captive fleets which cannot easily switch to BEVs and where vehicles provide a consistent hydrogen demand.

The TCO study by Li *et al.* [4] based in Southeast Asia (SEA) on FCEV road vehicle fleets of cars, buses, and trucks showed FCEVs were the least cost-competitive in forecourt and centralised production compared to BEVs, PHEVs and ICEVs. BEVs were the most competitive for all vehicle types except for passenger cars where ICEVs dominated. Thailand's low tax rates contributed towards a lower TCO than other SEA countries, and a high renewable energy system (RES) adoption promoted the use of ZEVs. In a future scenario which modelled a 50% reduction in fuel production cost, FCEV CAPEX, and distribution cost by 2030, the TCO of FCEV cars and buses fell below ICEVs, but not for trucks. BEVs remained more competitive than FCEVs due to the likelihood of future battery developments and falling prices. Similar findings were found in the work from Gray *et al.* [282] who conducted a TCO on trucks fuelled by both electricity and hydrogen, comparing results to a diesel baseline. Results showed that BEV trucks had significant savings over diesel despite higher purchase prices in the early years of uptake. These savings increased further in the future as costs continued to fall. For FCEV trucks though, costs did not show parity with diesel, largely due to higher fuel costs in addition to the high purchase costs. It was found the TCO was most sensitive to fuel costs and in order for FCEVs to reach parity with diesel, both the electrolyser efficiency and total electrolysis costs needed to improve. It was shown that FCEV TCO would only fall below diesel under a hydrogen price of €4/kg.

In contrast to the studies mentioned, [8] investigated the cost competitiveness of 3 FCEV trucks and found FCEVs were cheaper than BEVs per km. Each of the 3 FCEV truck segments showed great potential for cost reduction and economies of scale were vital between 2023-2030. Although these vehicles were 11-22% more expensive than diesel per km in 2023, they were cheaper than BEV trucks and showed promise of competitiveness with diesel by 2030. TCO was lower for long and medium haul FCEV trucks compared to BEVs, highlighting their advantage in high range scenarios. Large battery requirements also showed a negative impact on payload and productivity, with BEV trucks not expected to be competitive with diesel in 2030. These findings also align with the study by Lajevardi *et al.* [295] who report a TCO 22-66% higher for BEVs compared to diesel, due to costly battery packs. The impact of battery costs was also reported by Sharpe *et al.* [57] who provided an overview of the purchase costs for ZEV trucks and found that FCEVs generally have lower costs than BEVs due to the fact that BEV costs are dominated by the battery which is impacted largely by the driving range. The impact of high battery manufacturing and replacement costs was also highlighted by Sen *et al.* [77], who also found it led to a significant increase in BEV TCO as a result. A similar study was carried out by Oostdam *et al.* [10] who highlighted the high contribution of fuel costs on TCO. In this work, 7 hydrogen routes were considered but had a negligible impact on the TCO, leaving no preferred solution as they remained similar in range to diesel. They concluded FCEV trucks can be economically feasible but are strongly influenced by hydrogen price and vehicle CAPEX; two factors that were also highlighted by Gray *et al.* [282], expanding further to highlight the biggest cost contributors for the vehicle costs were the fuel cell and storage tanks respectively.

The Hydrogen Council [9] studied 3 FCEV bus applications (150km urban, 450km urban, and 500km coach buses) and compared them to BEVs and ICEVs from 2020-2050. FCEVs showed a higher TCO initially in all cases, but costs fell and reached parity with ICEVs by ~2025. This is similar to work from Morrison *et al.* [6] who highlights rapid cost reductions in FCEVs due to economies of scale. The TCO of FCEV buses in this study fell below BEV buses sooner in high range applications. However, local conditions greatly influence the suitable applications as electricity cost and infrastructure accounted for ~27% of the TCO. Similarly, Jones *et al.* [11] studied FCEV competitiveness against BEVs and ICEVs in UK urban logistics. The TCO of the ZEVs was particularly sensitive to mileage due to low operating costs. BEVs became more competitive than ICEVs once exceeding an annual mileage of 17,000 miles and electricity from renewable energy had little effect on competitiveness. This mileage influence did not extend to FCEVs using hydrogen, though the impact of congestion charges and an ultra-low emission vehicles (ULEV) grant had a big effect on the incentivisation of ZEVs. The minor impact of renewable electricity encouraged more renewable hydrogen generation in the future.

Although the vast majority of TCO studies focus on on-road vehicles, one study has recently been published in late 2022 aiming to target this gap. Gunawan *et al.* [283] conducted a TCO on off-road quarrying trucks using FCEVs and BEVs. They highlighted some of the factors influencing the suitability of on-road and off-road vehicles to different powertrains. For example, many off-road vehicles operate for long hours with a lower accessibility to refuelling infrastructure compared to on-road vehicles which have infrastructure along many of their major roads. This restriction favours FCEVs for off-road applications since they offer a longer range before refuelling is required. In contrast, the more accessible infrastructure along motorways enables BEVs to be used in more heavy duty on-road applications as recharging can be done frequently meaning they can use smaller batteries, for example.

After reviewing the published literature, the vast majority of studies surrounding the economics of ZEVs focus on passenger cars because these are the most common vehicle modes, they are often the first and easiest to transition, and they are responsible for the biggest portion of transport emissions. The majority of TCO studies that do consider HDVs are focused on buses or trucks, with very few considering a wider range or a mixed fleet of vehicle types, indicating a limitation which this work aims to address. Also, since the most common HDVs transitioning to ZEVs are road vehicles, even fewer of these studies considered off-road vehicles, highlighting another gap which this work aims to fill further.

Reviewing existing literature highlights the variability of FCEV TCO when compared to other powertrains and shows how the modelling conditions and underlying assumptions play a major role in whether or not they are cost competitive. Several of the studies reviewed in this section suggest FCEVs are more economical than BEVs for HDV applications in terms of TCO, whilst some disagree and highlight that this can only be achieved in future years or with the aid of financial incentives. Li *et al.* [4] highlights the impacts of such tools and reports in general the TCO of FCEV cars, buses, and trucks are not yet cost competitive with ICEVs or BEVs under standard conditions. However, after the addition of a financial subsidy in the case of cars, they become competitive with all powertrains. This is not only the case for FCEVs however as Jaller *et al.* [303] conclude that financial incentives are also required in some cases for BEVs to achieve a TCO lower than diesel, again highlighting the sensitivity of TCO analysis to the modelling conditions used.

2.7. Fuel Cell Vehicles and the Environment:

As countries commit to sustainability targets like net zero, more companies are being urged to use life cycle assessments (LCAs) as an analysis tool to gain a better understanding and to clearly report their environmental impacts. These are becoming more commonplace in industry with companies having dedicated sustainability teams working towards improving their carbon footprint. For example, in the transport sector, studies have been conducted focusing on the emissions from both the fuel and vehicle cycles. Now, since the emergence of electric vehicles and other low carbon transport fuels like hydrogen, LCAs have become an even more useful tool for comparing the different options available, providing a holistic view of their environmental impacts and identifying the hotspots along the fuel supply chain and the vehicles lifetime. Different transport fuels emit various quantities of emissions across the life cycle which can make it difficult to identify which option is the cleanest overall. For example, BEVs have zero emissions at their tailpipe (i.e. zero use phase emissions) but can have a higher energy intensity overall due to their more complex upstream fuel and/or vehicle supply chains compared to ICEVs, such as the sourcing of their battery components and the electricity they use.

The International Council on Climate Change [144] report that BEVs generally have lower use phase emissions compared to ICEVs due to the increased efficiency of electric motors and the ability to utilise low carbon electricity. This is a conclusion shared by many other authors including Gray *et al.* [282] who conducted a well-to-wheel (WTW) LCA on BEV and FCEV trucks against a diesel baseline. In this work it was found that even under a high energy intensity grid mix, BEV trucks led to 50% fewer WTW emissions compared to diesel, whereas FCEVs led to an increase in emissions due to their lower efficiency. This study did however omit emissions associated with vehicle production and end-of-life stages which are significant contributors and can greatly impact results. Despite these findings and as a trade-off to their higher efficiency, BEVs are known to have higher manufacturing emissions due to their battery components. These emissions will be highlighted later in this section respectively. As a result, the inclusion of this vehicle production stage could influence the conclusions of the study and therefore presents a great limitation which should be acknowledged.

Wong *et al.* [76] compared the light duty Toyota Mirai FCEV car (using hydrogen from both SMR and renewable electrolysis) and the Tesla Model 3 BEV and found the fuel cycle contributed greatly to total emissions in both cases. Since use phase emissions are zero for ZEVs, the method of fuel production was very influential to overall emissions, particularly for hydrogen. ~70 kg CO_2 was released from producing one tank of hydrogen using SMR technology, compared to only ~12 kg CO_2 from renewable wind electrolysis. For ICEVs and PHEVs, the equivalent emissions were ~36 kg CO_2 and ~21 kg CO_2 respectively, highlighting better sustainability in their production. However, if there are climate policies in place and sufficient renewable sources available to enable widespread electrolysis, this will help to give FCEVs a competitive edge in terms of their environmental impact, though this is dependent on the countries geography and energy mix. These findings align with other studies from Sen *et al.* [77] and Petrauskiene *et al.* [78] who found emissions of BEVs are also highly dependent on the source of their electricity but can offer significant improvements to emissions and air quality if renewable sources are used.

Petrauskiene *et al.* [78] found BEVs using grid electricity in 2015 had the highest global warming impact compared to gasoline and diesel ICEVs and PHEVs, with the use phase accounting for 60% of the total emissions, though this figure fell by 60-78% with a low carbon future electricity mix for 2020-2050. BEVs also had the highest CO_2 emissions from the end-of-life stage due to the complex battery treatment procedures required. Many of these studies faced limitations however, focusing only on LDVs and giving no insight into the emissions from battery manufacture, which is known to be a significant contributor.

In terms of HDVs, Gabriel *et al.* [79] compared the entire life cycle emissions of diesel and electric passenger bus fleets in Thailand and found electric buses were kinder to the environment across all impact categories, with a ~55% decrease in total damage to human and ecosystem health, with potential to achieve higher reductions using a cleaner gas grid. Electric buses had higher environmental impacts across all categories for their production compared to diesel counterparts, whilst the end-of-life phase contributed relatively little in comparison to production and use phases. This small contribution from the vehicle EOL phase was also highlighted by Ellingsen *et al.* [311] respectively. Similar to the other studies, Sen *et al.* [77] compared life cycle emissions from battery electric and diesel class 8 heavy duty trucks, including vehicle production and use phases, and found the impact of the electricity production was greatest for BEVs (contributing ~70% of the total) as results concluded that the use phase was the dominant contributor to overall emissions for both powertrain types. For BEV trucks, the high environmental load from electricity generation offset their zero emission operating advantages. However, despite this and their intensive battery production, they still gave lowest emissions overall compared to ICEVs. Marmiroli *et al.* [80] reviewed over 44 LCA studies and found only 3 which investigated vehicles that weren't cars, highlighting a potential gap that could be targeted further. Their study showed in the vehicle production phase, BEVs in LDV urban freight applications had the highest emissions in every impact category compared to ICEVs mostly due to the battery and electrical components. BEV advantages were said to be still under review as these give higher environmental emissions, though are balanced by their higher efficiency during the use phase and depend on the electricity mix used. If BEVs are to be used extensively for the transport of goods, then improvements in production technologies and a renewable-based grid is needed.

Several analyses on BEV life cycle emissions highlight that in addition to the electricity generation, the lithium-ion battery supply chain is one of the most energy intensive stages in its life cycle. For example, similar to other BEV emission studies mentioned, Alaswad *et al.* [84] highlights the strong influence of the vehicles fuel source on life cycle emissions which can largely impact the competitiveness of the powertrains, with electricity sourced from natural gas being more energy intensive than hydrogen from SMR using natural gas. The study also pointed to life cycle emissions from BEVs being higher than FCEVs due to the significant demand for battery materials required compared to fuel cells for a given range. A range of estimates from the ICCT [144] suggest that battery production is responsible for 56-494 kg CO_2 per kWh of battery capacity, depending on the methods of the study, the electricity mix, and the battery chemistry, for example. However, since these batteries retain high portions of their original capacity after use in a vehicle and are suitable for reuse in secondary applications, battery lifetime and total usage are increased which saves energy from the extraction of virgin materials. For example, use of second-hand batteries for energy storage can lead to emissions savings compared to more devoted solutions. Despite these factors, batteries still rely heavily on materials like lithium, nickel and cobalt that are scarce, and a lot of energy is required to provide hot and sterile conditions during the mining, conversion, and refining processes. They also demand lots of electricity for manufacturing and so the source of electricity has a large impact on the production emissions. The ICCT [144] state that the electricity used for battery manufacturing accounts for ~50% of the total emissions associated with battery production, and the importance of using renewable electricity is key to reducing BEV emissions further in the future. Similarly, Melin *et al.* [81] suggests that as much as 75% of the total energy consumption comes from the manufacture of the battery cells, with the remainder attributed to the battery management system and the battery pack. This is further supported by results from Dai *et al.* [82] which showed the cathode materials, aluminium, and cell production are the largest contributors to the environmental load of lithium-ion batteries. The battery life cycle energy consumption is split into the following stages below and shown in Figure 2-5:

1. Mining and extraction of the active materials. Nickel, manganese and cobalt are processed and converted into sulphates and lithium compounds which can account for ~20% of the cell’s energy demand, depending on the specific battery chemistry.

2. Conversion of the lithium compounds (lithium carbonate or lithium hydroxide) into cathode powder. This can represent ~27% of the energy demand.

3. Modelling from Wong *et al.* [76] also suggests other components like the anode, binder, current collector, separator, and electrolyte contribute ~27%.

4. The remaining ~25% is mainly attributed to the drying and heating processes which are required for the actual cell production.

Other studies offer more general estimates for the greenhouse gas emissions from cell production at 70-110 kg CO_2e/kWh and 60-70 kg CO_2e for the production, mining, and processing of the materials respectively [81].

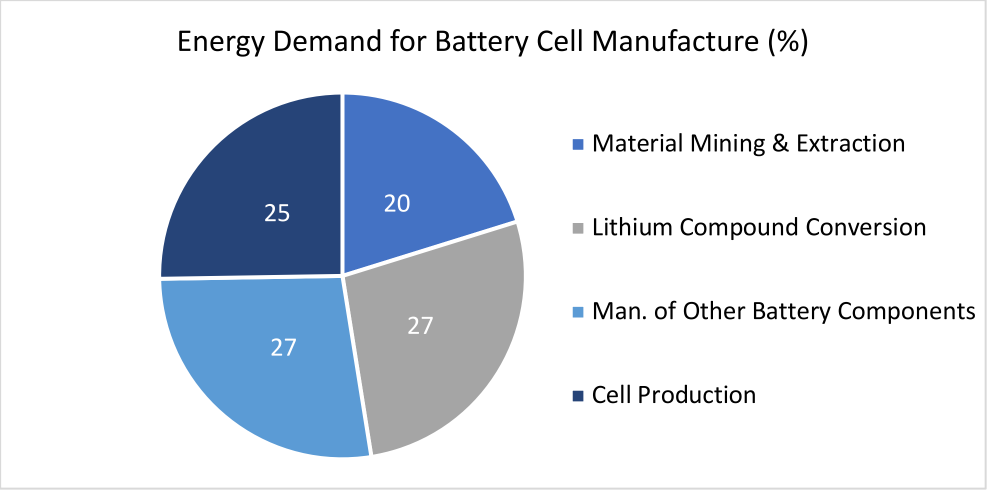


Figure 2-5 - Sources of energy demand for the manufacture of battery cells.

For the battery pack, the majority of the energy is associated with aluminium, and assembly accounts for the majority of the remainder. Aluminium is the material of choice due to its light weight, which is important for batteries, but the trade off to this is the energy for sourcing and processing is high. Studies have suggested the emissions associated with pack manufacturing are approximately 140 kg CO_2e/kWh [81].

Fewer studies in literature focus on the environmental impacts from FCEVs. This is supported by Lee *et al.* [83] who report scarce work focused on the LCA of FCEV heavy duty vehicles, highlighting a much larger collection of studies considering electric powertrains. This is because the technology is less widespread, partly due to its refuelling infrastructure compared to battery powered vehicles and their charging stations. As a result, the current FCEV market is small, and heavy-duty and off-road FCEVs are in use only in a select few transport applications, including city buses and forklifts. However, there are other vehicles in the demonstration phase which are expected to reach commercial scale in the coming years; including hydrogen excavators by JCB, refuse collection vehicles by Ballard, and trains by Porterbrook. For this reason, it is important that the environmental impacts of FCEVs are compared with BEVs and ICEVs to identify strengths and areas of environmental concern which can be minimised to successfully decarbonise all areas of transport and enable net zero targets to be reached.

In the case of FCEVs, Stropnik *et al.* [86] investigated the environmental impacts resulting from the fuel cell supply chain and found that the majority of the impacts came from the rare earth metals. LCA results for a 1 kW fuel cell system showed the stack contributed most towards manufacturing emissions since this required the majority of the precious metals, like platinum for its catalysts, which emitted harmful sulphur oxides during extraction. For example, to produce 1 kW of a PEM fuel cell, approximately 0.75g of platinum is needed which contributes ~60% to the total manufacturing emissions. However, impacts could be reduced if increased efforts are placed on the critical materials used and the use of proper recycling techniques at the fuel cells end of life. Other studies also highlight the lack of variation with regards to the emissions considered in the analysis, with global warming being the focus of the vast majority of these and air pollutant emissions being much less commonly investigated, despite being of increasing relevance and importance to transport operations in recent years [294].

After a review of the literature, similar to the TCO studies covered, the majority of work to date focuses on LDVs, with fewer studies examining HDV applications. The scarcity of current literature surrounding this topic was also highlighted by Gray *et al.* [282]. Candelaresi *et al.* [85] found that passenger cars operating on green hydrogen significantly reduced emissions across the fuel cycle, with vehicle infrastructure the highest contributor in all impact categories. FCEVs also had the highest emissions in terms of acidification potential out of all powertrains considered, largely due to the steel-based glider, carbon fibre for the fuel tank, battery components and the rare metals like platinum required. In fact, the vehicle production emissions in all impact categories were lower for ICEVs compared to FCEVs which highlights the need for increased low carbon steel production, alternative hydrogen tank materials and battery configurations, and platinum alternatives, for example. The large impact of the electricity mix on hydrogen compression and liquefaction processes was highlighted by Lee *et al.* [83] who compared FCEV and ICEV technology for use in heavy duty trucks. However despite this, FCEVs utilising hydrogen from SMR reduced petroleum use overall by 98% and greenhouse gas emissions by 20-45% respectively. This impact of electricity mix and hydrogen production route on the life cycle emissions was also covered in the work by Zhao *et al.* [307] who highlighted that these factors have a significant impact on the emissions reduction potential seen by FCEV use.

Many of the LCA studies covered in literature focus on one vehicle type only and fail to consider multiple zero-emission fuels and powertrains. The majority of studies to date focus either on BEVs as a means to decarbonise the transport sector or compare these BEVs to existing transport modes. Often, either low or zero emission powertrains are compared to conventional versions and their impacts are analysed. However, BEV and FCEV solutions have only begun to be compared directly over the past year or two, with gaps still present in the research. These studies are growing in number due to the rapidly evolving nature of the technology in alternative transport leading to growing markets and an increased push towards low carbon fuels by government policy, banning the sale of petrol and diesel vehicles in several countries including the US and Canada, the EU, and the UK. However, most of this work is still focused on the light duty sector.

2.8. Research Aim and Objectives:

The aim of this study and the overarching research question is to understand the suitability of a mixed fleet of heavy duty on-road and off-road FCEVs from an environmental and cost of ownership perspective and compare results to BEV and ICEV equivalents.

To help achieve this aim, the costs of owning and operating vehicles are estimated from the perspective of a fleet owner whilst environmental impacts are assessed both from a general perspective over the entire vehicle lifetime as well as from a fleet owner perspective under a specific operating period in a fleet. Estimates are therefore generated using both a generic mileage scenario and a fleet-specific mileage scenario using real mileage data collected from captive fleets based in the North of the UK. As a result, the novelty of this work lies in the integration of a much wider range of on and off-road heavy duty vehicles that can be scaled to meet demands for different fleets. Vehicles include city buses, long haul trucks, tippers, refuse collection vehicles and forklifts, alongside light duty passenger cars. This work considers the potential of hydrogen and fuel cell technology as a key enabler in the cost-effective decarbonisation of transport in the UK specifically and examines the feasibility of FCEV deployment in heavy duty off-road transport fleets, whilst also offering flexibility to allow similar insights to be generated for other regions, respectively.

The findings could be of interest to policymakers and fleet owners and could support the creation of successful business models to encourage and accelerate FCEV uptake, especially for transport modes currently dominated by diesel. The government estimated the UK currently has around 300 FCEVs in operation, though the majority of these are in the LDV sector [275]. Despite some FCEVs being used in bus fleets, there is still a huge portion of HDVs relying on diesel as there are very few alternative solutions suitable and available. This presents a great opportunity for a transition and leaves an area of unexplored potential available for research.

Considering the information outlined, this project aims to address the following research questions:

1. *Which parameters have the biggest influence on FCEV costs and emissions, and how does varying them alter FCEV competitiveness?*

2. *Can hydrogen offer a cost competitive solution to conventional fossil-based transport and how does it compare to electric vehicles?*

3. *Under what conditions will FCEVs become the most cost competitive transport solution, and how might their economics change between now and 2050?*

4. *Do FCEVs offer a significant benefit in terms of life cycle emissions compared to conventional diesel vehicles, and do they compete with electric vehicles both now and in the future?*

5. *How do the emissions from FCEVs compare when considering vehicle usage in one specific fleet?*

To support the overall aim and the research questions, the following objectives have been proposed:

- Analyse operating data from a selection of fleets in the North of the UK containing both light and heavy duty on and off-road vehicles. This real data can be used as a representation for the average vehicle mileage in UK fleets and as a realistic basis for economic and environmental calculations from the perspective of a fleet owner.

- Propose and develop a methodology to compare the ownership costs and environmental emissions of FCEVs, BEVs, and ICEVs under a present-day baseline scenario. (RQs 2 and 4)

- Investigate which input parameters have the greatest impact on the economics and emissions of fleet vehicles. Use this insight to analyse how modelling conditions can influence results and determine specific conditions under which FCEVs are most competitive. (RQs 1 and 3)

- Impose varied parameters into the environmental assessment and evaluate their impact on future FCEV competitiveness. (RQ 4)
- Develop and improve the base case methodology to focus the analysis and estimate the total emissions of vehicle ownership associated with a single fleet use case. (RQ 5)

3. Chapter 3 – Baseline Conditions

This chapter highlights the foundations of the study which are used within the methodologies of the economic and environmental assessments to generate their results. This aims to avoid repeating overlapping discussions in Chapters 4-8. First, an overview of the vehicle fleet composition is provided, covering the vehicle types and their models and specifications. This is followed by the vehicle's mileage scenarios, including the sources of mileage figures, the daily driving distances, and their fuel/energy consumption. Lastly, the fuel scenarios included in the assessment are presented, with extended details provided in later chapters, respectively.

3.1. Vehicle Types Considered:

The vehicles considered in this study are divided into on-road and off-road vehicles, where off-road vehicles are defined as those used for construction which have earth-moving functions. As a result, only forklifts in this vehicle stock list are considered off-road vehicles.

When selecting which vehicle models to include, the options chosen aimed to have as similar performance and specifications as possible to ensure fair comparisons between each of the 3 powertrains. The characteristics which were monitored included kerb weight, payload capacity, and vehicle power respectively. However, for some vehicles this was not possible as their technical data was unavailable and they face a severe lack of models currently available on the market, presenting a limitation which should be acknowledged. For example, the FCEV market for passenger cars is very limited with only two models available. There are even fewer models of fuel cell trucks, tippers, RCVs, and forklifts on the market in the UK, despite prototypes being developed. As a result, technical data for these vehicles is sourced from manufacturers where possible and estimated (shown by *) using other relevant data to fill any gaps. Although some inaccuracies are expected in the results due to the unknown specs of ZEVs still in their early stages of development, results still offer a valuable insight into the economic and environmental impacts and their sensitivities. Nevertheless, caution should be taken when comparing these results to other studies as their assumptions and boundaries may differ.

One assumption made for all HDVs (except forklifts) is that their payload capacity is the same regardless of powertrain. Often for BEVs their batteries add significant weight which can reduce the available payload capacity, hindering vehicle productivity. However, for simplicity, this work assumes an equal carrying capacity for all powertrains. Although payload losses may be present in some existing BEVs, these are being reduced due to improvements in energy density and space optimisation [264]. In addition, in this work the transport of deliverables and vehicle productivity is not the focus. The focus is to compare costs and emissions from different fuels and powertrains over the designated time periods, under a fuel consumption corresponding to full load operation, whatever that load might be. As the aim is not to assess costs and emissions over a specific number of deliveries, the exact vehicle load is not relevant in this case. Although not the focus of the study, the impact of payload highlights an area for future investigation which could add another layer of detail to this work.

3.1.1. Passenger Cars:

ICEV, BEV, and FCEV passenger cars are represented by the Mercedes E400d, Tesla Model 3, and Toyota Mirai. At present, there are a limited number of FCEVs on the market, but the Toyota Mirai is one of the most popular with the second-generation version released in 2021. This model offers a range of ~600 km and weighs roughly the same as an ICEV car [90]. For BEVs, there are more options available on the market. Since Tesla is leading the transition to BEVs, this work used a Tesla Model 3 as the reference vehicle. This is a popular model among the BEV market and is a more affordable option with a similar range and weight to the Mirai [89]. For ICEVs, the Mercedes E400d was used with a similar weight but a range of 1100 km [88].

Table 3-1 – Reference vehicles used for ICEV, BEV, and FCEV passenger cars.

	Mercedes E400d [88]:	**Tesla Model 3 (Long Range) [89]:**	**Toyota Mirai (2nd Gen) [90]:**
Kerb Weight (kg):	1900	1850	1850
Range (km):	1100	560-640	640
Engine Power (kW):	250	335	136
Battery (kWh):	-	80	1.24
Electric Motor (kW):	-	188 and 147 (335)	134
Fuel Cell (kW):	-	-	114
Storage Tank Cap:	66L	-	5 kg
Fuel Consumption (kWh fuel/100km):	65.9 (6.6L)	16	18.3 (0.55 kg H_2)

3.1.2. City Buses:

The buses in this work are all 12m single decker urban city buses, regularly used for transporting people around towns and cities. The specs for the ICEV, BEV, and FCEV buses are given in Table 3-2. The ICEV and BEV buses have a similar weight whilst the FCEV version is slightly lighter at 11t, and both ZEVs have a comparable range of ~350 km. The FCEV bus used as a reference is manufactured by Wrightbus with several models already in operation, with its performance proven in UK fleets against diesel versions.

Table 3-2 – Reference vehicles used for ICEV, BEV, and FCEV city buses.

	IVECO Crossway Intercity [91]:	**Ebusco All-Electric City Bus [92]:**	**Wrightbus FCEV Hydroliner [93]:**
Kerb Weight (kg):	12,000	12,850	10,000-11,000
Range (km):	-	350	350
Engine Power (kW):	250 kW	-	-
Battery (kWh):	-	350	20
Electric Motor (kW):	-	270	134
Fuel Cell (kW):	-	-	75
Storage Tank Cap:	220 L	-	30 kg H_2
Passenger Capacity:	58	45	49
Fuel Consumption (kWh fuel/100km):	240 (24L)	70	217 (6.5 kg H_2)

3.1.3. Heavy Duty Trucks:

All trucks have a gross vehicle weight (GVW) of 44t and are capable of carrying 26t of payload. Mercedes manufactures an electric version of their Actros which is used in this work, whilst for FCEVs data relating to the Hyzon Hymax was sourced from literature. All trucks consist of a cab (where the driver sits and controls the vehicle) attached to a chassis, with an attached trailer respectively.

Table 3-3 - Reference vehicles used for ICEV, BEV, and FCEV trucks.

	Mercedes Benz Actros 1863 [94]**:**	**Mercedes Benz eActros 300** [95]**:**	**HYZON HYMAX FCEV** [96]**:**
GVW (kg):	44,000		
Engine Power (kW):	460	400	-
Battery (kWh):	-	315	140
Electric Motor (kW):	-	400	450
Fuel Cell (kW):	-	-	240
Storage Tank Cap:	400 L	-	70 kg H_2
Payload Capacity (t):	26	26	26
Fuel Consumption (kWh fuel/100km):	194 (19.44L)	*100	343.6 (10.3 kg H_2)

3.1.4. Tipper Trucks:

Tipper trucks are similar in their structural design to long haul trucks but weigh less at 26t. The MAN TGM is a popular choice for diesel tippers and the Renault ZE electric range offers a similar performance. For this battery electric tipper, fuel/energy consumption data was not available and had to be estimated. In this case, figures for the ICEV tipper (211 kWh/100km) were used with the expected powertrain efficiency. Assuming an engine efficiency of 40% for the ICEV tipper, this equates to ~85 kWh/100 km being used. Then, after accounting for a typical BEV efficiency of 85%, this figure becomes 100 kWh/100km. Lastly, to acknowledge the expected additional energy consumed for their lifting operations, an excess of 30% was assumed, giving a final figure of 130 kWh/100km respectively. In this case, FCEV tippers are based on regional delivery trucks with a range of 400 km since specific data referring to tipper vehicles was unavailable in literature. 30 kg of hydrogen storage capacity is available, and the vehicle operates using smaller components than the long haul with an 80 kW fuel cell and a 70 kWh battery. All vehicles have a payload of 12t.

Table 3-4 - Reference vehicles used for ICEV, BEV, and FCEV tipper trucks.

	MAN TGM 6x4 (D0836) [97]**:**	**Renault D Wide ZE Electric** [99]**:**	**HYZON HYMAX FCEV** [96]**:**
GVW (kg):	26,000		
Engine Power (kW):	213	-	-
Battery (kWh):	-	265	70
Electric Motor (kW):	-	370	250
Fuel Cell (kW):	-	-	80
Storage Tank Cap:	200 L	-	30 kg H_2
Payload Capacity (t):	12	12	12
Fuel Consumption (kWh fuel/100km):	211 (21.1L)	*130	253 (7.59 kg H_2)

3.1.5. Refuse Collection Vehicles:

Refuse collection vehicles (RCVs) have similar performance characteristics and functions to tipper trucks, both characterised by frequent stops and starts and requiring additional energy to carry out lifting operations. The only differences are to the vehicle structure and body to allow waste to be collected, compacted, and stored. Taking this into account, and the fact that the BEV RCV is based on the same vehicle model as the BEV tipper, its fuel/energy consumption remains the same in this work. For RCVs, very few FCEV versions are available on the market, though some are being developed. One is manufactured by Ballard Power. Since this is one of the latest advancements in RCV technology, it has been used in this work. However, due to the lack of FCEV models on the market, it makes it very difficult to include vehicles with similar characteristics. As a result, the fuel consumption of fuel cell RCVs is much higher than ICEVs and BEVs, which presents a small limitation to the study. In future work and as more FCEVs are brought on the market, efforts should be made to consider vehicles with more comparable characteristics. All figures have been taken from manufacturer reports, respectively.

Table 3-5 - Reference vehicles used for ICEV, BEV, and FCEV tippers.

	Daimler Econic NGE-L62N [98]:	**Renault D Wide ZE Electric** [102]:	**Arcola/Ballard FCEV RCV** [131]:
GCVW (kg):	26,000	26,000	26,000
Engine Power (kW):	220	-	-
Battery (kWh):	-	200	30
Electric Motor (kW):	-	370	250
Fuel Cell (kW):	-	-	70
Storage Tank Cap:	200 L	-	30 kg H_2
Payload Capacity (t):	10	10	10
Fuel Consumption (kWh fuel/100km):	211 (21.1L)	*130	645.8 (19.4 kg H_2)

3.1.6. Forklifts:

Fuel consumption for forklifts is not reported per unit of distance. Instead it is typically given in terms of the VDI 60 cycle which aims to replicate real working conditions. In this cycle, the forklift operates based on the VDI 2198 test circuit where speed is adjusted to complete the cycle 60 times over 60 minutes at full load, with fuel consumption measured throughout. The test cycle ensures fair comparisons across models, similar to the worldwide harmonised light duty test procedure (WLTP) cycle for passenger cars. The cycle records 60 measurements of fuel/energy consumption in one hour, with the test including the movement of a loaded forklift to storage bay A, a load lift of 2m, load lowering, reversing out of bay A, driving a distance of 30m to bay B, another 2m load lifting, load lowering, and returning the loaded forklift [59]. In this work forklifts are assumed to operate to the same intensity as the VDI cycle.

Although FCEV forklifts are available and in use, their specifications and fuel consumption figures could not be sourced from manufacturers. After contact with Toyota, Linde, and Hyster-Yale, no data was available due to the sensitive nature of the request, with manufacturers refusing to offer information. In addition, limited data is available online and in published reports regarding FCEV vehicles as these are not often considered in academic studies, presenting a challenge in securing reliable and representative data. As a result, FCEV forklift specifications were based on comparable BEV forklifts. This highlights a limitation since data corresponding to BEV forklifts is likely to lead to some inaccuracies. The author encourages the use of more representative data sourced directly from manufacturers for specific FCEV models in order to generate more accurate estimates. This lack of data is recommended in future improvements.

All forklifts are characterised by a high kerb weight which ensures they are capable of transporting a large payload, which is necessary for various outdoor and off-road applications. For simplicity, the FCEV has the same total weight, capacity, and electric motor as the BEV version. However, is characterised by a smaller battery of 30 kWh, equal to one third of the BEV equivalent since batteries used in FCEVs are typically used as a buffer to provide for variable load power demands. Alongside this battery, a 25 kW fuel cell was used for this forklift which lies at the upper end of the 15-25 kW guideline range specified by Nuvera (via email contact). Since the forklift is large and has a substantial weight, a large fuel cell is required to power it. Nuvera manufacture fuel cells for forklifts which are made by their parent company Hyster Yale. Hydrogen capacity is assumed to be 12 kg which enables the vehicle to operate comfortably for 12 hours before refuelling. Finally, its fuel consumption was based on the figure reported by manufacturers for the RX 60-80/900 BEV forklift. Assuming a typical fuel cell conversion efficiency of 60% for PEM technology and using the BEV energy consumption of 17.7 kWh/h (with nearly a 100% energy efficiency battery), this equates to 29.5 kWh/h for the FCEV equivalent respectively.

For ICEV forklifts, data was sourced from manufacturers for the Kalmar FLT12 model via email correspondence and a fuel consumption of 5.8L per hour was given in accordance with the VDI 2198 cycle. Assuming the vehicles in this study operate for 12 hours under this test cycle, it gives a daily fuel consumption of 69.6L respectively.

Table 3-6 - Reference vehicles used for ICEV, BEV, and FCEV forklifts.

	Kalmar FLT12 [100]:	**RX 60-80/900 Electric** [101]:	**FCEV Forklift:**
Kerb Weight (kg):	18,215	15,430	*15,430
Engine Power (kW):	99	-	-
Battery (kWh):	-	90	*30
Electric Motor (kW):	-	21 (2 motors)	*21
Fuel Cell (kW):	-	-	25
Storage Tank Cap:	180 L	-	*12 kg H_2
Payload Capacity (t):	12	8	*8
Fuel Consumption (kWh fuel/100km):	694.6 (69.6L)	212.4	*354 (10.62 kg H_2)
Fuel Consumption (kWh fuel/h):	57.9 (5.8L)	17.7	*29.5 (0.89 kg H_2)

3.2. Generic Vehicle Mileage:

The daily mileage for each vehicle is taken from real mileage data across 2018-2020 prior to Covid-19 and shown in Table 3-7. The sources of these figures are outlined in Table 3-8 and include existing fleets, company fleet reports, and literature studies respectively. This mileage data is not specific to any particular region or fleet and is therefore considered a generic mileage scenario. In all references in Table 3-8, the vehicle operating frequency was omitted from the mileage figures, so this work estimates daily mileage using 350 days of vehicle operation per year, which is a reasonable assumption for fleet vehicles characterised by high usage rates. For vehicles that have multiple annual mileage figures (such as tipper trucks), averages are used.

Table 3-7 - Vehicle fuel consumptions and baseline daily mileages.

Vehicle Type:	Passenger Car	City Bus	Long Haul Truck	Tipper Truck	Refuse Collection	Forklift
Generic Daily Mileage (km):						
All Powertrains	64.4	99.1	496.4	33.2	54.7	29.8
Fuel/Energy Consumption (kWh/100km):						
ICEV	65.9	240	194	211	211	694.6
BEV	16	70	100	130	130	212.4
FCEV	18.3	217	343.6	253	645.8	354

Table 3-8 – Average annual mileage for fleet vehicles.

Vehicle:	**Comments:**	**Average Annual Mileage (km):**	**Source:**
Car	British Vehicle Renting and Leasing Association (BVRLA) surveyed 293 respondents to determine the average mileage of company cars across 2019/2020 (prior to Covid).	12,001-16,000 miles/year (eq. to 22,530 km/year – midpoint used)	[42]
City Bus	Annual statistics published by the DfT showed there were 1.165bn bus miles covered in England over 2018/2019 with 33,600 buses in operation.	34,673 km/year	[205]
Long Haul Truck	Figures reported from a Low Carbon Truck Trial by CENEX/Atkins in 2016 prepared for the DfT which included 315 44t long hauls. Ricardo published a report in 2019 for the CCC looking at Zero Emission HGV Infrastructure Requirements.	CENEX/Atkins: 170,000 km/year Ricardo: 507 km/day (eq. to 177,450 km/year assuming 350 days operation) Average: 173,725 km/year	[44] [45]
Tipper Truck	Figures recorded in Data Mill North Database for Leeds City Council fleet vehicles over 2018/2019. Average figure used. CENEX published a North East Scotland Fleet Review in 2021 which included 12 council fleets. Aberdeen City Council provided mileage data for rigid lorries.	Leeds City Council: 11,464 km/year (avg) Aberdeen City Council: 7,330 miles/year (eq. to 11,796 km/year assuming 350 days operation) Average: 11,630 km/year	[206] [47]
Refuse Truck	Figures recorded in Data Mill North Database for Leeds City Council fleet vehicles over 2018/2019. Average figure used.	19,141 km/year	[206]
Forklift	Very limited mileage data for forklifts. Operation typically reported in hours not distance. One 2019 study investigated fuel consumption and productivity of forklifts and reported average mileage from 285 vehicles.	29.8 km/day (eq. to 10,430 km/year assuming 350 days operation)	[48]

3.3. Fuel Scenarios:

This section covers the fuel scenarios used, including their production routes, conditioning processes, and distribution. For the vehicles in this work, alongside conventional diesel, hydrogen and electricity are also assessed. The 3 hydrogen production routes considered in this work are:

1. Steam Methane Reforming (SMR).
2. SMR with Carbon Capture and Storage (SMR with CCS)
3. PEM Water Electrolysis using Renewable Power.

Hydrogen production is assumed to be centralised around the Tees Valley region where roughly 50% of UK hydrogen production currently takes place and where many people have identified as a potential hydrogen hub for future projects [64]. Once produced, the hydrogen is transported an assumed distance of 200 km to its point of use in the vehicle fleet. This hydrogen distribution is carried out using the 3 most common methods available; compressed gaseous pipelines, pressurised tube trailers (TT), and liquid tankers (LT), respectively.

Green hydrogen from water electrolysis can use any renewable energy generation method, such as wind, solar, or hydropower but is dependent on several factors. For this work, wind power was chosen as it is the dominant renewable power in the UK [39]. For landlocked countries without the opportunity to use offshore wind, solar power is likely to be used instead. Green hydrogen in this work is produced on-site using 3 routes:

1. **225 kW Turbine (and Grid Power):** This is the only route considered 'fleet-specific' as it depends on the total hydrogen demanded by the fleet. A 225 kW wind turbine is installed on-site generating as much renewable electricity as possible which is used to produce hydrogen via electrolysis. This turbine is based on an existing hydrogen refuelling station in Sheffield, UK. When hydrogen demand is high and the turbine cannot generate enough electricity to produce all the hydrogen required, additional electricity is drawn from the grid to support this. As a result, hydrogen from this route could be produced entirely by renewable power or a combination of renewable and grid electricity, depending on the hydrogen demand.

2. **100% RES**: 100% renewable electricity from wind power.

3. **50-50 Split:** A 50-50% split in which half of the electricity for hydrogen production is sourced from wind power, and the other half is sourced from the UK grid.

Electricity generation for BEVs mirrors these 3 electrolysis scenarios and is carried out on-site, but also includes rapid chargers powered by UK grid electricity.

A summary of all fuel production and distribution pathways is given in Figure 3-1.

Diesel	Hydrogen	Electricity
•Delivered to Site via Tanker	•**Production:** •Steam Methane Reforming (SMR) •SMR with Carbon Capture (SMR & CCS) •Electrolysis via 225 kW Wind Turbine (+ Grid Power) •Electrolysis via 100% RES (Wind Power) •Electrolysis via 50-50 Split (50% RES, 50% Grid) •**Distribution:** •Pipeline •Tube Trailer •Liquid Tanker •On-Site (Electrolysis only)	•**Production:** •225 kW Wind Turbine (+ Grid Power) •100% RES (Wind Power) •50-50 Split (50% RES, 50% Grid) •Rapid Charger (100% Grid) •**Distribution:** •On-Site

Figure 3-1 - Fuel production and distribution options.

4. Chapter 4 - Economic Assessment of FCEVs

This chapter investigates the total cost of ownership (TCO) of a mixed fleet of on-road and off-road FCEVs against their BEV and ICEV equivalents. The TCO is examined from the perspective of a fleet owner in order to help support the decision-making process in their transition to ZEVs. The study includes a sensitivity analysis of present day results, varying several input parameters such as vehicle purchase cost and fuel price to assess impacts on TCO and identify conditions under which FCEVs are most cost effective. The TCO is also examined across a wider timescale from 2021 to 2050 to assess the impact of time-sensitive parameters, such as technology efficiency, electricity price, and financial incentives/deterrents on the cost competitiveness of FCEVs. This chapter addresses the questions: How cost competitive are FCEVs compared to BEVs and ICEVs, and under what conditions do FCEVs become most economical?

First, an introduction to TCO is presented, followed by a step-by-step methodology. After, results are highlighted and discussed, and a sensitivity analysis examines the impact of variable inputs on FCEV cost competitiveness.

4.1. Introduction and Model Structure:

Total Cost of Ownership (TCO) analysis is a useful tool for vehicle owners and operators to compare the costs of different vehicles and identify the most economical option. Comparing multiple costs can quickly become a complex procedure so TCO compares a single figure on a like-for-like basis. This process involves summing all purchase and operating costs and dividing by distance travelled to give a single cost, often reported per km.

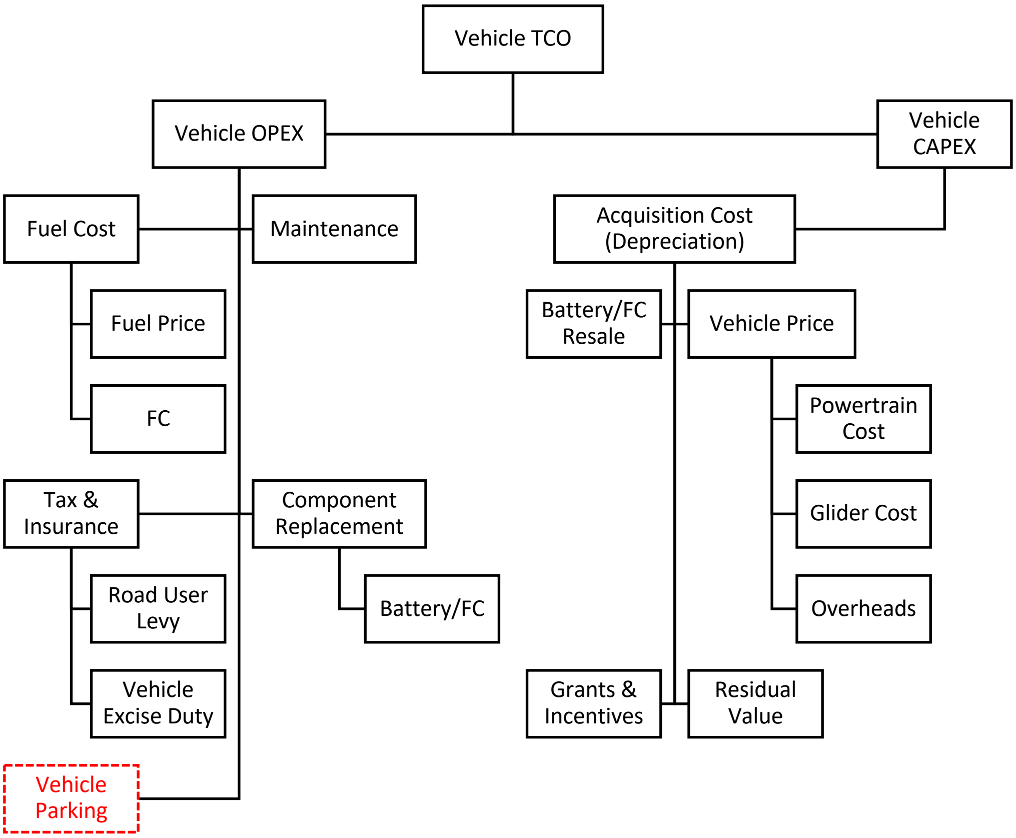


Figure 4-1 - Breakdown of the TCO components included in the model.

Figure 4-1 highlights the boundaries of the TCO model in this work. Within this, other conditions can be added to increase flexibility and consider potential changes resulting from government and policy decisions.

4.2. Base Case Conditions:

All vehicles operate on a 10-year ownership period and are not subject to financial incentives or deterrents. Since Battelle [25] report polymer electrolyte membrane (PEM) fuel cells (FCs) have a 20% recoverable value, and Endacott *et al.* [26] expect batteries to be repurchased for 30% of their original cost, these residual value (RV) figures have been applied. The RV for the remainder of the vehicle will vary depending on its condition but is given a modest value of 25% in this work since the ownership period is 10 years with only one previous owner. The conditions of the base case are shown in Table 4-1.

Inputs like purchase grants, taxes, component costs, and energy prices are adjusted later in a sensitivity analysis and future outlook to account for expected technological improvements and policy changes over time.

Table 4-1 – Baseline conditions.

Condition:	**Baseline Value:**
Modelling Year	2021
Quantity of Each Vehicle	1
Ownership Period (years)	10
Vehicle Operation (days/year)	350
Fossil Tax	No Tax Applied
ZEV Purchase Grant	No Grant Applied
Road Use Tax	No Tax Applied
Fuel Cell and Battery RV	20% and 30%
Glider RV	25%

4.3. Methodology:

4.3.1. Fuel Supply Costs:

This section builds on the foundations presented in Section 3.3 and highlights the costs associated with each of the transport fuels.

Since most fleets operate by purchasing diesel on an ad-hoc basis for a fixed price inclusive of delivery, the same approach was used in this work. Fuel prices reports in 2019 reported average diesel prices of approximately £1.30/L, inclusive of tax [308]. However, after the impacts of Covid-19 and the Ukraine war on energy security, a 25% premium is added to reflect current UK prices, giving a final delivered diesel price of £1.60/L.

Costs of hydrogen production were sourced from a techno-economic analysis of large-scale hydrogen production systems by Kayfeci *et al.* [13] and reported at £1.59/kg for SMR and £1.74/kg for SMR with CCS respectively. Although costs are dependent on several parameters such as infrastructure availability, feedstock price, and production capacity, this source aims to provide reliable figures that are representative of typical costs. For the 3 delivery routes previously outlined in Section 3.3, the costs of conditioning (i.e compression and liquefaction) were calculated based on the electricity consumption using an assumed price of £0.144/kWh for grid electricity in 2021, based on average prices for the UK mix, taken from [14]. In addition to conditioning, costs of diesel consumption in tube trailers and liquid tankers were included, along with vehicle OPEX (which was 5% of the CAPEX, taken from Cadent [12] respectively).

The costs of green hydrogen from electrolysis using wind power are dominated by electrolyser OPEX, which equated to £38/kW based on Christensen *et al.* [55], and the demand for grid electricity in the event of shortages in renewable generation. Additional costs are also associated with water desalination via reverse osmosis. Here, water costs approximately £1.10/m^3 with 3-4 kWh of electricity needed for osmosis [17]. Although desalination is not necessary in areas with plentiful water supply, it was included in this work to offer a conservative and holistic estimate. However, the impact on the final hydrogen price is low and equates to only ~£0.01/kg H_2.

In this work, all renewable electricity generation is considered free of charge. In many instances, instead of being curtailed during periods of lower demand, surplus renewable power can be converted to hydrogen and stored for long periods of time until demand outweighs supply, or like electricity it can be used directly in transport applications. This is one of the main advantages of hydrogen as an energy carrier. Only additional electricity required where renewable generation cannot provide the full demand is paid for.

A summary of the final delivered costs of all fuels is given in Table 4-2 respectively.

Table 4-2 - Final delivered fuel costs.

	Delivered Fuel Cost:			
Fuel Scenario:	**Cost (£):**	**Unit:**	**Cost (£):**	**Unit:**
Diesel	1.60	L	0.16	kWh
H_2 – SMR (Pipeline)	2.18	kg	0.07	kWh
H_2 – SMR (Tube Trailer)	6.41	kg	0.19	kWh
H_2 – SMR (Liquid Tanker)	6.99	kg	0.21	kWh
H_2 – CCS (Pipeline)	2.33	kg	0.07	kWh
H_2 – CCS (Tube Trailer)	6.56	kg	0.20	kWh
H_2 – CCS (Liquid Tanker)	7.14	kg	0.21	kWh
H_2 – Electrolysis (225 kW)	7.52	kg	0.23	kWh
H_2 – Electrolysis (100 RES)	2.26	kg	0.07	kWh
H_2 – Electrolysis (50-50 Split)	5.86	kg	0.18	kWh
Electricity – 225 kW	0.00	kWh	0.00	kWh
Electricity – 100% RES	0.00	kWh	0.00	kWh
Electricity – 50-50 Split	0.08	kWh	0.08	kWh
Electricity – Rapid Charger	0.24	kWh	0.24	kWh

Comparing the estimates in Table 4-2 to those in literature can be challenging as fuel costs vary widely with the specific conditions used, such as production capacity, grid price, distribution distances, and production efficiencies. However, several reports offer estimates which align with those above, indicating the figures are reasonable. Costs of green hydrogen pathways reported by Dawkins *et al.* [65] align with the highest costs recorded coming from decentralised production using grid-dependent electrolysis ranging from £7.60-14.10/kg H_2. Similarly, Collis *et al.* [67] report figures of between €6.5-14/kg H_2 for European green hydrogen, whilst Caspersen *et al.* [68] offer lower estimates of $3-6.5/kg H_2. In contrast, several studies highlight the lowest cost pathways come from centralised grey hydrogen using SMR as it is a mature technology and makes use of cheaper fossil fuels [68]. Studies also show that distribution using pipelines is often the most cost-effective form of delivery for hydrogen over short distances, which agrees with the figures in this study respectively [66]. One takeaway from Table 4-2 is the fact that in general, the price of hydrogen is greater than electricity per kWh. Aside from rapid chargers, electricity is significantly cheaper to source and is partly due to the fact that electricity does not incur any conditioning costs, nor do they require distribution since generation takes place on-site.

For both green and liquefied hydrogen in particular which incur these additional costs and show the highest prices per kWh, it presents an obstacle for FCEV uptake which needs to be targeted. One solution is to incentivise the production of hydrogen to increase its capacity and bring costs down through economies of scale. This is being done by increasing the low carbon hydrogen capacity in the UK from 5 to 10 GW by 2030 and introducing subsidies which promote low carbon hydrogen production further. An example of this is the Clean Hydrogen Subsidy Scheme which was introduced in the UK in July 2022 and aimed to help fund the first 1 GW of green and 1 GW of blue hydrogen projects using a contracts for difference style approach [63]. Others have been introduced which will encourage green hydrogen production and support cost drops in the future. In addition to scale up of production, electrolyser efficiency is expected to increase through scale up and learning-by-doing as more projects are brought online, and other incentives may be used to promote the production and use of green hydrogen such as regulations on CO_2 pricing, tax reliefs and discounts, for example. Later in this work a sensitivity analysis investigates the impact of various financial tools on vehicle TCO respectively.

4.3.2. Time-Sensitive Parameters:

This work also acknowledges input conditions which change based on the modelling year. The values of many parameters will change between now and 2050 when net zero targets are due, which must be considered to provide realistic and accurate estimates of vehicle costs. Due to the large number of variables this study includes, not all will be discussed in this chapter. Instead, only a few of the most important parameters are covered. Variable inputs selected are fuel consumption, electricity price, electrolyser efficiency, and hydrogen drivers and diesel deterrents. Rationale and justification for each are given in this section respectively.

4.3.2.1. Fuel/Energy Consumption:

Fuel cost is a major contributor to TCO so fuel consumption figures should be representative of the vehicles used under real conditions. Figures for ICEVs used the best diesel engines and were sourced from published data by manufacturers and do not consider significant future improvements. This is because the technology is already mature and due to be phased out, along with the fact that diesel engines are not the focus of this study. For those BEVs and FCEVs currently available on the market, fuel consumption data was sourced from manufacturers, OEMs, and Cadent [12] and is inclusive of battery and fuel cell efficiency. In the cases where fuel consumption data was not available, estimates were made based the performance of prototypes and vehicles of a similar performance and specification.

In order to estimate the rate of improvement in the fuel consumption of FCEVs, the study by Benitez *et al.* [15] was used which employed the first-generation Toyota Mirai as the vehicle of interest. In the study, its current-day fuel consumption (in 2020) was reported at 0.76 kg H_2/100km whilst the future value was expected to fall to 0.58 kg H_2/100km (~24% lower), largely due to developments in PEM fuel cell technology along with weight reductions associated with hydrogen storage tanks. Since estimates for the future fuel consumption of FCEV HDVs are not yet available due to their current market size, this LDV assumption was applied to all the FCEVs in this work. Unfortunately, the exact year of this future value was not specified in the study so has been assumed 2050. As a result, a 5% drop in consumption every 5 years is assumed which is in line with these figures. The fuel consumption for all vehicles is given in Table 4-3.

For BEVs, a similar method was used to estimate changes in energy consumption over time and was based on future estimates by Transport and Environment [54]**.** Here, the energy consumption of BEV regional delivery trucks was predicted to fall from 1.44 kWh/km in 2020 to 1.15 kWh/km in 2030, equivalent to a 20% decrease, largely due to developments in battery energy density. As a result, the energy consumption in this work decreases in line with these figures but is also assumed to continue to fall at the same rate until 2040 since BEVs (especially HDVs) are still limited in use and are expected to increase in efficiency further as more models are brought to market. Developments in these vehicles are expected until diesel HDVs are phased out by 2040. After 2040, energy consumption is not expected to change significantly and therefore remains fixed.

Table 4-3 - Change in fuel consumption for all vehicles from 2021-2050.

ICEV (kWh/100km)	**2021-2050**						
Car	65.9						
Bus	240.0						
Truck	194.0						
Tipper	211.0						
Refuse	211.0						
Forklift	694.6						
FCEV (kWh/100km)	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Car	18.3	17.4	16.5	15.7	14.9	14.2	13.5
Bus	217.0	206.2	195.8	186.1	176.7	167.9	159.5
Truck	343.6	326.4	310.1	294.6	279.9	265.9	252.6
Tipper	253.0	240.4	228.3	216.9	206.1	195.8	186.0
Refuse	645.8	613.5	582.8	553.7	526.0	499.7	474.7
Forklift	354.0	336.3	319.5	303.5	288.3	273.9	260.2
BEV (kWh/100km)	**2021**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Car	16.0	14.4	13.0	11.6	10.5	10.5	10.5
Bus	70.0	63.0	56.7	51.0	45.9	45.9	45.9
Truck	100.0	90.0	81.0	72.9	65.6	65.6	65.6
Tipper	130.0	117.0	105.3	94.7	85.2	85.2	85.2
Refuse	130.0	117.0	105.3	94.7	85.2	85.2	85.2
Forklift	212.4	191.1	172.0	154.8	139.3	139.3	139.3

It should be made clear that this work uses a constant fuel consumption from manufacturers reported figures which does not account for variations in vehicle payload. The author acknowledges the fact that in reality fuel consumption is a function of payload and will greatly fluctuate with vehicle weight and driving conditions, and this factor presents a limitation which must be conceded. Similar to payload, temperature is another factor which impacts the fuel/energy consumption of vehicles. Cold weather has been proven to significantly reduce the efficiency of BEVs, increasing their energy consumption by as much as 50% due to the increased demand for cabin heating and the prevention of powertrain freezing [69]. Although the impacts of weather on ICEVs and FCEVs are much lower, for BEVs this factor should be acknowledged as it can have an indirect financial impact. For example, if a BEVs range is reduced during cold periods, the requirements for charging increase which can lead to greater downtime and a less productive fleet.

As an alternative to more frequent stops, if a larger battery is installed to compensate for these cold-weather losses it can also lead to issues in terms of payload which should be acknowledged. BEVs often face this criticism from sceptics highlighting a potential loss of payload as a result of the large batteries required to achieve a comparable driving range to ICEVs and FCEVs. For example, tipper trucks in this work have a 265 kWh battery weighing ~1700 kg. Assuming cold weather leads to battery efficiency falling 50%, double the battery capacity is required to carry out the same functions and this extra 1700 kg will now reduce the available payload. At a weight of approximately 12t, the payload decreases to ~10.3t (~15%) after the addition of this battery, reducing the vehicle's productivity. In this case, if a fleet of 7 tippers was used, the total loss in payload is equivalent to ~12t. Now, to compensate for this loss, another vehicle must be purchased, offsetting any cost savings seen by BEVs, and potentially making FCEVs more cost-effective solution.

For this study the impacts of temperature on powertrain efficiency are considered outside of the scope, though they should be considered in future work along with payload effects on fuel consumption. These omissions could be included to generate a more accurate result and are therefore considered areas of improvement, respectively.

4.3.2.2. Electricity Price:

The UK electricity grid price is unlikely to remain fixed between 2021-2050. With multiple energy sources making up the mix, it is difficult to predict the future composition and price. However, prices increased due to the impacts of Covid-19 and the events in Russia/Ukraine which have negatively affected natural gas availability, as well as the ongoing shrinkage of fossil fuel reserves which increase the demand for renewable energy, contributing a greater share of total power generated. As a result, electricity prices in this work are predicted to increase for the foreseeable future so a 10% increase in electricity cost every 5 years is assumed, starting at £0.144/kWh in 2021 and rising to £0.255/kWh in 2050 [16]. Table 4-4 shows the electricity price profile to 2050.

Table 4-4 - UK grid electricity prices per kWh from 2021-2050.

	2021	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Electricity Price (£/kWh):	£0.144	£0.158	£0.174	£0.191	£0.210	£0.231	£0.255

4.3.2.3. Electrolyser Efficiency:

Some of the hydrogen production routes in this study have the potential to significantly increase in efficiency in the future. The electrolysis process is a relatively new production route which currently accounts for only ~4% of global hydrogen production and has great potential to grow in the future as renewable energy generation increases (from more offshore wind projects coming online in the UK) and electrolyser technology develops further. This is considered globally as a true green hydrogen production route which is one of the most promising solutions for achieving climate targets. As a result, it is receiving significant investment from both public and private sectors and is at the centre of hydrogen research and development.

However, for other hydrogen production routes like SMR which currently accounts for 48% of global production, the technology is already mature having been in use for several decades. Although SMR can be carried out with other fuels, traditionally it involves the use of fossil fuels which the world is trying to limit. As a result, many industry experts resist the use of SMR technology and see it as a way to lock in the use of fossil fuels for longer. Furthermore, the use of SMR alone is not enough to produce the quantities of hydrogen required to reach future demand. Consequently, the efficiency of SMR is not expected to improve significantly in the future. Also, it is uncertain as to whether this technology will even be in operation in the future since the hope of achieving net zero targets will likely be affected by its use. Similarly, blue hydrogen using SMR with CCS also faces worldwide scrutiny over its place in the hydrogen mix since CCS technology has yet to be proven on the large scale with limited demonstration plants in use, along with uncertainty regarding the security of carbon sequestration. SMR with CCS is unlikely to be the option selected for new plants built in the coming years as other technologies show better efficiency and economics; one being autothermal reforming with CCS. For these reasons the SMR production process is not considered and focus will lie solely on electrolytic hydrogen.

Currently, the electrical efficiency of PEM electrolysers for hydrogen production is estimated at ~65% [17]. However, several sources including the IEA and ICCT predict this efficiency to increase in the future, with exact figures varying depending on economies of scale, technological breakthroughs, and general operating conditions. In this work, a modest future efficiency of 74% is assumed, based on the work by Christensen *et al.* [55] and predictions by the IEA [17] respectively. As a result, this work assumes the efficiency of PEM electrolysers increases steadily and consistently every five years until it reaches its maximum of 74% in 2050.

Table 4-5 - PEM electrolyser efficiency from 2021-2050.

	2021	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
PEM Electrolyser Eff (%):	65%	66.5%	68%	69.5%	71%	72.5%	74%

4.3.2.4. Hydrogen Drivers and Diesel Deterrents:

Tools for hydrogen and electric incentivisation, and diesel discouragement are also variable. Purchase grants for ZEVs alleviate high upfront costs and encourage uptake in early adoption stages, whilst fossil tax on top of existing fuel duty pushes motorists away from fossil-based fuels to consider a switch to sustainable alternatives. Both of these are discussed later in Section 4.3.3.2.

In addition to time-sensitive input parameters, the future value of money must also be discounted to a present-day value. This work discounts future costs using a real discount rate of 0.7%, which was taken from UK government in March 2021 [20]. Although a fairly low rate, it aims to reflect the current low interest rates seen in the UK and offers a more realistic estimate considering the economy at the time. Furthermore, the impacts of using a higher rate are not likely to cause significant changes to the conclusions of this work since the only future costs being discounted in this work are from component replacements and vehicle residual value. Component replacements are not required for ICEVs whilst for most ZEVs they contribute a minor share of the TCO in comparison to other costs such as fuel, shown later in this chapter.

4.3.3. Vehicle Purchase Costs:

The automotive market currently lacks a broad inventory of BEVs and particularly FCEVs. Some vehicles do not yet have ZEV versions commercially available making it difficult to source real purchase costs. To estimate these, literature and reports were used to offer initial figures, whilst for other vehicles not yet available, purchase prices have been estimated based on vehicles with similar characteristics. These are given in Table 4-6.

Table 4-6 - Purchase cost estimates for each vehicle type.

	Car	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
BEV	£60,000	£350,000	£400,000	£150,000	£357,000	£40,000
FCEV	£60,000	£500,000	£300,000	£150,000	£400,000	£45,000
ICEV	£30,000	£290,000	£250,000	£75,000	£152,500	£30,000

- **Cars –** The average price of a diesel car is ~£30,000 and was sourced from [29] and used as a guideline. This price also aligns with the study by Cadent [12], solidifying this value. For ZEVs, prices are generally higher due to their smaller market size and expensive components. For the second-generation Toyota Mirai prices hover around £65,000 for the latest model, though have fallen compared to the first-generation version [30]. BEVs range more widely since there are more options available, with basic models starting at ~£20,000, standard models like the Model 3 Long Range starting at £58,000, whilst higher spec cars like the Model S start at £95,000 [56] [31]. In this work a figure of £60,000 was used to represent BEVs and FCEVs respectively.

- **Buses –** The purchase prices of buses were based on a TCO report by Cadent [12] which offered estimates for ICEV and BEV city buses at £290,000 and £350,000 respectively. FCEV buses are estimated at £500,000 which is based on the cost of the FCEV buses currently used in Transport for London fleets [32].

- **Trucks –** Similar to buses, estimates for Class 8 long haul trucks were also based on information from Cadent [12] as well as Sharpe *et al.* [57] who analysed the purchase costs of ZEV trucks using estimates from studies by the National Renewable Energy Laboratory and Argonne National Laboratory. Analysis highlighted that there are currently no FCEV long haul trucks commercially available in North America or Europe so real figures are unavailable. However it did provide a range of estimates for different truck types and showed in general a higher purchase price for BEV trucks compared to FCEVs due to the sensitivity of the retail price to the size of the powertrain and the maximum daily driving range that the energy system can provide for. Estimates used in this work are in alignment with these figures and range from £250,000 for ICEVs to £300,000 for FCEVs and £400,000 for BEVs.

- **Tippers -** The study by Cadent [12] was also used to derive purchase costs for rigid tipper trucks. The cost of a 25t diesel HGV was given at just over £70,000, whilst estimates for FCEV tippers were taken from the same source at £150,000 respectively. The cost of BEV tippers is assumed to be the same as FCEVs at £150,000 since these vehicles have a similar availability with few models currently on the market.

- **Refuse –** Based on a Manchester City Council TCO report [26]. Costs of £152,500 for ICEVs and £357,000 for BEVs were used. Although FCEV refuse vehicles are now being developed and are entering operation in some regions of the UK, their purchase costs are not available in literature, so estimates of £400,000 were made due to their lower technology maturity and production volumes.

- **Forklifts -** The price for ICEV forklifts varies greatly. However, several prices were sourced online from different manufacturers to derive an initial estimate for this work of £30,000 for ICEVs, representing an average spec vehicle. Several electric forklifts are on sale ranging from £20,000-£50,000 which was used as a guideline for ZEVs. As a result, a premium of £15,000 and £10,000 was applied for FCEV and BEV versions.

4.3.3.1. Powertrain Costs:

Powertrain costs were calculated by splitting the vehicles into their major components. For BEVs, the powertrain included the lithium-ion battery and electric motor. For FCEVs, it included the fuel cell, hydrogen storage tank, battery, and electric motor. Finally, for ICEVs, the combustion engine and fuel system. The costs for each component were taken from various literature sources including a BEV TCO study by Bubeck *et al.* [33], as well as equipment manufacturers, and scaled based on their requirements, giving the total powertrain cost for each vehicle. Individual components costs are given in Table 4-7.

These powertrain component costs were estimated using work by Bubeck *et al.* [33] and a state-of-the-art review on zero emissions trucks by Delft [28]. For the hydrogen tanks, it was assumed Type 3 (HDVs) and Type 4 (LDVs) tanks cost the same since their material inventories are so similar [70].

Table 4-7 - Powertrain component costs.

Component:	Cost (£/kW or £/kWh):
PEM Fuel Cell	162.00
Electric Motor	16.20
Li-ion Battery	139.50
H_2 Storage Tank	10.30
Combustion Engine	54.00
ICEV Fuel Tank	1.70

Overhead Costs:

Estimates for overhead costs were taken from Vyas *et al.* [19] and included production (engineering and R&D), sales, and profit. These cost contributors were assigned an individual share of the vehicle manufacture price, with the total overheads equalling 75% of the manufacturing (vehicle) cost respectively.

Glider Costs:

Since automakers often withhold sensitive information regarding vehicle costs to stay competitive, and due to a lack of inventory for ZEVs, glider costs could not be sourced in literature. As a result, it presents a limitation to

the study which should be revisited in the future. If possible, more accurate cost estimates should be sourced for the gliders directly from manufacturers. For the sake of this work however, and to overcome this issue, crude cost estimates were estimated using Equation 9-Equation 11 and are given in
Table 4-8 respectively.

$$\text{Vehicle Purchase Cost} = \text{Glider} + \text{Powertrain} + \text{Overheads} \qquad \text{Equation 9}$$

$$\text{Vehicle Manufacture Cost} = \text{Glider} + \text{Powertrain} \qquad \text{Equation 10}$$

$$\text{Glider Cost} = \text{Vehicle Purchase Cost} - \text{Powertrain Cost} - \text{Overhead Cost} \qquad \text{Equation 11}$$

Table 4-8 - Glider costs for each vehicle.

	Car	Bus	Truck	Tipper	Refuse	Forklift
ICEV:	£3,218	£151,789	£128,932	£30,993	£74,889	£11,629
FCEV:	£13,422	£268,294	£162,150	£58,630	£208,677	£17,015
BEV:	£17,699	£146,801	£121,006	£42,753	£170,106	£9,962

4.3.3.2. Financial Incentives and Deterrents:

Generally, many BEVs and FCEVs are characterised by high purchase costs, so financial incentives (or deterrents on ICEVs) are imposed in the early stages to encourage their uptake and/or discourage fossil fuel use. Examples used in this work include purchase grants and fossil tax, whilst road use charges are also used to recover funds lost from fuel duty. Another example of incentivisation is free parking for ZEV owners (shaded red in Figure 4-1). However, since most TCO analyses exclude this component, and this work is focused on vehicles for fleet use with refuelling in areas where parking is not an issue, this factor is omitted.

Purchase Grants:

Since battery and fuel cell production still lacks the economies of scale and relies on expensive materials, these components add a significant cost to the overall purchase prices of BEVs and FCEVs, accounting for a large portion of the price premium against ICEVs. For this reason, two rates of discount are applied to alleviate burdens associated with high upfront costs, deterring customers, shown in Figure 4-2. The high grant discount is double that of the standard, which for BEVs is a maximum of 20%, and 40% for FCEVs in 2021, reducing over time as the government ban on new diesel vehicles comes into effect. For this reason, BEV purchase grants are applied from 2021-2030, whilst for FCEVs the grant runs through to 2035 to account for the lower current technology readiness of FCEVs, slowing uptake.

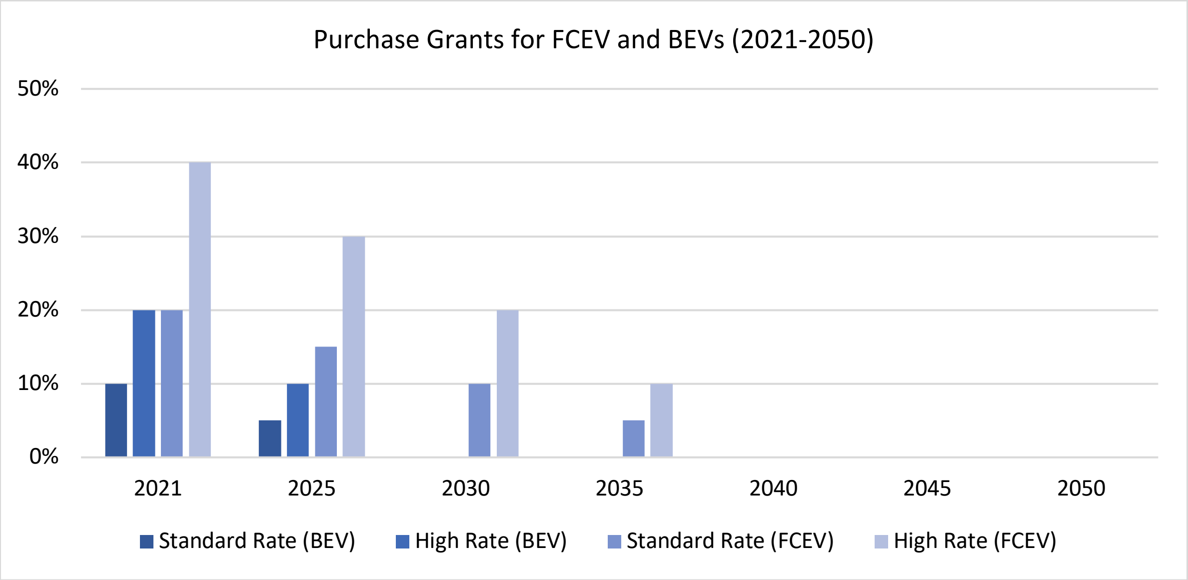


Figure 4-2 - BEV and FCEV purchase grants from 2021-2050.

Fossil Tax:

An additional tax on the use of fossil fuels can be applied to diesel on top of existing fuel duty charges. This tool aims to discourage users from ICEVs and force them to consider using a ZEV. Two dynamic fossil tax rates are included in this model shown in Figure 4-3: a low rate and high rate (double the low rate). Rates start at 5% and 10% in 2021 and increase over time to 40% and 80% by 2050 as the UK's net zero climate targets draw closer.

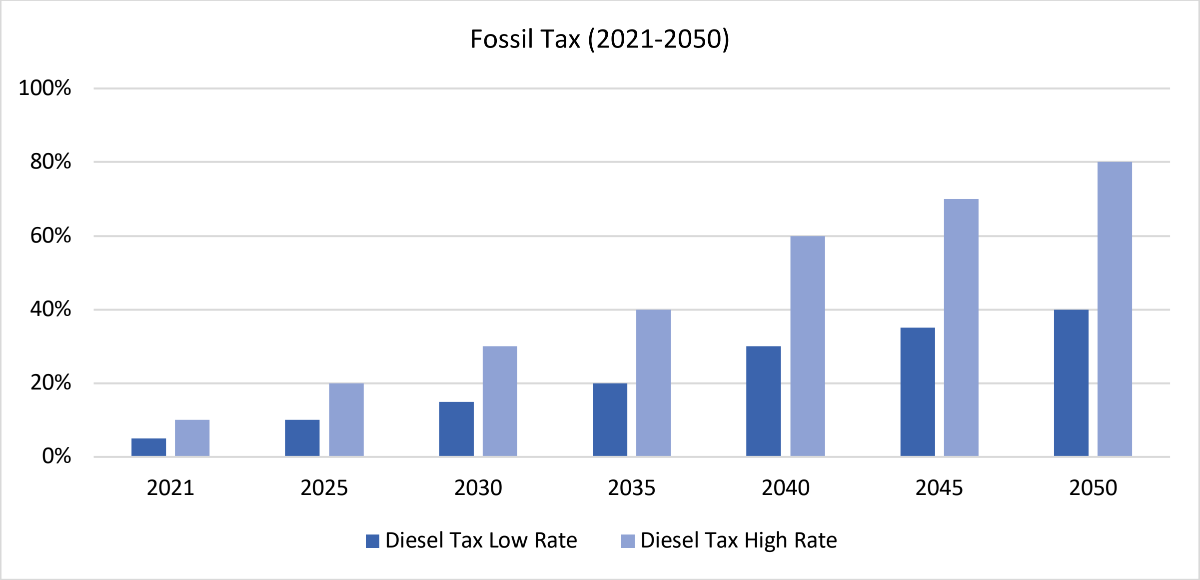


Figure 4-3 - Fossil tax rates from 2021-2050.

Road Use Charge:

Fuel duty is a tax embedded in the cost of diesel and was approximately 58p/L in 2019/2020, bringing in considerable funds to the UK government. Over this period, the total revenue generated was approximately £28.4bn [34]. As the UK transitions towards low carbon transport, this revenue will be lost so new schemes will be needed to recover it. One solution which can be used in this work is a road use charge where users pay an equivalent tax per km travelled. This is calculated using Equation 12-Equation 15.

$$\text{Current Fuel Duty Tax} = \frac{£0.58}{\text{L}} \qquad \text{Equation 12}$$

$$1\text{L Diesel} = 9.96\text{ kWh} \qquad \text{Equation 13}$$

$$\text{Equivalent Cost} = \frac{£0.58}{9.96\text{ kWh}} = \frac{£0.0582}{\text{kWh}} \qquad \text{Equation 14}$$

$$\text{Road Use Charge} = \frac{£0.0582}{\cancel{\text{kWh}}} \text{x Fuel Consumption} \frac{\cancel{\text{kWh}}}{\text{km}} = £/\text{km} \qquad \text{Equation 15}$$

4.3.4. Depreciation:

Depreciation often accounts for the largest portion of a vehicles TCO and is therefore of high interest and importance to fleet owners purchasing new vehicles. It is calculated by subtracting the salvage value from the initial purchase cost (inclusive of any grants and subsidies) and divided by the service life. This gives the vehicle CAPEX in terms of annual depreciation. In this work, the glider is sold after primary use in the vehicle since it holds residual value and can be reused in secondary applications outside of fleet operations. This residual value profile is shown in Figure 4-4.

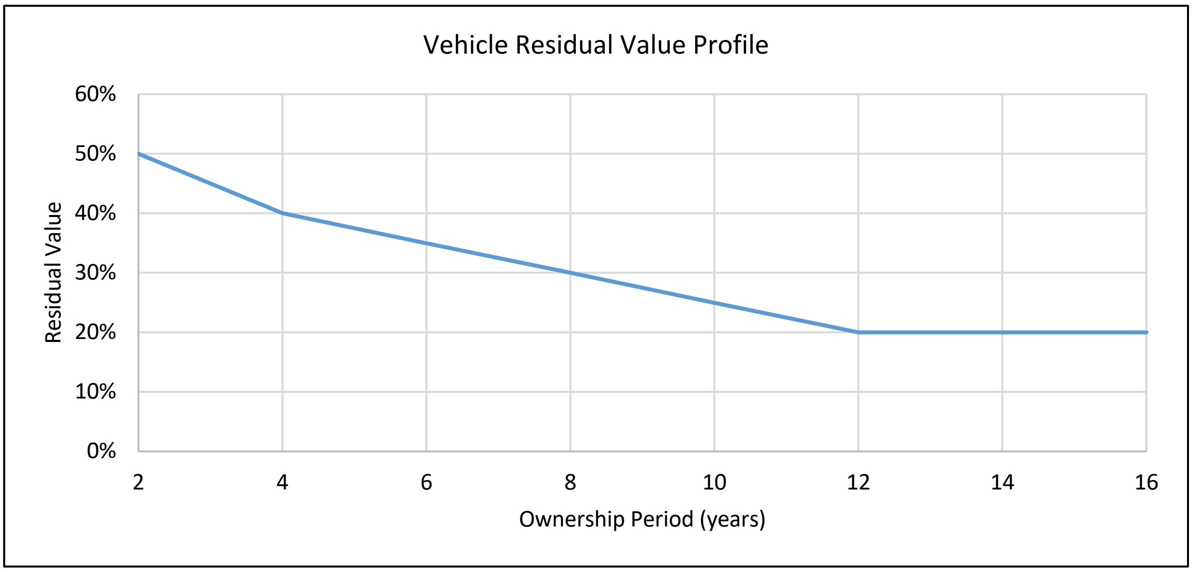


Figure 4-4 – Relationship between vehicle residual value and service life.

Depreciation is a complicated and non-linear process making it difficult to estimate and predict since it is influenced by several factors such as the mileage accrued, powertrain used, brand perception, vehicle features, rarity, condition, fuel prices, and government regulations, for example. However, several finance models targeted towards new vehicle ownership provide general estimates for depreciation of up to 40% after the first year, with [36] stating the average new vehicle may lose ~60% of its value after 3 years. For ZEVs, the depreciation rate may vary significantly because many of these vehicles have not yet reached their end of life, leaving limited historical data and showing great uncertainty regarding their future uptake, making it more challenging for predictions to be made. In the case of BEVs, a growing coverage of charging points and popularity, as well as government bans on diesel cars by 2030 has led to their residual value increasing since their introduction, with several high-end BEVs now retaining ~60% of their initial value after 3 years, according to research conducted by Propfe *et al.* [23]. For FCEVs, the outlook is less clear since refuelling stations are currently sparse and uptake is lower. However, these are predicted to grow in interest over the coming years as government funding for hydrogen increases and the transition towards low carbon transport continues.

This study sets a residual value of 50% for ICEVs after the first two years of ownership, with this rate slowing over time as ownership increases towards its maximum of 16 years. After 12 years of ownership, depreciation ceases and RV drops to 20% where it remains thereafter. A recent report published by Element Energy [22] found that there is a minimal difference in the rate of depreciation across powertrain types. After taking this and uncertainties associated with ZEVs into consideration, the same depreciation rate is applied to BEVs and FCEVs respectively.

4.3.5. Battery and Fuel Cell Replacement and Resale Value:

As mentioned earlier in Section 2.2, the FCEVs in this study use PEM fuel cells which are the most common for transport applications. For BEVs, lithium-ion batteries are used since they offer low maintenance, high energy density, and fast charging compared to alternatives [40].

Component replacements are not expected during the service life of ICEVs but are for BEVs and FCEVs. Casals *et al.* [24] report that many BEVs now offer 10 year warranty for lithium-ion batteries whilst other studies estimate a typical useful life in a vehicle of between 200,000 to 250,000 km before replacements are needed [55]. PEM fuel cell predictions are more difficult since vehicles using the technology are scarce and haven't yet reached their end of life, providing limited data [24]. However, Propfe *et al.* [23] reviewed studies using published operating hours and service lifetimes of fuel cell systems in automotive applications and referenced two reports quoting lifespans of 200,000 km and 247,000 km respectively. As a result, this model sets a limit of either 10 years of vehicle service or 200,000 km before expected degradation and capacity losses demand battery and/or fuel cell replacements.

In terms of battery and fuel cell end of life, Casals *et al.* [24] suggests after 10 years of operation, batteries are no longer appropriate for automotive use, but still retain ~80% of their original capacity which could be used in other applications outside of transport. For this reason, after replacement they are sold rather than disposed. Battelle [25] reported that PEM FCs have a 20% recoverable value, whilst a TCO study by Endacott *et al.* [26] said they expect batteries to be repurchased for 30% of their original cost. These resale figures are applied to this study and salvage value is deducted from the vehicle purchase cost, so depreciation accounts for these savings.

4.3.6. Vehicle Tax:

Vehicle tax in the UK is composed of an annual vehicle excise duty (VED), with a road user levy (RUL) also applied to HDVs to cover wear and tear of the road surfaces, shown in Table 4-9. For ICEV LDVs, VED is £155/year whilst for HDVs this figure varies based on vehicle weight, though for most of the vehicles in this study the cost is £300/year. RUL varies with weight across a wider cost range, with all figures sourced from UK government and DVLA road tax databases [27]. Since it is difficult to predict future tax rates and structures, these taxes are assumed to stay the same over the 2021-2050 period. All ZEVs are exempt from VED and RUL [26].

Table 4-9 - Annual tax estimates for all fleet vehicles.

VED (£/yr):	**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
ICEV	£155	£330	£300	£300	£300	£0
RUL (£/yr):	**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
ICEV	£0	£94.50	£900	£315	£315	£0
Total Tax (£/yr)	**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
ICEV	£155	£425.50	£1200	£615	£615	£0

4.3.7. Insurance and Maintenance:

Since this study considers a mixed fleet of light and heavy duty vehicles using different powertrains, some of which are not yet commercially available, it is difficult to accurately estimate annual insurance costs. Many businesses take advantage of fleet insurance which covers all vehicles with one fixed annual cost, however this complicates things in terms of individual vehicle TCO estimation as it becomes difficult to assign portions of this total fee to each vehicle. Estimating the insurance for individual vehicles is also complex as these will be operated by several drivers and costs are highly influenced by driver characteristics like age, gender, accident history, location, as well as vehicle-related factors. To overcome this, work published by the Hydrogen Council [9] on zero emission trucks has been used as a guideline and estimates annual insurance costs at 1.5% of the purchase costs, respectively.

Table 4-10 - Maintenance and insurance costs for fleet vehicles.

Maintenance Cost (£/yr):	**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
ICEV	£1,250	£16,000	£13,630	£8,100	£5,000	£3,676
FCEV	£875	£11,200	£9,541	£5,670	£3,500	£2,573
BEV	£875	£11,200	£9,541	£5,670	£3,500	£2,573
Insurance (£/yr):	**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**
ICEV	£450	£4,350	£3,750	£1,125	£2,288	£450
FCEV	£900	£7,500	£6,000	£2,250	£6,000	£675
BEV	£900	£5,250	£4,500	£2,250	£5,355	£600

Vehicle maintenance costs are inclusive of services, MOT, repairs, and tire replacements. Maintenance is highly influenced by factors such as vehicle application, duty cycle, powertrain, weather conditions, and driver behaviour, among others. Endacott *et al.* [26] report 30% lower maintenance costs for ZEV refuse collection vehicles compared to their ICEV counterparts since they benefit from the absence of a combustion engine, experience less temperature stresses, less brake pad wear, and avoid oil changes. This cost reduction has been taken forward and applied to all ZEVs in this work to give the maintenance and insurance costs summarised in Table 4-10.

Insurance and maintenance costs are assumed to stay the same throughout the 2021-2050 period. Various sources including council fleet operator reports, TCO reports, and direct quotes have been used as a guide for the estimates of diesel maintenance costs in this model. These are summarised in Table 4-11.

Table 4-11 - Sources used to estimate diesel vehicle annual maintenance costs.

Car:	**Bus:**	**Truck:**	**Tipper:**	**Refuse:**	**Forklift:**
Estimates for cars vary widely in literature depending on the application. Estimates for diesel fleet vehicles were taken from Challen *et al.* [51] giving figures of £1,250/year.	[12] report figures of £16,000 per annum for the maintenance associated with 12m diesel city buses.	Annual maintenance figures for diesel trucks were taken from a Road Haulage Association (RHA) and Freight Haulage Association (FHA) report by Challen *et al.* [51] in 2018 prior to Covid-19. Quoted figures of £8,700 were given for the tractors of articulated 44t long hauls with £4,901 for the trailer, giving a total cost of £13,630. For tipper trucks costs are lower at £8,100/year.		[26] report average annual costs of £5,000 for the service, repair, and maintenance of their 27 diesel RCVs over a 10-year lifespan. Electric versions are expected to have annual costs of £3,500.	Maintenance costs for diesel forklifts of £3,676 were taken from the RHA and FHA relating to a 12-14t HDV. [51] This estimate is well aligned with others from [52], generated using a cost calculator under specific driving conditions.

4.4. Results and Discussion:

In this section the TCO for all ICEV, BEV and FCEV fleet vehicles are analysed under current (2021) base case conditions (shown in Section 4.2) with the generic mileage figures shown in Table 3-7 in Chapter 3. These fuel and powertrain scenarios are compared to highlight their current cost competitiveness and help predict likely changes in TCO competitiveness in the future as technology advances, economy of scale increases, and government policies are introduced. A sensitivity analysis follows to identify the most impactful parameters on the TCO.

In addition to present-day TCO, results are estimated for future years from 2021-2050 to take into account the effects of time-sensitive parameters on the TCO, outlined previously. This offers insight into how ZEV and ICEV TCOs converge over time and allows identification of when ZEVs become favourable in terms of cost per km.

4.4.1. Base Case Results:

Figure 4-5 shows the contributions that each component has on the TCO for diesel vehicles. Similar breakdowns for BEVs and FCEVs under all fuel scenarios can be found in Section 10.1 in Appendix 1. From these, for each vehicle and powertrain type, the depreciation, maintenance, tax and insurance, and component replacement costs are fixed per km regardless of the fuel scenario. The fuel cost is the only variable influencing the overall TCO and the subsequent percentage contribution each parameter makes to the total cost per km. From Figure 4-5, fuel costs make up anywhere between 20% (tipper) and 56% (truck) of the TCO for diesel HDVs. For ZEVs, this range is even wider and for this reason, analysis will focus mainly on fuel costs.

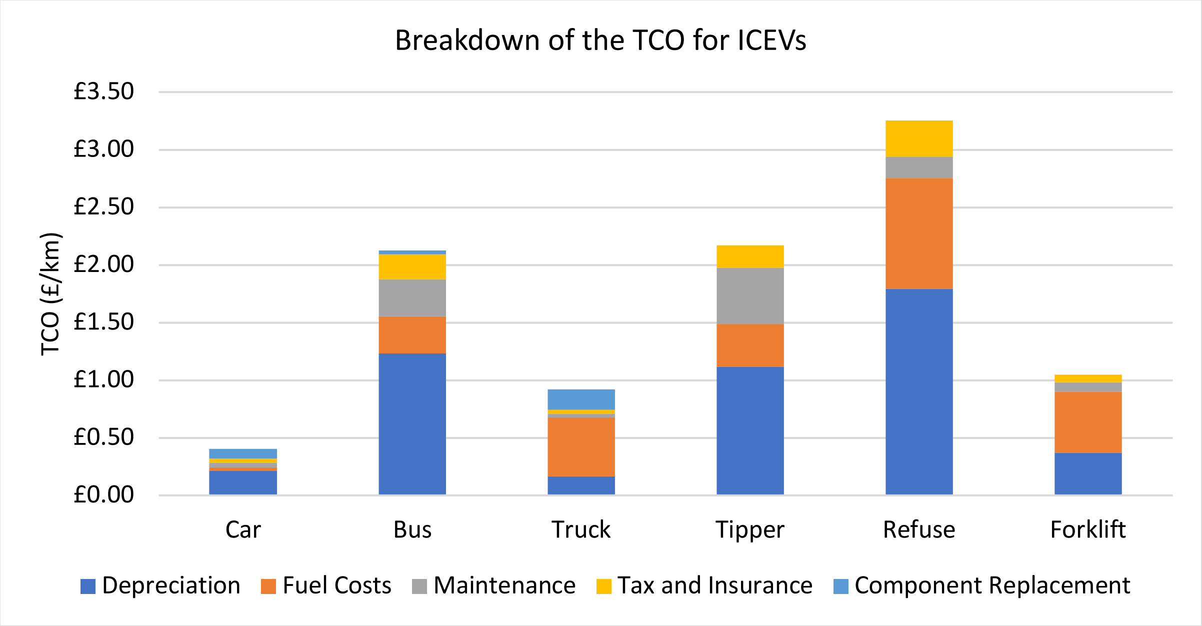


Figure 4-5 - Breakdown of cost components making up TCO of ICEVs.

4.4.1.1. Fuel Costs:

The box plot in Figure 4-6 shows the total variation in fuel costs in £/km across all vehicle types in the fleet and each of the 3 powertrains. In the case of FCEVs, the fuel costs range from a minimum of £0.01/km to a maximum of £1.45/km which is a much wider variation when compared to electricity and diesel. This is because the hydrogen can be produced and delivered in more ways, each with a different cost depending on the distribution route and its conditioning. In general, electricity is the cheapest fuel with a maximum of only £0.51/km whilst for diesel this value is £1.12/km. Since fuel costs are one of the largest contributors to the TCO, these figures are very influential to the cost competitiveness of ZEVs and especially FCEV technology. The higher the fuel cost, the greater its contribution is to the vehicles total cost per km. This is evidenced in the tables in Section 10.1 in Appendix 1 as FCEVs utilising high-cost hydrogen all show larger contributions from their fuel in the TCO composition breakdown.

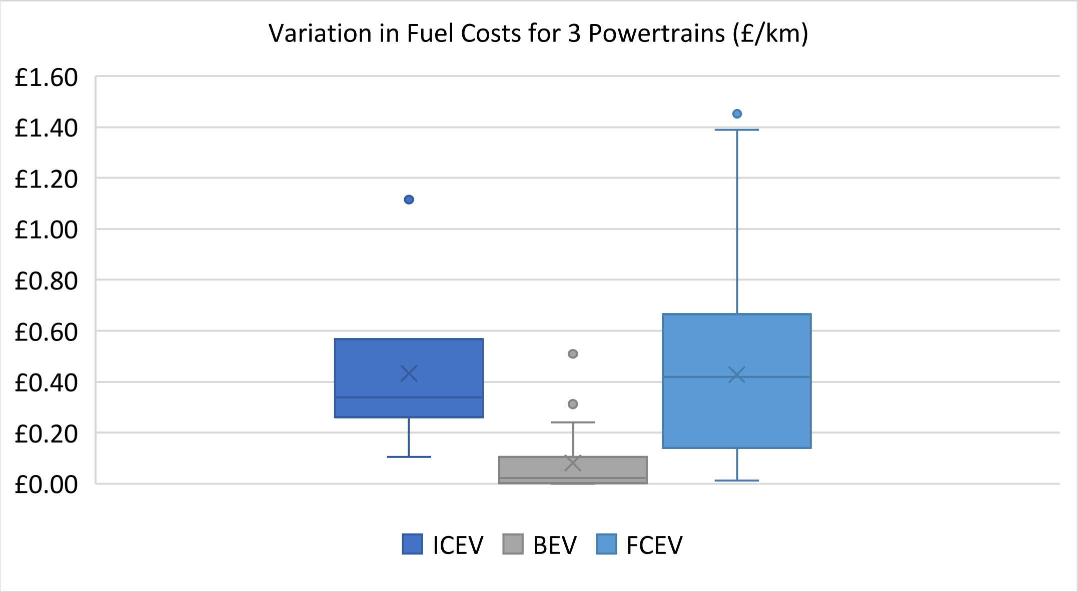


Figure 4-6 - The total variation in fuel costs for all vehicles in the study for each powertrain.

Figure 4-7 and Figure 4-8 support the previous statements and show the variation in the percentage contribution fuel costs have to the overall TCO for ZEVs. For FCEVs, long haul trucks show the highest max contribution at 65% of the TCO, whilst cars have the lowest max contribution of only ~10%. This gives the total range that fuel cost can contribute towards the TCO for FCEVs. For BEVs in Figure 4-8, this range is much narrower for several of the vehicles, though BEV forklifts and trucks have the largest maximum contribution of 53% and 41%, compared to the minimum value of 0% in the case of renewable electricity.

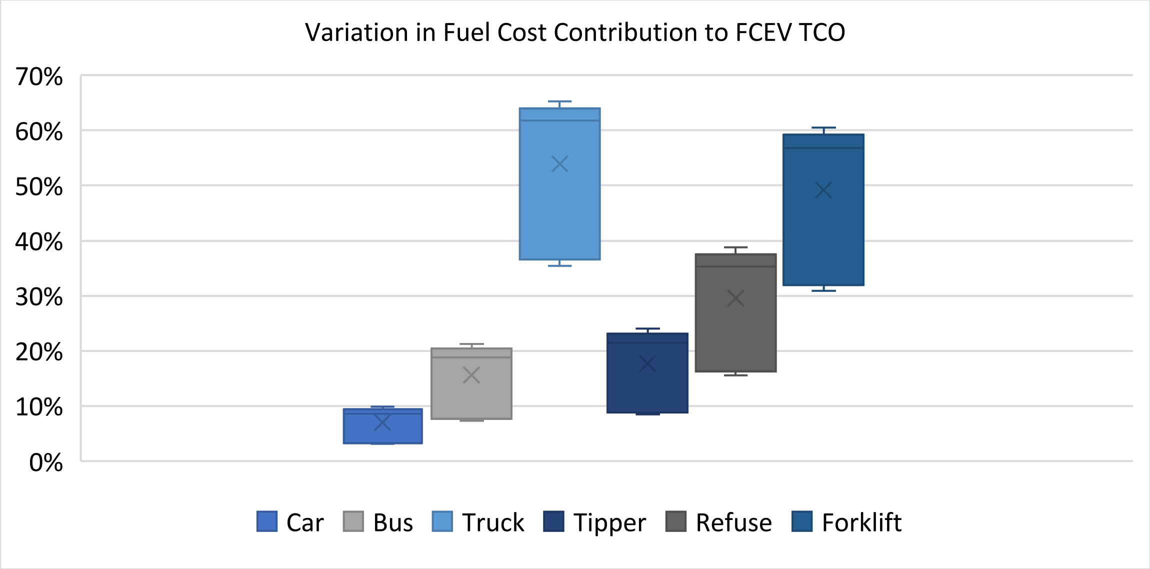


Figure 4-7 - The total variation in fuel cost TCO contribution for FCEVs.

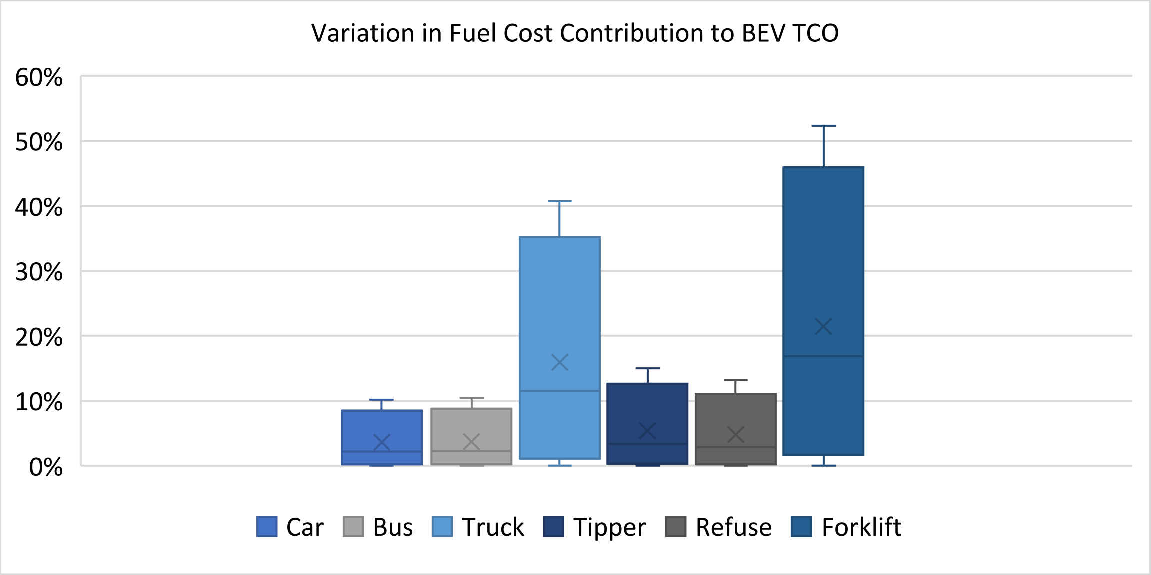


Figure 4-8 - The total variation in fuel cost TCO contribution for BEVs.

4.4.1.2. Base Case TCO:

The differences in baseline TCO between ICEV, BEV, and FCEV for each of the fleet vehicles is given in Figure 4-9 as an absolute value in £/km and as a percentage of the diesel baseline in Figure 4-10.

Looking back at Figure 4-5 and the tables in Section 10.1 in Appendix 1, for the vast majority of vehicles and fuel scenarios considered, the cost components with the greatest contribution to TCO are fuel and depreciation. For ZEV scenarios, the portion accounted for by depreciation is higher due to their increased purchase costs compared to ICEVs. The impacts of battery and fuel cell component replacement can also be significant for particular vehicle types and shows a variable impact across their TCO. For example, tippers, refuse, and forklift vehicles do not require replacements during their lifetime and therefore show a zero contribution from component replacement in their TCO. However, for cars, buses, and trucks, since they have much higher generic mileage requirements (shown in Table 3-7), battery and fuel cell replacements are necessary in order to maintain operation. The large variation in the contribution of these replacements to TCO is evidenced in the tables of Appendix 1 which for FCEV cars ranges from 19-21%, whilst for buses is only 1.5-1.8%. Although both vehicles only have one fuel cell replacement throughout their lifetime, this differential is largely attributed to the fact that passenger cars have a much lower initial purchase price (£60,000 compared to £500,000) and also have a larger fuel cell (114 kW compared to 75 kW), which accounts for a much larger portion of the total lifetime costs. For FCEV long haul trucks, the contribution of fuel cell replacements is also significant and ranges from 15-28%. Although the high mileage demands from trucks allows the costs to be spread out over more use, it means more replacements are required which incurs more costs.

Maintenance costs are fixed annual costs and have a significant impact on diesel HDVs, specifically for buses which incur the highest costs of £16,000/year but also for tipper trucks which have both low mileage and sizeable costs of £8,100/year. These costs are lower for ZEVs as they benefit from fewer moving parts in their powertrains, so the fraction of the TCO from maintenance is lower.

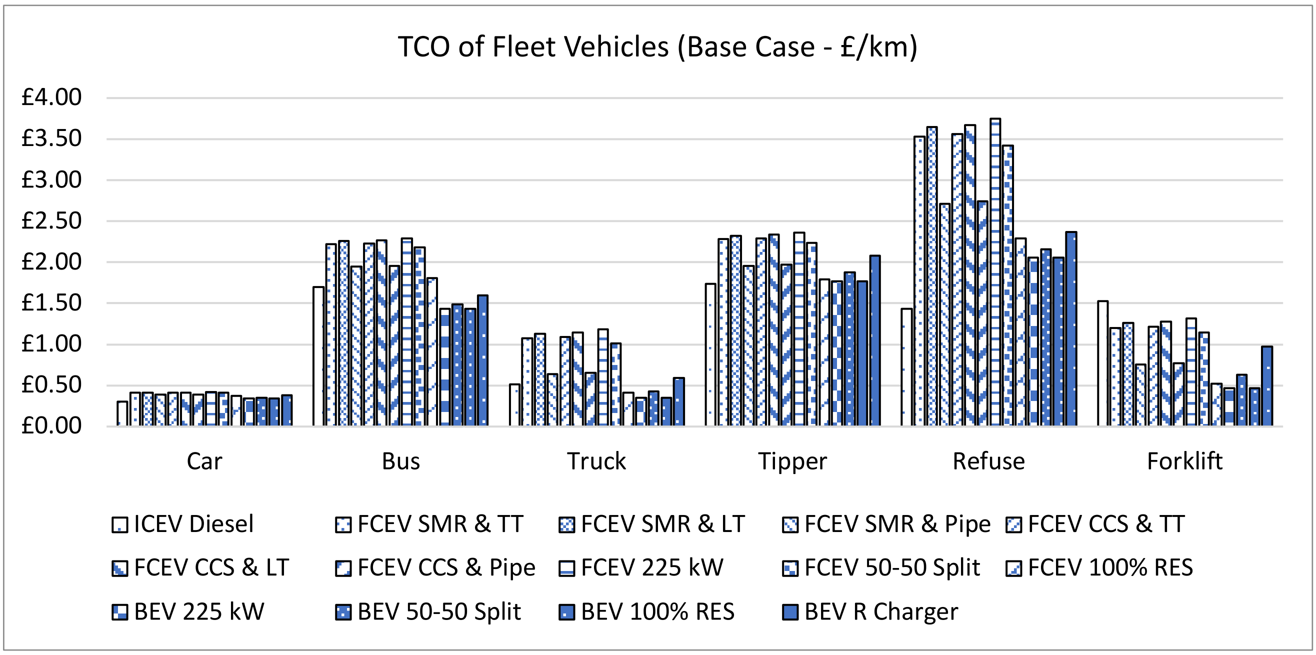


Figure 4-9 - TCO of all vehicles in the baseline scenario.[1]

[1] SMR: Steam Methane Reforming, CCS: Carbon Capture and Storage, 225 kW: 225 kW Turbine, 50-50 Split: Grid and Renewable Electricity, R Charger: Rapid Charger, TT: Tube Trailer, LT: Liquid Tanker, Pipe: Pipeline

Figure 4-9 shows that for all passenger car fuel scenarios, the TCO remains below £0.50/km. All BEV passenger cars offer cost advantages when compared to FCEVs and are the closest fuels considered to achieving diesel parity. The 225 kW turbine, 50-50 Split, and 100% RES electricity scenarios are only 12-16% more costly than diesel per km in 2021 (Figure 4-10), at £0.339/km, £0.352/km, and £0.339/km despite their higher vehicle purchase costs. Since BEV passenger cars benefit from their electricity being generated locally on-site, they avoid distribution costs which several hydrogen fuel scenarios incur. As most of the cost parameters are the same for FCEVs and BEVs (i.e. ZEV cars have the same purchase price, annual maintenance, tax and insurance, and component replacement frequency), the fuel cost is the only variable parameter to the TCO. As a result, the electricity price is critical to ensuring ZEV competitiveness. Consequently, the high cost of electricity from rapid chargers (£0.24/kWh) leads to a higher total cost per km. Therefore, cars fuelled using rapid chargers are currently 25% more expensive to run per km compared to diesel and are the most expensive electric fuel option.

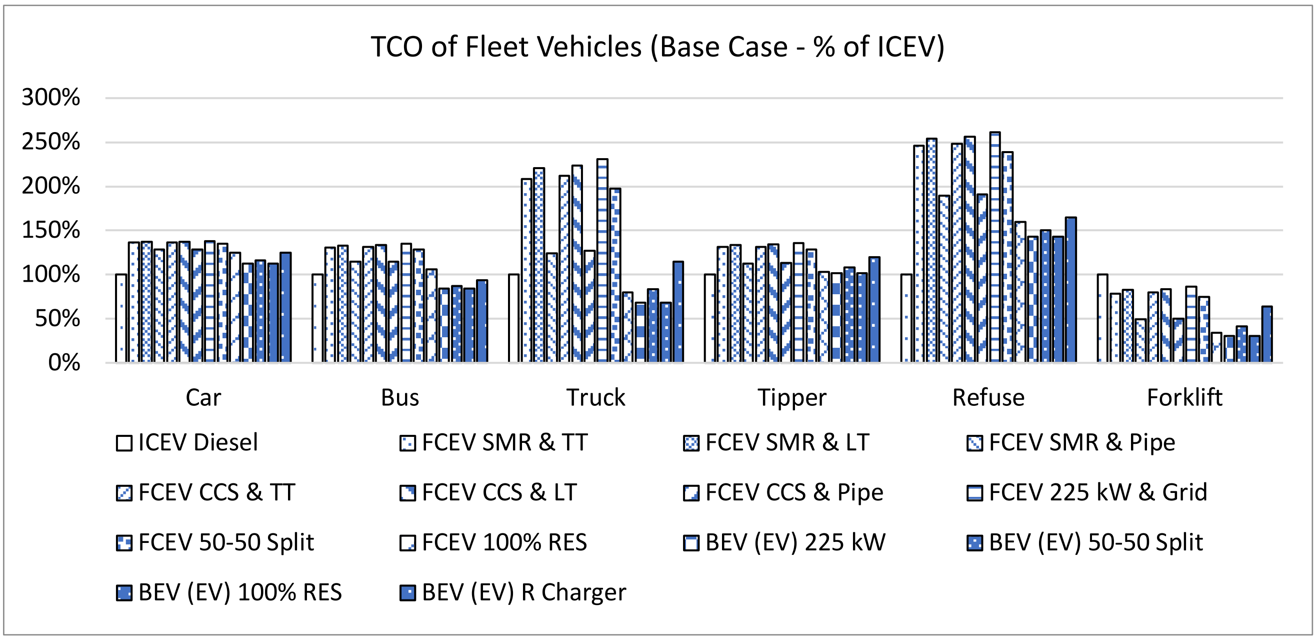


Figure 4-10 - TCO of all vehicles in the baseline scenario as a percentage of their diesel equivalent.

For FCEVs, costs must fall if they are to reach parity with other fuels. FCEV passenger cars in all hydrogen scenarios are more expensive than their ICEV equivalent. The most competitive scenario is 100% RES hydrogen, with a TCO of £0.377/km, which is still 25% higher than diesel and equal to the costliest BEV scenario (using rapid chargers). All other hydrogen scenarios give a higher TCO. The second most competitive route is hydrogen from SMR using pipeline distribution, which is still 29% more expensive than diesel per km. In terms of the costliest FCEV car scenario, liquefied hydrogen from SMR with CCS has a TCO of £0.416/km, 38% higher than diesel. This is largely due to the additional electricity demand associated with the liquefaction process, which requires 10 kWh/kg H_2. In addition, hydrogen transported using diesel powered tube trailers and liquid tankers incurs additional costs which should be acknowledged. It is evident from these figures that electricity currently offers greater cost advantages in terms of TCO in the passenger car sector when compared to hydrogen, partly due to its efficient generation but also because of the absence of conditioning and distribution stages.

For HDVs, ZEV refuse collection vehicles are the most expensive of all vehicles considered in the study with their TCO ranging from a minimum of £2.054/km (BEVs using 100% RES electricity) to a maximum of £3.746/km (FCEVs using 225 kW electrolytic hydrogen). This is because refuse vehicles have one of the highest purchase prices of all vehicles considered, a low daily mileage which reduces the spreading of costs per km, and a very high fuel consumption, especially in the case of FCEVs with 19.4 kg H_2/100km. Furthermore, as insurance is equal to 1.5% of purchase costs, refuse vehicles have one of the highest annual insurance costs. The largest cost component in the ZEV powertrain is the battery or fuel cell which is more expensive for HDVs with greater power demands. For diesel refuse vehicles however, TCO is much lower at only £1.435/km largely because of the difference in purchase price. Here, the diesel refuse vehicle costs only £152,500 compared to £357,000 and £400,000 for the BEV and FCEV equivalents.

Focusing on purchase prices, a number of FCEV HDVs (buses, trucks, and refuse vehicles) generally have a much higher TCO compared to their BEV equivalents. This is primarily because these vehicles have a high cost difference in their purchase prices, which has the greatest impact on overall TCO, since they directly influence annual depreciation and insurance costs. The difference in purchase cost for BEV and FCEV buses, trucks, and refuse vehicles is approximately £150,000, £100,000, and £43,000 respectively, shown previously in Table 4-6. In contrast, since the purchase costs of FCEV and BEV cars, tippers and forklifts are similar, they share a TCO that is more competitive.

Under these 2021 base case conditions, several BEV HDVs are already cost competitive with diesel. For FCEVs however, only forklifts are competitive. BEV buses, trucks, tippers, and forklifts are either below the diesel TCO baseline or close to reaching it. In particular, BEV trucks using 225 kW and 100% RES electricity are much cheaper on a per km basis than diesel or hydrogen, both at only £0.349/km. This is because the high mileage requirements and high fuel demands from trucks benefit from low renewable electricity costs. All FCEV forklifts are currently competitive with diesel, as are trucks with 100% RES hydrogen, though buses using hydrogen from 100% RES, SMR with pipeline, and SMR & CCS with pipeline are very close to reaching competitiveness being only 6%, 14%, and 15% more expensive per km. This data shows that hydrogen is only competitive with diesel in particular HDV applications and is yet to compete with battery electric since none of the FCEV TCOs are equal to their BEV equivalent.

4.4.2. Base Case Sensitivity Analysis:

Sensitivity analysis is a tool used to assess how changes in input data affect changes in output results. In this section several input parameters are now changed to examine their impact on TCO and the competitiveness of the powertrains. Variable inputs are split into two categories in Table 4-12: Common parameters applicable to all powertrains, and fuel-specific parameters applicable to either ICEVs, BEVs, or FCEVs. The variance of this new TCO against the base case is calculated and the TCO under each new condition is presented in radar plots to identify the impactful parameters; some of which some are taken forward and analysed further. Examples of these radar plots are given in Figure 4-11 and Figure 4-12; one for a FCEV passenger car, and one for a FCEV bus. Plots were made for all vehicle and fuel scenarios and are given in Sections 10.2-10.3 Appendix 1.

Table 4-12 - Common and fuel-specific input parameters considered for the sensitivity analysis.

Common Parameters	Fuel-Specific Parameters (ZEV)	Fuel-Specific Parameters (ICEV)
Ownership Period	Purchase Grant	Fossil Tax
Maintenance Cost	Road Use Charge	Diesel Price
Fuel Price	Fuel Price	Engine Price
Powertrain Price	Battery/Fuel Cell RV	
Powertrain RV	Battery Price	
Fleet Size	Fuel Cell Price	

The radar plots in Figure 4-11 and Figure 4-12 show the common parameters of ownership period and maintenance lead to the most significant changes in TCO, whilst parameters of residual value, powertrain price, and fleet size are less important with only minor impacts. For fuel specific parameters, the most impactful parameters were purchase grant, battery price, hydrogen fuel price, and battery and fuel cell residual value, highlighted in Table 4-13. To understand their effects on the competitiveness of ZEVs, TCO figures under these new conditions are calculated and discussed further using Figure 4-13 to Figure 4-20.

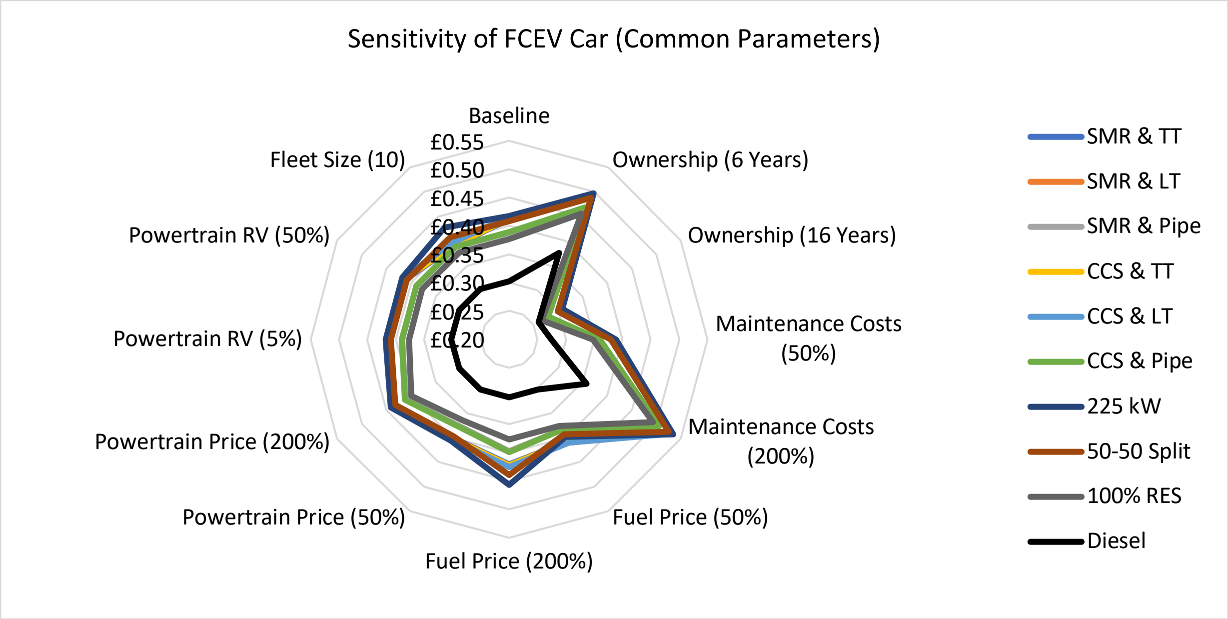


Figure 4-11 - Sensitivity of a FCEV car TCO to changes in common parameters (in £/km).

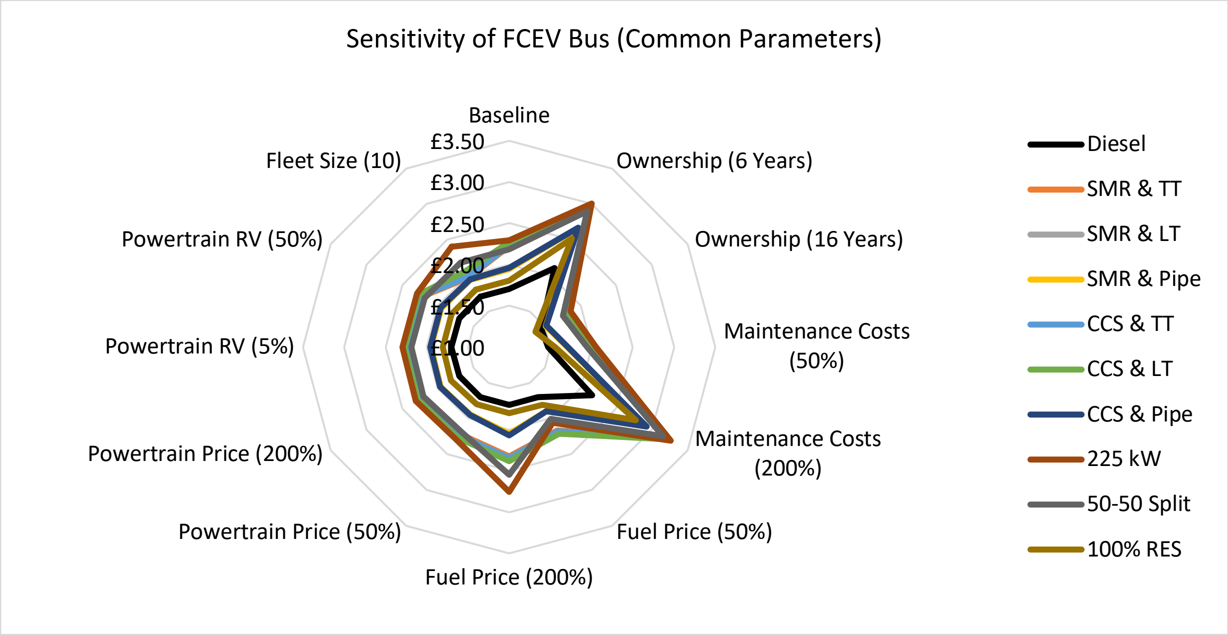


Figure 4-12 - Sensitivity of a FCEV bus TCO to changes in common parameters (in £/km).

Table 4-13 – The most impactful input variables on ICEV, BEV, and FCEV TCO.

Common Parameters	Fuel-Specific Parameters (FCEV-Focus)
Vehicle Ownership Period	Battery and Fuel Cell Residual Value
Maintenance Cost	Hydrogen Fuel Price
	Battery Price
	Purchase Grant

Table 4-14 – Values of parameters chosen in the sensitivity analysis.

Common Parameter:	**Comments:**
Ownership Period	A minimum and maximum ownership period of 6 and 16 years was applied in the sensitivity using Leeds City Council (LCC) fleets used as a guide. LCC typically use a 5-year replacement cycle for their vehicles, however some can last longer depending on the vehicle type and condition. The base case TCO used a 10-year service life which aligns with Glasgow City Councils 2020-2030 ZEV fleet strategy plan and considered both LDVs and HDVs [35]. This figure also aimed to encompass the average lifetime of a HDV in the UK, at 12 years [41].
Maintenance Cost	Maintenance costs can be highly variable and depend on a number of parameters such as the driving and weather conditions, driver behaviour, vehicle function, and powertrain maturity, for example. As a result, maintenance costs in the sensitivity range from 50%-200% of the base case values respectively. Although it is unexpected for maintenance costs to rise significantly due to the technology developments and increasing maturity of these vehicles, this upper bound aims to offer a conservative range in the event of severe maintenance issues taking place. Similarly, the lower bound value used was no lower than 50% due to the fact that vehicle service and maintenance will always be required by law, regardless of technological advancements.
Fuel Specific Parameter:	**Comments:**
Electricity and Hydrogen Price	Fuel costs are highly variable and depend on the production route, energy availability, and production volume, for example. To account for these factors, the prices in the sensitivity range from 20% lower to 20% higher than base case figures. Although fuel production and energy generation costs can fall over time due to scale up of technology or a change in weather condition (which is acknowledged by a 20% drop in fuel cost), for ZEV fuels the sensitivity also considers increasing costs as a result of energy security issues. For example, electricity prices have increased over the past 10 years with the average energy bills rising 36% between 2020 and 2021 due to the impacts of Covid-19 and an increased demand [53]. Although renewable electricity can be used, this can suffer from intermittency issues and so a high reliance is still placed on grid electricity where the costs per kWh are highly influenced by external factors. This 20% rise aims to account for these potential impacts.
Battery and Fuel Cell RV	Battery and fuel cell residual value is varied from a minimum of 5% to a maximum of 50% of its original price in the sensitivity. RV can vary depending on the condition of the components and their applicability to (as well as demand from) secondary applications. Powertrain components are not expected to be disposed without upgrading and secondary use due to the expensive materials they contain, along with the emissions savings associated with the evasion of raw material extraction and virgin production. However, faulty components which are unsuitable for second use are dismantled and recycled and therefore have a lower economic value.

	As a result, there is expected to be monetary value contained in even the most degraded components after first use, which is reflected by a 5% minimum imposed for their RV. On the other hand, since batteries are capable of retaining up to 80% of their original capacity after first use in a vehicle, and fuel cells can be used as backup generators or energy storage systems, they also have the potential to recover a sizeable portion of their original cost when resold, which is reflected by a 50% RV. Unfortunately, because BEVs and FCEVs are still relatively new to the transport sector and limited numbers have reached their EOL, there are no historical records or published documents which are available that can offer an accurate figure for the RV of their powertrain components, therefore estimates have had to be made.
Battery and Fuel Cell Price	The battery and fuel cell components of ZEVs contribute greatly towards their high upfront costs and have been falling in price substantially over the past decade. In this work a minimum value for battery and fuel cell components is given at £100/kWh and £100/kW. This figure for lithium-ion batteries is in line with predictions by EDF [49] who state that these cost reductions are likely to continue in the future, largely driven by a UK government target on BEVs which aims to see 50% of all new vehicles sales in 2030 being electric. Fuel cell costs have also been falling due to scale up of production volumes and as a result, the price of FCEVs has fallen ~65% over the past decade. With the Department of Energy having a target of achieving fuel cell costs under £100/kW for an annual production of 150,0000 systems/year, this target is used as the basis for this lower bound [50]. For the upper bound costs, estimates were difficult to source in literature since these depend largely on production volume and scale. As a result, the lower bound costs are doubled giving costs of £200/kW and £200/kWh respectively.
Purchase Grant	The two rates of purchase grants in the 2021 base year were covered previously in Section 4.3.3 and are aimed to reduce the high upfront costs associated with ZEVs to incentivise their uptake. These rates differ for FCEVs and BEVs based on their maturity.

4.4.2.1. Vehicle Ownership:

The ownership period was varied from a minimum of 6 years to a maximum of 16 years which aimed to encompass the average lifetime of a HDV in the UK, which is 12 years [41]. This is shown in Figure 4-13 and Figure *4-14*. The only components of the TCO influenced by ownership are depreciation and component replacement, since batteries and fuel cells are replaced after 10 years of operation. Fuel costs in the base case analysis are fixed at 2021 prices and it is assumed that maintenance, tax, and insurance costs remain consistent over each year the vehicle is owned. Diesel vehicles benefit from low purchase prices (and depreciation costs) compared to ZEVs, though their higher fuel costs gradually reduce this advantage over an increasing ownership period.

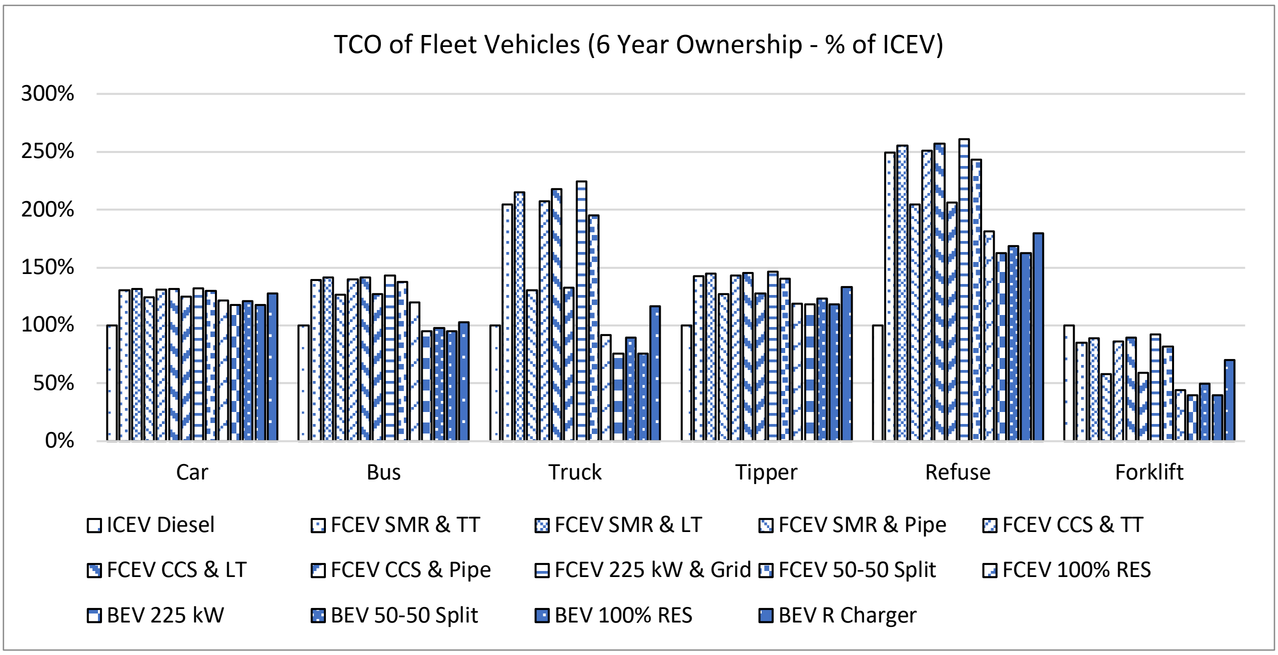


Figure 4-13 - TCO of fleet vehicles with a 6 year ownership period.

For a short service life of 6 years, all ZEV cars have a higher TCO compared to diesel; none of the vehicles are competitive under these conditions. This is partly due to the fact that ZEVs have lower operating costs compared to ICEVs and if they are not used for a time period long enough for the benefits to be seen, their higher purchase prices will not be offset. The cheapest hydrogen scenario comes from 100% RES hydrogen with a TCO of £0.456/km, compared with only £0.376/km for diesel cars; equivalent to a 21% premium per km. As for electricity, the cheapest is from 225 kW and 100% RES, both at £0.442/km which is still not yet competitive with diesel, being roughly 18% higher, though it is still 3% (or £0.014/km) less than the cheapest FCEV scenario. As a result of reducing ownership from the 10 year base case to 6 years, the lowest FCEV TCO increases from £0.377/km to £0.456/km (21%), whilst for BEVs this rise is even higher at 30%.

Increasing ownership to 16 years allows the full benefits of ZEV low operating costs to be appreciated. The TCO of cars using 100% RES hydrogen drops by £0.11/km (29%) to £0.267/km compared to base case figures and they now closely approach competitiveness with diesel cars, which are only 3% more per km, down from 25%. FCEV cars using hydrogen from SMR and SMR & CCS with pipelines also closely approach parity with diesel, now only 7% and 8% more per km, both at £0.28/km compared to £0.26/km. Despite hydrogen fuel scenarios closely approaching diesel parity for car applications, 3 out of the 4 BEV fuel scenarios surpass diesel TCO, with only electricity from rapid chargers remaining more expensive (by 9% per km). These results suggest electricity remains the lowest cost option for LDV transport under both 6 and 16 year ownership periods, respectively.

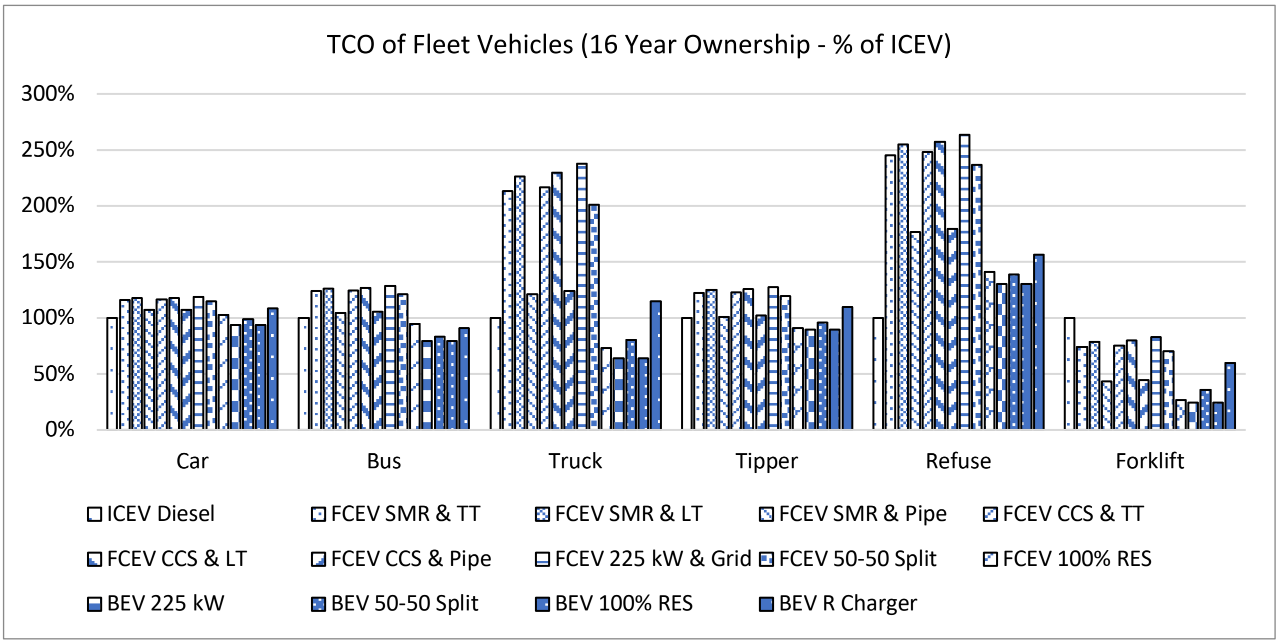


Figure 4-14 - TCO of fleet vehicles with a 16 year ownership period.

FCEV trucks running on 100% RES hydrogen, and forklifts running on hydrogen from all fuel scenarios are already competitive with ICEVs under a 6 year ownership period. The economics of FCEVs improves further with the extension of the ownership period to 16 years as buses utilising 100% RES hydrogen now also become competitive, as do tippers running on hydrogen from 100% RES and SMR and SMR & CCS with pipeline transport. The TCO of all other vehicles and hydrogen fuels remain higher than their ICEV equivalents.

Increasing ownership to 16 years from 6 years sees improvement in the competitiveness of some FCEV HDVs against ICEVs. One reason why the TCO of some vehicles (such as trucks and refuse vehicles) remains high compared to diesel and change is minimal is because under a 16 year ownership fuel cell and battery replacements are now required, incurring additional costs raising their TCO. For larger vehicles with high battery and/or fuel cell requirements, this cost counteracts any savings over the increased lifetime.

Figure 4-13 and Figure *4-14* highlight that 100% renewable hydrogen gives lowest costs across all HDV types. For buses using this fuel, the saving is £1.15/km from 6 to 16 years, and £0.43/km from the 10 year baseline condition (Figure 4-9) to a 16 year ownership. Hydrogen from SMR and SMR & CCS with pipeline transport remain the second cheapest fuels for FCEVs. Buses and tippers with these fuel scenarios have very similar costs per km to their diesel counterparts after 16 years of ownership. The most expensive FCEV TCO figures are from trucks and refuse vehicles utilising on-site electrolytic hydrogen from a 225 kW turbine at £1.309/km and £4.76/km with a 6 year ownership. After 16 years these costs fall to £1.117/km and £3.137/km; equivalent to a 15% and 34% reduction.

4.4.2.2. Purchase Grant:

The high purchase grant applied to the TCO was shown in Figure 4-2 and applies to ZEVs as a financial incentive to reduce the high upfront costs and encourage users to switch to low carbon transport modes. In the 2021 base year, this grant discount is 20% for BEVs and 40% for FCEVs. ICEVs are not subject to discounts since they are mature and likely to be phased out once the diesel ban comes in effect.

Compared to base case results, the use of a purchase grant for BEVs and FCEVs has a positive impact on their TCO. The highest cost comes from refuse vehicles utilising 225 kW hydrogen which was £3.75/km in the base case, now falling to £2.91/km; a reduction of over 22%. For the costliest electricity scenario in the base case, refuse vehicles using rapid chargers had a TCO of £2.37/km, falling to £1.99/km with the grant applied. This is a reduction of over 15%. The impact of this discount is greater for FCEVs since the discount is double that of BEVs, but also because FCEVs generally have higher upfront costs so see a larger absolute saving. The reason for this higher FCEV discount is because their market is not fully developed and uptake is low. BEVs are much more common and are popular new purchases so do not need high discounts.

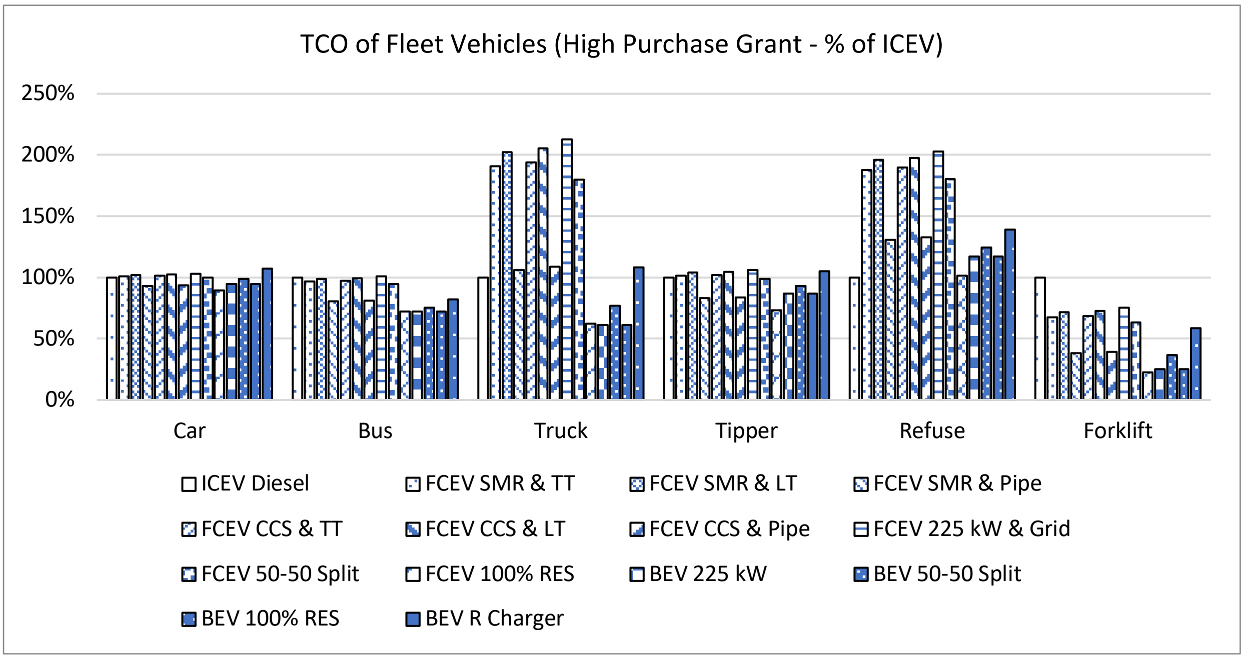


Figure 4-15 - TCO of all fleet vehicles with a high purchase grant.

After the addition of a purchase grant, Figure 4-15 shows that for most FCEVs, the TCO is now roughly equal to or below ICEVs regardless of the fuel scenario used. The only vehicles which have a TCO higher are trucks and refuse vehicles. However, if hydrogen from SMR or SMR & CCS with pipeline transport is used the TCO of trucks is only 6% and 9% higher per km. For all vehicles except trucks, the lowest TCO from all fuel scenarios comes from 100% RES hydrogen. The fuel which gives trucks the lowest TCO, and the majority of other vehicles their second lowest TCO is BEVs utilising 100% RES electricity respectively. Only cars and tippers have three hydrogen fuels which offer a TCO lower than electricity (100% RES, SMR and SMR & CCS with pipeline). Trucks and refuse vehicles running on hydrogen with tube trailers or liquid tankers, as well as electrolytic grid hydrogen, are still far from competitive with diesel or electricity because of their high fuel costs per kg. This is amplified by the high mileages of trucks and the high fuel consumption of refuse vehicles. In terms of the lowest cost HDV FCEV, this comes from trucks operating on 100% RES hydrogen at only £0.41/km, dropping to £0.32/km with the grant, making it the third lowest truck TCO of any fuel in the study, now significantly cheaper than the diesel scenario and similar to BEVs. However, unlike BEVs, FCEV trucks do not suffer any indirect impacts from their batteries, which have been known to restrict payload capacity and impact productivity because of refuelling times, which should be considered outside of TCO analysis. This is discussed in more detail in later sections, respectively.

Since several FCEVs are economically competitive with BEVs after addition of this grant, if it was only applied to FCEVs many of the BEVs would lose their edge and it would create a more attractive business case for hydrogen as a transport fuel for HDV use. Figure 4-16 shows the TCO of fleet vehicles with only the FCEVs in receipt of the high purchase grant. In this case, the lowest TCOs for each vehicle arise from FCEVs, not BEVs.

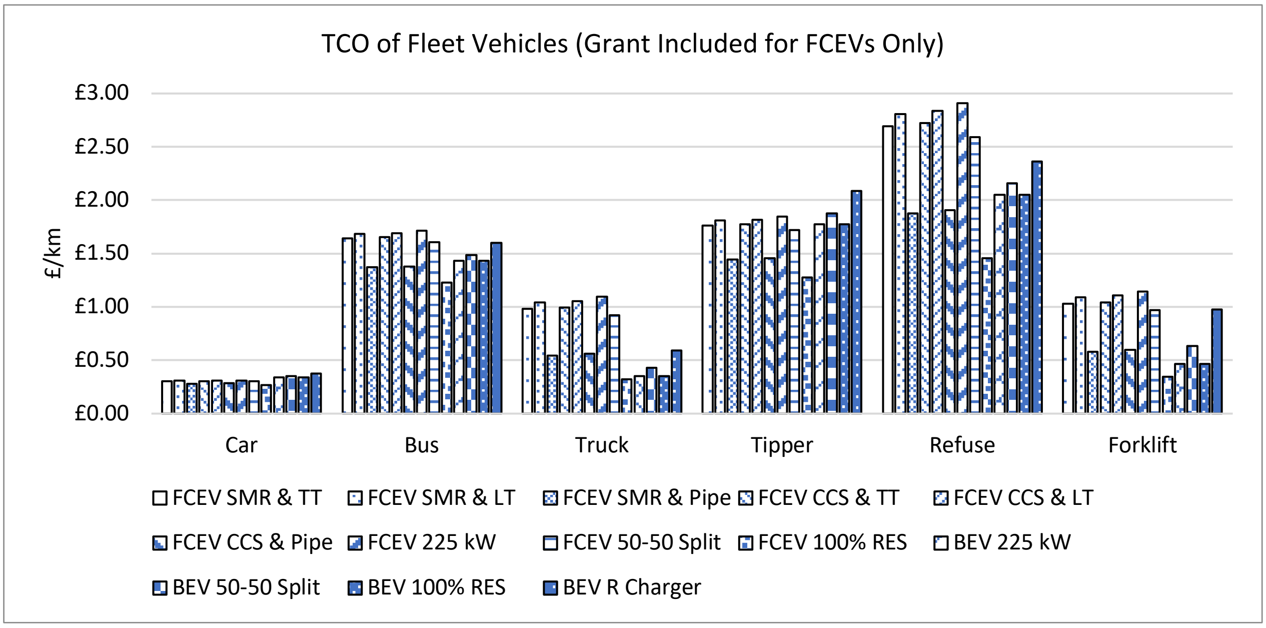


Figure 4-16 - TCO of fleet vehicles with grant included for FCEVs only.

4.4.2.3. Battery and Fuel Cell Residual Value:

Once a battery or fuel cell reaches its end of life, it must be replaced to maintain a high vehicle efficiency. However, these components still retain a significant portion of their original capacity. Casals *et al.* [24] suggest that lithium-ion batteries are capable of retaining up to 80% after 10 years of operation, which could be used in other applications outside of transport. Spent fuel cells can also be used for backup power applications, replacing diesel generators. Since these components still hold value, many batteries and fuel cells are resold rather than being disposed or recycled. In this work a baseline residual value for batteries and fuel cells of 30% and 20% was used, which is in line with current estimates from Battelle [25]. The sensitivity analysis considers a maximum value of 50% since these components are likely to increase in value as uptake increases. The results of a high RV on the TCO for ZEVs are shown in Figure 4-17.

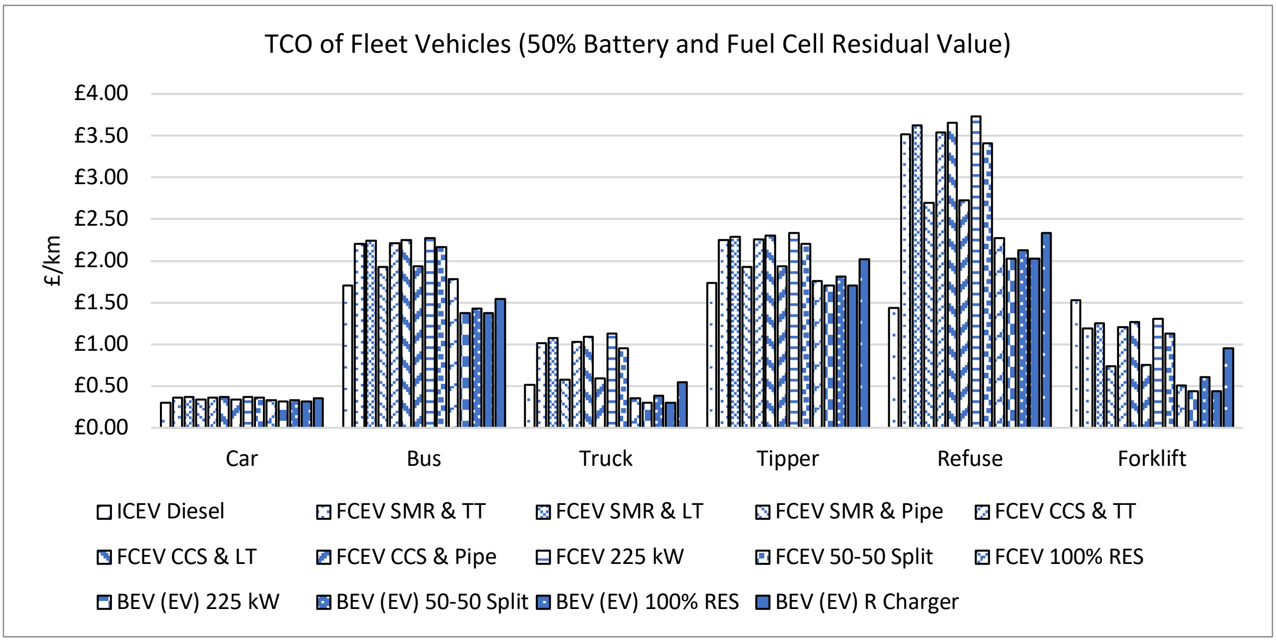


Figure 4-17 - TCO of all fleet vehicles with a 50% battery and fuel cell residual value.

Since ICEVs do not have batteries or fuel cells, their results remain unchanged from the base case. However for ZEVs, a residual value of 50% leads to lower depreciation over the vehicle life and reduced costs overall per km since a larger resale amount is deducted from the initial purchase cost. For buses and trucks requiring large batteries and fuel cells to provide for their longer duty cycle requirements, they will retain a larger cost when sold compared to smaller vehicles with smaller powertrain requirements. However, the impact of this increased RV has only a minor influence on FCEV competitiveness. For example, buses running on hydrogen from SMR with tube trailers with a 50% fuel cell RV have a cost of £2.20/km compared to their base case of £2.22/km, which is a decrease of only £0.02/km (~1%). For a FCEV bus, the highest TCO is £2.27/km from a 225 kW turbine and the lowest TCO is only £1.78/km with 100% RES. For BEV buses the TCO is lower, with the minimum and maximum ranging from £1.374/km using 100% RES to £1.542/km with rapid chargers.

4.4.2.4. Fuel Price:

Fuel cost is the only variable influencing the percentage contribution each parameter makes to the total cost per km. The total variation in fuel costs in £/km across all vehicle types for each of the 3 powertrains was given earlier in *Figure 4-6*. For FCEVs, fuel costs differ from £0.012/km to £1.453/km; a much wider range compared to electric fuel scenarios and diesel. This is because hydrogen fuel is produced and delivered in more ways, each with a different cost depending on the distribution route and its conditioning requirement. For example, hydrogen transported using diesel powered tube trailers and liquid tankers incurs additional costs associated with the driver salary and vehicle OPEX, something that pipeline transport and electrolysis scenarios avoid. Generally speaking, electricity is the cheapest fuel option with a maximum of only £0.51/km whilst for diesel this is £1.12/km. Since fuel costs are significant to the TCO, these figures are very influential to the competitiveness of ZEVs and FCEV technology in particular.

For HDV FCEVs, trucks show the highest contribution from fuel cost ranging from 37-65% of the TCO depending on fuel used, whilst tippers have the lowest contribution with 9-25% (Section 10.1 in Appendix 1). This gives the total contribution range fuel cost can give towards the TCO for HDV FCEVs. For BEVs the range is narrower with forklifts having a maximum contribution of 52% compared to the minimum of 0% for renewable electricity.

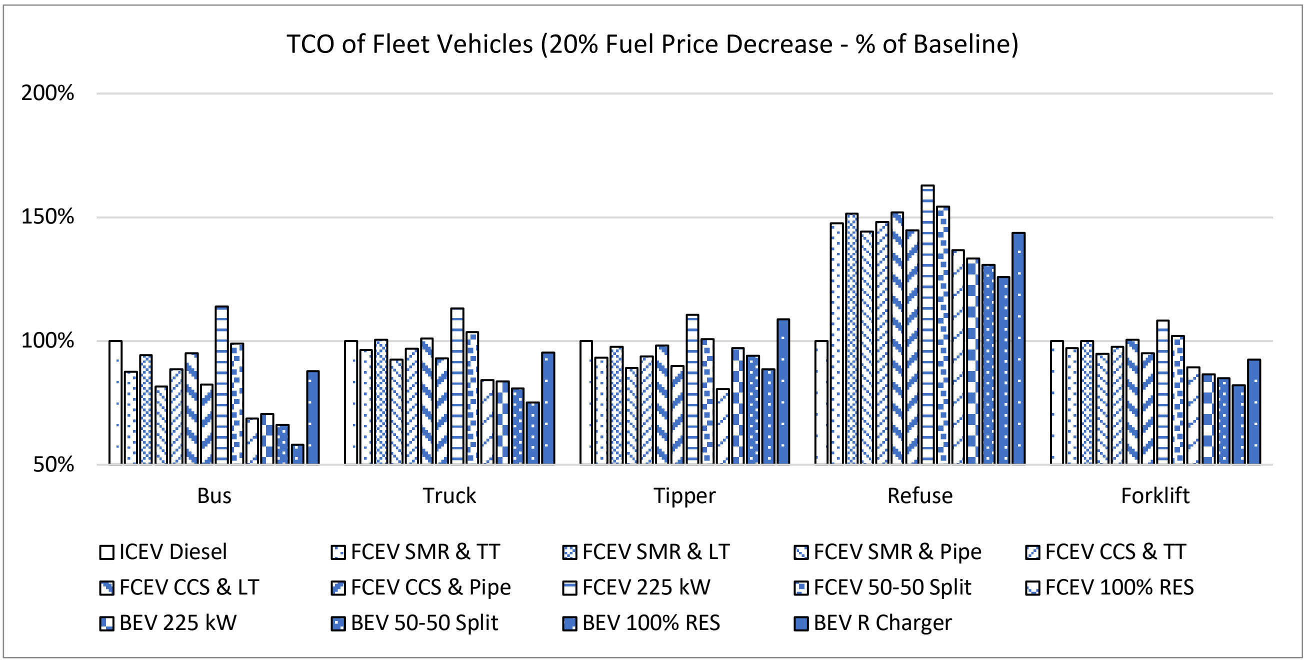


Figure 4-18 - TCO of all fleet vehicles when subject to a 20% reduction in fuel price.

The price of hydrogen is expected to fall in the future due to improvements in electrolyser efficiency and scale up of production as a result of an increased demand due to a growing market. In addition, the cost of green hydrogen from renewables has been predicted to fall below grey or blue hydrogen per kg due to the ongoing conflict in Ukraine/Russia where natural gas prices have soared due to supply issues [63]. To reflect these changes, a hydrogen cost 20% lower than the base case scenario is assumed. Since this has no bearing on ICEVs and BEVs, the TCO for vehicles using these fuels remains unchanged. The impact of this reduction is that all FCEV buses, trucks, tippers, and forklifts running on hydrogen from any fuel scenario (except for 225 kW electrolytic hydrogen) has a TCO equal to or lower than diesel (Figure 4-18). However, this 20% fuel price reduction is still not enough to bring all FCEV costs below BEVs, which still remain the cheapest powertrains for most vehicles. Only electricity from rapid chargers remains higher than several hydrogen scenarios.

4.4.2.5. Battery Price:

Average lithium-ion battery prices were reported at ~£711/kWh in 2010 and have dramatically fallen over the last decade with batteries reaching approximately £101/kWh in 2020 [314]. Future projections see these prices continuing to fall due to the introduction of new pack designs, expected growth in BEV sales, and the subsequent production volume scale up, and are expected to fall below £80/kWh by 2023. As a result, the sensitivity of the TCO to a drop in battery price was investigated using a cost of £100/kWh, with results shown in Figure 4-19.

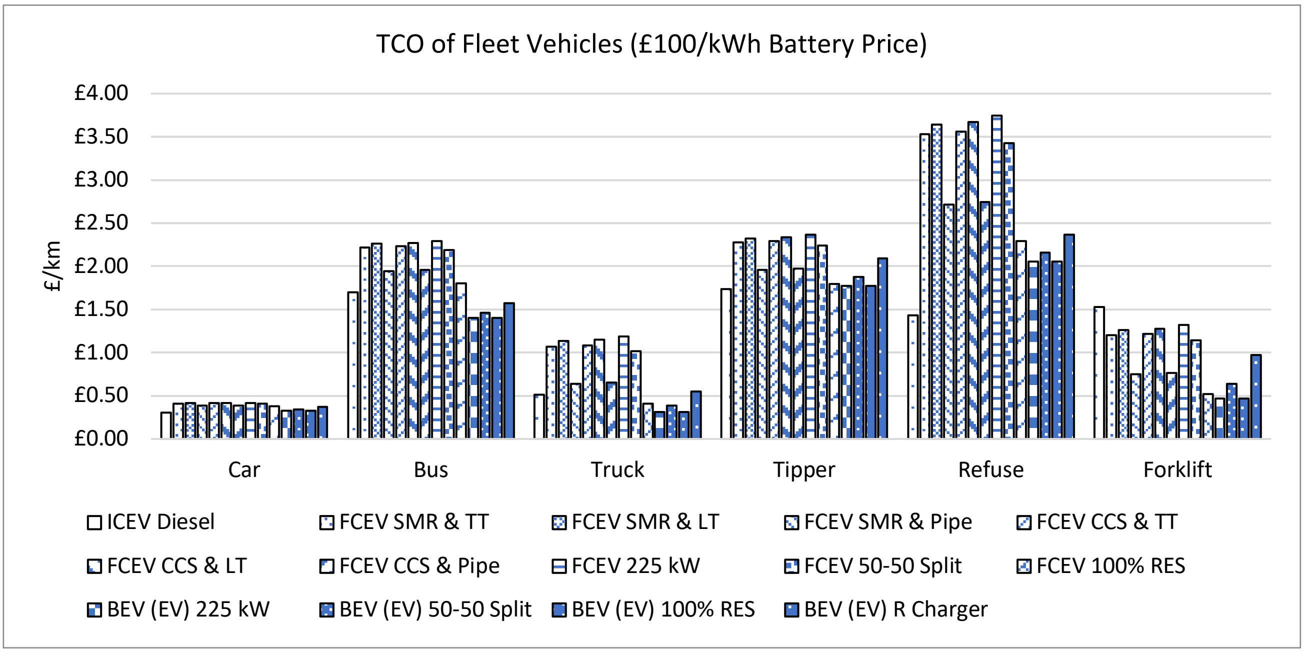


Figure 4-19 - TCO of all fleet vehicles with a £100/kWh battery price.

Since ICEVs don't have batteries their TCO remains unchanged. As for FCEVs, although these vehicles have electric batteries, since their size is small the impact of this battery price change on the TCO is negligible and doesn't alter the competitiveness of the vehicles. For example, a FCEV bus has a 20 kWh battery and assuming hydrogen from SMR with TT is used its TCO in the base case is £2.22/km. After reducing the battery costs, this value remains the same. This is the same for other HDVs, with no noticeable changes to their costs per km.

This battery price drop doesn't appear to have much of an impact on light duty BEVs either. For cars using rapid chargers, the base case costs were £0.38/km and after reductions this figure fell to £0.37/km, which is a decrease of only ~2%. Even for HDV buses and trucks with much greater batteries, when using rapid chargers the impact of battery prices was low with the base values of £1.60/km and £0.59/km falling to £1.57/km (1.6% drop) and £0.55 (6.6% drop). Therefore, in order for battery price to have any significant impact on lowering TCO, it must fall much lower than £100/kWh in the future.

4.4.2.6. Maintenance Cost:

In the early stages of uptake where only a small number of FCEVs are available on the market and where specialised fuel cell mechanics are limited, the issues surrounding their operation are not as well understood as ICEVs and therefore more maintenance may be required. Despite this, maintenance costs are likely to fall in the future due to the increasing number of ZEVs on the road improving the knowledge and understanding of their operation, meaning the issues can be prevented sooner. As a result, an annual maintenance cost equal to 50% of the base case figure for each vehicle is used to identify this impact on the TCO, shown in Figure 4-20.

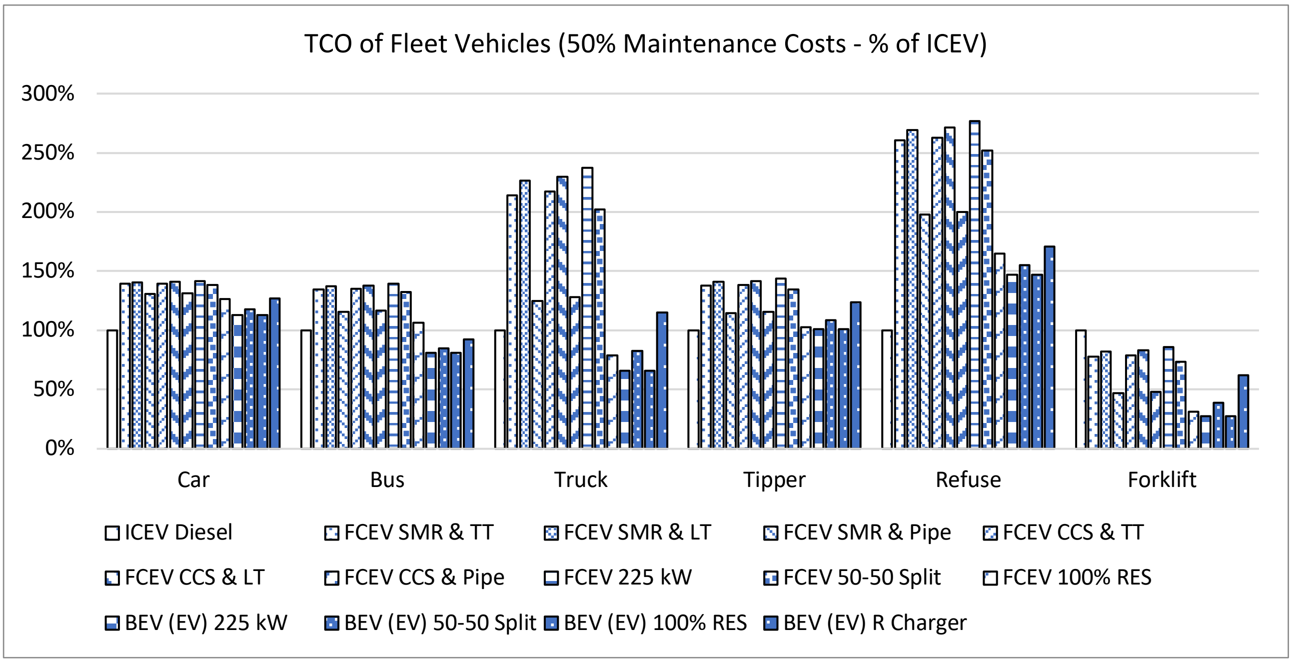


Figure 4-20 - TCO of all fleet vehicles with a 50% reduction in maintenance costs.

The annual maintenance costs in the base case scenario were highest for diesel buses and trucks at £16,000/year and ~£14,000/year, whilst all costs were 30% lower for their ZEV equivalents. As a result, the impact of reducing annual costs by 50% is seen more clearly by ICEVs benefitting from a larger saving on a per km basis. This is because all vehicle types carry out the same mileage irrespective of their powertrain and all the other parameters remain unchanged. As a result, the TCO of ICEVs falls further per km compared to ZEVs, so the cost competitiveness of ZEVs is worsened. This is shown in Figure 4-20 as the difference between the TCO of ZEVs and ICEVs for each vehicle increases after the reduction of maintenance cost. In the case of buses which have the highest costs, across all the FCEV buses in the base case (9 fuel scenarios), the TCO ranged from 6-35% higher per km compared to ICEV buses, with no FCEV buses cost competitive with diesel. After this maintenance cost drop, the range now increases from 6-40% respectively, worsening competitiveness.

4.4.3. Fleet-Specific Mileage:

All TCO results to this point have used the generic mileage figures presented earlier in Table 3-7 and Table 3-8 which were taken from a range of different fleets and locations and used to represent a generic scenario for fleet vehicles. Now, more specific mileage figures taken from a fleet in Leeds (UK) are used to examine the influence of mileage on TCO. The fleet used in this case is Leeds City Council (LCC) respectively.

All annual mileage data collected from LCC refers to the 2018/2019 year. Data over this time period was desirable since one of the impacts of Covid-19 was a reduction in the demand of various services, therefore vehicle fleets saw a reduction in their average mileage. As a result, mileage figures from 2020 onwards are not considered to be an accurate representation of typical figures. Data from LCC was taken from the Data Mill North online datastore and all annual mileage figures for each individual vehicle were averaged and the final figures were used as the basis for this analysis. Final figures are summarised in Table 4-15.

Table 4-15 - Annual mileage figures for LCC fleet for the 2018/2019 year.

	Average Annual Mileage (km - top) and Quantities (bottom)			
Fleet (& Year):	**Car**	**Bus**	**Tipper**	**Refuse**
LCC (2018/2019)	18,524	28,759	11,464	19,141
	12	23	21	23

Whilst LCC operates an extensive number of vehicles, they do not own or operate long haul trucks or forklifts which are considered in the vehicle stock list of this study. As a result, no mileage data is available which can be used to represent these vehicle types. In order to overcome this, mileage data was sourced from other council fleets outside of Leeds. Freedom of Information requests were made to councils which operate these vehicles. Data for long haul trucks was sourced directly from Moray Council (MC) in Scotland for the 2018/2019 year, whilst data for forklifts was estimated using the study by Zajac *et al.* [59]. This study investigated methods to determine forklift energy consumption and recorded the time taken to complete the VDI 2198 cycle with no set speed limit restrictions. Using this information, the average speed of the forklift was calculated in Table 4-16, along with the annual mileage using the average annual operation of a typical forklift (given at 2,000 hours/year), taken from Toyota Material Handling [60]. A summary is given below.

Table 4-16 - Estimate of annual mileage for a typical forklift.

VDI Cycle Total Distance (m)	Cycle Time (s)	Forklift Speed (km/h)	Average Operation (h/year)	Annual Mileage (km/year)
78.6	81.52	3.47	2,000	(3.47 x 2000) = 6,939

Since a complete set of mileage data from LCC was unavailable, the truck and forklift annual mileage figures in Table 4-17 have been assumed representative of a typical council fleet.

Table 4-17 - Annual mileage for long haul trucks and forklifts.

Vehicle Type	Council (& Year)	Annual Mileage (km)
Long Haul Truck	Moray Council (2018/2019)	134,532
Forklift	Based on work by Zajac *et al.* [59]	6,939

Similar to the graphs already covered in this section, Figure 4-21 shows the TCO of fleet vehicles under these new mileage figures in £/km respectively.

For the majority of vehicles, annual fleet-specific mileage figures shown in Table 4-15 and Table 4-17 are lower than the generic mileage figures from Table 3-7, albeit with varying extents. Long haul trucks have a generic annual mileage in the base case scenario of 173,740 km, compared to only 134,532 km in Table 4-17 when using data from MC, equivalent to a ~23% reduction. However, for refuse vehicles, fleet-specific annual mileages are the same as the generic scenario. Similarly, tipper trucks also show an annual mileage close to the base case scenario with a small decrease of only 166 km/year. Taking these changes into account, the TCO of refuse vehicles in Figure 4-21 remains unchanged to the base case, so is not discussed. For tippers, their change in TCO is also negligible so they will not be discussed extensively either. As a result, this section focuses on cars, buses, trucks, and forklifts.

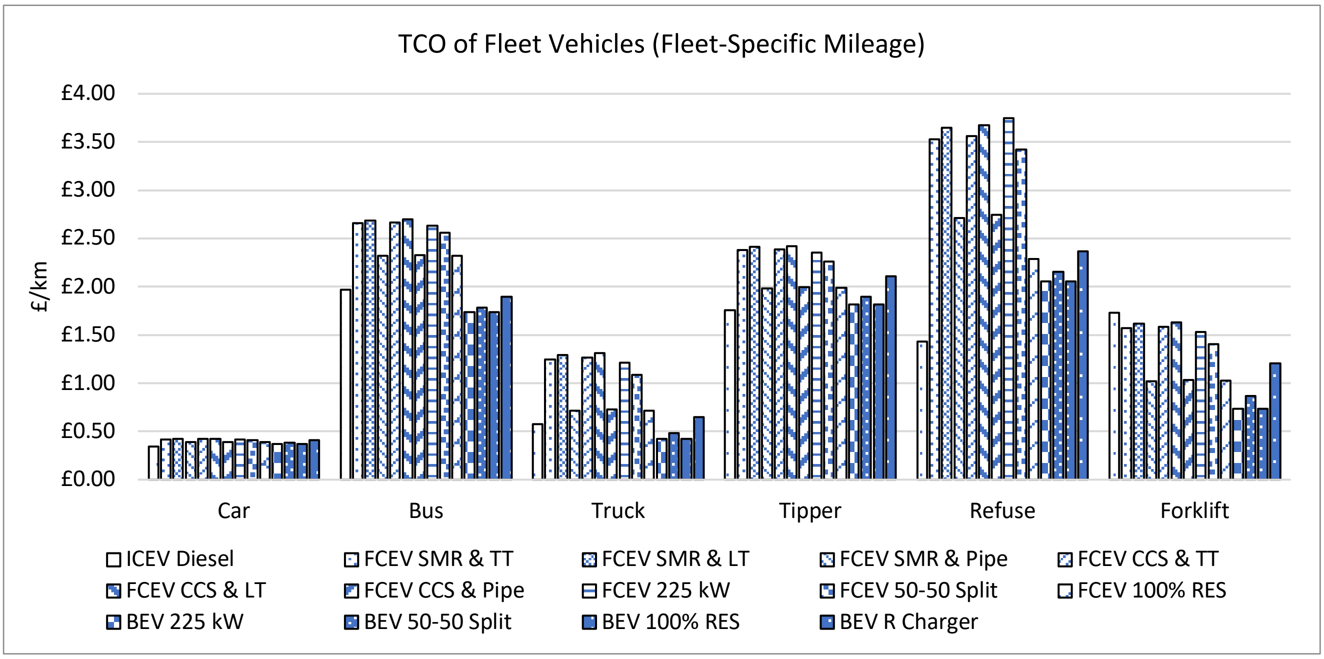


Figure 4-21 - TCO of fleet vehicles under a fleet-specific mileage scenario.

Since the annual mileage of cars, buses, trucks, and forklifts is now reduced when using this new data, their TCO when running on any of the fuel scenarios (in Figure 4-21) increases as a direct consequence compared to the base case (in Figure 4-9), since the costs are spread over fewer kilometres. The extent of this increase depends on the severity of the mileage change, respectively. However, the impacts can be illustrated using the minimum and maximum TCO figures. For example, the TCO for buses and trucks in the base case (Figure 4-9) ranged from

£1.43-£2.29/km (buses) and £0.35-£1.19/km (trucks). Now, when using these lower fleet-specific mileage figures, their TCO rises to £1.74-£2.70/km (buses) and £0.41-£1.31/km (trucks), shown in Figure 4-21.

In addition to the spread of costs, because ZEV powertrains generally show cost advantages over long service periods due to their lower operating costs, the impacts of a reduced mileage contribute further to these increased costs per km. This is a similar pattern to vehicle ownership in Section 4.4.2.1. In terms of the cost competitiveness of the fuels for each vehicle, for the vast majority considered, these do not change from the base case. Across all vehicle types, BEVs still remain the most cost competitive powertrains and electricity from both 225 kW and 100% RES remain the cheapest BEV fuels.

For the four vehicle types covered, only hydrogen from the 225 kW turbine becomes a more competitive solution compared to the base case. For example, in the base case (Figure 4-9), cars, buses, trucks, and forklifts using 225 kW hydrogen had the highest FCEV TCO, largely due to the reliance on grid power to provide the remaining electricity to produce the hydrogen required. However under fleet-specific mileages, Figure 4-21 shows this 225 kW hydrogen scenario now becomes more cost competitive and is no longer the most expensive hydrogen fuel scenario for these vehicles, as some non-electrolytic hydrogen scenarios become more costly per km. The reason for this change in competitiveness is due to the fleet-specific nature of the 225 kW hydrogen production route. In this case, as the vehicle mileage is reduced under these new conditions, the hydrogen consumption falls, and the quantity of electricity required to produce the hydrogen is lower. This means the turbine accounts for a larger portion of the total energy required and less electricity is drawn from the grid, reducing hydrogen costs, which are reflected by these changes.

One other factor impacted by these mileage changes is the component replacement costs. As mentioned in Section 4.3.5, battery and fuel cell replacements are carried out after either 10 years have passed or when vehicle mileage exceeds 200,000 km. Under the new mileage conditions, the only vehicle which shows a change in component replacement frequency is trucks. In this case, the impact of a reduced annual mileage leads to fewer replacements over its lifetime. In the base case, trucks required 8 replacements which incurred additional costs of £311,000 (for fuel cells) and £352,000 (for batteries) spread over their lifetime. Now, under the new conditions in Table 4-17 only 6 are required, leading to cost savings of ~£78,000 (for fuel cells) and ~£88,000 (for batteries), encouraging the TCO to fall. However, despite these cost reductions, the impact of spreading total costs over a significantly lower number of kilometres (39,208 km) still leads to a higher TCO than the base case.

4.4.4. Future Outlook:

To complement the analysis of the 2021 base case, a future outlook examines the change to the TCO from 2021 to 2050 due to time-sensitive parameters like electricity price, electrolyser efficiency, and vehicle component costs. This offers insight into the years which ZEV TCOs intersect ICEVs and become more favourable.

This section first showcases the TCO for each vehicle and fuel scenario with no added incentives or deterrents (the future base case), with results provided in Figure 4-22 and Figure *4-23*. After this, model conditions are changed and two rates of fossil tax and purchase grants are applied to assess their impact on the TCO of FCEVs. As highlighted previously, when assessing the TCO of each vehicle type using the same powertrain (i.e. all FCEV buses, all BEV trucks etc.), the only parameter that varies in cost per km is fuel cost. Since this work targets the suitability of hydrogen for HDV applications, the future TCO analysis will focus on these fuel costs. To limit the size of these sections, they will only showcase results for buses and trucks since these HDVs are the two most common with FCEV versions already in use in many fleets and with others in development.

4.4.4.1. Future Base Case:

In the base case future outlook, fossil tax is not applied and because combustion technology is mature, fuel consumption for ICEVs remains constant. As a result, TCO for diesel vehicles remains unchanged throughout the time period. Analysis therefore focuses solely on ZEVs.

The variation in TCO for a bus from 2021 to 2050 is shown in Figure 4-22 and is very small for the majority of fuels. The only noticeable changes in TCO over this time period are seen by buses using fuels highly dependent on grid electricity, such as electrolytic hydrogen (225 kW and 50-50 split), and electricity from rapid chargers. Since the diesel TCO remains constant at £1.70/km, ZEV fuel scenarios have the opportunity to intersect over this period and become competitive. However, none of the fuel scenarios show a TCO low enough to achieve this. Although diesel TCO is not intersected, buses running on hydrogen from SMR and SMR & CCS using tube trailers show a falling TCO from 2021-2050 and intersect the TCO of buses using 50-50 split hydrogen (shown by the red circle). In 2021, the TCO of FCEV buses running on hydrogen from SMR with tube trailers is £2.23/km and falls to £2.18/km by 2050, becoming cheaper than 50-50 split hydrogen per km in 2040.

For FCEV buses using electrolytic hydrogen from a 225 kW turbine and non-electrolytic hydrogen from CCS with liquid tankers, the TCO is the highest in 2050 at £2.25/km and £2.22/km respectively. The TCO in the liquid tanker scenarios takes longer to fall because it includes more distribution costs like vehicle OPEX which gives it a higher cost per kg compared to electrolytic hydrogen. Liquefied hydrogen also has a high grid electricity demand and since the cost of grid electricity increases from £0.144/kWh in 2021 to £0.255/kWh in 2050, it contributes to the higher TCO. For electrolytic hydrogen, because of rising grid electricity costs and slow changes to the electrolyser efficiency, TCO stays fairly consistent over the time period, though does show gradual reductions to 2050. In addition to the electrolyser efficiency, costs also fall slightly because hydrogen does not require transport and distribution, which avoids extra electricity consumption for conditioning stages like compression, for example.

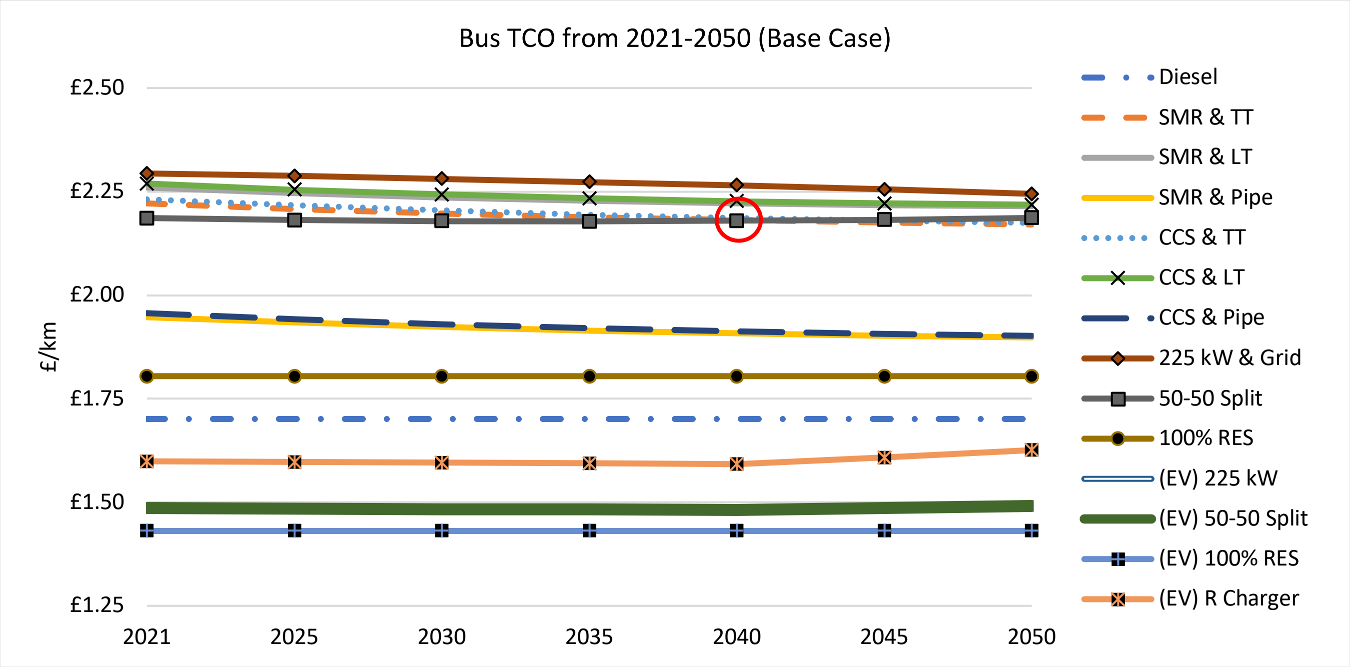


Figure 4-22 - Future bus TCO from 2021-2050.

All BEV buses show a lower TCO than ICEV and FCEV buses from 2021 to 2050. The TCO of 100% RES, 50-50 split, and 225 kW electricity scenarios stays the same across the 30-year period, with only electricity from rapid chargers showing a TCO that increases from £1.60/km in 2021 to £1.63/km in 2050, where it closes in on ICEVs. Their TCO rise after 2040 is attributed not only to the consistent rising cost of rapid charger electricity from £0.24/kWh in 2021 to £0.43/kWh in 2050, but also due to the effect of energy consumption changes for BEVs, with efficiency gains ceasing after 2040 (see Table 4-3). The electricity from these rapid chargers comes at a premium for its convenience and is more expensive than grid electricity, priced at £0.24/kWh in 2021. Since many BEV bus scenarios (such as 100% RES and 50-50 split) do not change significantly across the 2021-2050 period, this suggests that battery price has a little impact on the TCO, despite prices falling ~£65/kWh over the 30-year period. This supports the earlier statement that ZEV TCO is most greatly impacted by fuel price.

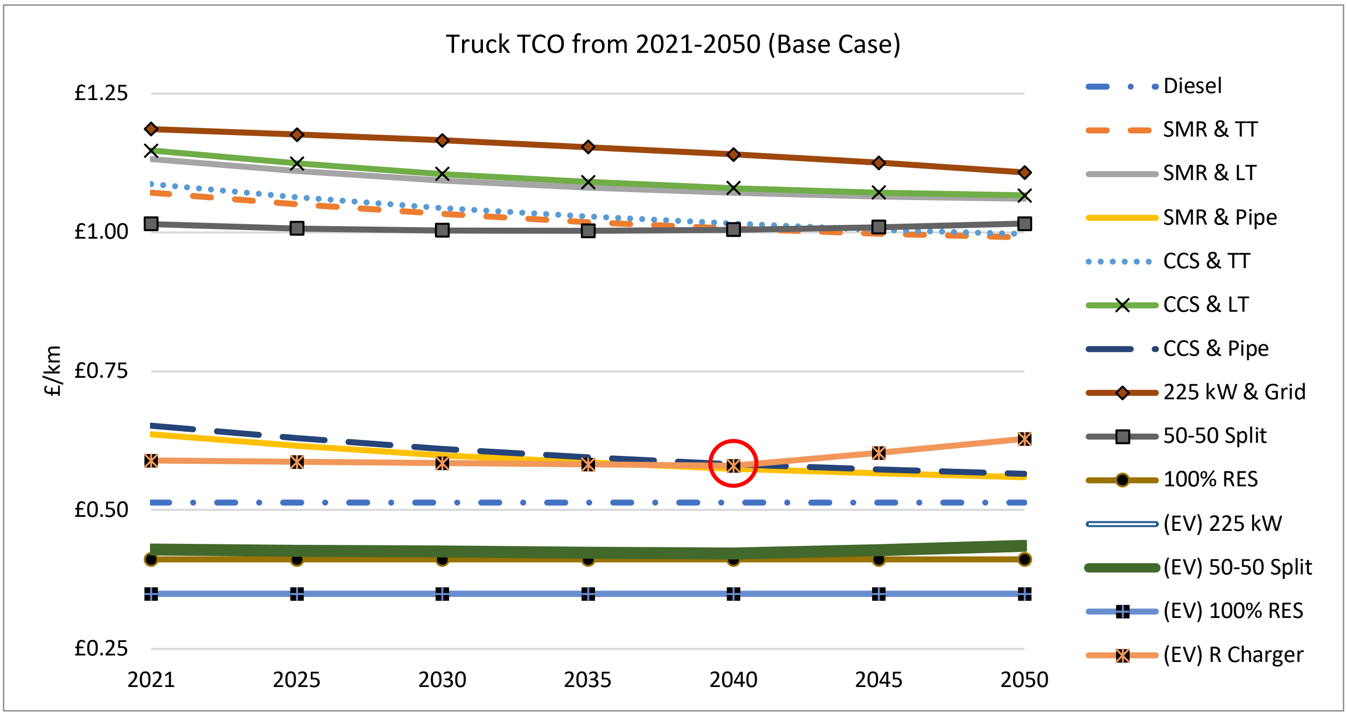


Figure 4-23 - Future truck TCO from 2021-2050.

Similar to buses, the base case future outlook for long haul trucks shown in Figure 4-23. Most fuel scenarios follow the same order and pattern as Figure 4-22 except costs are significantly lower per km, partly due to a reduction in fuel consumption for ZEV trucks and also due to a greater mileage of 496 km/day compared to 99 km/day. In this case, BEV scenarios generally remain the lowest in cost per km with 3 out of 4 electric fuels well below the diesel TCO and much more competitive than hydrogen, peaking in 2050 at only £0.44/km. However for BEV trucks using rapid chargers, in 2021 the TCO is higher than diesel at £0.59/km compared to £0.51/km, and similarly to BEV buses, the TCO increases steadily over time due to the change in electricity price to a peak of £0.63/km. During this rise, in 2040 FCEV trucks utilising SMR with pipe and CCS with pipe hydrogen intersect and become cost competitive per km (shown by the red circle). No FCEV scenarios are competitive with BEVs in bus applications, so this highlights a more economical application of hydrogen in transport.

Results suggest that compared to buses, hydrogen is more competitive for heavy duty trucks since a higher number of hydrogen fuels (3) offer a lower TCO than electricity (from rapid chargers) by 2050. The only hydrogen scenario that can compete with diesel and renewable electricity is 100% RES hydrogen at £0.41/km. Diesel truck TCO is fixed at £0.51/km whilst BEVs utilising 225 kW and 50-50 split electricity are also more expensive per km than 100% RES. Hydrogen is economically better suited for trucks than buses under the conditions of this study since more hydrogen fuel scenarios reach competitiveness with electricity and diesel by 2050.

4.4.4.2. Future Outlook – Fossil Tax Added:

The impact of applying a fossil tax on diesel and improving FCEV competitiveness is examined in this section. The future base case from 2021-2050 now includes an additional tax on diesel fuel. The two tax rate profiles were shown previously in Figure 4-3 and start at 5% (low rate) and 10% (high rate) in 2021, rising to a maximum of 40% and 80% by 2050. TCO results for buses and trucks with the tax are given in Figure 4-24 to Figure 4-27, respectively.

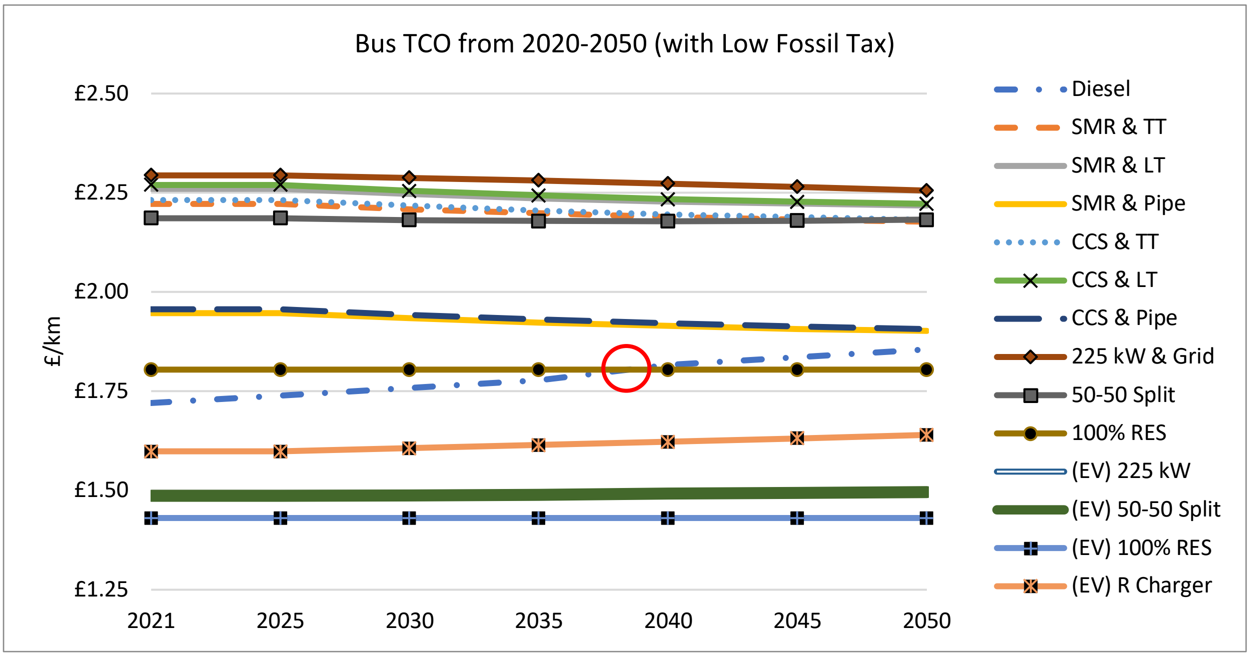


Figure 4-24 – Bus TCO with low fossil tax applied from 2021-2050.

Since the fossil tax only applies to diesel, changes to the TCO of ICEVs is seen, but for ZEVs the TCO remains the same as the future base case in Figure 4-22 and Figure *4-23*. Unlike the future base case where ICEV costs per km remained constant, now for buses the TCO increases from £1.72/km in 2021 to £1.86/km in 2050, surpassing one other fuel (100% RES hydrogen) by 2050 in terms of TCO. All BEV bus fuel scenarios have a lower TCO than diesel in 2050, whilst for FCEV buses the only fuel scenario cheaper than diesel is 100% RES hydrogen. Figure 4-22 showed FCEV buses using 100% RES hydrogen did not become cost competitive with diesel by 2050, peaking at £1.80/km in 2050 compared to £1.70/km for diesel. However, due to this fossil tax this fuel scenario now reaches cost parity in 2038 (circled in red), making hydrogen from 100% RES a more economical option for use in these HDVs. The effect of a small fossil tax brings forward the time that this hydrogen scenario is competitive by more than 12 years. However, this is only true for 100% RES hydrogen as no other fuels reach parity with diesel under these conditions. These results suggest that if a government deterrent like this was introduced, the severity of the tax should be increased further if more hydrogen fuels are to be competitive with diesel or electricity.

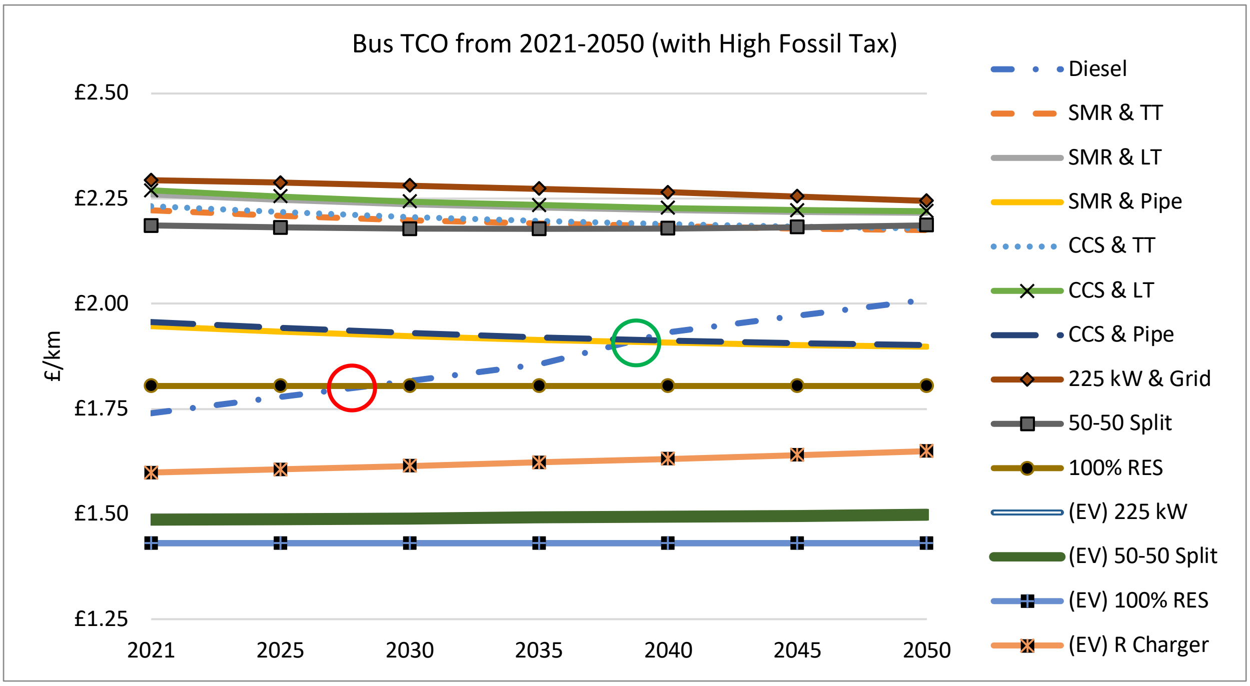


Figure 4-25 – Bus TCO with high fossil tax applied from 2021-2050.

Results are amplified using a high fossil tax as now the diesel bus TCO reaches a peak of £2.01/km in 2050 (Figure 4-25); an increase of ~18% from the future base case. Now, the year at which electrolytic hydrogen from 100% RES becomes competitive with diesel is even sooner in 2027 respectively (circled in red). The impact of increasing the fossil tax from the low rate (40%) to the high rate (80%) has accelerated the time at which diesel parity is seen by over 10 years. In the low rate scenario, this 100% RES hydrogen was the only hydrogen scenario that achieved diesel parity before 2050. However, now hydrogen from both SMR and SMR & CCS with pipeline transport intersects and becomes cheaper per km in 2037 (circled in green). Purchasing a diesel bus in 2021 with a high fossil tax applied is more costly than 4 of the 13 ZEV fuels, but after 2037 this increases to 7 fuels.

TCO for trucks under low and high fossil tax from 2021-2050 is shown in Figure 4-26 and Figure 4-27. Results follow a similar pattern to buses with all ZEV truck scenarios having a TCO equal to that of the future base case (Figure 4-23). In Figure 4-26, hydrogen from SMR and SMR & CCS transported using pipeline reaches parity with diesel in 2037 at £0.59/km (circled in red). In the future base case, these ZEV fuels never reached parity with diesel which means the low tax was the difference between FCEV trucks being financially advantageous over ICEVs. Truck TCO using electricity from rapid chargers still remained more costly per km over the 2021-2050 period despite the diesel tax, though the 3 other electricity fuel scenarios gave the lowest truck TCOs recorded, reaching a peak of only £0.443/km in 2050 (50-50 split). After a high fossil tax is added in Figure 4-27, 6 of the 13 ZEV fuels showed a TCO below diesel. FCEV trucks using hydrogen from SMR and SMR & CCS with pipeline reach diesel parity 7 years faster than the low tax, now in 2029 (circled in red). The impact of increasing the tax did not lead to a higher number of hydrogen fuel scenarios achieving parity however, with still only 3 of the 9 fuels below diesel per km by 2050.

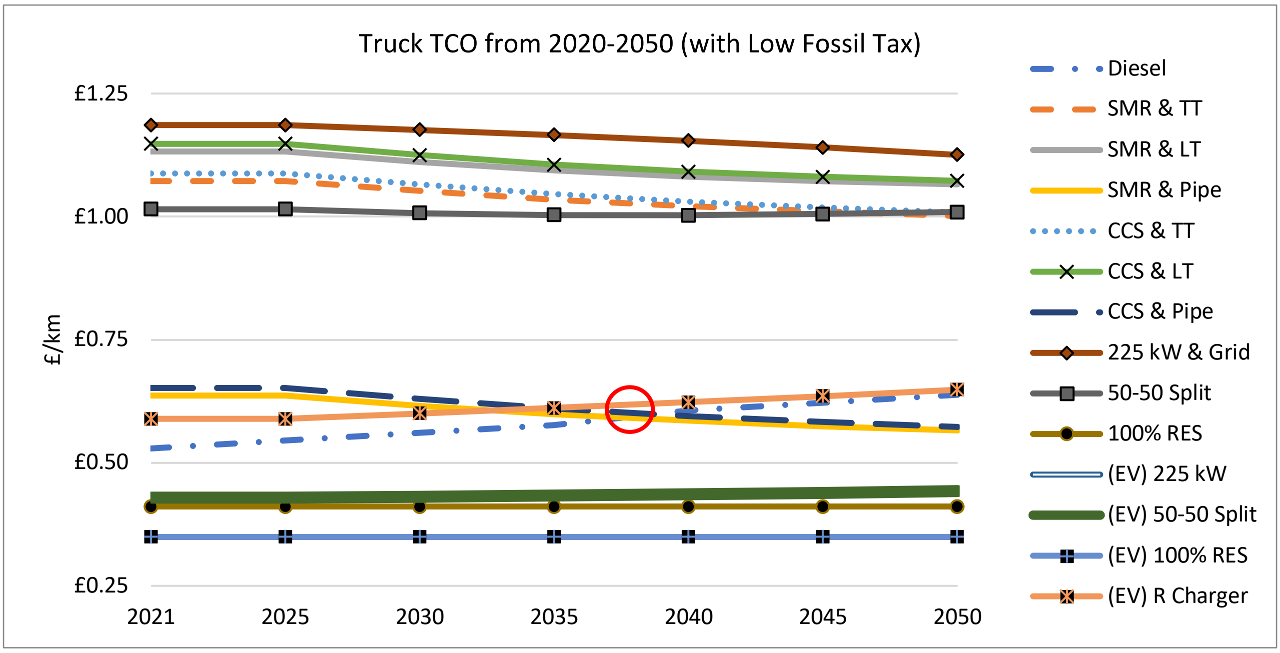


Figure 4-26 - Truck TCO with low fossil tax applied from 2021-2050.

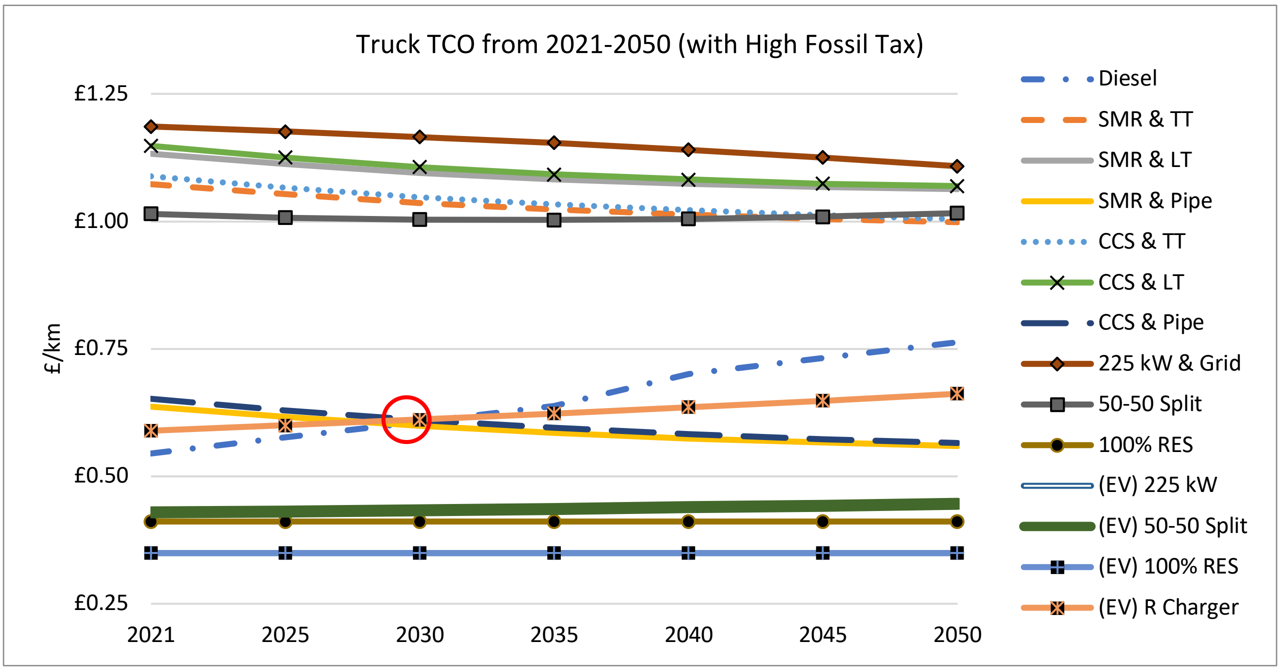


Figure 4-27 - Truck TCO with high fossil tax applied from 2021-2050.

4.4.4.3. Future Outlook – Purchase Grant Added:

In this section the future base case TCO across the 2021-2050 period now includes a purchase grant on ZEVs to reduce their high upfront costs and incentivise their uptake. The two rate profiles (standard and high) for ZEVs were given in Figure 4-2 and vary in discount depending on the powertrain type. In 2021 FCEVs are discounted up to 40% whilst BEVs are discounted up to a maximum of 20% since they are more mature. Although a date is set for the end of sale for new diesel cars and vans, no official date has been set for HDVs, though projections have been made for 2040 [41]. As a result, grants are active from 2021-2040, with FCEVs discounted only 5% in 2040 whilst BEVs are excluded from grants by this point. After 2040 vehicles must be paid in full, since the market is assumed well established by this point and the ban on diesel vehicles now forces consumers to purchase ZEVs regardless of their price. As a result, the purchase grant works to improve the cost competitiveness of ZEVs in the early years of uptake only and its benefits are not seen after 2040. By 2040, vehicle purchase costs rise from the previously discounted value to their base case figures for that year, shown by an increase in TCO after 2040 in the following graphs.

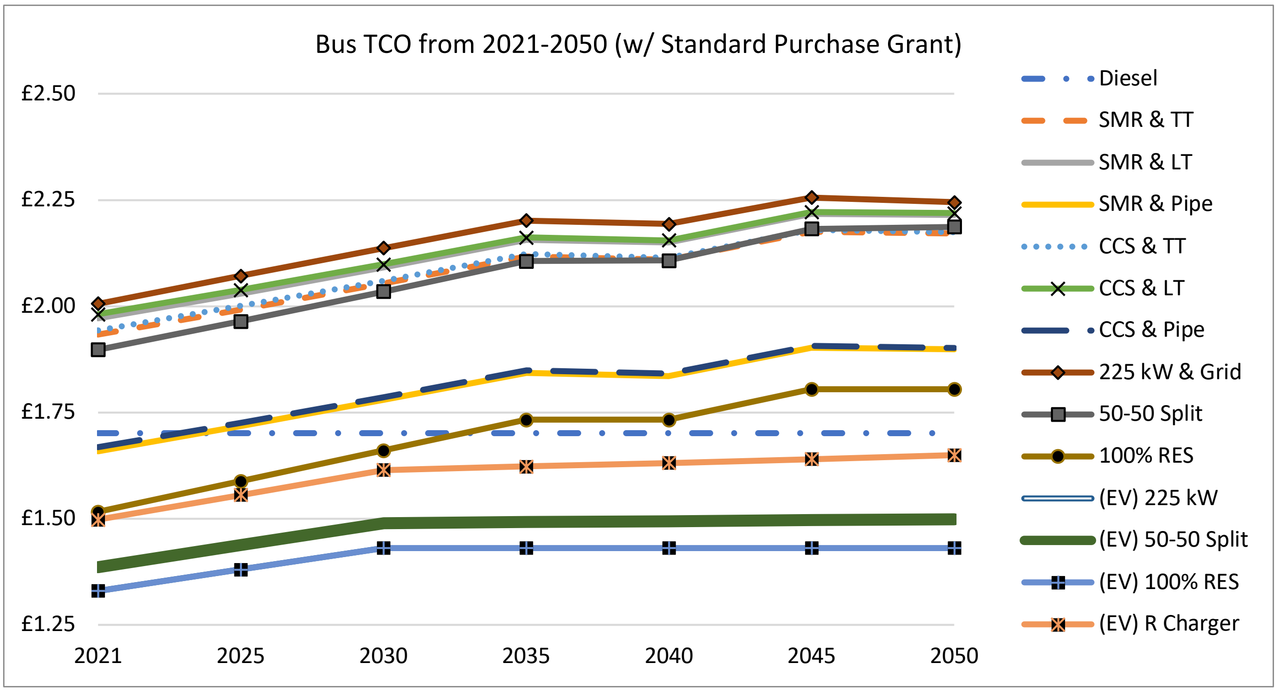


Figure 4-28 - Bus TCO with standard purchase grant applied from 2021-2050.

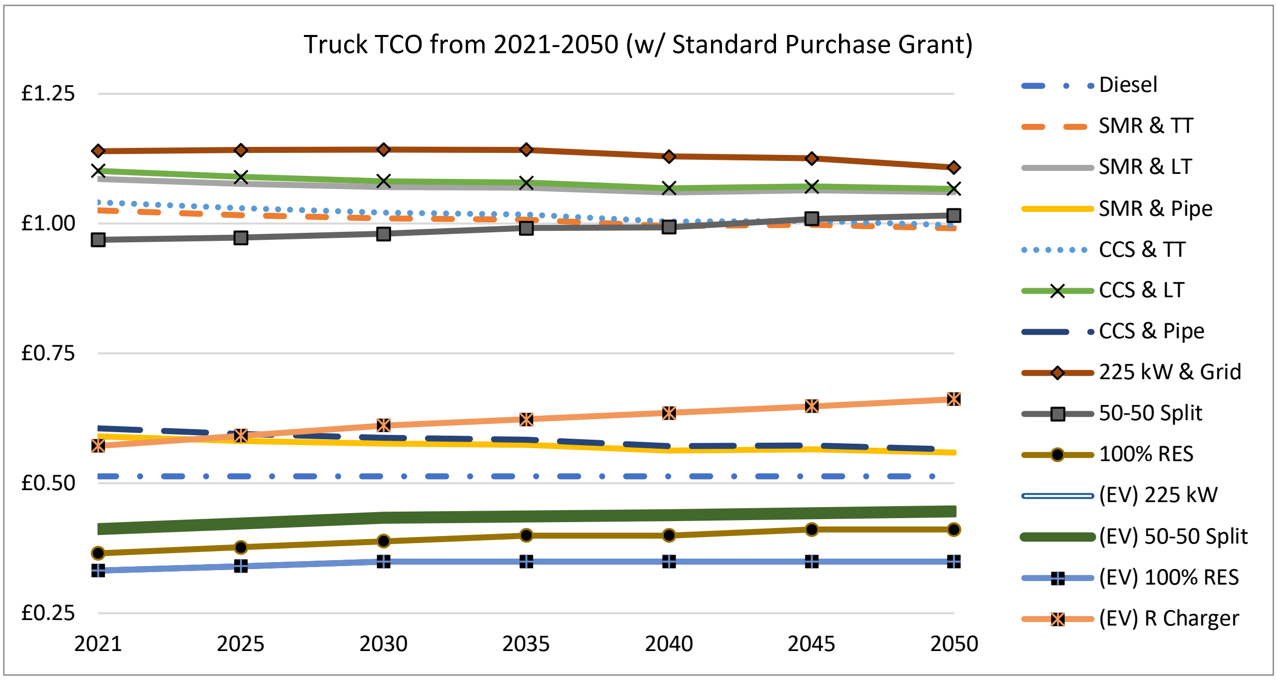


Figure 4-29 - Truck TCO with standard purchase grant applied from 2021-2050.

Figure 4-28 and Figure 4-29 show the TCO profiles for a bus and a truck under standard purchase grants. Since this only applies to ZEVs, diesel bus and truck TCO is fixed at £1.70/km and £0.51/km; the same as the future base case in Figure 4-22 and Figure *4-23*.

For ZEVs, the impact of this purchase grant is quite low. For BEV buses and trucks using rapid chargers, the TCO in 2021 (when the grant is highest) is £1.50/km and £0.57/km, compared to their base case values in 2021 of £1.60/km and £0.59/km respectively. This is only a reduction in cost per km of ~6% and ~4%. As the purchase grant for BEVs is only applied from 2021 to 2025, the TCO in 2030 onwards falls back to this more consistent future base case level with no discounts applied. For other BEV bus and truck scenarios, the effect of this purchase grant is even smaller and has a negligible impact on competitiveness. The impact of the discount is that it helps ZEVs achieve parity with diesel in the early stages to increase their attractiveness to consumers and fleet operators. Over time, these benefits are lost as ZEVs become the dominant powertrains in transport. For example, in the future base case for FCEV buses, those running on SMR and SMR & CCS with pipeline hydrogen are more costly per km than diesel in 2021, with their TCO both at £1.95/km compared to £1.70/km for ICEV buses. However, after the inclusion of the standard purchase grant, their TCO in the year 2021 now falls just below that of diesel, achieving cost parity. This creates a better business case for FCEV buses operating on these fuels and encourages uptake in the earlier stages.

Comparing FCEV bus and truck TCO in 2021 (with the grant applied) to their future base case values shows similar results to BEVs. In the 225 kW electrolytic hydrogen scenario, bus and truck TCO is £2.29/km and £1.19/km in 2021 which falls to £2.00/km and £1.14/km with the application of the grant. This is a slightly higher reduction compared to BEVs at 13% and 5% but since the grant was double, the influence on TCO is still low. Figure 4-28 clearly shows the difference in TCO between the base case and this standard grant condition falls slowly from its maximum in 2021 (when the grant is highest) to 2035 for the hydrogen scenarios, and then the rate of this decrease in cost per km slows thereafter before eventually being removed.

Whilst the grant is active, it also alters the competitiveness of the fuels, as the TCO of some hydrogen scenarios falls below diesel in the early years. This is important because if a purchase grant like this is a key difference between people choosing to use diesel and using hydrogen fuels, and will encourage people to purchase ZEVs earlier and accelerate carbon savings and the transition to more sustainable transport, it should be considered. This tool shows effectiveness for lowering the TCO closer to or below ICEVs in the early stages of ZEV uptake.

If the grant is increased further, the effect on bus and truck TCO is shown in Figure 4-30 and Figure 4-31. As the discount for FCEVs falls from its highest point in 2021 (40%) to its lowest point in 2040 (5%), for several hydrogen scenarios it leads to an increase in TCO compared to the previous year, but a lower TCO than the future base case for that year. For example, in 2021 for FCEVs the purchase grant is 40% but in 2025 it falls to 30%. Since this discount is lower in 2025 it leads to a higher cost per km compared to the 2021 cost as the depreciation component of the TCO increases per km, and so on. This response increases after each reduction in discount until 2040 when the TCO matches its future base case value without discounts. This explains the slow change in cost thereafter due to time-sensitive inputs which were covered in the future base case. This increase in TCO after each reduction in grant discount is seen clearly in the hydrogen scenarios in Figure 4-30 and Figure 4-31, such as SMR with pipeline, showing a steep rise in TCO between 2021-2030 as the severity of the grant falls. The reason for the decline in TCO between 2035 and 2040 is due to the purchase grant used over time. From 2021 to 2035, the grant decreases 10% every 5 year period, but in 2035 and 2040, the grant remains the same at 10% which is its lowest value in the high grant scenario. As a result of this stagnation, the TCO falls and closely approaches its future base case value.

After addition of a high purchase grant, 10 of the 13 ZEV buses are already below the ICEV TCO in 2021. For trucks which have a lower purchase price however, this number is lower and no new hydrogen fuels become cheaper than diesel in 2021, though some closely approach it. This makes the economics of owning and operating a ZEV much more attractive in the early stages of uptake as this is typically when their costs are highest and ICEVs have an advantage from their more developed market.

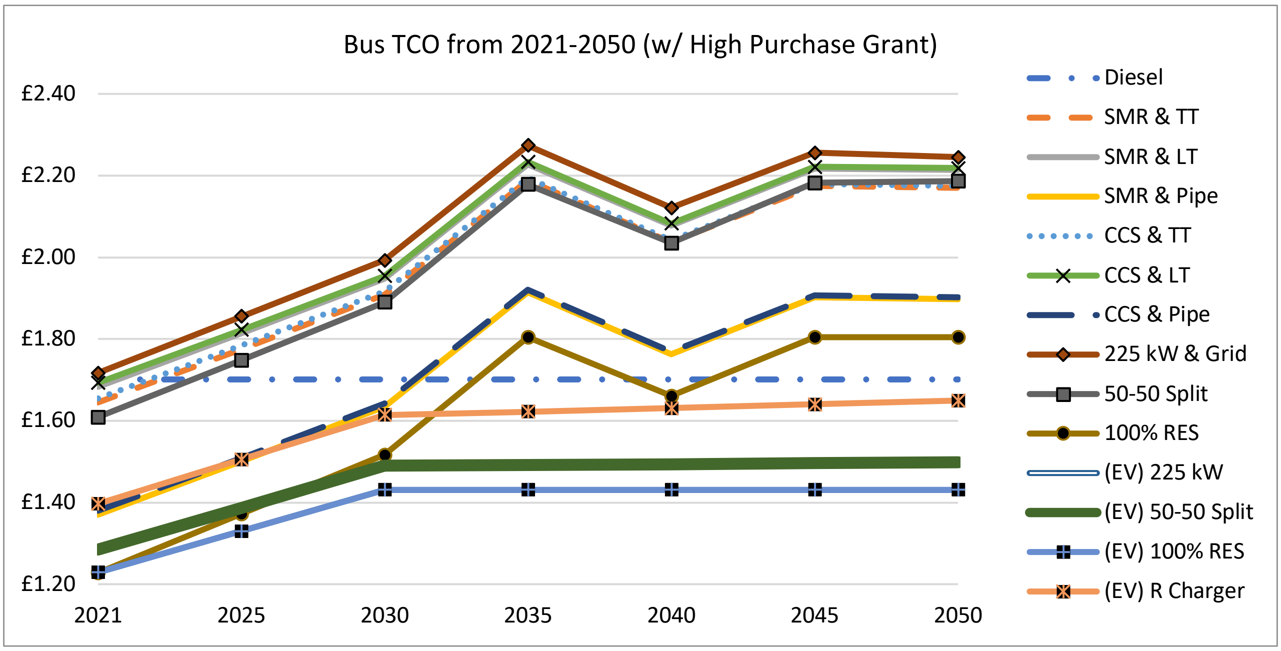


Figure 4-30 - Bus TCO with high purchase grant applied from 2021-2050.

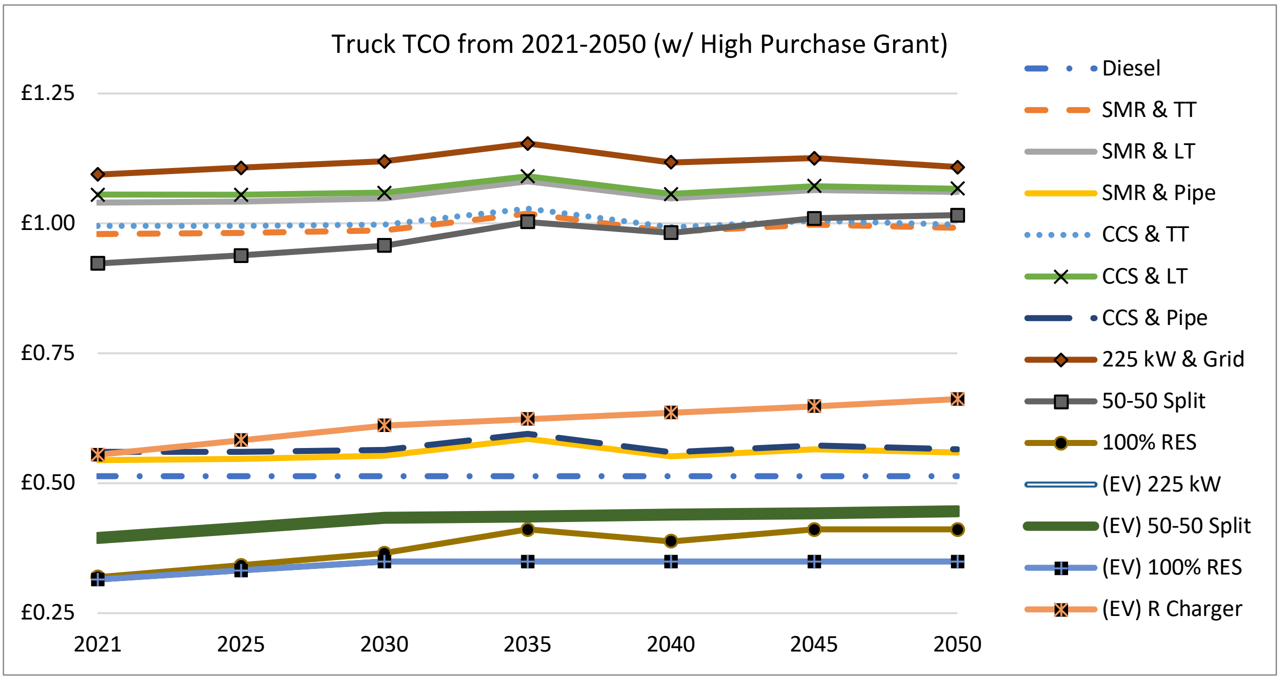


Figure 4-31 - Truck TCO with high purchase grant applied from 2021-2050.

4.5. Chapter Summary:

This chapter presented an economic analysis of heavy duty on and off-road vehicles powered by hydrogen, electricity, and diesel by estimating their total cost of ownership per km. Results show that for all vehicles, the lowest TCO in 2021 under base case conditions used electricity as the power source, with BEV technology powered by renewable sources offering cost advantages over electrolytic and non-electrolytic hydrogen powered vehicles, as well as diesel. Despite this, a number of hydrogen powered vehicles still offered a lower TCO than diesel in 2021, including buses, trucks, tippers, and forklifts using hydrogen from SMR and SMR with CCS using pipeline, tube trailer and liquid tanker transport, as well as 100% RES hydrogen generated on-site.

Results from a sensitivity analysis showed when subject to specific hydrogen-favourable conditions like fuel price reductions and purchase grants, all vehicle types have the potential to become cheaper than diesel per km if using hydrogen from 100% RES as their fuel, with several other hydrogen fuels also giving lower TCOs than ICEV and even BEV counterparts in some cases. Both a high purchase grant and low hydrogen fuel price can significantly reduce FCEV TCO, though for the majority of vehicles all electricity scenarios (except for electricity from a rapid charger) remained a cheaper option in terms of TCO. Under a high purchase grant and a 20% fuel price reduction, for buses and trucks in particular, 8 of the 9 hydrogen fuels gave a TCO below diesel, with some FCEV scenarios also falling below BEVs. This proves that FCEVs have the potential to be the lowest cost option for HDVs when the conditions are favourable. A similar pattern was observed on the TCO when ownership period increased. High mileages allowed the benefits of ZEV low operating costs to be fully appreciated, which led to cost reductions against the 2021 base case. In this case, the cheapest option for all the vehicles used electricity as its fuel, except for tippers using 100% renewable hydrogen.

By 2050, the majority of hydrogen fuel scenarios will still not have a TCO lower than diesel, and for most of the vehicles considered, BEVs remain the cheapest per km unless specific FCEV incentives are implemented. For buses and trucks, the year in which many FCEV TCO scenarios become cheaper than diesel is significantly shortened with the addition of a fossil tax, though this does not impact BEVs which still remain economically advantageous. Although BEVs appear to have the lowest financial costs overall, non-financial costs like reduced load capacities from large batteries, cold weather effects, and long recharging times should be taken into consideration which is likely to cause disruption to operating patterns and reduce vehicle and fleet productivity. These non-financial impacts may harm the vehicle owner more than the financial costs of using hydrogen vehicles.

5. Chapter 5 - Creation of a Transport Emissions Model

Similar to Chapter 4 which conducted an economic assessment of FCEVs and compared results to ICEVs and BEVs, an investigation will now be conducted into the cradle to grave life cycle emissions of the vehicles. Due to the quantity of information and the level of detail this will contain, the investigation will be reported in a 3-part series across Chapters 5-7. This chapter first provides a step-by-step breakdown of the methodology used to generate life cycle emissions for each vehicle. Chapter 6 then reports the base case results for the vehicles in Chapter 3 from a general perspective, before a future outlook in Chapter 7 considers the impact of a decarbonised electricity grid, among other factors, on the life cycle emissions and the environmental competitiveness of FCEVs.

This work is relevant because the government has now committed to achieving net zero carbon emissions by 2050. As the sale of new diesel cars is banned from 2030 (and a ban on diesel HDVs proposed from 2040), sustainable transport options must become available to support and accelerate a smooth transition. But how environmentally competitive are hydrogen vehicles compared to electric and conventional diesel vehicles? Under what conditions do FCEVs become most sustainable? Where are the environmental hotspots along their supply chains? These are some of the questions that this 3-chapter series aims to answer.

5.1. Introduction to Life Cycle Assessment:

Life Cycle Assessment (LCA) is a tool used to estimate and analyse the environmental impacts associated with a product or process and can help support decision-making by highlighting the most efficient process routes. A conventional LCA (Figure 5-1) includes all stages of the products life cycle, from its cradle (raw material extraction) to grave (product disposal), though some LCAs are defined by narrower system boundaries depending on what the focus of the study is. For example, LCAs concerned only with emissions between raw material extraction and the factory gate prior to the products use, are called cradle to gate LCAs. LCA is a useful tool which can help highlight the most energy intensive stages over the products life cycle (called hotspots), allowing for adaptations to be made which can reduce its overall environmental impact.

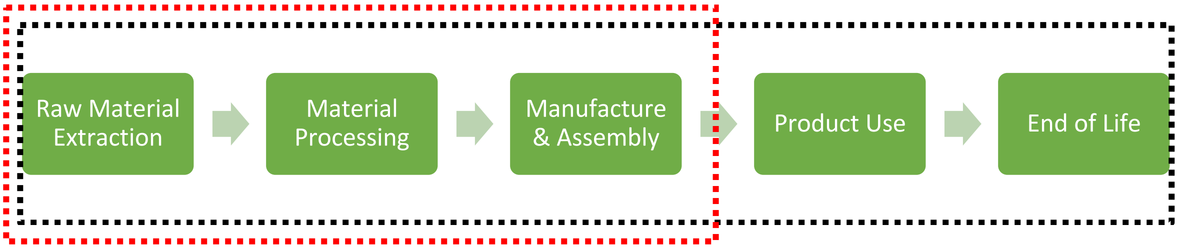


Figure 5-1 - System boundaries associated with a cradle to grave (black) and cradle to gate (red) LCA.

Typically, an LCA is defined by four stages, bulleted below and shown in Figure 5-2:

1. **Goal and Scope:** What is the purpose of the study, what will define the functional unit, who is the intended audience, what are the system boundaries, what are the data requirements, and other study conditions.

2. **Inventory Analysis:** The collection, validation, and aggregation of input and output data to quantify material and energy requirements, emissions to both the environment and technosphere, as well as waste flows.

3. **Impact Assessment:** The use of impact categories, category indicators, characterisation models, and weighting factors to convert raw data from stage two into more insightful data relating to environmental and human impacts, for example. Impact categories are used to group different emissions into one effect on the environment. Since emissions vary in their units it can be difficult to identify their contribution and impact so by categorising them it allows these emissions to be converted into a single unit. For example, when examining the climate change impact category in this work, reported in kg CO_2e, all other greenhouse gas emissions are converted to a CO_2 equivalent using their 100-year potential, giving one final value for climate change.

4. **Interpretation:** This is carried out throughout all three previous stages to assess the results in terms of the goal and scope outlined. This stage is where all results are presented, analysis is conducted, and conclusions are made. Results from the study must show significant environmental impacts and offer insight into methods for reducing material and energy use and minimising environmental damage.

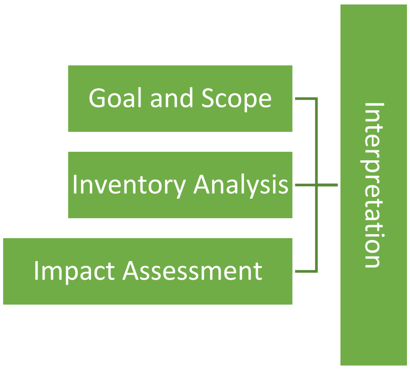


Figure 5-2 - The four stages of an LCA (ISO 14040).

There are also different universal standards that LCAs must adhere to which allows them to be compared more easily. The leading international standards on LCA are ISO 14040, which covers the principles and framework of the standard itself, and ISO 14044 which outlines the specific requirements and guidelines respectively.

This work uses SimaPro 9.1 to conduct emissions modelling. This is one of the most popular LCA software's, having been on the market for over 15 years and used in over 80 countries. Since it is internationally recognised and trusted by both industrial and academic bodies following the ISO 14040 and 14044 standards, it means results can be understood on an international scale. The software is also integrated with life cycle inventory (LCI) databases like Ecoinvent; the world's largest and most consistent library [87]. Most inventory data used in this work is sourced in literature but in cases where data is absent, gaps are filled using this database. This approach is common in many LCAs including work by Aydin *et al.* [254]. Table 5-1 compares different LCA software respectively.

Table 5-1 - Summary of leading LCA software.

	Pros:	Cons:
SimaPro:	▪ More than 10,000 users over the past 30 years, so is well established in industry and academia. ▪ Includes Ecoinvent. ▪ Highly flexible. ▪ User friendly. ▪ Good integration with other tools (e.g. Microsoft Excel). ▪ Complies to ISO 14040 and 14044 standards.	▪ Expensive to purchase. ▪ Only accessible with Windows.
GREET:	▪ Low cost. ▪ Open access. ▪ Allows results comparisons.	▪ Does not come with Ecoinvent (incurring additional costs). Its database is fairly small and limited only to transport. ▪ Not as commonly used as some other software (e.g. SimaPro). ▪ Focused more closely on estimating US vehicle-related emissions, using US data. ▪ Uses emission factors instead of reporting data, reducing its reliability.
Gabi:	▪ Compliant with ISO 14040 and ISO14044 standards. ▪ On the market for > 25 years. ▪ Well established software used internationally. ▪ Gabi databases available (Thinkstep). ▪ Fast modelling and scenario analysis.	▪ High purchase price. ▪ Ecoinvent not included. As this is widely considered to be the largest, most consistent and detailed database available, it is a big drawback.
openLCA:	▪ Free to use. ▪ Flexibility to adapt software and add specific tools. ▪ Simple and easy to use. ▪ Processes displayed in graphical forms. ▪ Provides results comparisons. ▪ Compliant with ISO 14040 and ISO14044 standards.	▪ Doesn’t include Ecoinvent. ▪ Databases come at an additional cost. ▪ Not as widely used as other software so less understood than others.

5.2. Base Case Conditions:

This LCA employs the use of the Ecoinvent 3.6 database, which was updated as of September 2019. This is used as the main source of inventory data for modelling the more generic (secondary) background processes, whilst more specific (primary) foreground data relating to the products or systems being compared is sourced directly from manufacturers where possible or drawn from existing literature. The LCA employs a functional unit of 1 unit-km travelled for each vehicle type, where unit-km refers to a unit quantity of emissions per km (car), per passenger-km (bus), or per tonne-km (all other HDVs) respectively (e.g. gCO_2e/km for a car).

Since transport has significant effects on climate change and air quality, the environmental impact assessment method selected was Global Recipe Midpoint H which covers the most relevant environmental issues on freight transport, including global warming potential (GWP) [211]. Climate change is the most important and relevant impact category due to the fossil energy content associated with the use phase of diesel vehicles, as well as the emissions resulting from electricity generation and battery and fuel cell production for BEVs and FCEVs. In addition to climate change, the impacts of vehicle and fuel use on air quality are also significant and have gained attention over the past decade with new emission standards introduced to minimise their impacts.

It should be noted that those processes which show high contributions to climate change may not have high contributions across other impact categories. Some environmental impacts do not change in line with climate change which suggests it might not be the best indicator for total environmental burdens. For processes involving fossil combustion, such as the use of diesel vehicles, there is likely to be a strong correlation between climate change and other impact categories [218]. However, as the electrification of transport progresses, it increases the importance of including other impact categories in the assessment as it minimises burden shifting, which is the process of reducing environmental impacts in one category at the expense of increasing another. It should be made clear that SimaPro does not include NOx as an impact category and other categories which are included are not directly linked to transport, therefore they are not considered in this work. As a result of this and the air quality concerns mentioned, particulate matter (PM) formation and fossil scarcity (FS) are other categories examined. By including these, it increases the level of depth compared to other comparative transport LCA's which often consider only one impact category.

One base case assumption is that all vehicles have a 15-year lifespan from their production to end of life (EOL), which is reasonable for vehicles with high mileages operating for the majority of the year, also aligning with typical UK fleet figures [262] [263]. Other study conditions are presented in Table 5-2, respectively. In this base case, since the assessment considers the entire lifetime of the vehicles, results are not reported from the perspective of a fleet owner (as was the case in Chapter 4), but instead aim to offer a broader overview of total accumulated emissions from the vehicles. However, Chapter 8 later investigates the emissions associated with vehicle service in a specific fleet, varying service period under two scenarios, and therefore offers findings from the perspective of a fleet owner.

Table 5-2 – Baseline conditions.

Condition:	Baseline Value:
Quantity of Each Vehicle:	1
Vehicle Lifetime (years):	15
Vehicle Operation (days/year):	350

Table 5-3 - Impact categories examined.

Impact Category:	**Abbreviation:**	**Unit:**
Climate Change	GWP	kg CO_2 eq
Fine Particulate Matter Formation	PM	kg $PM_{2.5}$ eq
Fossil Scarcity	FS	kg oil eq

5.2.1. Electricity Mix:

Figure 5-3 provides a breakdown of the electricity mix used in this work. Figures were published by the National Grid referring to the average UK mix for the year 2022 and used in Ecoinvent to model electricity use. The electricity used in this LCA has a carbon intensity of 0.243 kgCO2e/kWh respectively.

Despite data being taken from a reputable source, new government grants and energy schemes introduced in the UK (like increased offshore wind generation) contribute to a mix that is constantly and rapidly changing. As a result, the start of 2023 has seen greater portions of electricity generated from renewables, as well as reductions in fossil fuels compared to the mix shown below. For example, from Jan 2022 to Jan 2023 natural gas usage fell 10% whilst wind power increased by 9% [304]. Since it is difficult to keep up with these ongoing changes and conduct modelling with data in real-time, it presents a limitation to the study which must be acknowledged. To address this and to account for expected changes in the future mix, this work assesses another electricity mix in a future outlook later in Chapter 7. Nevertheless, in future work this information should be updated to represent the mix as closely as possible at that particular time.

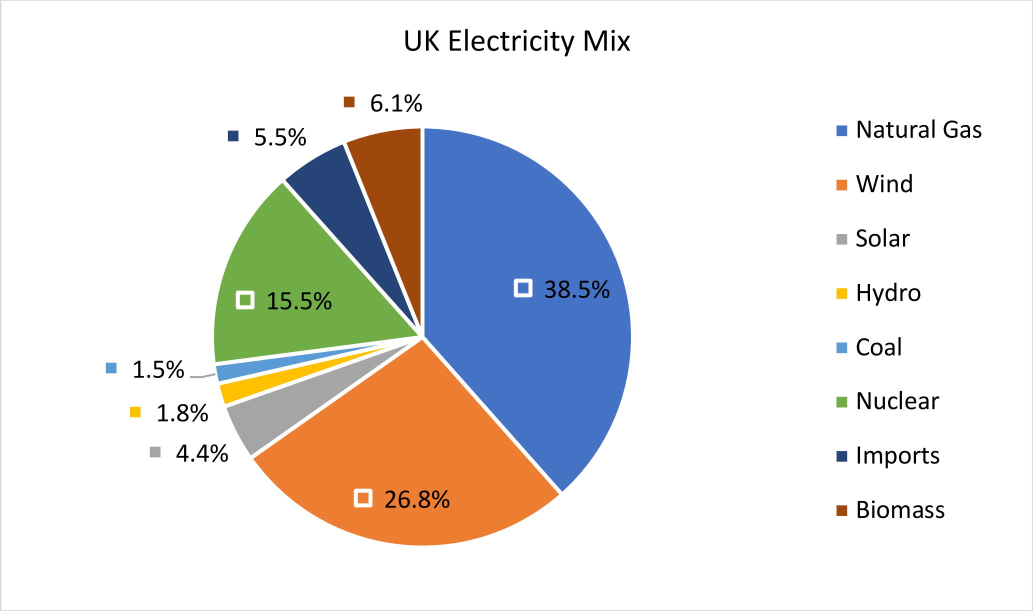


Figure 5-3 – UK electricity mix used in the base case.

5.2.2. Goal and Scope:

The goal of this LCA is to examine the full cradle to grave environmental impacts of hydrogen as a sustainable transport fuel in heavy duty on-road and off-road vehicles, and to compare these emissions to electric and diesel vehicles. In order to achieve this goal, the following scope is considered: as well as the fuel cycle, the study will also consider the vehicle cycle (including the manufacture of the glider and powertrain components), the vehicles use, and its end of life scenario. The study does not include the construction of equipment like electrolysers, pipelines, turbines, manufacturing and assembly plants, or refuelling/recharging stations.

Emissions from all life cycle stages are collated and used to identify which fuel offers the lowest life cycle emissions and is best suited to a transition towards sustainable low carbon heavy duty transport.

5.2.3. System Boundaries:

This study is a cradle to grave life cycle aiming to estimate life cycle emissions, encompassing the fuel and vehicle cycles respectively from the extraction of the virgin raw materials to the dismantling of the vehicle at a recycling facility.

The energy intensity associated with the manufacture of vehicle components can be easily and often disregarded, with much of the focus in previous years being placed on only the tailpipe emissions. Such an attitude was seen for BEVs and some early hybrid electric vehicles like the Toyota Prius, with many media outlets hailing it at the time as an environmental success due to its low or zero tailpipe emissions (depending on the fuel used). However, they failed to consider the upstream emissions from the electricity sources it used, as well as the energy intensive processes that go into sourcing and transporting the precious metals for its battery components, for example [103]. In addition, battery end of life has also been an area which raised concerns for many people since it required more extensive treatment compared to conventional combustion engines. This is true for battery components that are welded together, making recycling more challenging to dismantle, and the complex processing which is required to retain valuable components such as lithium, for example [104]. This issue contributed to an increase in second-hand battery use since many batteries retain a high portion (up to 80%) of their original capacity after use in a vehicle. LCAs are a useful way to clearly identify where the damaging processes lie and can aid solutions to improve them in the future.

Figure 5-4 provides an overview of the LCA model used. It is split into the vehicle and fuel cycles respectively, both of which come together to give the entire life cycle system boundaries. The fuel cycle considers the production, transport, conditioning, distribution, and use in the vehicles. The vehicle cycle considers the material extraction/production, component manufacture, transport to the assembly facility, vehicle assembly, distribution and delivery, and use, before the end of life scenario which includes collection and delivery of the vehicle to the recycling facility and the subsequent processing of materials.

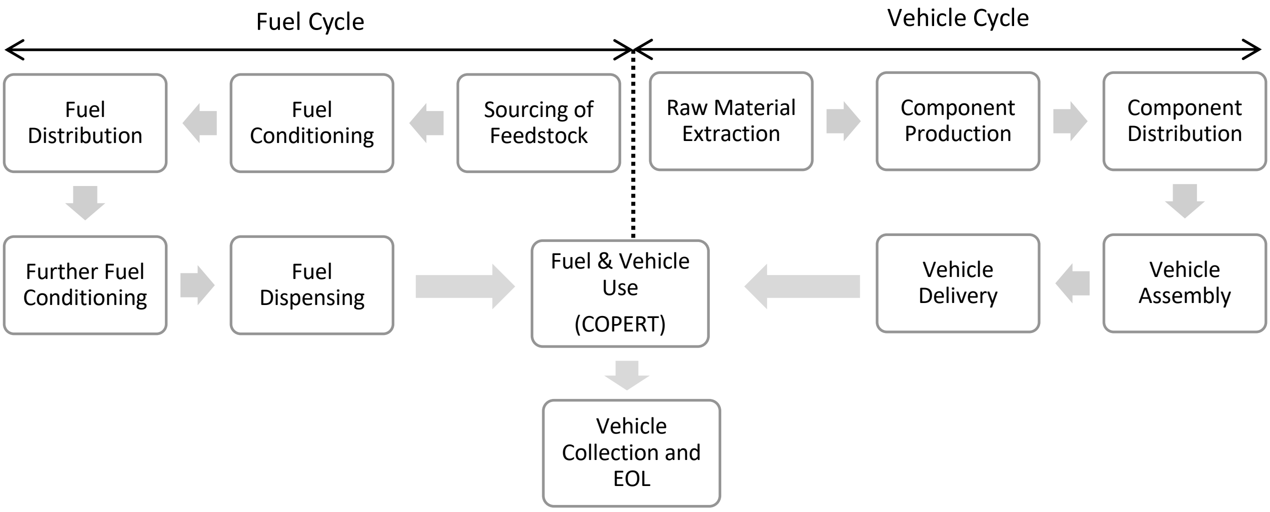


Figure 5-4 - Structure of the LCA model.

5.3. Methodology:

5.3.1. The Fuel Cycle:

This section covers the fuel cycle and builds on the overview of the production routes covered previously in Chapter 3. It outlines the methods and assumptions associated with fuel production, distribution, and conditioning, followed by its use in the vehicles.

5.3.1.1. Fuel Production:

For diesel, since many fleets like Leeds City Council (LCC) operate by purchasing diesel on an ad-hoc basis, the same approach was used in this work. For hydrogen, production routes considered include steam methane reforming (SMR), SMR with carbon capture and storage (SMR with CCS), and electrolysis. Typically, hydrogen is produced at an outlet pressure of 20 bar prior to distribution, so this is assumed along with a purity suitable for use in a fuel cell vehicle (99.999%) [105] [107].

Diesel:

Diesel fuel in Ecoinvent considers ultra-low sulphur diesel from petroleum refinery operation, but it isn’t specified whether it conforms to a particular standard like EN590. Despite this, because the use of the reference vehicles is modelled using COPERT software (covered in Section 5.3.3), diesel fuel in Ecoinvent is only used by the distribution vehicles (i.e. tube trailers and liquid tankers) over short distances, and the impact of this on final emissions is expected to be negligible. It is assumed the diesel production process takes place at Teesside, UK where there is significant oil and gas engineering infrastructure in place, including Teesside Oil Terminal and Teesside Liquid Storage Terminal. From here, it is transported using diesel trucks to the fleet base where it is consumed by the vehicles. It is assumed that the tanker operates at full load and is capable of carrying approximately 20,000 litres of diesel (17,000 kg load), which is common for diesel tankers used in the UK [142].

Conventional Steam Methane Reforming, and CCS:

SMR is a standard industrial process for hydrogen production, and CCS is a relatively new technology that came to use in recent years aimed at capturing the carbon emitted from various processes in an attempt to reduce their environmental impacts. The captured CO_2 is typically stored either in underground salt caverns or dedicated storage facilities for extended periods of time.

In this work, the natural gas input is taken from Ecoinvent and refers to high pressure gas production modelled for the UK which considers offshore production in the North Sea. Figures from BEIS showed that “domestic production of natural gas met 46% of the UK’s gas supply in 2019 (prior to Covid-19), with the vast majority of this supplied from North Sea offshore production” [106]. It is assumed that this natural gas produced offshore is transported to the Teesside region approximately 100 km using a long distance natural gas pipeline directly to the SMR site where it then reacts with steam to produce hydrogen. The CO by-product is then reacted in a second process step called the water-gas shift with excess steam to increase the yield of hydrogen and produce carbon dioxide as another by-product (Equation 16 and Equation 17).

$$\mathrm{CH_4 + H_2O \rightarrow\ 3H_2 + CO} \qquad \text{Equation 16}$$

$$\mathrm{CO + H_2O \rightarrow\ H_2 + CO_2} \qquad \text{Equation 17}$$

Inventory used in SimaPro to model the emissions from the production of hydrogen from SMR is based on the work by Dai *et al.* [161] and Idaho Lab [232] respectively. First, the approach commonly used to generate the high temperatures required for SMR is to combust a small amount of fuel [232] [305]. It is assumed in this work that more steam is produced during the process as a by-product than is required as an input. This assumption is based on a study by Spath *et al.* [214] in which 144% of the input steam required for SMR was generated directly from the waste heat recovery system. This heat recovery captures the heat contained in the flue gases (at temperatures of 500-600°C) at the outlet of the furnace; an approach also highlighted by Inui *et al.* [297]. As a result, the excess steam generated is assumed to be exported and/or consumed within other processes so they don’t have to generate the steam themselves (avoiding more natural gas combustion). To model this, the emissions from steam production (by fuel combustion) are listed as avoided products and given as credits in the process. The steam required to produce 1 kg of hydrogen from SMR was taken from Dai *et al.* [161] at 6.4 kg and its energy content of 2.75 MJ/kg meant its total energy is 17.6 MJ/kg H_2. However, from Ecoinvent, to produce this steam requires 23.04 MJ of energy. Data relating to steam generation for hydrogen production in the UK could not be sourced so Ecoinvent was used instead. In this case, energy comes from a variety of sources based on average steam production in the European chemical industry, with 215 steam plants examined and used as the basis for these figures, taken from the work by Boustead *et al.* [236] respectively. These sources are:

- 62% from natural gas.
- 21% from oil.
- 14.6% from coal.

- 1.4% from nuclear.
- 1% from hydropower.

GWP associated with the production of steam for SMR is approximately 2.16 $kgCO_2e/kg$ H_2. By avoiding this steam production, these emissions are saved from the SMR process.

If using CCS, CO_2 can be captured using a variety of methods, but the most common industry standard includes capture from the shifted syngas using absorbents such as monoethanolamine, as used by Dai *et al.* [161]. Other methods are available which give CCS technology a CO_2 capture rate in the range of 56-90% [193]. This work considers a reasonable capture rate of 70% which lies in the middle of this range. The captured gas is then transported using a natural gas pipeline to a suitable offshore location for geological storage. Unfortunately, Ecoinvent does not include dedicated CO_2 pipelines, only natural gas and petroleum pipelines are available. However, research suggests the majority of the existing offshore oil and gas pipelines can be reused and are suitable for the transport of CO_2 to geological storage, so it is assumed these pipelines are suitable for transporting CO_2 [164]. Also, since the transport distance is short, emissions generated from the natural gas pipeline process are not likely to differ significantly from a CO_2 pipeline process.

It is assumed the storage of CO_2 takes place in the Endurance saline aquifer in the Southern North Sea, approximately 150 km away from the production site assumed to be placed at Teesside, where there is a reported 450m tonne capacity for CO_2 storage [162]. In addition to this aquifer, there are other nearby storage options with a combined capacity of 1bn tonnes [162]. For the CO_2 sequestration process, life cycle inventory was unavailable due to the lack of large scale carbon sequestration practices. As a result, estimates for the energy required for CO_2 injection were sourced from Viebhan *et al.* [163] and Khoo *et al.* [237] at approximately 0.007 kWh/kg CO_2, which equates to roughly 0.0175 kWh per kg hydrogen produced. Energy required for CO_2 recompression at the well was also taken from the same source and given at 0.011 kWh/tkm respectively.

Once hydrogen is produced, it is purified to a quality high enough for use in FCEVs using pressure swing adsorption and transported to the fleet location at Leeds where it will be used, using either a gas pipeline or in gaseous or liquid form using diesel-powered tankers. It is predicted by many industry experts that Teesside will be one of the major hubs for hydrogen production in the future, covering the majority of hydrogen demand and making it the central production point for much of Yorkshire. This is because it is home to existing heavy industry and is already responsible for ~50% of the UK's hydrogen production, using SMR, with many plans to incorporate CCS technology soon in the future [165]. Also, its location is close to the North Sea with good transport links from Tees port and major motorways. As a result, this work assumes the hydrogen produced at Teesside will provide for all consumers within a 200 km radius, as shown in the map in Figure 5-5. This 200 km catchment radius was also chosen because the majority of hydrogen transported by trucks is for delivery distances less than 300 km [17]. Distances exceeding 200 km begin to make the transport process impractical from a logistics point of view as the return journey for the empty vehicles is long so only a few trips are made each day, reducing productivity.

Input quantities for SMR and SMR with CCS were sourced from Dai *et al.* [161] per kg of hydrogen and used in this work respectively. All process conditions are outlined in Table 5-5 and further details regarding the fuel conditioning and delivery will be given in the upcoming sections.

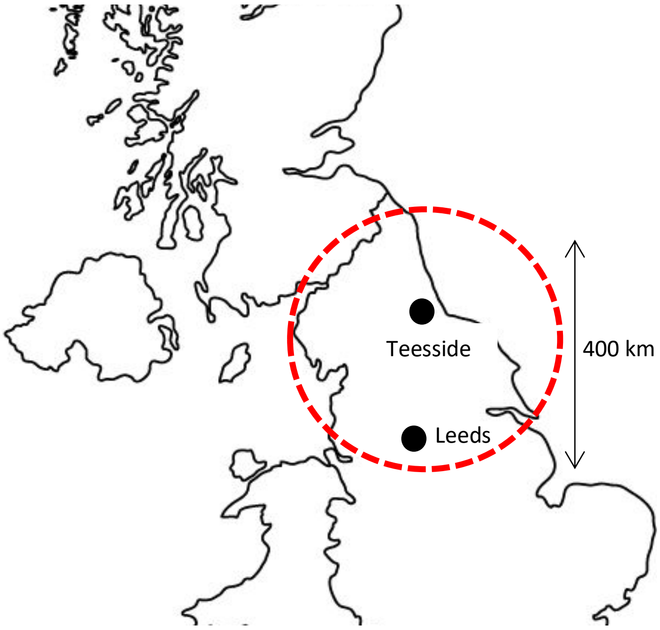


Figure 5-5 - Hydrogen production at Teesside provides for consumers within a 200 km radius.

Electrolysis:

The theoretical minimum energy requirement for hydrogen production from electrolysis is 40 kWh/kg H_2 [315]. However studies suggest this technology has an energy efficiency ranging from 60-80%, depending on the specific technology used**,** while the IEA estimates current electrical efficiencies of 56-60% for PEM electrolysis specifically [108] [17]. This work assumes an efficiency of 65%, giving an actual electricity requirement of approximately 61.5 kWh/kg H_2. This figure is also inclusive of the energy required for water desalination. Water is needed for the electrolysis process and its consumption should be taken into account in an LCA. Approximately 9 kg of deionised water is required per kg of hydrogen, calculated using Equation 18-Equation *21* below [109]. This is to reduce degradation of the equipment, such as the porous layer of the PEM, and help maintain a long operating lifetime of the electrolyser. Several literature studies investigating water scarcity from electrolysis confirm that its consumption will not be a major barrier for renewable hydrogen production, nor will it negatively impact the water supply of geographical regions, hence no further attention is given to this issue [109].

$$2\mathrm{H_2} + \mathrm{O_2} \rightarrow 2\mathrm{H_2O} \qquad \text{Equation 18}$$

$$\text{Molar Ratio} = 2:1:2 \quad \text{Equation 19}$$

$$\text{Mass Ratio (kg)} = 4:32:36 \quad \text{Equation 20}$$

$$\text{Mass of Water per kg } H_2 = \frac{36\text{ kg}}{4} = 9\text{ kg} \quad \text{Equation 21}$$

Capacity factor is defined as the ratio between the actual consumption, output, or throughput over a specific time period to the theoretical maximum over the same period respectively. Since the daily hydrogen demand is very low (Table 3-7), the electrolyser required to produce the hydrogen is small. Also, since this electrolyser is grid connected, and because the wind turbine for renewable generation is comparatively large, it is assumed the electrolyser operates with a 100% capacity factor. This assumption is based on work by Nock *et al.* [320] and Christensen *et al.*[55] respectively. Nock *et al.* [320] report high electrolyser capacity factors under small electrolyser to turbine capacity ratios. The use of this capacity factor also helps to ensure efficiency is high and costs are low, which is vital in the early stages of hydrogen adoption. In terms of the turbine, [194] state that wind turbines have average capacity factors of approximately 20-30%, though this will vary based on several factors, like the countries geography. As a result, the 225 kW turbine in this work is assumed to have a capacity factor of 25%, which is in line with figures for existing wind turbines [271]. Under these conditions, the total daily electricity generation is calculated using Equation 22 and is 1350 kWh.

$$\text{Energy (kWh)} = \text{Power (225 kW)} \times \text{Time (24h)} \times \text{Capacity Factor (25\%)} = 1350\text{ kWh} \quad \text{Equation 22}$$

This renewable electricity is used to produce hydrogen required for the vehicles. However, this generation is not enough to cover the total daily hydrogen demand from all the vehicles in Chapter 3. From the fuel consumption and mileage figures in Table 3-7, the total daily hydrogen demand is approximately 74 kg, shown in Table 5-4. Since the electrolysis process (61.5 kWh/kg H_2) and associated conditioning (3.7 kWh/kg H_2) requires a total of 65.2 kWh/kg H_2, roughly 4844 kWh is required to provide for all of the vehicles, calculated in Equation 23. This means that the 1350 kWh from the turbine only provides ~28% of the energy required, leaving the remaining 72% to be sourced using grid electricity.

Table 5-4 - Daily hydrogen demand for the fleet vehicles.

	Car	**Bus**	**Truck**	**Tipper**	**Refuse**	**Forklift**	**Total**
Daily Mileage (km):	64.4	99.1	496.4	33.2	54.7	29.8	-
Fuel Consumption (kWh/100km):	18.3	217	343.6	253	645.8	354	-
H_2 Demand (kg):	0.35	6.45	51.17	2.52	10.60	3.17	74.3

$$\text{Energy} = 65.2\left(\frac{\text{kWh}}{\text{kg } H_2}\right) \times 74.3\text{ kg } H_2 = 4844\text{ kWh} \quad \text{Equation 23}$$

For BEVs, for electricity generated from the 225 kW turbine, since the total daily consumption of the fleet from Table 3-7 is approximately 754 kWh and this turbine generates 1350 kWh, no grid electricity is required. In this case, there is an excess of nearly 600 kWh of renewable electricity which is not used by the fleet. This remaining electricity has the potential to be exported to other fleets or facilities and could avoid emissions from the generation of electricity from non-renewable sources, leading to significant savings. As a result, a credit could be applied in this case. However, since the emission savings are not associated with the life cycle of the fleet vehicles, this credit would be attributed to the facility generating the renewable power. As a result, the credit is considered outside of the system boundaries. Despite this, it is important that this is acknowledged, and excess electricity does not go unused. This aspect could be included in future work if system boundaries are widened.

Table 5-5 - Summary of inputs and process conditions for 1 kg of hydrogen production.

	Unit:	**Value:**
SMR:		
Natural Gas	m^3	3.5
Water (deionised)	kg	16.42
Electricity	kWh	0.483
Steam	kg	6.4
Temperature	°C	900°C
H_2 Production Pressure	bar	20
Final H_2 Purity	%	99.999
SMR with CCS:		
Natural Gas	m^3	3.28
Water (deionised)	kg	11.31
Electricity	kWh	1.104
Steam	kg	0.8
Monoethanolamine	g	10.32
Temperature	°C	900°C
CO_2 Capture Rate	%	70%
H_2 Production Pressure	bar	20
Final H_2 Purity	%	99.999
Electrolysis:		
Efficiency	%	65
Electrolyser Type	-	PEM
Electricity	kWh/kg H_2	61.5
Water (deionised)	kg	9
H_2 Production Pressure	bar	20
Final H_2 Purity	%	99.999

5.3.2. Fuel Conditioning, Delivery, and Precooling:

Figure 5-6 gives a brief summary of the hydrogen supply chain used which will be covered further in this chapter.

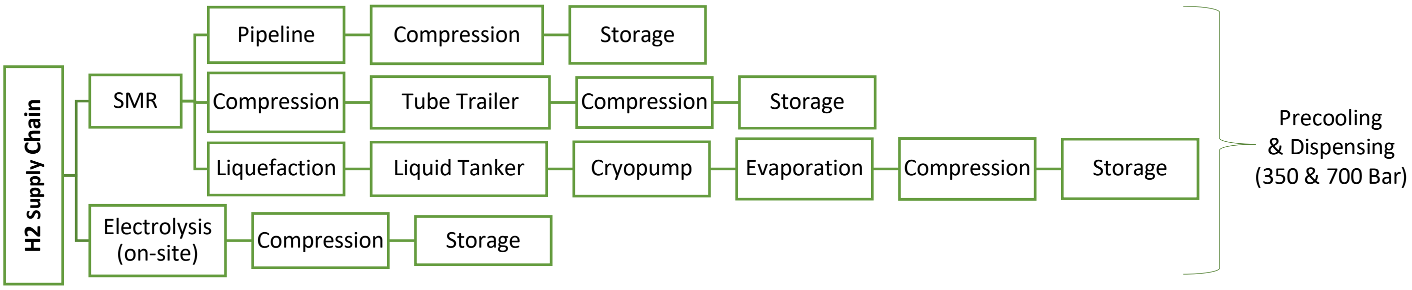


Figure 5-6 - Summary of the hydrogen supply chains.

Hydrogen is produced from all routes at an outlet pressure of 20 bar and distributed using some of the most common methods available; by compressed gaseous pipeline, 350 bar pressurised tube trailers, and liquid road tankers [105]. In order for these distribution routes to be used, all hydrogen must be compressed or liquefied prior to transport, buffer storage, and dispensing in a refuelling station.

For hydrogen from SMR and SMR with CCS, compression and liquefaction is carried out using UK grid electricity. However, for electrolytic hydrogen from 225 kW, 50-50 Split, and 100% RES scenarios, as much as possible of the conditioning processes are carried out using renewable electricity generated from wind power, with any additional electricity demand sourced from the UK grid.

Similar to CO_2 transport, research by Varney *et al.* [164] suggests that ~70% of the existing onshore oil and gas pipeline length is suitable for transporting hydrogen, with the remainder considered promising for reuse. The pipeline system modelled in this work uses natural gas lines (made primarily from steel, iron, and polyethylene) because Ecoinvent does not include pipelines specifically designed for hydrogen transport. Despite their absence in the database and the risk of hydrogen embrittlement in steel pipelines, Section 5.2.2 highlighted the emissions associated with the construction of pipeline infrastructure is outside of the system boundaries, therefore this process has no impact on the results of this study. Although not required in this work, one interview with National Grid reported by Burgess *et al.* [111] provided insight into the feasibility of the gas grid transporting various blends of hydrogen and covered the effects of hydrogen embrittlement. Due to the iron mains replacement programme, the majority of the gas network now uses high density polyethylene pipes suitable for transporting hydrogen. National Grid reported that embrittlement is more common in chemical processing where hydrogen is used in its ionic form and is not as common in transmission and distribution [111]. Further, results from the HyDeploy project at Keele University which trialled a 20% hydrogen blend in the gas network showed no adverse chemical interactions, with predictions based on these initial results suggesting embrittlement should not be a significant area of concern [298]. These predictions are also supported by [299] who found no hydrogen embrittlement or strength changes when using polyethylene piping. The transport of pure hydrogen in polyethylene pipes and the impact of embrittlement is still an ongoing area of research and therefore should be carefully investigated if included in the scope of other works.

Since pipeline construction is excluded, emissions associated with hydrogen pipelines are from gaseous compression prior to distribution and its recompression to ensure a pressure differential to maintain the flow of gas. Also, fugitive emissions can be generated by leaks, though these account for a much smaller proportion.

High pressure natural gas distribution pipelines operate between 7 and 30 bar in the UK and once adapted they can be used to transport pure hydrogen directly at its outlet production pressure of 20 bar all the way to the point of end use [110]. The pipeline distance is assumed to be short with a maximum of 200 km and according to work by Baufume *et al.* [309] and Graf *et al.* [310], recompression stations for hydrogen transport are not necessary for distances under 250 km. As a result of these factors and considering low frictional resistances which are expected in newly built pipes, the pressure differential is assumed to remain high enough to transport the gas through the pipeline without the need for recompression. Based on this information and the findings by Dodds *et al.* [110] no significant pressure drop is expected to occur as a result. This is backed further by work from Wlodek *et al.* [313] who investigated piped transport of pure hydrogen and found very low pressure drops across distances of 0-200 km. Similarly, although not pure hydrogen, other studies focusing on low hydrogen blends with natural gas have shown negligible pressure drops which has aided this assumption [306]. The overall lack of studies in literature covering this topic pin it as an area for further research. As a result, assumptions should be revised as more studies are published in the future.

In terms of fugitive emissions in pipelines, there are very few published studies which suggests the current understanding of hydrogen leakage remains uncertain [166]. However, one study suggested hydrogen leakage is similar to natural gas (at 0.1-0.2%) and because of the current lack of knowledge on this topic, it will be necessary to make assumptions [173]. Since Cadent also stated that the new polyethylene pipes do not leak hydrogen and natural gas leakage from transmission pipelines only occurs during maintenance, this work assumes hydrogen leakage is similar to natural gas and is negligible since leakage rates of only 0.3-0.5% are reported in distribution pipes as of 2022, with this falling by 99% after upgrading to polyethylene [173]. Also, as the transport distance is short, it is unlikely to release a significant quantity of hydrogen.

After delivery, compression takes place prior to buffer storage, from its production outlet pressure of 20 bar to ~440 bar for HDV use or ~800 bar for LDV use. These storage pressures are higher than those required on-board the FCEVs to account for the temperature increase (and pressure drop) seen during the dispensing process. In terms of gas compression, this can be either adiabatic or isothermal. Adiabatic compression is characterised by no heat transfer to or from the gas, whilst isothermal compression occurs at constant temperature. Ideally, the adiabatic route requires rapid compression in order to avoid heat exchange, whilst the isothermal route needs to occur slowly so the gas temperature doesn't change. As a result, actual compression takes place somewhere between these two extremes [319]. Since isothermal compression is more efficient, multistage compression with interstage cooling is used to achieve as close to isothermal conditions as possible. The solid black line in Figure 5-7 shows these energy requirements, though its exact values can vary from case to case.

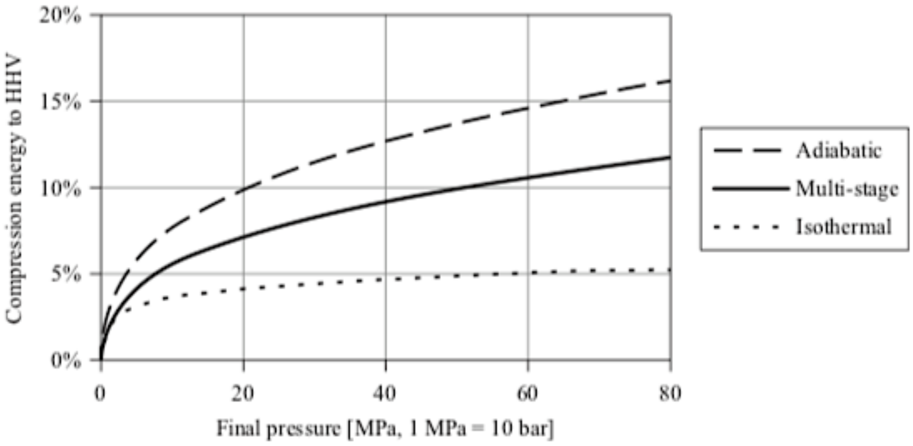


Figure 5-7 – Compression energy based on H_2 higher heating value (142 MJ/kg). [318]

As this work aims to target close to isothermal conditions, and compression energy tails off after ~500 bar in Figure 5-7, the additional energy to compress hydrogen from 440 to 800 bar is very small. As a result, the final energy to compress hydrogen from 20 bar to 440 and 800 bar is approximately 3 kWh/kg H_2 and 3.25 kWh/kg H2, based on Figure 5-7 and [300] [301] [302] [317] respectively. Lastly, since this compression stage plays a minor role in the total energy consumption and has a negligible impact on total emissions, the use of higher compression energy values are not likely to lead to noticeable changes.

Tube trailers carry hydrogen at various pressures depending on the type of trailer used. Composite trailers are capable of transporting high quantities of hydrogen (>1000 kg) at pressures of up to 500 bar, whilst conventional steel trailers are limited by weight regulations to a maximum hydrogen payload of 270 kg at 200 bar [112]. This work modelled the use of a tube trailer with a hydrogen capacity of 500 kg at 350 bar, with compression from a 20 bar outlet pressure to 350 bar carried out after production. Similar to pipeline distribution, it is assumed that pressure drops are negligible over the short transport distance so no intermediate recompression is required. Once the hydrogen is delivered to the point of end use, it must be compressed a second time to the buffer storage pressures (at 440 bar or 880 bar depending on the vehicle used).

For liquid tanker transport, the gaseous hydrogen produced must undergo an energy intensive liquefaction process to convert it to liquified hydrogen. This process requires more electricity than compression (approximately 10 kWh/kg H_2) and once the hydrogen is liquefied, it is loaded into cryogenic tankers (16-32t Euro 6 tankers in Ecoinvent), which are capable of transporting quantities of >4000 kg at atmospheric pressure [113]. Typical hydrogen boil-off losses associated with cryogenic transport and storage have been estimated at approximately 0.3% per day [143]. However, because the liquefaction plant and the cryogenic tanker are assumed to be in close proximity of each other, and the distances travelled between the point of production and the point of use are short, it is assumed that these losses are negligible [113]. After delivery, a cryogenic pump (requiring 1.3 kWh/kg H_2) passes the hydrogen through an evaporator where passive heating with ambient air converts the hydrogen to a gaseous form ready for dispensing [114]. Since energy requirements for this process could not be sourced in literature, Amgad Elgowainy, senior scientist at Argonne National Laboratory, confirmed this process and stated no energy is needed for this passive heating process.

In addition to the compression and liquefaction processes, electricity is also required for the precooling of hydrogen after storage and prior to dispensing in a refuelling station. Hydrogen must be precooled to -40°C using a refrigerant and a heat exchanger in a precooling unit (PCU) to account for the Joule Thompson (JT) effect during refilling. This describes the temperature change of a gas when it's forced through a plug/valve under adiabatic conditions (i.e. no heat transfer with the environment during the expansion). All gases have an inversion temperature where their JT coefficient is equal to zero and no heating or cooling changes are seen (shown by the red line in Figure 5-8). This JT coefficient is defined as the ratio of the temperature drop to the pressure drop, respectively. In the case of high pressure hydrogen, because its inversion temperature is much lower than room temperature at -80°C (200K), it will always have a negative JT coefficient during the process and the maximum pressure drop that could be seen can cause its temperature to rise by up to 40°C when dispensing [316]. The opposite is true for the vast majority of other gases however, which see a temperature drop [107]. As this work assumes FCEV cars use Type 4 carbon fibre composite hydrogen tanks (which are commonly used for FCEVs), precooling is required for all 700 bar refills. For 350 bar refills for HDVs, precooling is only required in cases where the refuelling station use is high [173]. Since hydrogen is used for back-to-base fleets, it is reasonable to expect their utilisation to be high.

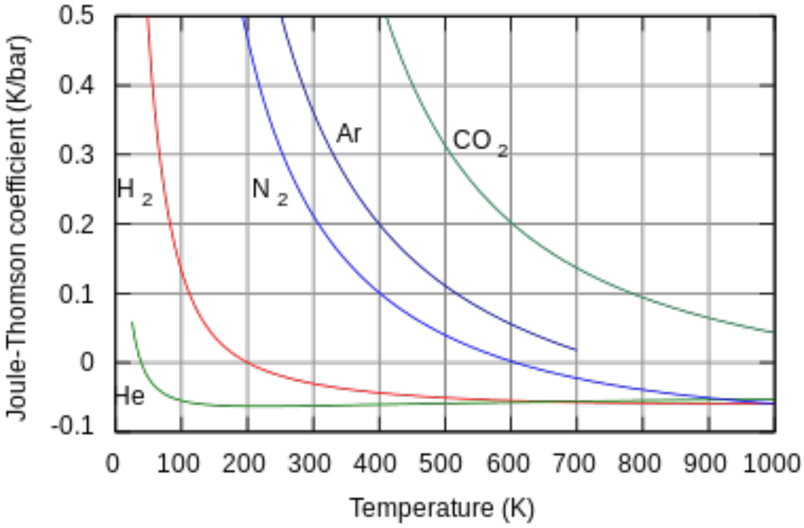


Figure 5-8 - The JT coefficients under different temperatures and pressures.

The energy requirement for the precooling unit is taken from Li *et al.* [115], assuming a hydrogen refuelling station (HRS) with high utilisation. This gives an energy requirement of 0.3 kWh/kg H_2 respectively. In addition, the PCU requires 45 kWh/day for general day-to-day maintenance [116] [117]. Taking into account the expected daily hydrogen demand shown previously in Table 3-7, this gives an overall estimate for the PCU electricity requirement of 2.5 kWh/day respectively (Table 5-6).

Table 5-6 - Summary of calculations used to estimate precooling energy. [116]

$\text{PCU EI} = \frac{\text{CEI}_{\text{refuelling}} + \left(\frac{\text{DCE}_{\text{overhead}}}{\text{DDH}_2}\right)}{\text{COP}} = \frac{\text{CEI}_{\text{refuelling}}}{\text{COP}} + \frac{\text{DE}_{\text{overhead}}}{\text{DDH}_2}$	Equation 24
$\text{PCU EI} = \frac{2.66}{1.02} + \frac{45}{74} = 2.5\,\frac{\text{kWh}}{\text{kgH}_2}$	
$\text{CEI}_{\text{refuelling}} = \left(\frac{\text{DE}_{\text{total}} - \text{DE}_{\text{overhead}}}{\text{DDH}_2}\right) \text{ x COP}$	Equation 25
$\text{CEI}_{\text{refuelling}} = \left(\frac{186.2 - 45}{74}\right) \text{ x } 1.02 = 1.95$	
$\text{COP} = 1.6 \text{ x } e^{(-0.018 \text{ x } T_{\text{amb}})}$	Equation 26
$\text{COP} = 1.6 \text{ x } e^{(-0.018 \text{ x } 25)} = 1.02$	

PCU EI: Precooling unit energy intensity (kWh/kg H_2)

$\text{CEI}_{\text{refuelling}}$: Cooling energy intensity during refill (kWh/kg H_2)

$\text{DE}_{\text{overhead}}$: Daily overhead energy (kWh/day)

DE_{total}: Total overhead energy (kWh/day)

DCE: Daily overhead cooling energy (kWh/day)

DDH_2: Daily dispensed hydrogen (kg H_2/day)

COP: Coefficient of performance

Table 5-7 - Summary of all hydrogen conditioning and distribution parameters.

	Unit:	**Value:**
Compressed Pipelines:		
Pipeline Material	-	Polyethylene
Length (Natural gas transport)	km	100
Max Length (H_2 transport)	km	200
Pressure (min)	bar	7
Pressure (max)	bar	30
Gaseous Tube Trailers:		
Hydrogen Capacity per Truck	kg	500
Pressure	bar	350
Max Transport Distance	km	200
Liquid Tankers:		
Hydrogen Capacity per Truck	kg	4000
Max Transport Distance	km	200
Pressure	bar	1
Distribution and Dispensing:		
Refuelling Pressure (LDVs)	bar	700
Refuelling Pressure (HDVs)	bar	350
Utilisation	-	High
Compression Energy (20-440 bar)	kWh/kg H_2	3
Compression Energy (20-880 bar)	kWh/kg H_2	3.25
Liquefaction Energy	kWh/kg H_2	10
Cryogenic Pump Energy	kWh/kg H_2	1.3
Precooling Energy	kWh/kg H_2	2.5

5.3.3. Fuel Use:

Methods used to estimate emissions from fuel and vehicle use will be covered in Section 5.3.4.2 respectively. However, similar to Chapter 4, the fuel consumption (FC) figures used in this LCA must be accurate, and representative of the vehicles outlined in Chapter 3. Figures for all ICEVs were sourced from data published by manufacturers. For those BEVs and FCEVs currently on the market, fuel consumption data was also sourced from manufacturers and is inclusive of battery and fuel cell efficiency. In the cases where this information was not available, estimates were made based on assumptions and on the performance of prototypes and vehicles of a similar performance and specification. It must also be made clear that in this section the same limitations apply as those highlighted previously regarding payload losses and BEV efficiency drops in cold weather. Both of these issues have been acknowledged and are highlighted as areas for future work later in Chapter 9 respectively.

5.3.4. Vehicle Cycle:

The vehicle cycle is inclusive of raw material extraction, component production, vehicle assembly, distribution, usage, and the end of life scenario. Since each of the vehicle types and powertrains require different components of varying sizes, they will incur a range of emissions as a result of varying upstream processes. This section outlines the key components for each of the vehicles manufacture and assembly stages and describes the methods and processes used to obtain the relevant material inventory data. Table 5-8 highlights the major components of each powertrain that were included in this LCA study.

Estimates for the component weights for each of the vehicles in Chapter 3 can be found in Section 11.1 in Appendix 2. Weight estimates are taken from manufacturers where possible but are also based on published studies and Ecoinvent data where availability of manufacturer data is low, such as for ZEVs with a low current market penetration.

Table 5-8 - Key components associated with the manufacture of ICEV, BEV, and FCEV passenger cars.

Component:	**ICEV:**	**BEV:**	**FCEV:**
Glider	✓	✓	✓
Vehicle Fluids	✓	✓	✓
Gearbox	✓		
Electronics for Control Unit	✓		
Fuel Cell (PEM)			✓
Electric Motor & Inverters		✓	✓
Battery (Li-Ion)		✓	✓
H_2 Storage Tank			✓
Combustion Engine	✓		
Diesel Tank	✓		
Power Control Unit	✓	✓	✓
Starter System	✓		
Balance of Plant		✓	✓

5.3.4.1. Vehicle Production and Assembly:

Component Inventory:

Since council fleets are not typically responsible for the manufacturing of their vehicles, no primary data was taken from councils to support the modelling of the vehicle manufacture. Instead, inventory data was taken from original equipment manufacturers (OEMs) where possible as well as existing literature studies and adapted where necessary to meet the requirements of this work. Other supporting inventory data was taken from the Ecoinvent database, respectively.

The material inventory required for the manufacture of several vehicle components was taken from Candelaresi *et al.* [85]. In this literature study, inventory data was scaled from Notter *et al.* [137] based on the vehicle engine power (kW) to meet the requirements of their vehicle. This work uses the same approach for each of the fleet vehicles since inventory data could not be sourced directly from OEMs, despite several emails and phone calls. This was due to data sensitivity and the complexity of supply chains which made it challenging for the suppliers to provide material breakdowns. The components assembled in SimaPro based on inventory from Candelaresi *et al.* [85] included:

- Gearbox (ICEVs) – Consists mainly of low alloyed steel and aluminium. The gearbox is required for ICEVs only.

- Cooling System (ICEVs) – For the transfer of heat away from the engine using a water coolant via a series of channels in the engine compartments. This is made from steel, aluminium, and polyethylene materials.

- Diesel Fuel System (ICEVs) - Made from reinforcing steel, the fuel system is needed to help transfer the fuel from the tank to the engine of the vehicle for combustion.

- Diesel Fuel Tank (ICEVs) – For storage of the fuel on board the vehicle; this is made from high density polyethylene (HDPE) granulate with injection moulding. Inventory for a gasoline tank was used since diesel tank inventory could not be sourced in literature. However, these high density polyethylene (HDPE) tanks are also suitable for storing large quantities of diesel fuel and have an expected lifespan of over 20 years, which is more than enough for the vehicle lifetime [190]. Furthermore, when considering the minute differences in material quantities and the negligible impact on production emissions, this approach was deemed reasonable to allow progress to be made. It is assumed the fuel tank can withstand the high temperatures achieved by the vehicles and no weakening occurs affecting its performance.

- Starter System (ICEVs) – Consists of the alternator, starter motor, and starter battery. These components provide the torque needed to achieve the minimum cranking speeds required to start the vehicles engine.

- Electric Motor (ZEVs) – The electric motors use alternative current (AC) where the flow of electricity can take place in any direction. AC electricity is fed into the car during charging (for BEVs) and is converted immediately into direct current (DC) for use in the battery. Large quantities of low-alloyed steel, aluminium, and copper dominate the production of this component.

- Vehicle Fluids – This includes all fluids needed for the vehicle to maintain operation and will be covered in greater detail in later sections. Lubricating oil is used to model engine oil, brake and transmission fluid. For powertrain coolant and windscreen wash, a 40:60 mix of decarbonised water and ethylene glycol is used.

- Balance of Plant (ZEVs) – Composed mainly of steel and aluminium materials. It consists of auxiliary and supporting components to deliver the vehicles energy.

- Hydrogen Fuel System (FCEVs) – Made from copper and polyvinylchloride to help support the transfer of hydrogen from the storage tank to the fuel cell for the generation of electrical power.

The inventory for other components was sourced from literature and included:

- Combustion Engine and Exhaust System (ICEVs) – The engine is the source of power generation for diesel vehicles. The combustion engine is covered in more detail later in this section respectively. For the exhaust system, this comprises 3 major components. First, a diesel oxidation catalyst (DOC) containing precious metals (including platinum and palladium) oxidises carbon monoxide and any hydrocarbons from incomplete combustion into carbon dioxide and water, as well as oxidising NO to NO_2. This component can be integrated with a silicon carbide-based particulate filter (DPF), which is followed by selective catalytic reduction (SCR) respectively. These are required so the exhaust emissions are low enough to conform to the Euro 6/VI standards, with the SCR aimed to reduce NOx emissions and the DPF targeting soot (PM) reduction. Inventory for the DOC and SCR components was taken from the Ecoinvent database and scaled to the vehicles in this study using insight from Ummel *et al.* [160].

  For the DPF, insight was taken from Larsson *et al.* [167] and Yan *et al.* [168] since specific material inventory and quantities were very limited in availability. In this case, the majority of DPFs for cars weigh approximately 3 kg with the vast majority of this attributed to a ceramic wall-flow monolith of silicon carbide, packed into a steel housing [169]. Vermiculite surrounds the DPF within this housing and is expanded to secure it in place, minimising damage during vehicle operation. Since there is no catalyst required for the DPF when used with a DOC and SCR, it is made solely from these three materials. The material weight distribution in the DPF is assumed to be 85% silicon carbide, 10% steel and 5% vermiculite respectively. These assumptions were made due to a lack of information on DPFs, but the portions of steel and vermiculite are expected to be small due to their role in the component. It should be noted that although these are rough estimates, since they are minor components in the exhaust system, the difference in emissions between estimates and real values is likely to be small overall. For heavy duty trucks, estimates for the weight of the DPF were taken from Berg *et al.* [195] and are reported at approximately 45 kg. This figure has been applied to all the HDVs in this study due to a lack of available data, and all DPFs are assumed to have the same material composition.

- Electronics for Control Units (ECUs) – This comprises a steel housing, plastics, wiring boards and cables for the control of electronic subsystems and engine parameters within the vehicle, such as the delivery of fuel for ICEVs. Inventory for this component was taken from the Ecoinvent database and quantities were provided by Candelaresi *et al.* [85] for a car. As a result, the ICEV passenger car in this study is assumed to have the same quantity of ECUs in its inventory. For ZEVs however these functions are carried out using the power control unit (PCU). Also, the electric motor includes a number of electrical components, so this is not required.

- Power Control Unit (ZEVs) – This component manages the flow of electricity from the battery to the electric motor of a ZEV. It includes the AC/DC and DC/DC converters, battery charger, and power distribution unit respectively. Inventory was taken from Habermacher *et al.* [153] and scaled to the vehicles in this study.

The inventory for more specific ZEV components was scaled on a per-unit basis to the size required for the reference vehicles. These components will be discussed in greater detail in the following sections.

Vehicle Gliders:

The weight of the gliders of the reference vehicles is not provided by manufacturers. As a result, the glider weight for ICEVs is first estimated. For each vehicle type the weight of the glider is estimated by subtracting the weight of the powertrain from the kerb weight, since the glider includes all components not specific to the powertrain [138]. This ICEV glider weight is assumed to represent all ZEV gliders since most gliders are identical, regardless of powertrain. Several other studies use this approach when modelling vehicle life cycles respectively.

Recently, due to concerns surrounding the lower driving range of BEVs, some manufacturers have started adapting their gliders by 'lightweighting' them, which involves using more lightweight materials in the frame, such as aluminium, carbon fibre, and plastic composites [155]. Unfortunately, and similarly to the modelling of some of the components listed in the previous section, material inventory data for the vehicle gliders could not be sourced directly from manufacturers due to the sensitivity and complexities associated. When contacting companies such as Mercedes, Toyota, STILL, and Volvo, and talking with them directly, they highlight the difficulty in providing this information, with staff explaining the data is simply too sensitive and giving it to the public could impact their competitiveness with other manufacturers. Others outlined the complex procedure required in order to request information of this kind and the timeframe for this to all be completed would likely be too long given the time left to complete the project. In order to overcome this and continue making progress, the modelling of the glider production was carried out using inventory data from literature.

It should first be acknowledged that vehicles are likely to require upgrading and/or general repairs to damaged components at some stage during their operation. To account for this, a 20% repair factor was applied to all the materials of the vehicle gliders. This approach is based on the work by Lagnelov *et al.* [136] and is applied in this study for all vehicles since the majority of existing LCA studies fail to acknowledge this. All glider material inventory quantities therefore include a 20% excess to their initial requirement to account for this. More information on repairs is given in Section 5.3.4.3.

For passenger cars, the glider dataset was taken directly from the Ecoinvent database and scaled to meet the requirements of the cars in this study. A similar approach was used in the work by Benitez *et al.* [15] respectively. The glider is inclusive of the car structure and accessories, consisting of the wheels, body, braking, steering, and suspension, in addition to other smaller components.

Gliders for HDVs are not provided in Ecoinvent so were sourced from literature. For buses, the LCA by Lie *et al.* [138] investigated emissions from electric and diesel buses, and gave data relating to their reference bus which was a Volvo 7900; a 12m single deck diesel with a weight of 12.5t and a passenger capacity of 40-68, similar to the reference diesel bus in this work. Here, the weight of each component was given along with the percentage contributions of each material used, shown in Table 5-9 and Table *5-10*. Since the powertrain is not included in the glider, the weight of the powertrain was subtracted from the total to derive a glider weight of 11,000 kg (Table 5-9). This is similar to the glider weight of the reference bus in this study at 11,178 kg, highlighting the similarity between these two vehicles. From here, it was assumed the same material contributions applied in this work, so the quantities of each material could be calculated accordingly and entered in SimaPro. Lastly, it was assumed that from Table 5-10, the material category 'other' was synthetic rubber, since this was not specified in the literature study. Synthetic rubber was chosen as it is commonly used in vehicle manufacturing for parts such as the tyres, door and window profiles, seals, and flooring [191]. The final material inventory for the bus glider used in this work is given in Table 5-11.

Table 5-9 - Mass of each bus component in the literature study by [138].

Vehicle Component:	**Mass (kg):**
Chassis and Frame	5625
Other Body Parts	3125
Body and Panels	2250
~~Powertrain~~	~~1500~~
Glider Total	**11,000**

Table 5-10 - Percentage contribution of each material. [138]

Material:	**% Contribution**
Steel	57%
Plastic	11%
Aluminium	8%
Wood	6%
Copper	3%
Iron	8%
Glass	5%
Other (Synthetic Rubber)	2%

Table 5-11 - Material inventory for the bus glider in this study.

Material:	Contribution %	Weight (kg):
Steel	57%	7645.8
Plastic	11%	1475.5
Aluminium	8%	1073.1
Wood	6%	804.8
Copper	3%	402.4
Iron	8%	1073.1
Glass	5%	670.7
Other	2%	268.3
Total	**100%**	**13,414**

For the gliders of heavy duty trucks, Wolff *et al.* [129] offered inventory data that was scalable and that could be adjusted to suit all of the remaining HDVs in this work. In the study, the trucks were Class 8, 44t trucks which aligned with the long haul truck in this work. The total glider weight was separated into the frame, wheels, suspension, cab, and trailer, with all the materials and quantities to produce these provided. In addition to this was the energy requirements associated with the assembly of the glider. In order to derive inventory for the heavy duty vehicles in this work, all inventory was scaled based on the weight of the glider respectively. The glider weight in this study was divided by the glider weight in the literature study to give a scaling factor which all materials were multiplied by to give an estimate for the materials needed since OEM data was unavailable. Table 5-12 shows the list of materials and energy required to produce the gliders in both the literature study and in this study respectively.

For forklifts it was highlighted in the LCA by Fuc *et al.* [134] that “a lack of inventory data within LCA databases in relation to the use of forklifts has been identified.” Here, they state that Ecoinvent only includes inventory data relating to tractors, trailers, and loaders, with other databases such as the European reference life cycle database (ELCD) only providing information for excavators. As a result, and taking into account the issues encountered previously regarding the collection of glider inventory for HDVs, the material data from Wolff *et al.* [129] has also been applied to forklifts. This presents a limitation to this study since forklifts also include other components vastly different from trucks based on their functions, such as forks. However since manufacturers including Kalmar, Hyster Yale, Toyota, and Linde are not able to offer any insight into the materials used and their quantities, and limited studies exist on the subject (with the majority focusing on on-road vehicles), this approach has been used as a means to making progress considering the time limit set on the study. If time was not a constraint more efforts would be placed on communication for sourcing inventory for the glider of a forklift.

Table 5-12 - Material inventory for the production and assembly of HDV gliders.

<table>
<tr><th colspan="6">Glider Weight Composition (kg):</th></tr>
<tr><td>-</td><td>Study Ref:</td><td>Long Haul:</td><td>Tipper:</td><td>RCV:</td><td>Forklift:</td></tr>
<tr><td>Frame:</td><td>854</td><td>3301.1</td><td>2662.8</td><td>3057.9</td><td>3567.2</td></tr>
<tr><td>Wheels:</td><td>658.8</td><td>2546.5</td><td>2054.2</td><td>2359.0</td><td>2751.8</td></tr>
<tr><td>Suspension:</td><td>1600</td><td>6184.7</td><td>4988.9</td><td>5729.1</td><td>6683.3</td></tr>
<tr><td>Cab:</td><td>1386.7</td><td>5360.2</td><td>4323.8</td><td>4965.3</td><td>5792.3</td></tr>
<tr><td>Others:</td><td>633.7</td><td>2449.5</td><td>1975.9</td><td>2269.1</td><td>2647.0</td></tr>
<tr><td>Total:</td><td>5,133.2</td><td>19,842</td><td>16,005.6</td><td>18,380.4</td><td>21,441.6</td></tr>
<tr><td colspan="6">Material Inventory (kg):</td></tr>
<tr><td>Steel:</td><td>3204.8</td><td>12387.9</td><td>9992.7</td><td>11475.4</td><td>13386.6</td></tr>
<tr><td>Iron:</td><td>400</td><td>1546.2</td><td>1247.2</td><td>1432.3</td><td>1670.8</td></tr>
<tr><td>Rubber:</td><td>280.7</td><td>1085.0</td><td>875.2</td><td>1005.1</td><td>1172.5</td></tr>
<tr><td>Aluminium:</td><td>152.3</td><td>588.7</td><td>474.9</td><td>545.3</td><td>636.2</td></tr>
<tr><td>Duroplast:</td><td>471.3</td><td>1821.8</td><td>1469.5</td><td>1687.6</td><td>1968.6</td></tr>
<tr><td>Thermoplast:</td><td>257.2</td><td>994.2</td><td>802.0</td><td>921.0</td><td>1074.3</td></tr>
<tr><td>Copper:</td><td>119.3</td><td>461.1</td><td>372.0</td><td>427.2</td><td>498.3</td></tr>
<tr><td>Glass:</td><td>159.1</td><td>615.0</td><td>496.1</td><td>569.7</td><td>664.6</td></tr>
<tr><td>Organic:</td><td>39.8</td><td>153.8</td><td>124.1</td><td>142.5</td><td>166.2</td></tr>
<tr><td>Magnesium:</td><td>1</td><td>3.9</td><td>3.1</td><td>3.6</td><td>4.2</td></tr>
<tr><td>Zinc:</td><td>0.4</td><td>1.5</td><td>1.2</td><td>1.4</td><td>1.7</td></tr>
<tr><td>Other:</td><td>0.6</td><td>2.3</td><td>1.9</td><td>2.1</td><td>2.5</td></tr>
<tr><td>Paint:</td><td>46.9</td><td>181.3</td><td>146.2</td><td>167.9</td><td>195.9</td></tr>
<tr><td colspan="6">Material Inventory (Cont):</td></tr>
<tr><td>Water (m^3):</td><td>41.04</td><td>158.6</td><td>128.0</td><td>147.0</td><td>171.4</td></tr>
<tr><td>Oxygen (kg):</td><td>0.19</td><td>0.7</td><td>0.6</td><td>0.7</td><td>0.8</td></tr>
<tr><td>Acetylene (kg):</td><td>0.15</td><td>0.6</td><td>0.5</td><td>0.5</td><td>0.6</td></tr>
<tr><td>Nitrogen (kg):</td><td>0.22</td><td>0.9</td><td>0.7</td><td>0.8</td><td>0.9</td></tr>
<tr><td>Carbon Dioxide (kg):</td><td>2.19</td><td>8.5</td><td>6.8</td><td>7.8</td><td>9.1</td></tr>
<tr><td>Natural Gas (kg):</td><td>3.98</td><td>15.4</td><td>12.4</td><td>14.3</td><td>16.6</td></tr>
<tr><td>Surface Area (m^2):</td><td>16</td><td>61.8</td><td>49.9</td><td>57.3</td><td>66.8</td></tr>
<tr><td>Welding (m):</td><td>1.5</td><td>5.8</td><td>4.7</td><td>5.4</td><td>6.3</td></tr>
<tr><td>Compressed Air (m^3):</td><td>69.82</td><td>269.9</td><td>217.7</td><td>250.0</td><td>291.6</td></tr>
<tr><td>Compressed Air (m^3):</td><td>125.7</td><td>485.9</td><td>391.9</td><td>450.1</td><td>525.1</td></tr>
<tr><td colspan="6">Assembly Energy:</td></tr>
<tr><td>Electricity (kWh):</td><td>1917.47</td><td>7411.8</td><td>5978.8</td><td>6865.9</td><td>8009.4</td></tr>
<tr><td>Heat (MJ):</td><td>2974.08</td><td>11496.1</td><td>9273.3</td><td>10649.3</td><td>12422.9</td></tr>
</table>

Inventory for vehicle tyres was sourced directly from Dong *et al.* [197] and scaled up based on the number of tyres required throughout the vehicle's lifetime. The main materials used in the production of a vehicle tyre includes synthetic and natural rubber, and carbon black respectively.

Lithium-Ion Battery:

Older versions of the Toyota Mirai (which is the FCEV reference vehicle in this work) used a Nickel Metal Hydride (NiMH) battery, but the newest version now uses a lithium-ion battery. Previously, Tesla used Nickel Cobalt Aluminium (NCA) cathode chemistry in the majority of their batteries, however in recent years the Tesla Model 3 (the reference BEV car in this study) and other models now use a Lithium Iron Phosphate (LiFP) cathode chemistry in order to reduce the use of cobalt and nickel [118]. Unfortunately, due to a severe lack of inventory data relating to batteries, highlighted by Crenna *et al.* [118], and after direct contact with Tesla manufacturing, inventory for this battery chemistry could not be sourced, so it was assumed that all ZEVs in this study use Nickel-Manganese-Cobalt (NMC111) lithium-ion batteries. This is because the majority of all other BEV automakers utilise this battery chemistry due to its high energy density and durability. These batteries also require low maintenance and offer fast charging times compared to alternatives [40].

The cathode of NMC111 batteries is split into thirds of nickel, manganese, and cobalt giving an improved lifetime compared to older battery chemistries [118]. Nickel increases the energy density, whilst cobalt and manganese offer thermal and structural durability. However, for future sustainability many manufacturers are now trying to limit the cobalt contained in the batteries by increasing the nickel fraction. This is because cobalt is a critical raw material (CRM) limited in supply and sourced as a by-product of copper and nickel mining, making it difficult to obtain. Cobalt is also expensive, and roughly 50% comes from the Democratic Republic of Congo where child labour is prevalent. As a result, it can largely impact the overall cost and life cycle impact of the battery [141].

The battery inventory data in Ecoinvent was not used for this work as it is considered outdated for the purposes of this study. Ecoinvent contains only the lithium manganese oxide (LMO) chemistry which is steadily being replaced by NMC in transport applications. As a result, for the battery, inventory data and the total bill of materials was sourced from Crenna *et al.* [118] and made use of the most recent data from available literature. This inventory covers all activities and processes from the raw material extraction to the final manufacture of a lithium ion battery. A breakdown of the main battery components is bulleted below and shown in Figure 5-9.

- **Modules and Battery Pack:** Many individual unit cells are connected to form modules which convert chemical energy into electrical energy. Multiple modules are then arranged with various protective systems to form the battery pack which is installed on-board a vehicle. The majority of the pack mass is attributed to the external aluminium casing box and structural support. However, this also includes an insulation layer, copper terminals and the battery management system (BMS). Alongside aluminium, plastics (polyethylene) are also included as they are corrosion-resistant, light, and relatively cheap [141]. The BMS is contained in the pack and includes the electronic components. It is also responsible for the thermal management which is required to maintain power during charging and discharging cycles and ensure high cycle life and capacity.

- **Battery Cells:** The modelling of the battery cells included the cathode, anode, separator, and electrolyte. Inventory also included energy in the form of heat and electricity for the necessary processing stages. The battery in this work consists of 140 individual 46-Ah prismatic cells per pack, made from layers of polyethylene terephthalate for high strength, polypropylene for secure sealing, and aluminium for permeability properties. The battery cells produced are assembled in a dry room under controlled conditions and follow a number of stages including stacking, current collector welding, electrode filling and cell closing respectively.

- **Cathode:** The battery chemistry corresponds to a Li-NMC cathode, typical of current lithium-ion batteries in use. The cathode and anode include aluminium and copper current collectors [118]. The quantity of NMC111 oxide active material is also a significant input which largely influences the energy density of the cells. This is produced from a multi-step reaction with NMC111 hydroxide and lithium carbonate.

  To produce the transition metal oxide required for the cathode, first the NMC111 hydroxide precursor is produced from the co-precipitation of sulphates, namely nickel, manganese, and cobalt. This process incurs high energy demand for their production. Once the sulphates have mixed and dissolved in the solution, sodium hydroxide and ammonium hydroxide are added, the reactor is heated to 50°C, and the solid product of $NMC(OH)_2$ is filtered out and dried to produce the NMC precursor. After, this is mixed with lithium carbonate and calcined to produce the oxide active material [141].

- **Anode:** The cathode is coupled with a graphite-based anode with carbon black, and a binder made from carboxymethyl cellulose and styrene-butadiene rubber [118]. In this case, graphite accounts for the majority of its mass. Deionised water is used as the solvent to prepare the anode slurry and approximately 30% less electricity is used to mix, cut, and calendar the anode slurry when compared to the cathode.

- **Electrolyte:** The battery also consists of an electrolyte made from lithium hexafluorophosphate and ethylene carbonate which promotes ion dissociation and mobility [118] .

- **Separator:** The main aim of the separator is to prevent the electrodes from touching one another and allow the movement of electrons in the electrolyte to pass with minimal resistance. Here, the separator is made using polyethylene with a silica coating layer [118].

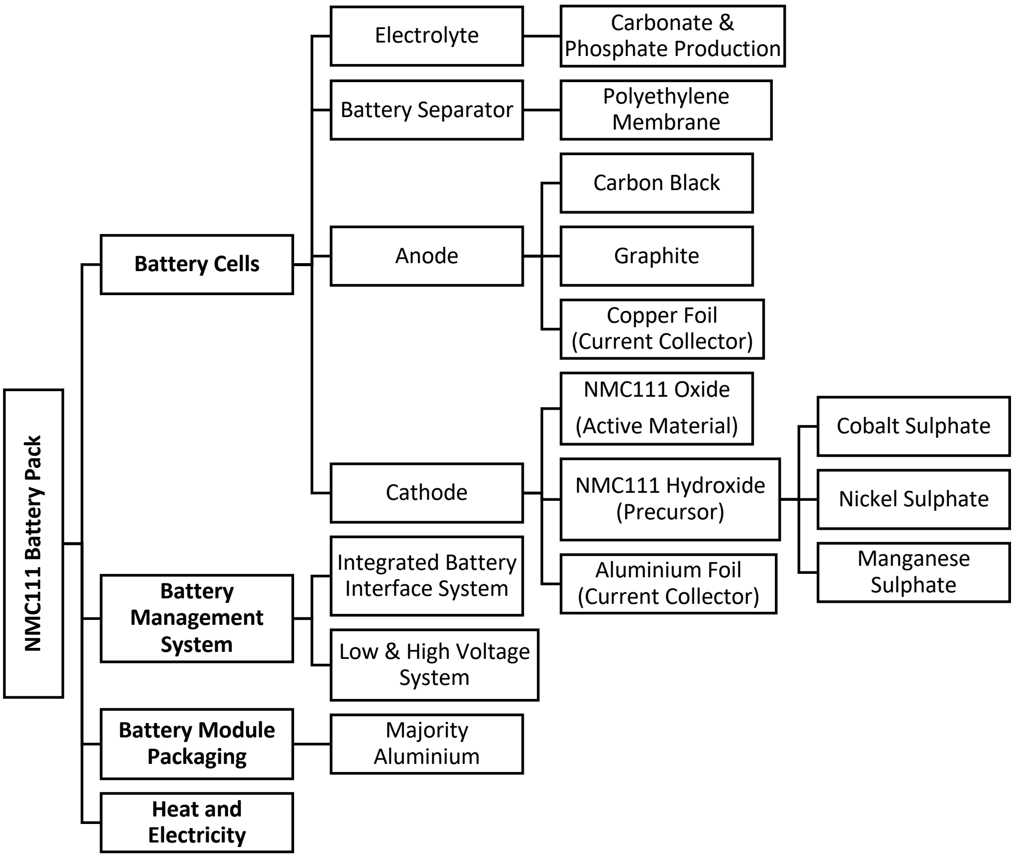


Figure 5-9 - Overview of the major components in the NMC111 lithium-ion battery.

All battery inventory was scaled to meet the demands of each reference BEV. Battery weight was taken from vehicle manufacturers where possible, however since HDV BEVs are still under development and this data isn't often available, this approach was not executed frequently. Instead, most vehicle battery weights were estimated using Equation 27 and an energy density of 250 Wh/kg (at the pack level), which aims to reflect the top end of Li-ion battery technology [155]. This high energy density aims to model predicted figures in the near future based on the historical improvement rate in battery technology [257]. In 2020, several manufacturers were capable of producing Li-NMC batteries with an energy density closely approaching 300 Wh/kg (at the cell level) [256]. Alongside the cell energy density, many companies are now focused on finding new ways to optimise the cell packing to increase the overall pack density further [259]. In addition to cell packing strategies, further weight reductions are expected in battery pack housing as aluminium can be substituted with plastic fibre composites leading to a 40% reduction which indirectly improves the pack energy density [258]. As a result of these factors, the energy density selected in this work is considered a reasonable estimate for NMC technology.

The battery inventory provided by Crenna *et al.* [118] however refers to a slightly lower energy density not representative of the latest battery technology. Due to an absence of detailed data on state-of-the-art NMC batteries, the author could not source inventory referring to an energy density of 250 Wh/kg in the literature. As a result, the inventory from Crenna *et al.* [118] has been assumed to represent an NMC111 battery with an energy density of 250 Wh/kg at the pack level. As previously mentioned, the quantity of active material (NMC111 oxide) largely influences the energy density. Since the production of this material relies on cobalt and sulphates which are responsible for a significant portion of total battery production emissions (shown in Chapter 6), to increase the energy density requires more of these materials which will contribute to higher emissions. Therefore, the use of this inventory presents a limitation which must be acknowledged.

Equation 27 shows the calculation used to estimate battery weight while Equation 28 shows an example for the weight of the battery for the electric bus in this study.

$$\text{Battery Weight (kg)} = \frac{\text{Battery Size (kWh)}}{\text{Energy Density (Pack Level)}\left(\frac{\text{kWh}}{\text{kg}}\right)} \qquad \text{Equation 27}$$

$$\text{Battery Weight (kg)} = \frac{350\ \text{(kWh)}}{0.25\left(\frac{\text{kWh}}{\text{kg}}\right)} = \sim 1400\ \text{kg} \qquad \text{Equation 28}$$

Polymer Electrolyte Membrane Fuel Cell:

All FCEVs make use of proton-exchange membrane (PEM) fuel cells (FC) which are the most commonly used for transport applications due to their high energy density, compactness, maturity, and high durability. The fuel cell system in this work has a specific mass of 1.55 kg/kW which was used to derive the fuel cell weight in each individual FCEV, given in Section 11.1 in Appendix 2. Material inventory for the production of the PEM fuel cell is based on Stropnik *et al.* [86] and Gerboni *et al.* [267] per kW of stack and scaled to match the size of the fuel cells used in each of the reference vehicles given earlier in Chapter 3.

The fuel cell is composed of a membrane electrode assembly (MEA) and includes the PEM which separates two electrodes (anode and cathode) and acts as a barrier for the reactant gases. The anode and cathode catalyst layers are made using platinum and is where a large portion of the fuel cells production emissions and costs originate from. The main material in the stack is graphite with small quantities of platinum for the catalyst components. The balance of plant consists of a range of materials including steel, aluminium, iron, and polyethylene. The major fuel cell components are:

- **Membrane –** This is one of the most important components of the fuel cell and is held within the MEA. In the case of PEM fuel cells, the membrane is a solid polymer and acts as a buffer for the ionic transfer of protons between the anode and cathode as well as separating the reactant gases. Here, protons are conducted from the anode to the cathode whilst electrons are rejected due to its large resistance, forcing them to travel around an external circuit generating electricity. The membrane is made from perfluorosulfonic acid which is one of the most common membrane materials due to its low cost and easy manufacture [119]. It's important that this layer is thin in order to minimise the resistance during transport, but this faces a trade-off with reduced mechanical strength. As a result, manufacturers have been working to reduce this membrane thickness in recent years whilst maintaining durability. For this reason, values vary widely in literature, though the membrane in the Toyota Mirai FCEV has a thickness of around 12.5 μm, taken from Usai *et al.* [255] which is used in this work.

- **Bipolar Plates –** These help to disperse reactants from an external source to the surface of the electrodes and over the active areas using flow-field channels. It is important that their design is lightweight and inexpensive and so in this work the plates are assumed to be made from stainless steel with a titanium and graphite coating, which is the approach used in the Toyota Mirai FCEV. Efforts are being made to replace these materials with plastics in the near future however, as this would enable lower cost production techniques to be used [267].

- **Catalyst and Gas Diffusion Layers –** Catalyst layers offer a surface for where the electrochemical reactions can take place. In PEM fuel cells, the reactions between hydrogen and oxygen take place at a very slow rate under normal conditions so catalysts are needed to speed the process up. Each electrode has a catalyst layer which is supported by a gas diffusion layer to increase its durability and strength since these are relatively weak. Since a high surface area is most important to improve the efficiency and performance, platinum is used as it is one of the most active species and can be dispersed widely on to the substrate. In this work, 0.75g of platinum is used per kW for the fuel cell and is deposited on a porous layer of carbon black to provide the best performance whilst also ensuring a sufficient lifetime. As platinum is expensive efforts are being made to reduce the quantities used, however this can potentially lead to cell voltage losses and a reduced efficiency [267].

- **End Plates –** These hold the fuel cell together in the form of a stack and control the flow of reactants into the fuel cell as well as the exhaust outlet. End plates are made from aluminium and the tie rods are made from steel, but glass fibre was also used in their modelling respectively.

- **Membrane Electrode Assembly –** The membrane electrolyte, gas diffusion layer, and electrode components are attached to form the main MEA. The membrane is hot-pressed to the gas diffusion layer using thermoforming. Polyethylene was also used for the MEA sub-gaskets.

- **Balance of Plant –** Consists of essential components for the operation of the fuel cell, such as the system management and reactant and coolant flows, for example. The inventory materials include steel, aluminium, and polyphenylene sulphide respectively.

Hydrogen Fuel Tank:

For LDVs which store hydrogen on-board at high pressures of 700 bar, inventory for the hydrogen tank was based on work by Rossi *et al.* [120] and Elgowainy *et al.* [70]. These studies consider a Type 4 carbon fibre tank with a 5 kg useable hydrogen capacity (typical of FCEV cars), and a total weight of approximately 95 kg. For HDVs which hold hydrogen in tanks at lower pressures of 350 bar, Type 3 hydrogen tanks were used with their inventory provided by the same sources. This inventory also related to the manufacture of a 5 kg useable hydrogen capacity tank. As a result, for HDVs which require larger quantities of hydrogen on board to provide sufficient driving ranges, instead of modelling the manufacture and assembly of a single tank, several 5 kg tanks can be installed and included in the vehicles assembly. This approach is based on real applications as it is used by many FCEVs in use in public fleets, including the Van Hool FCEV city bus deployed in Aberdeen, which holds 35 kg hydrogen using 7 separate tanks [121]. This approach was discussed and validated by LCA expert, Dr Rob White of Johnson Matthey.

The differences between Type 3 and Type 4 hydrogen tanks in terms of material quantities are shown in Table 5-13. Type 3 pressure vessels typically consist of a thin metal liner and are wrapped with a high strength carbon fibre composite, capable of withstanding the intense pressures of up to 450 bar. For Type 4 tanks, these use a polymer liner and are wrapped in carbon fibre resin composite making them very light and capable of withstanding higher pressures of 1000 bar [172].

The process of making carbon fibre is a complicated one and can be carried out in a number of ways. Many studies highlight that this manufacturing process is the largest contributor to the GWP of both Type 3 and Type 4 tanks, dominating total production emissions as a result of its high energy intensity [15] [248]. When modelling the manufacture of the tanks in this work, inventory for the carbon fibre production process in the study by Rossi *et al.* [120] uses base chemicals of ammonia and propylene which produce the acrylonitrile monomer (and polyacrylonitrile polymer). This is the major building block and molecular backbone of 90% of current carbon fibre production, with the remaining 10% coming from rayon-based precursors [247]. One of the difficulties in modelling carbon fibre production accurately that should be acknowledged comes from the fact that manufacturers are keen to withhold information regarding the materials used and their quantities to remain competitive with rival companies. As a result, it can lead to significant differences in the inventory used as information isn't always available, and assumptions differ across studies. When taking this into account, and the fact that the carbon fibre production is highly energy intense accounting for the majority of tank emissions, it can often lead to a wide range in the production emissions generated. Results from the production of the tanks is covered later in Chapter 6 respectively.

Table 5-13 – Material inventory for Type III and Type IV hydrogen tanks.

Material:	**Unit:**	**Type 3:**	**Type 4:**
Ammonia (Liquid)	kg	21.2	27
Electricity	MJ	404.9	514.9
Propylene	kg	53.0	67.4
Chromium Steel Pipe	kg	4	4
Glass Fibre Reinforced Plastic	kg	6.1	4.6
Polyethylene Granulate, High Density	kg	11.4	8
Polymer Foaming	kg	5.2	4
Silicon, Electronics Grade	kg	1	1
Steel, Low Alloyed	kg	14.5	13.7

Internal Combustion Engine:

Inventory data for the internal combustion engine was modelled using data from Wolff *et al.* [129] and scaled based on engine power. The weight of the engine in each reference case was estimated from Fries *et al.* [122] using the torque in Equation 29. The main materials used for the combustion engine included steel, iron, and aluminium, as well as carbon fibre and copper.

$$\text{Engine Weight (kg)} = 0.406 \times \text{Torque (Nm)} + 147.7 \qquad \text{Equation 29}$$

Vehicle Assembly and Delivery:

Once inventory data was collected for each vehicle component, emissions associated with their transport to a final assembly facility were estimated. Wolff *et al.* [129] report that due to complex supply chains and the last-minute production mode for commercial vehicles, component production and assembly stages do not often occur at the same location. Instead, components are transported to a separate assembly facility using road transport.

To do this, instead of estimating the emissions from the transport of every individual component, the assembly of the vehicles was based on work by Lie *et al.* [138] in which components were grouped into either the glider or the powertrain. The components included in each of the three powertrains are bulleted below, whilst the glider is assumed to include all remaining items respectively.

- ICEV: combustion engine, gearbox, and diesel tank.
- BEV: battery, power control unit (PCU), and electric motor.
- FCEV: fuel cell, electric motor, hydrogen tank, PCU, and battery.

Considering the current status of ZEVs, it is common for many of their components to be manufactured in countries outside of the UK and transported to a final assembly point, sometimes coming from specific and highly skilled producers who have more resources, experience, developed markets, or better facilities. Taking this into account, specialist European and global manufacturers have been identified and selected for the production of ZEV powertrain components (some of which are listed in Table 5-14). For these components imported from outside of the UK, this work considers the road transport emissions from the shipping port at Teesside to the assembly point in Leeds, which is a distance of 107.2 km, highlighted in Table 5-14. Transport emissions from the component manufacturing sites outside of the UK to the port at Teesside are assumed outside the scope of this work since there are multiple routes and transport methods and the complexity of this task is high.

For ICEVs, since their markets are more mature and experience in the field is higher, the UK manufactures a variety of components in-house. For example, in 2019 over 1.3m cars were manufactured in the UK with 80% of

these exported to other countries [139]. For these components, an assumption has been adopted from the work of Wolff *et al.* [129]. As a result, ICEV powertrain components and the gliders for all vehicles are assumed to be manufactured and assembled locally within a 200 km radius of the midlands where several manufacturing plants are based, within reach of the point of use at Leeds (
Figure 5-10).

Using the approach by Helmers *et al.* [103] as a guideline, Table 5-15 gives the distance between the manufacturing and assembly points, the mode of transport used, the total weight of the vehicle gliders and powertrains, and the final tkm values. These payload-distance figures were used in Ecoinvent to model the associated diesel emissions. These will be covered later in Chapter 6 respectively.

Table 5-14 - Manufacturers of the major ZEV powertrain components.

Component:	**Manufacturer:**	**Location:**	**Dist. (km):**	**Comments:**
Fuel Cell	Toyota	Motomachi Plant, Japan	107.2	Major Toyota manufacturing plant.
Battery	CATL	Fujian, China	107.2	Controls ~35% of the BEV battery market.
Electric Motor	Siemens	Berlin, Germany	107.2	Large supplier of BEV motors.
Hydrogen Tank	Toyota	Shimoyama Plant, Japan	107.2	Major Toyota manufacturing plant.

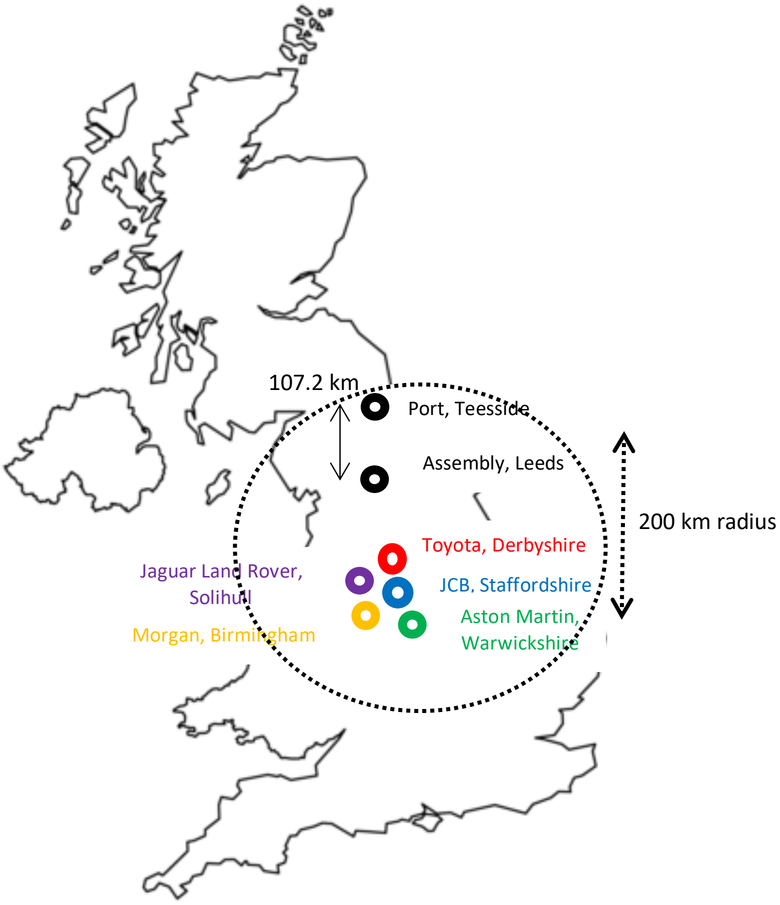


Figure 5-10 – Map showing some midlands vehicle manufacturing plants and final assembly site in Leeds.

Table 5-15 – Journey details from the production to assembly facilities.

Component:	Start Point:	End Point:	Dist. (km):	Transport Method:	Vehicle:	Weight (kg):	Payload Dist. (tkm):
Glider	Midlands, UK	Leeds, UK	200	16-32t Lorry	Car	1,263	252.6
					City Bus	12,686	2,537.2
					Long Haul	19,310	3,682
					Tipper	15,614	3,122.8
					Refuse	17,965	3,593
					Forklift	20,859	4,171.8
Powertrain (ICEV)	Midlands, UK	Leeds, UK	200	16-32t Lorry	Car	637	127.4
					City Bus	1,485	297
					Long Haul	1,954	390.8
					Tipper	1,018	203.6
					Refuse	1,061	212.2
					Forklift	874	174.8
Powertrain (BEV)	Tees Port, UK	Leeds, UK	107.2	16-32t Lorry	Car	656	70.3
					City Bus	1,543	165.4
					Long Haul	1,472	157.8
					Tipper	1,256	134.6
					Refuse	996	106.8
					Forklift	371	39.8
Powertrain (FCEV)	Tees Port, UK	Leeds, UK	107.2	16-32t Lorry	Car	347	37.2
					City Bus	825	88.4
					Long Haul	2,472.5	265.1
					Tipper	1094.5	117.3
					Refuse	919	98.5
					Forklift	1270	136.1

Once delivered to the final facility, the components are assembled for use. Manufacturers assemble vehicles using different methods and these vary widely depending on the level of automation, the type of vehicle, and its powertrain, for example. For passenger cars, the electricity requirement for assembly was based on Benitez *et al.* [15] at 700 kWh respectively. For buses, figures were based on work by Spielmann *et al.* [196]. This report provided energy consumption tailored to the final assembly of heavy duty trucks across all lorry classes and weight categories. However, because of a lack of data relating to the assembly phase of buses, these values have been used in this study. Table 5-16 highlights the total energy requirements for the assembly of a bus.

Table 5-16 - Energy requirements for the assembly of a bus. [196]

Input:	Unit:	Quantity:
Natural Gas	MJ	26,800
Electricity	kWh	3,350
Light Fuel Oil	MJ	153
Diesel	kg	111
Drinking Water	m^3	15.8
Ground Water	m^3	65.5
Rainwater	m^3	43.6

For all remaining HDVs, the inventory for the vehicle gliders taken from Wolff *et al.* [129] included energy requirements for vehicle assembly, shown previously in Table 5-12. As a result, no additional energy is needed for these vehicles.

5.3.4.2. Vehicle Use:

This section outlines the methods used for modelling the use of the vehicles. It highlights the inputs and outputs used to generate emissions on a per unit-km basis (i.e. per km, pkm, or tkm respectively).

Diesel Vehicles:

One of the limitations of this work lies in the fact that the emissions from the vehicle use phase do not correspond to real driving emissions. As a result of a lack of resources and availability, tailpipe emissions from the operation of ICEVs were estimated using the emissions modelling software COPERT (Computer Program to calculate Emissions from Road Transport). This is a free tool that allows users to enter specific conditions and driving characteristics. COPERT was chosen as opposed to Ecoinvent or GREET because it is designed solely for estimating transport emissions and allows the user to input detailed driving conditions which are used to generate more accurate estimates; something that these other software options don't offer. It is for these reasons that COPERT is widely used in modelling studies across Europe. The software was also developed by the Laboratory of Applied Thermodynamics and is part of Atmospheric Emissions Inventory Guidebook and is used by the vast majority of EU member states in official reporting of emission inventories for road transport, highlighting its suitability as a reliable emissions tool for this work [186]. Unlike COPERT which is regularly updated, the vehicle data in Ecoinvent is relatively old in comparison with a lot of data unchanged from several years ago, failing to offer an accurate representation of present-day technology. This is important when considering the rapid pace of change seen in the transport sector as new technologies are introduced, such as exhaust aftertreatment systems, for example. Ecoinvent also cannot model vehicle usage under a regulated driving cycle like the worldwide harmonised light duty test procedure (WLTP), however because COPERT allows the user to enter specific driving conditions, cycles like WLTP can be closely replicated. To emphasise these points, Rial *et al.* [312] conducted an LCA study and collected emission factors from different LCA software including Ecoinvent, GREET, COPERT, VECTO, and AFLEET and ranked COPERT highest with one advantage being that it considers a wider range of exhaust emissions compared to GREET and AFLEET, which exclude NH_3, N_2O, and CH_4.

Typically, the majority of transport emission inventories are based on emission factors obtained by testing a range of vehicles (approx. 10-20) of a particular size and engine power and with specific emission control technologies [178] [269]. Often, vehicles run on a chassis dynamometer under a set of driving conditions with their emissions recorded. These emissions are divided by the distance driven to give equations that describes the vehicle's emission profile and generate an average emission factor which, because chassis dynamometer tests are time consuming and expensive, is then assumed representative of other vehicles of a similar size and technology operating under the same conditions. There are limitations to this method however as it can yield large errors in fuel use and emissions if the dynamometer tests don’t reflect real driving, meaning some vehicles may not be accurately represented [270]. Despite this, due to the time constraints and the availability of real emissions data, COPERT was used in this study as a suitable approach.

The modelling software provides a number of speed-dependent emission factors for pollutants. For diesel HDVs, the emission factors used in COPERT are taken from the handbook on emission factors for road transport (HBEFA) which follows a similar process to the one described in the previous paragraph [178]. In HBEFA, emission factors are generated from simulations, expanding the chassis dynamometer emission factors since the vast number of vehicle types and driving conditions make it impossible to measure real data in a practical time and under a reasonable cost [187]. This emissions data recorded from emission maps is expanded using the passenger car and heavy duty vehicle emission model (PHEM) simulation tool to generate fuel consumption and emissions of road vehicles under all driving cycles. Emission maps are generated from PHEM by organising the instantaneous measured emissions into standardised maps according to the engine power and speed. To produce representative engine maps from vehicle tests, several vehicles should be included, and realistic driving conditions should be considered. To do this, both portable emissions measurement system (PEMS) data and measured chassis dynamometer data is used (for LDVs) as well as engine test stands (for HDVs) to give a broad vehicle sample for the PHEM simulation [188]. This explanation of COPERT software was confirmed by the developers via email contact in February 2023.

Emission factors selected are determined by the driving conditions, such as the portion of driving carried out on urban, rural, and high speed roads. The type of roads used give an indication of the vehicles typical speeds which are used to determine the cold mile percentage, with COPERT using average speeds of each vehicle respectively. Other input variables used to generate emissions include mileage and climatic conditions (which also impact the time it takes for the vehicles to warm up, impacting cold engine emissions) [178].

The following tables highlight the data types (Table 5-17) required to estimate each pollutant (Table 5-18) respectively. From Table 5-18 the speed-dependent emission factors are NOx, CO, and NMVOCs respectively.

Table 5-17 – Methods for vehicle emissions estimation (A-D) and the input data required by COPERT.

Method:	Hot Emissions:	Cold Emissions:
A	• Total annual km driven per vehicle. • The share of km driven under different driving modes. • **A1:** Average speed of the vehicles under different driving modes. • **A2:** Driving mode dependent emission factors.	• The average trip length per vehicle trip. • The average monthly temperature, trip length, and catalyst technology dependent cold stat correction factor.
B	• Total annual km driven per vehicle. • The share of km driven under different driving modes. • **B1:** Average speed of the vehicles under different driving modes. • **B2:** Driving mode dependent emission factors.	• No cold start emission calculations.
C	• Total annual km driven per vehicle. • The share of km driven under different driving modes. • Driving mode dependent emission factors.	• No cold start emission calculations.
D	• Total annual fuel consumption of the vehicle category. • Fuel consumption related emission factors.	• No cold start emission calculations.

Table 5-18 - Data code required to estimate each diesel vehicle emission.

Vehicle:	NOx	CO	NMVOC	CH_4	N_2O	CO_2
Car	A1	A1	A1	A1	C	D
Bus	B1	B1	B1	C	C	D
Truck	B1	B1	B1	C	C	D
Tipper	B1	B1	B1	C	C	D
Refuse	B1	B1	B1	C	C	D

All input data used in the COPERT emissions model is summarised in Table 5-19 with vehicles complying to the latest EURO 6/VI standards (for LDVs/HDVs), and their generic activity data taken from Table 3-7 in Chapter 3. The share of the vehicle usage to different traffic scenarios is also taken into account. These include urban peak, urban off-peak, rural, and highway conditions which are set based on expected operating patterns for council fleets. These classifications are often distinguished based on their morphology or functions, since traffic is often related. Urban roads are located within the boundaries of a built-up area, rural roads are low-to-moderate capacity roads outside of urban areas, and high-speed roads are motorways, dual carriageways, and other main roads respectively. For vehicle speeds, these were estimated based on the national speed limits for LDVs and HDVs in the UK [276]. For example, heavy duty trucks over 7.5t are limited to a maximum speed of 60 mph (96 km/h) on UK motorways and dual carriageways, and 50 mph (80 km/h) on single carriageways. These limits are considered in the 'high speed roads' column in Table 5-19, which includes all of these road types. All vehicles are modelled under full load operation and the size and weight classes in COPERT refer to the GVW. In the case of passenger cars, the weight was assumed 1600 kg which Ecoinvent states is average weight for a medium sized car. For buses, the capacity was not specified in COPERT but was assumed to be 60 passengers, which lies within the typical range for current single deck medium sized 12m urban city buses in the UK [192].

Table 5-19 - Vehicle circulation data used in the COPERT emissions model.

Vehicle:	**Segment:**	**Circulation Data (Share):**					**Circulation Data (Speed - km/h):**			
		Load (%):	**Urban (Peak):**	**Urban (Off-Peak):**	**Rural:**	**High Speed Roads:**	**Urban (Peak):**	**Urban (Off-Peak):**	**Rural:**	**High Speed Roads:**
Car	Medium	-	50%	50%	0%	0%	32	48	-	-
City Bus	Urban Mid (<15t)	100	50%	50%	0%	0%	32	48	-	-
Truck	Artic 40-50t	100	10%	10%	30%	50%	32	48	64	80
Tipper	Rigid 26-28t	100	40%	40%	0%	20%	32	48	-	96
RCV	Rigid 26-28t	100	50%	50%	0%	0%	32	48	-	-

When estimating exhaust emissions in COPERT, one issue that arose was the fact that the software was not able to generate figures for the particulate matter (PM) from HDVs. After contacting COPERT, they reported that this is a bug that can occur in the case of Euro VI HDVs and that they aim to fix in the next version of the software. In order to overcome this issue, speed-dependent PM emission factors for all vehicles were estimated using equation coefficients provided in the COPERT handbook. Each vehicle type has a unique set of coefficients which vary based on a number of factors including the vehicle class, exhaust aftertreatment technology, and speed. These coefficients are used in Equation 30 to generate the emission factors associated with the use of the vehicle, in g/km. An emission factor is calculated for each individual mode share. For example, if the vehicle is used on urban peak and off-peak roads, two separate emission factors are calculated (one for each mode share). The default units of g/km were then converted to the appropriate unit for that vehicle type (i.e. g/km, g/pkm, or g/tkm).

$$\mathrm{EF_i}\ (\mathrm{g/km}) = \frac{\left[(\alpha \times \mathrm{V}^2) + (\beta \times \mathrm{V}) + \left({}^{\delta}/_{\mathrm{V}}\right)\right]}{[(\varepsilon \times \mathrm{V}^2) + (\zeta \times \mathrm{V}) + \eta] \times (1 - \mathrm{RF})} \qquad \text{Equation 30}$$

Where:

- $\mathrm{EF_i}$ = Emission factor of vehicle *i* under specific modelling conditions.
- RF = Reduction factor.
- α, β, δ, ζ, V, ε, η = equation coefficients (After contact with COPERT, they explained the coefficients don't have a physical explanation but are formed mathematically to represent actual emissions data).

For non-exhaust emissions, input quantities used in Ecoinvent for passenger cars were calculated based on existing data for a medium sized passenger car in Ecoinvent, whilst for HDVs these were based on a 44t lorry. The input quantities for these two vehicles in Ecoinvent were scaled using GVW and/or passenger capacity where required to give figures on a per unit-km basis. This approach is considered reasonable since Ecoinvent states that non-exhaust emissions are linearly scalable to gross vehicle weight.

The non-exhaust inputs used to generate emissions are shown in Table *5-20* and include brake, road, and tyre wear. As mentioned, for HDV brake wear (Equation 31-Equation *32*), quantities entered in Ecoinvent were calculated using existing values per km for a 44t lorry. This value was converted to a per tkm basis for HDVs, or a per pkm basis for buses and in each case was then multiplied by a scaling factor to account for the number of tyres (i.e. brakes) the vehicles have. For cars (Equation 33), brake wear inputs were estimated by multiplying the existing value for a 1.6t passenger car by a scaling factor derived using the reference car weight respectively (1.8t).

Tyre wear inputs (Equation 34-Equation *36*) were calculated in the same way as brake wear. Since the reference car uses only 4 tyres and the lorry uses 12, the total number of tyres each vehicle uses was divided by these references to give a scaling factor. The equation used to calculate road wear inputs was provided in Ecoinvent and shown in Equation 37-Equation *38*. This is the same for all vehicles, except for buses which are divided by passenger capacity to generate inputs on a per pkm basis.

$$\text{Brake Wear (Bus)} = \frac{(7.441 \text{ x } 10^{-4})}{\text{Passenger Capacity}} \text{ x } \frac{\text{Number of Tyres}}{12}$$ Equation 31

$$\text{Brake Wear (HDVs)} = \frac{(7.441 \text{ x } 10^{-4})}{\text{GVW}} \text{ x } \frac{\text{Number of Tyres}}{12}$$ Equation 32

$$\text{Brake Wear (Car)} = (9.33 \text{ x } 10^{-6}) \text{ x } \frac{1.6}{\text{GVW}}$$ Equation 33

$$\text{Tyre Wear (Bus)} = \frac{(7.37 \text{ x } 10^{-3})}{\text{Passenger Capacity}} \text{ x } \frac{\text{Number of Tyres}}{12}$$ Equation 34

$$\text{Tyre Wear (HDVs)} = \frac{(7.37 \text{ x } 10^{-3})}{\text{GVW}} \text{ x } \frac{\text{Number of Tyres}}{12}$$ Equation 35

$$\text{Tyre Wear (Car)} = \frac{(1.2 \text{ x } 10^{-4})}{\text{GVW}} \text{ x } \frac{\text{Number of Tyres}}{4}$$ Equation 36

$$\text{Road Wear (Car and HDVs)} = (7 \text{ x } 10^{-9}) \text{ x GVW}$$ Equation 37

$$\text{Road Wear (Bus)} = \frac{(7 \text{ x } 10^{-9}) \text{ x GVW}}{\text{Passenger Capacity}}$$ Equation 38

Table 5-20 – Input quantities used to generate non-exhaust emissions for ICEVs.

			Input Quantities (kg/km, kg/pkm, or kg/tkm):			
Vehicle:	**Capacity/GVW: (passengers/tonnes)**	**Tyres:**	**Brake Wear:**	**Road Wear:**	**Tyre Wear:**	**Total:**
Passenger Car	N/A	4	1.050E-05	2.310E-05	1.351E-04	1.687E-04
12m Bus	60	4	6.201E-06	1.400E-06	6.144E-05	6.904E-05
44t Truck	44	12	1.691E-05	3.080E-04	1.676E-04	4.925E-04
26t Tipper	26	6	1.431E-05	1.820E-04	1.418E-04	1.963E-04
RCV	26	6	1.431E-05	1.820E-04	1.418E-04	1.963E-04

In addition to omitting non-exhaust emissions, another limitation of COPERT (and the vast majority of other emission software tools) is that it does not consider forklifts in its vehicle stock list. For their non-exhaust emissions, these were estimated in the same way as the other vehicles and based on GVW (Table 5-21).

Table 5-21 - Input quantities used to generate non-exhaust emissions for ICEV forklifts.

			Input Quantities (kg/tkm):			
Vehicle:	**GVW: (t)**	**Tyres:**	**Brake Wear:**	**Road Wear:**	**Tyre Wear:**	**Total:**
Forklift	30.2	4	8.213E-06	2.114E-04	8.138E-05	3.010E-04
			Input Quantities (kg/tonne-hour):			
			2.040E-05	5.250E-04	2.021E-04	7.475E-04

For exhaust emissions, similar to the material inventory for their gliders, there is a severe lack of data in LCA databases regarding forklifts. No processes in Ecoinvent refer to these vehicles and there is a large gap in literature surrounding their operating emissions, with Fuc *et al.* [134] reporting that existing LCA studies do not measure exhaust emissions directly, but instead simply calculate these using conversion factors. Furthermore, despite there being data in Ecoinvent related to the combustion of fossil fuels in combustion engines used by some forklifts on the market, these emissions are reported in terms of passenger transport (i.e. per km), not goods transport (per tkm) and since the engines used in cars operate under different conditions to forklifts, this makes it difficult to apply emissions to these vehicles.

In order to generate the exhaust emissions for the diesel forklift in this study, air pollutant emissions were taken from literature and used as a basis for estimations. The study by [182] considered a 43 kW diesel forklift with a fuel consumption of 3L/hour, also in accordance with the VDI 2198 cycle, similar to the reference forklift. Since this is a recent study and the reference forklift in this work is modern with both forklifts using Stage 5 engines (conforming to stricter emission standards for non-road mobile machinery), it is assumed that the engine technology is the same and because exhaust emissions are given per hour of operation, they are assumed to be related to engine power. This assumption is supported by several studies which highlight fuel consumption (and emissions) is a function of engine power [265]. Typically, emission assessments are carried out on an engine basis for HDVs since there is such a wide variety of potential configurations available, with engines being used in different vehicle bodies. As a result, both the reference forklift from Table 3-6 and the forklift used in [182] are compared to give a scaling factor based on engine power which is used to estimate the emissions. All air pollutant emissions for the study forklift are given below in terms of g/tonne-hour respectively. Air pollutant and greenhouse gas emissions for the reference forklift will be showcased in Chapter 6. Since GHG emissions were omitted from the literature study, these were estimated using fuel consumption, which was provided by Kalmar via direct email contact, covered in Chapter 3, and the most recent emission conversion factors available.

Table 5-22 – Emissions of the study forklift, and fuel consumption data for both forklifts.

	Forklift in Literature:	**Forklift in Study:**	
Model:	DFG 425s	Kalmar FLT12	
VDI 2198 FC (kWh fuel/h):	29.9 (3L)	57.9 (5.8L)	
VDI 2198 FC (kWh fuel/day):	-	694.6 (69.6L)	
Engine Power (kW)	43	99	Scaling Factor: 2.3
Emissions (g/tonne-hour):			
CO	4.2		
VOC	1.3		
NOx	12.7		
$PM_{2.5}$	0.8		

Hydrogen Fuel Cell Vehicles:

When modelling the consumption of hydrogen in a PEM fuel cell and the use of FCEVs, the only inputs to generate electricity are the hydrogen fuel and oxygen. The overall chemical reaction is given in Equation 39. Two moles of hydrogen react with oxygen at a 2:1 stoichiometric ratio to produce water vapour as the only product.

$$2H_2 + O_2 \rightarrow 2H_2O \qquad \text{Equation 39}$$

However, it is impractical to use pure oxygen for this reaction since it will lead to complex and costly issues with regards to its collection and purification, so it is more practical to source the oxygen from the air [133]. To account for this, the vehicles hydrogen consumption is converted into moles of hydrogen using Equation 40 and halved based on reaction stoichiometry to give the moles of oxygen. Water vapour is calculated in the same way and has a 1:1 molar ratio with hydrogen.

Using the moles of oxygen, the moles of nitrogen can be calculated based on its ratio in air (79:21) giving the total moles of air required to complete the reaction. However, if only a stoichiometric quantity of air is used, the air leaving the fuel cell would be completely devoid of oxygen, which is impractical. To overcome this, an excess quantity is used, typically equal to double stoichiometric quantity [133]. Once the moles of reactants and products are known, the moles can be converted back into mass using the molecular weight to determine how much is needed for the reaction to go and how much product is made. These quantities refer to 1 km of transport in each vehicle (at full capacity). However, these figures need to be converted to a per passenger-km or per tonne-kilometre basis to account for their payload and make them comparable. This is done by dividing the total input and output quantities (in kg/km) by the vehicle's capacity (shown in Section 3.1 - passengers for buses and tonnes for trucks, tippers, RCVs, and forklifts). These input and output quantities are given in Table 5-23 and used in Ecoinvent to model the operation of the FCEVs per unit-km.

$$\text{Moles of Hydrogen} = \frac{\text{Mass of Hydrogen (g)}}{\text{Hydrogen Molar Mass } (\frac{\text{g}}{\text{mol}})} \qquad \text{Equation 40}$$

Table 5-23 - Input and output quantities for the operation of a PEM fuel cell.

			(kg/km)			**(kg/km, pkm, or tkm)**		
			Inputs:		**Outputs:**	**Inputs:**		**Outputs:**
Vehicle:	**FC (kg H2/100km):**	**Capacity/GVW (passengers/tonnes):**	**H_2**	**Air**	**H_2O Vapour**	**H_2**	**Air**	**H_2O Vapour**
Passenger Car	0.55	N/A	0.006	0.76	0.1	0.006	0.76	0.099
12m Bus	6.5	49	0.065	8.97	1.17	0.001	0.18	0.024
44t Truck	10.3	44	0.103	14.22	1.85	0.002	0.32	0.042
26t Tipper	7.59	26	0.076	10.48	1.36	0.003	0.40	0.053
RCV	19.4	26	0.194	26.79	3.4	0.007	1.03	0.134
Forklift	10.62	23.4	0.106	14.66	1.91	0.005	0.63	0.082

For non-exhaust emissions, the same method was used as ICEVs, shown in Table 5-24. However, because ZEVs utilise regenerative braking where the electric motor runs in reverse when the accelerator is up or when the brakes are down, it means the brake discs are used less often and brake pad wear emissions are lower compared to ICEVs. One example is the C&C taxi fleet which used the Nissan Leaf, and still operated using its first set of brake pads after travelling 100,000 miles [175]. Both Timmers *et al.* [176] and Hamatschek *et al.* [260] highlight that literature focused on the impact of this reduced brake pad use on brake wear emissions is very limited, making it difficult to assign a scaling factor to account for their lower usage. As a result, the same approach was used as Timmers *et al.* [176] in which all brake wear emissions for ZEVs in this work are assumed to be zero. This is a rather crude assumption since data on ZEV brake wear is limited and so it presents a limitation to the work as a result. Emissions from brake wear should continue to be investigated as new studies are published which could lead to more accurate estimates.

For other ZEV non-exhaust emissions, these may be higher due to their increased weight from heavier components like the fuel tanks and batteries, leading to increased friction with the road.

Table 5-24 - Input quantities used to generate non-exhaust emissions for FCEVs.

			Input Quantities (kg/km, kg/pkm, or kg/tkm)			
Vehicle:	**Capacity/GVW (passengers/tonnes):**	**Tyres:**	**Brake Wear:**	**Road Wear:**	**Tyre Wear:**	**Total:**
Passenger Car	N/A	4	0	1.295E-05	1.388E-04	1.518E-04
12m Bus	49	4	0	1.571E-06	7.523E-05	7.680E-05
44t Truck	44	12	0	3.080E-04	1.676E-04	4.756E-04
26t Tipper	26	6	0	1.820E-04	1.418E-04	3.238E-04
RCV	26	6	0	1.820E-04	1.418E-04	3.238E-04
Forklift	23.4	4	0	1.638E-04	1.050E-04	2.688E-04

Battery Electric Vehicles:

Since BEVs run only on electricity and have no other inputs, modelling their use phase is simpler than ICEVs or FCEVs. The quantity of electricity required by the vehicles (in kWh/100km) was taken from the fuel/energy consumption in Section 3.1 and converted to a per unit-km basis in the same way as ICEVs and FCEVs mentioned previously. These final quantities were used to model the use phase in Ecoinvent.

Table 5-25 - Input quantities for the operation of BEVs per unit-km.

Vehicle:	Fuel Cons. (kWh/100km):	Capacity/GVW (passengers/tonnes):	Input (kWh per km, pkm, or tkm)
Passenger Car	16	N/A	0.16
12m Bus	70	45	0.016
44t Truck	100	44	0.023
26t Tipper	130	26	0.050
RCV	130	26	0.050
Forklift	212.4	23.4	0.091

For non-exhaust emissions, the same method was used as FCEVs respectively.

Table 5-26 - Input quantities used to generate non-exhaust emissions for BEVs.

			Input Quantities (kg/km, kg/pkm, or kg/tkm)			
Vehicle:	**Capacity/GVW (passengers/tonnes):**	**Tyres:**	**Brake Wear:**	**Road Wear:**	**Tyre Wear:**	**Total:**
Passenger Car	N/A	4	0	2.374E-05	1.388E-04	1.734E-04
12m Bus	45	4	0	1.999E-06	8.192E-05	9.219E-05
44t Truck	44	12	0	3.080E-04	1.676E-04	4.925E-04
26t Tipper	26	6	0	1.820E-04	1.418E-04	3.381E-04
RCV	26	6	0	1.820E-04	1.418E-04	3.381E-04
Forklift	23.4	4	0	1.638E-04	1.050E-04	2.794E-04

5.3.4.3. *Repair and Maintenance:*

This section covers the likely repair and maintenance required for each of the vehicles throughout their lifetime, including tire changes and battery replacements, for example.

Battery and Fuel Cell Replacements:

Diesel engines are not expected to need replacing as these are known for high reliability and durability, with several sources reporting that their operation can easily surpass 1,000,000 km, greatly outlasting petrol engines [212] [261]. It is uncommon for diesel cars to require engine replacements during their operating life and literature suggests these can operate for as long as 30 years before requiring major work is needed [261]. For ZEVs, lithium-ion batteries and/or PEM fuel cells are less durable and therefore may need replacing to avoid degradation and ensure reliable and consistent operation is maintained. As a result, this LCA includes battery and fuel cell replacements for those vehicles characterised by high lifetime mileages.

Many manufacturers now provide warranties on lithium-ion batteries, stating that they can operate for 10 years before replacements are needed. Other studies estimate current lithium-ion batteries have a typical useful life in a vehicle of between 200,000 to 250,000 km before replacements are needed [58]. For fuel cells, Propfe *et al.* [23] reviewed studies using recorded operating hours and service lifetimes of fuel cell systems in automotive applications and identified two reports quoting similar lifespans to batteries of 200,000 km and 247,000km respectively. In addition, manufacturers now offer guarantees on these components. For example, Hyundai announced in August 2021 they are initiating a buy-back programme for their FCEV NEXO models if they need a fuel cell replacement before 250,000 km are reached [213]. Based on this information, this work sets a limit of 200,000km before battery and/or fuel cell replacements are needed.

Tire Replacements:

Tires must be replaced periodically throughout the vehicle's lifetime. The frequency of their replacement is highly dependent on several factors including the tire manufacturer, vehicle weight, driving style, vehicle function, and road conditions. However, as a general rule of thumb automakers suggest tires should be changed after 50,000 km for LDVs and 75,000 km for HDVs respectively [135]. These figures were used as a guide to estimate the total number of tires required for each vehicle over their 15-year operating life. These final quantities were added to the assembly of the vehicle glider.

Table 5-27 - Total number of tires each vehicle uses throughout its lifetime.

Vehicle:	Daily Mileage (km):	Annual Mileage (km):	Number of Tyre Replacements:	Tires on Vehicle:	Total Tires:
Car	64.4	22,540	(22,540 x 15)/50,000 = 7	4	28
12m Bus	99.1	34,685	(34,685 x 15)/75,000 = 7	4	28
44t Truck	496.4	173,740	(173,740 x 15)/75,000 = 35	12	420
26t Tipper	33.2	11,620	(11,620 x 15)/75,000 = 3	6	18
RCV	54.7	19,145	(19,145 x 15)/75,000 = 4	6	24
Forklift	29.8	10,430	(10,430 x 15)/75,000 = 3	4	12

From Table 5-27, the highest total number of tires required comes from long haul trucks. Across their 15-year lifetime a total of 420 tires are required. Although this appears to be high it only equates to one full set replacement every 6 months, which is reasonable for vehicles with very high mileage demands and 12 tires.

Vehicle Fluids:

Fluids are constantly consumed throughout the vehicle's operation. Fluids consumed by ICEVs include engine oil, brake fluid, transmission fluid, adhesives (i.e. lubricating oil), powertrain coolant, and windscreen wash (modelled as a 60:40 mixture of ethylene glycol and water) respectively. ZEVs consist of the same fluids with the exception of engine oil. Also, Burnham *et al.* [189] highlight that many manufacturers are now transitioning to an electric power steering assist system since it contains less parts, requires less maintenance, and is lighter than older system using fluid. Manufacturers like Mercedes state that the majority of their vehicles now come with this technology as standard. As a result, it is assumed that all vehicles in this study utilise electric power steering and therefore inventory for power steering fluid is not included.

Inventory for vehicle fluids was based on Candelaresi *et al.* [85] and scaled accordingly to give quantities shown in Table 5-28. Fluid quantities are scaled according to the mileage of the vehicles, so are not periodically replaced after a fixed mileage. For simplicity and considering the minor impact of fluid production on total emissions, it has been assumed that all vehicle types consume fluids of the same composition and at the same rate per km.

Table 5-28 – Inventory for vehicle fluids, consumed per km.

Vehicle Fluid:	Quantity – ICEV (g/km):	Quantity – ZEV (g/km):
Lubricating Oil	0.115	0.019
Decarbonised Water	0.029	0.045
Ethylene Glycol	0.043	0.043

General Repairs:

In addition to replacements, vehicles may also need general repairs or upgrading to damaged components, for example. To account for this, the same approach was used as Lagnelov *et al.* [136] in which a 20% repair factor was applied to the materials of the vehicle glider. This literature study focused on a heavy duty tractor but the assumption has been applied to this work for all vehicles as several other LCA studies omit the consideration of vehicle repairs. To cover this, all glider material inventory quantities in Section 5.3.4 include a 20% increase, with powertrain components excluded as these components are replaced periodically.

5.3.4.4. Vehicle End of Life:

Once vehicles reach their end of service after 15 years, they must be treated in an end-of-life (EOL) scenario. The stages included in EOL treatments and their energy intensity can vary depending on the powertrain. For ICEVs, waste oils and hazardous liquids are extracted first and purified so they can be used as a consumable resource elsewhere. Oil filters retain large quantities of waste oil which can be reused with specific filter presses prior to recycling, and antifreeze and motor fuels must be purified and sent through to further chemical treatment processing before reuse [123]. Typically in the UK, vehicle EOL treatment takes place in a scrapyard by skilled mechanics using heavy machinery capable of removing components piece by piece before sorting. The remaining bulk of the vehicle is crushed and shredded and sorted where materials are recycled and reused [124].

According to the End of Life Vehicles (ELV) Directive 2000/53/EU, a vehicle EOL reuse, recycling and recovery target of 95% by weight is imposed [125]. However, the UK failed to meet these targets for the past 3 years highlighting further action must be taken. In 2018, the UK ranked 23rd in the EU with a rate of 92.8%, down 1.3% from the previous year [125].

There are different approaches that can be taken when modelling a vehicles EOL in an LCA. The approach used and the system boundaries must be clearly defined since the environmental impacts will vary significantly depending on which products incur the benefits of avoiding virgin raw material extraction and which incur the burdens of the recycling processes. The two most common approaches are:

1. 100/0 Upstream Cut-Off (Figure 5-11): Allocates all environmental burdens directly to the product causing them. Many studies have offered different opinions on where to set the cut-off point, but many

suggest the energy associated with raw material extraction is accounted for by the product that is being made, whilst the recycling processes and the avoided virgin raw material extraction in the second life are associated with the product using the recycled material. Products which use recycled materials as their inputs for production account for both the advantages and drawbacks associated with recycling.

2. 0/100 Downstream Cut-Off: All the energy and burdens associated with the recycling process are accounted for in the life cycle of the product being recycled. A credit is also given for avoiding virgin raw material extraction in the second life of the product.

Emissions included in the boundaries of this study and attributed to the vehicles are:

- Collection and transport of the used vehicles from their base to the recycling/treatment facility.
- Disassembly of the vehicles into their powertrain and glider.
- Shredding of the vehicle components and the material separation and sorting.
- Savings from avoiding virgin material extraction as a result of recycling PEM fuel cells.

Emissions that are not within the boundaries of this study are:

- Recycling of all the separated vehicle materials.
- Any upgrading processes required and/or emissions savings from the reuse of lithium-ion batteries.

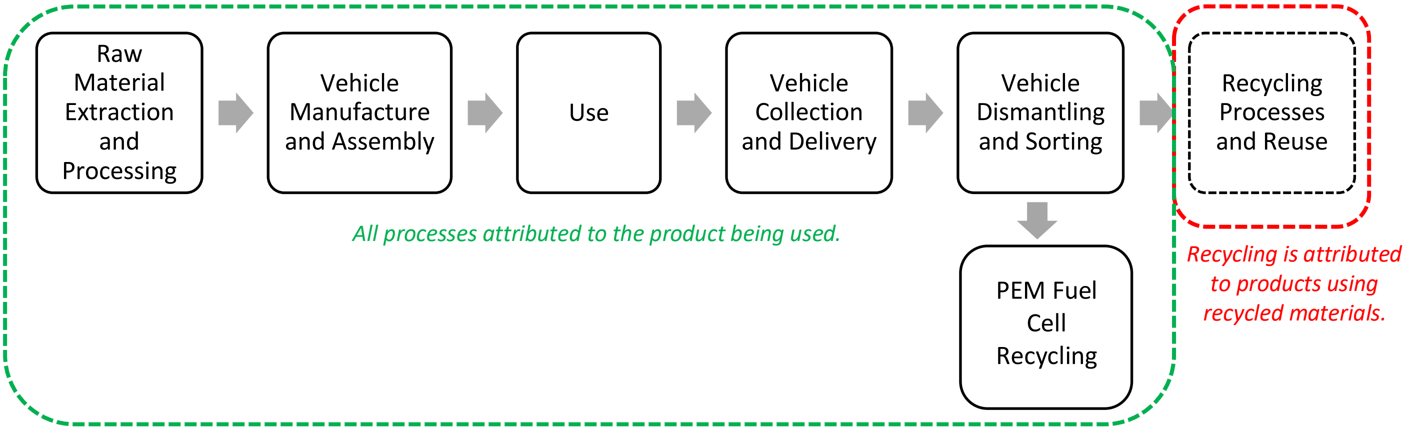


Figure 5-11 - 100/0 upstream cut-off approach.

With the government keen to increase the percentage of materials recycled in accordance with the ELV Directive, the majority of the materials used for the production of the vehicles are sent to recycling facilities where the emissions generated are attributed to the next product. In the case of the hydrogen fuel tank, of which a large proportion is made from carbon fibre, it is reported by the ICCT that these plastics are not commonly recycled, but instead incinerated or sent to landfill. Benitez *et al.* [15] also highlights that the use of recycled carbon fibre is uncertain as recovered fibres show a lower tensile strength when compared to virgin fibres. Despite this, it is expected that these materials may soon be recycled and reused due to future developments in the technology [144]. As a result, in the meantime to minimise the emissions associated with the fuel tank, a reduction in material use should be targeted with an increase in its production efficiency, highlighted by [244].

Vehicle Transport to Recycling Facility:

Once vehicles have reached the end of their life, they are collected using a diesel lorry and transported a distance of approximately 20 miles (32 km), from their base in Leeds to a treatment facility assumed to be located in Bradford, where there are numerous facilities close by (Figure 5-12).

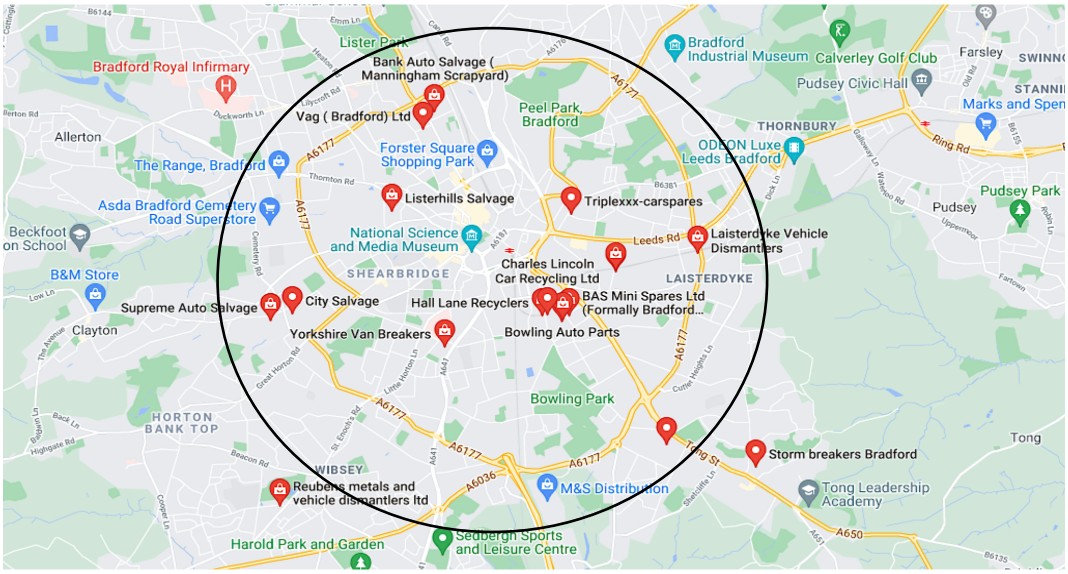


Figure 5-12 - Map highlighting the available vehicle scrapyards in Bradford.

Dismantling and Shredding of Vehicles:

Once vehicles reach the recycling/treatment facility, they are dismantled and separated into their major powertrain and glider components. Typically, batteries and fuel cells are removed before shredding, prior to material separation. Shredded materials are then sorted for either disposal in landfill, incineration, recycling, or upgrading/refurbishment for reuse in secondary applications, depending on their properties and suitability.

The differences in powertrains must be considered when dismantling and shredding since ICEVs lack many of the components in ZEVs, making their processing easier. This is supported by a wealth of previous experience treating ICEVs. For ZEVs which have not been handled as extensively and contain components like Li-ion batteries, fuel cells, high voltage lines, and storage tanks, they can create additional safety hazards which must be considered [127]. As a result, these vehicles generally require more attention during their dismantling, and may require manual handling since components need to be isolated and discharged. These additional processes are likely to lead to varying energy requirements which should be acknowledged.

In Ecoinvent, for ICEV cars the dismantling step is modelled using the process *“manual dismantling of used passenger car with internal combustion engine”* where the dataset refers to the manual dismantling of 1 kg of an ICEV car into its glider and drivetrain components. For vehicles containing an electric battery, a similar process is given which considers BEVs. Since Ecoinvent does not have a process for FCEV dismantling, it is assumed that the same process can be used to treat FCEVs since they also use a Li-ion battery and have similar components in their powertrain. Also, since emissions from dismantling are relatively low in comparison to the total life cycle emissions, the difference between BEV and FCEV dismantling is expected to be minor. For the glider shredding process, similar to dismantling, the Ecoinvent dataset is used for a passenger car respectively. Under these Ecoinvent processes, the energy requirements per kg of material processed is given.

A dismantling process for HDVs is not listed in Ecoinvent, but estimates were sourced from a literature report by [140] and used as a guideline. This report focused on heavy duty agricultural machinery and highlighted roughly 139 kWh is required per tonne of machinery for disassembly and shredding. Before applying this figure to all HDVs, it is important to acknowledge the fact that since a lack of experience handling ZEVs at their EOL has been highlighted, and their batteries are hazardous and complex systems to dismantle, there is a high likelihood that additional energy is required. Wegener *et al.* [266] highlight some of the issues associated with complex battery dismantling such as the wide range of design chemistries available, high voltages, and chemicals contained within the systems. These factors contribute towards greater energy requirements. Although additional energy is required to dismantle the battery system in ZEVs, there is a trade-off present since less energy is required for the shredding process as the total weight to be shredded is less once the powertrain system is removed. For BEVs, their batteries are often used in secondary applications outside of transport and not disposed, so less material requires shredding. It is uncertain what portion of energy is saved from reusing the battery, but this factor must also be considered in the assumptions made. As a result of these factors, this work has assumed the energy requirement for ZEV HDV dismantling and shredding is 50% higher than ICEVs, giving a value of 208.5 kWh/t. Although the HDVs in this study have different material compositions and structures to agricultural machines, this figure has been assumed appropriate for all HDVs due to a lack of available data, since many LCAs omit the end of life phases in their boundaries. Contact was made to several vehicle scrapyards to query whether ZEVs require additional energy, however the majority of these vehicles have not yet reached their EOL so numbers entering the facilities are very low, leaving no experience to offer insight. It must be made clear that this 50% excess for ZEVs is not taken from any literature sources but is based on the factors highlighted and is used to show consideration of this expected additional energy requirement. This highlights a limitation to this study which must be acknowledged. It is recommended that in future work more information is sourced on the exact dismantling energy for HDVs and especially ZEVs to generate more accurate estimates.

Recycling and Reuse of Batteries:

Despite routine replacements every 200,000 km, batteries still retain a significant portion of their original capacity prior to being repurposed or recycled. For this reason, they should not be disposed immediately after use in a vehicle. Battery EOL should also be delayed as long as possible because they rely on precious materials like lithium and cobalt for their manufacture, and it is vital that these are retained to become part of a circular economy, as a reduction would worsen already increasing pressure on their supply chains.

In terms of vehicle battery recycling, this is a relatively uncommon and unattractive process since there is great potential for the battery to be reused in secondary applications before its life cycle ends. This early recycling approach offers a limited benefit as the emissions from its production are not spread across a wide range of uses. Regardless of timing however, and similar to fuel cells (covered in the next section), battery recycling is a very complex process due to the wide range of potential chemistries, the structure of the packs, and the wide range of treatment processes that might be required, such as mechanical separation and pyrometallurgical and hydrometallurgical treatment [126]. The difficulty in modelling this is amplified by the under-development of the battery recycling process as a whole since the number of batteries leaving vehicular use is low (providing almost no learning-by-doing experience), and the number of specific processes that can be carried out depending on the conditions is high [126]. Similarly, the European Environment Agency [155] points to current battery recycling rates being low due to three main reasons: small battery volumes reaching EOL, a lack of knowledge on battery design, and a lack of cell and pack marking. Accardo *et al.* [141] outlined that the uncertainties associated with the use of particular battery materials and energy requirements in the recycling processes (due to limited data available) has led to many researchers omitting battery recycling from EOL phases of LCA studies. As a result, fewer studies are available which consider the end of life for vehicular batteries.

A better alternative to recycling considers the fact that many batteries retain ~80% of their original capacity after use and offer good suitability for repurposing outside of transport in applications like energy storage buffers for intermittent renewable electricity. These secondary uses help to spread the emissions from the battery production across greater use and maximise their benefits. As an outsider to these secondary industries, it is unreasonable to expect accurate modelling and quantification of the emissions savings from this reuse due to the specific processes taking place and the uncertainties surrounding the battery lifetime in these applications [144]. As a result, these repurpose and reuse emissions are considered attributable to those industries utilising the battery in its second life and are not placed within the boundaries of the vehicles considered in this study. However, it has been suggested in several studies that this second use stage for batteries can potentially decrease the vehicle emissions from the battery by ~50%, though this is highly dependent on the specific conditions used [159].

Recycling and Reuse of Fuel Cells:

For FCEVs, as their uptake increases and more vehicles enter the market, the demand for platinum (both a critical and expensive metal) for the PEM fuel cell catalysts is expected to rise. By reusing or recycling these components it can reduce the environmental load associated with its production and ensure a better availability of these materials in the future. For fuel cells, secondary use and recycling processes are less common than batteries due to the fact that almost all of the (already limited number of) FCEVs have only been in operation for a short period of time and haven't yet reached their EOL. Whittstock *et al.* [127] highlights that the automotive industry is the largest consumer of platinum and for passenger cars only ~50-60% of the exhaust gas catalysts containing platinum are recycled. To amplify this, FCEVs use >10x the platinum used by ICEVs, highlighting the importance of recycling and reuse if a widespread deployment of FCEVs is to take place.

Although the reuse of components is preferred over recycling due to the energy intensity of these processes, issues limit fuel cell reuse in secondary applications. Fuel cell failure is often the result of degradation to the membrane electrode assembly and efforts to replace this can often lead to irreversible damage to other components [127]. It is also unlikely that the fuel cell will be reused immediately after transport applications as the components are likely to require upgrading before health and safety approvals. These processes will incur emissions and will rely on dedicated treatment facilities which are currently sparse considering the state of the fuel cell market. Much of their disassembly will also be done manually, with tie rods and end plates being removed first, followed by the removal of the individual stack layers, inclusive of the bipolar plates, gas diffusion layers and MEA. However, this process is unlikely to be the same for all fuel cells, especially if a dedicated facility is used which handles fuel cells from all areas of use, not just transport applications. These factors make it very challenging to model without information on the treatment being carried out, the ease of disassembly, availability of parts for replacement, degree of automation, and location of the facility, for example [128]. For these reasons, fuel cell recycling is generally favoured and targets the recovery of platinum as the major incentive, along with other high-value materials. Similar to fuel cell reuse though, there are a variety of methods associated with the recycling of fuel cell subsystems and components which increase the complexity of accurately modelling emissions if data cannot be sourced. These processes include the technologies available to process the materials, manual dismantling of individual components, chemical recovery, and mechanical treatment for example [128].

To bypass these barriers, fuel cell EOL inventory was based on data from Stropnik *et al.* [86] given on a per kW basis and is summarised in the Table 5-29 along with fuel cell production inventory**.** The table highlights the total input quantities required to manufacture 1 kW of PEM fuel cell. For recyclable materials, the percentage recycled is given. In this case, 76% of platinum is recycled which aligns with other studies that suggest it is feasible to recycle platinum to high degrees in the order of 75-80% [244]. All remaining waste material is disposed using the most suitable waste treatment scenario for that material.

In this study, since the library used in Ecoinvent is ‘allocation, cut-off by classification’, the emissions generated from the recycling processes are empty as this is cut off and attributed to the recycled materials in the next product life cycle. In these recycling process descriptions, Ecoinvent state that in order to include the benefits and costs of recycling, the material production process should be entered as an avoided product, since recycling material significantly reduces the generation of emissions from the production of virgin material. As a result, this work estimates the emissions of avoided products (which would have been generated by the production of virgin material had recycling not have taken place), not the emissions of the recycling processes themselves (since these are cut off). The portion of recycled material given in Table 5-29 is listed in Ecoinvent as an avoided product, and the portion of material wasted is listed under the appropriate waste treatment scenario. Production, EOL, and net emissions generated from the PEM fuel cell are covered in Chapter 6 respectively.

Table 5-29 – Inventory for the manufacture and EOL per kW PEM fuel cell.

PEM Fuel Cell Manufacture:			**PEM Fuel Cell End of Life:**				
	Material:	**Input (kg):**	**Recycled?**	**Fraction to Recycle (%):**	**Avoided Product (kg):**	**Waste (kg):**	**Waste Treatment:**
Stack	Graphite	4.5	-	-	-	4.5	Hazardous Waste (UG Deposit)
	PVC	1.1	-	-	-	1.1	
	Aluminium	0.3	✓	96	0.288	0.012	Sanitary Landfill
	Chromium Steel	0.1	✓	88	0.088	0.012	Hazardous Waste (UG Deposit)
	Glass Fibre	0.1	-	-	-	0.1	Hazardous Waste (UG Deposit)
	Perfluorosulfonic Acid	0.07	-	-	-	0.07	
	Carbon Black	0.0008	✓	76	0.00061	0.00019	
	Platinum	0.00075	✓	76	0.00057	0.00018	
Balance of Plant	Steel Product	3.7	✓	88	3.256	0.444	Inert Landfill
	Polyethylene	1.5	✓	84	1.26	0.24	Unsanitary Landfill
	Chromium Steel	1.1	✓	88	0.968	0.132	Hazardous Waste (UG Deposit)
	Cast Iron	0.8	✓	88	0.704	0.096	
	Aluminium	0.75	✓	96	0.72	0.03	Sanitary Landfill
	Polypropylene	0.25	✓	84	0.21	0.04	Sanitary Landfill
Other	Electricity	16.9	-	-	-	-	-

5.4. Chapter Summary:

This chapter provided an introduction to life cycle assessment as a tool for environmental investigation and SimaPro as the emissions software of choice. It also outlined the base case conditions, scope, and system boundaries used for the generation of emission estimates. A detailed step by step breakdown of the methods used to model each individual life cycle stage was highlighted, including vehicle and fuel production, fuel distribution and conditioning, vehicle usage (including COPERT software), repair and maintenance, and vehicle end of life, respectively. Emissions from each of these stages are estimated next in Chapter 6 and combine to offer a detailed insight into the environmental competitiveness of FCEVs in HDV transport.

6. Chapter 6 - Environmental Assessment of FCEVs

This chapter presents all of the results generated from the emissions model described in Chapter 5 and analyses the environmental competitiveness of FCEVs in heavy duty transport, offering detailed breakdowns of the emissions from each life cycle stage respectively.

6.1. Emissions from Vehicle Production:

This section gives both a general overview and a detailed breakdown of the emissions from the production of the vehicles in the study. Analysis of the production emissions is centered around GWP but also includes particulate matter (PM) and fossil scarcity (FS). All emissions are generated prior to first use and are not inclusive of component replacements which occur after the initial production. In addition to the figures in this section, snippets taken from SimaPro showing the GWP networks of HDV trucks with a 2.5% contribution cut-off can also be found in Section 11.3 in Appendix 2, with complete production emission breakdowns also given for each vehicle type in Section 11.4 showing the contribution from each individual vehicle component. This will be covered later in this section respectively.

The bullet points below aim to highlight the structure of this section and the approaches used:

- This section is split into 3 parts: one for each powertrain type (ICEVs, BEVs, and FCEVs) respectively.

- Although this study is focused primarily on HDVs, discussion includes passenger cars since these vehicles are the most popular and are the focus of a wide range of emissions studies already published in literature. This allows comparisons to be made and conclusions to be drawn more easily. For those ZEV HDVs not yet on the market, results cannot be compared to or validated by existing work as easily.

- Due to space constraints, not all vehicles are covered in the analysis. Instead, discussion of HDVs centres around buses and long haul trucks, since these vehicles are widely considered the most suitable for hydrogen use in the future with several already in use and prototypes in development for the near future.

- Despite some vehicles being overlooked in this section, since many of the individual component compositions are the same (e.g. all the lithium-ion batteries have the same underlying material composition), much of the analysis relating to passenger cars also applies to HDVs. The differences in production emissions largely originate from the material quantities used, not the material type. Several of the material production and processing stages are shared across different vehicles.

Figure 6-1 shows the total emissions from the production of all reference vehicles from Chapter 3 for the global warming potential (GWP) impact category in terms of tCO_2e and will be the main focus of discussion. Similar graphs showing particulate matter (PM) and fossil scarcity (FS) are given in

Figure *6-2* and Figure *6-3* respectively, with individual component breakdowns for cars, buses, and trucks given in the main body and in Section 11.4 in Appendix 2 for tippers, refuse, and forklift vehicles. It must be made clear that these figures are inclusive of the 20% excess raw material for the gliders, which is aimed to account for damages and repairs over the vehicle lifetime, discussed earlier in Section 5.3.4 of Chapter 5.

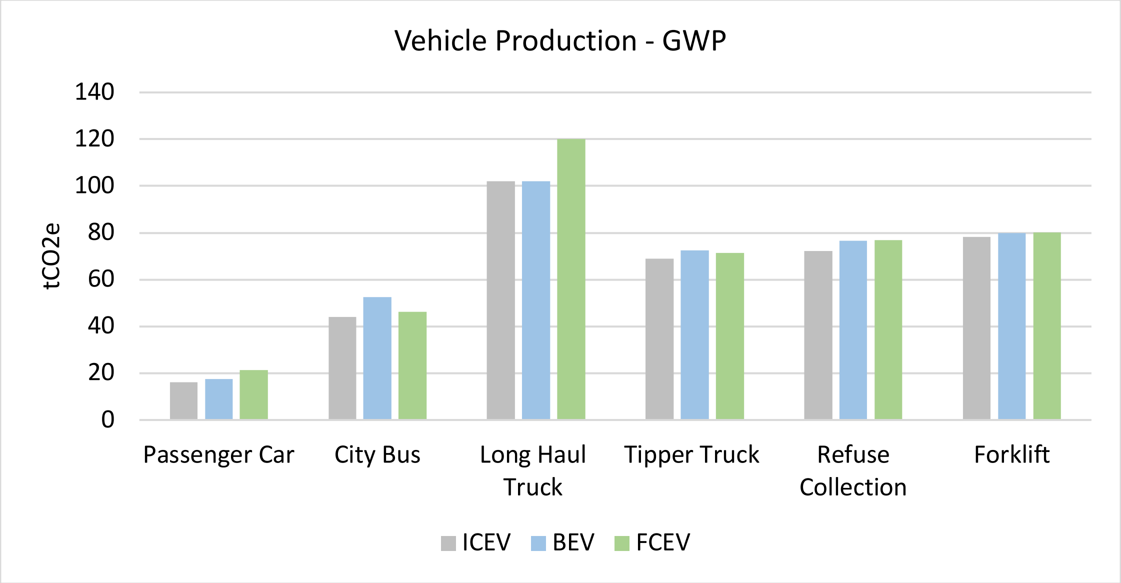


Figure 6-1 – Production emissions for ICEV, BEV, and FCEVs.

Generally, across all 3 impact categories, the production emissions from ICEVs are the lowest. For passenger cars, ICEVs have the lowest production emissions with approximately 16 tCO_2e. For context, production emissions from 3 different size-class ICEV cars were reported by Berners-Lee *et al.* [146], with 6 tCO_2e generated for a Citroen C1 (small), 17 tCO_2e for a Ford Mondeo (medium), and 35 tCO_2e for a Land Rover Discovery (large). In comparison to these reported figures, those generated in this study appear reasonable. However, it should be taken into account that this is influenced greatly by the operations within each individual company, as one may utilise more renewable power or sustainable materials than others, for example. BEV cars show higher emissions at 17.5 tCO_2e whilst FCEV car production is the most intensive with 21.3 tCO_2e. Similar to ICEVs, research has been conducted on the embodied emissions from BEV car production. Hausfather *et al.* [147] reported a figure of 13.2 tCO_2e for the Tesla Model 3, Nealer *et al.* [148] reported 14.9 tCO_2e for a Tesla Model S, and Brennan *et al.* [149] reported 20.4 tCO_2e for a mid-sized BEV with one battery replacement (and 14.5 tCO_2e without). EEA [155] and Kim *et al.* [242] also report that when comparing production emissions of similar size ICEVs and BEVs, BEVs show a GWP ranging from 1.3-2 times greater than ICEVs. In this work from Figure 6-1, BEV cars are roughly 1.1 times greater. In terms of PM, the same sources reported this range at approximately 1.5-2.5, with this work giving a value of 1.5, based on results for cars shown in

Figure *6-2* [155]. Although slightly low, this is considered reasonable when considering the unknowns faced during the modelling stages. For FCEVs, car production emissions could not be sourced from manufacturers or reports due to the current infant market. However, studies by Evangelisti *et al.* [245], Miotti *et al.* [244], and Benitez *et al.* [15] give estimates of 16 tCO_2e, 18.8 tCO_2e, and 22 tCO_2e for FCEV car production. Obviously, it should be acknowledged that each of these studies vary in their assumptions and modelling conditions, nevertheless they offer some validation for the estimates made in this work. It is reasonable to assume that since FCEV markets are small and supply chains have not had the opportunity to develop fully, emissions are likely to be higher than ICEVs and similar to BEVs.

For HDVs, diesel buses have emissions of 44 tCO_2e, FCEVs have ~46 tCO_2e and BEV buses have the highest overall with ~53 tCO_2e. Total emissions estimates for HDVs are scarce in literature but one report offered an estimate of 100 tCO_2e for the manufacture of a BEV bus. Although this is much higher than 53 tCO_2e calculated in this work, the study examined production in China using grid electricity with an energy intensity of 0.7 $kgCO_2e/kWh$, compared to only 0.243 $kgCO_2e/kWh$ in the UK [170]. As a result, it is expected that their estimates will be higher considering the electricity demands for battery production and other processes. This is supported further by Hao *et al.* [243] who estimated greenhouse gas emissions from Chinese battery production were up to 3 times higher compared to the US. A second study offered estimates of 85 tCO_2e and 102 tCO_2e from the production of ICEV and BEV buses in Norway [138]. The buses modelled were both 12m city buses with the BEV using a 200kWh lithium ion battery. Although this is smaller than the battery used in the reference bus of this work (350 kWh), a replacement was required during its lifetime. Breakdowns of the total production emissions per component were also given in the literature and this battery was responsible for 24 tCO_2e, so this accounts for a significant portion of the difference compared to Figure 6-1 [138]. In addition, the buses also contained more aluminium which incurs higher production emissions compared to steel. Considering these points, if only one battery was used with a smaller portion of aluminium in its glider, emissions are expected to be more comparable.

As mentioned previously, the networks showing the breakdown of emissions from truck production are given in Section 11.3 in Appendix 2. This helps to clearly showcase the components of long haul trucks that contribute the most towards their overall emissions. From Figure 6-1, for all trucks in this study, ICEVs have the lowest emissions. For long hauls in particular, ICEVs generate 102 tCO_2e and FCEVs have the highest at 120 tCO_2e. Although the trucks modelled are not manufactured from Volvo, Volvo's website has a tool that allows emissions from vehicle production to be calculated. This can offer some insight into truck production emissions and give ballpark figures to help validate emissions from all long haul, tipper, and refuse trucks in this study. Emissions for a Volvo FM diesel truck are ~21 tCO_2e. Although this is far lower than the estimates in Figure 6-1, it should be made clear that this figure refers to the day cab and chassis only and does not include the trailer, which is a significant addition to total production emissions [171]. Truck cabs range in weight but common figures are reported at ~8t. Taking this into account, it is reasonable to expect the weight of the entire truck (cab, chassis, and trailer) with a total kerb weight of 18t to incur significantly more emissions. It also states on the website that production emissions are inclusive of credits from material recycling which is not included in the estimates in Figure 6-1. Volvo state they are capable of recycling 85-90% of the vehicle materials which significantly reduces the total manufacturing emissions reported, with approximately one third of each new truck made from recycled materials [171]. The impact of including a 20% material excess for damages and repairs should also be acknowledged as this will lead to greater emissions compared to those reported by manufacturers.

FCEV tippers have slightly lower emissions compared to BEVs with 71.3 tCO_2e, and both ZEV refuse vehicles show similar estimates of ~77 tCO_2e, with ICEVs at 72 tCO_2e. All forklifts have similar emissions ranging from 78-80 tCO_2e with BEVs and FCEVs generating roughly 2 tCO_2e more than ICEVs. These vehicles are similar to tippers and refuse vehicles in their weight and composition. Unfortunately, after contact with several forklift manufacturers including Toyota, Linde, and STILL, emissions figures for their manufacture could not be provided due to the sensitive nature of the request.

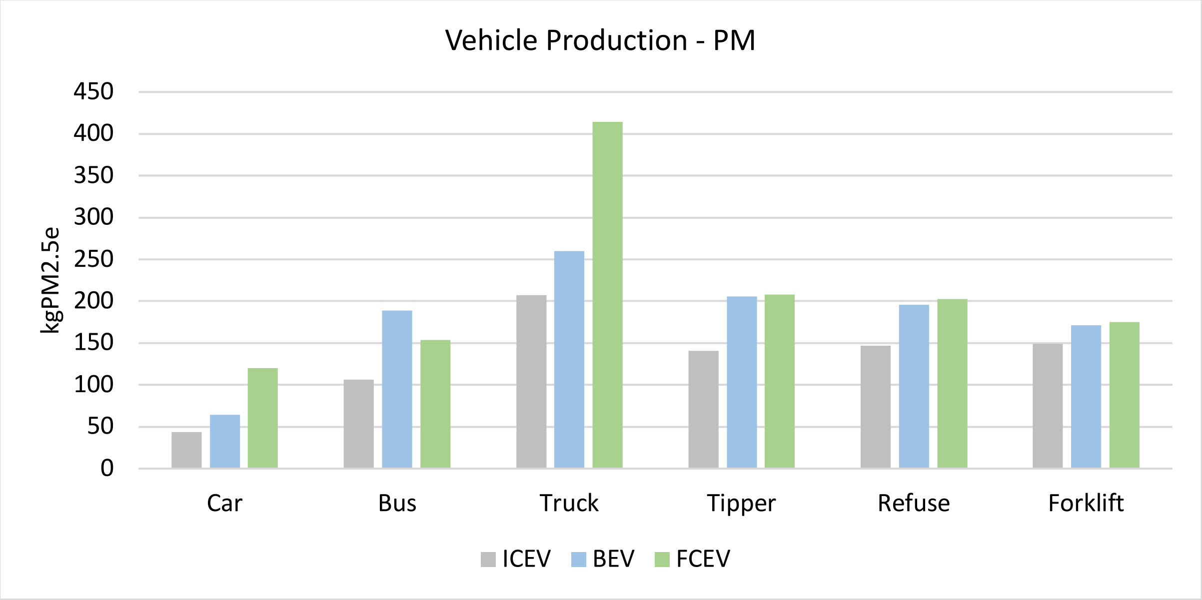


Figure 6-2 - PM from vehicle production.

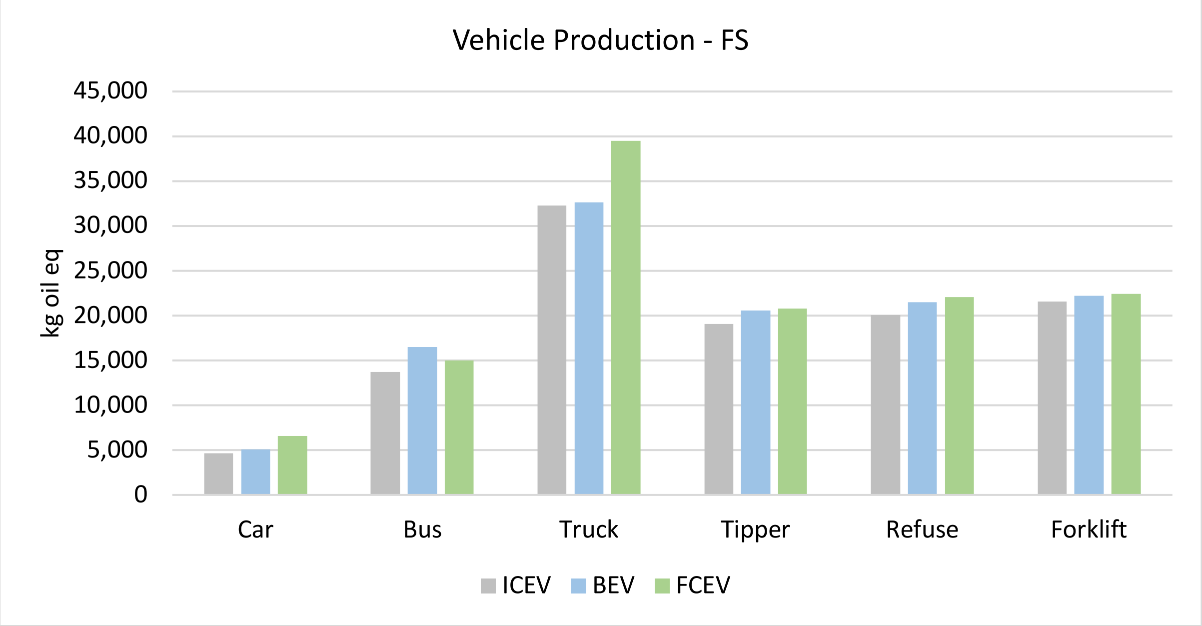


Figure 6-3 - FS from vehicle production.

Figure *6-2* and Figure *6-3* highlight vehicle production emissions in terms of PM and FS respectively. ICEV cars offer the lowest emissions in all impact categories compared to their ZEV equivalents with 44 kg $PM_{2.5}e$ and 4,660 kg oil eq. Furthermore, for each vehicle type considered, the ICEV versions show the lowest emissions in each impact category. For PM, this is likely due to the fact that ZEVs require a greater electricity demand for their powertrain components. In this case, nickel sulphate required for battery production shows a very high contribution to PM generation. Air quality emissions from bus production show their lowest values from ICEVs with PM of 106 kg $PM_{2.5}e$ whilst their highest values are 189 kg $PM_{2.5}e$ from BEVs. This is largely due to nickel sulphate production which is required for the lithium-ion battery which incurs substantial emissions of 67.6 kg $PM_{2.5}e$ (36%) making it the highest contributor to the total emissions of particulates. In comparison, for ICEV buses the largest contributor is steel production primarily for use in the glider which accounts for 46.1 (or 43.5%) of the 106 kg $PM_{2.5}e$ emissions. For trucks however, PM and FS are highest from FCEVs with 414 kg $PM_{2.5}e$ and ~40,000 kg oil eq respectively, which is approximately 50% and 18% higher than their ICEV counterparts. In terms of air quality, PM is largely due to fuel cell production which is very energy intensive as the platinum required accounts for 183 kg $PM_{2.5}e$ (or 44%) of the total 414 kg $PM_{2.5}e$ emissions. For FS from trucks, the greatest contributor is steel production, which is also true of ICEV and BEV trucks, however FCEVs also incur additional emissions of 4,160 and 4,800 kg oil eq from platinum and glass fibre production required for the fuel cell and storage tanks. Finally for tippers, refuse, and forklift vehicles, all PM and FS follows a similar pattern with ICEVs showing the lowest emissions increasing to BEVs and then FCEVs respectively. The reason for the variation in emissions between trucks and all other vehicles is largely due to the size difference in their powertrain components. For example, FCEV trucks use a 240 kW fuel cell whilst buses and tippers use 75 kW and 80 kW.

Table 6-1 aims to validate these vehicle production emissions by comparing them to figures reported in literature. However, because of the sensitive nature surrounding embodied emissions, many manufacturers withhold this information making it difficult to obtain estimates. Contact was made with several manufacturers, but no figures could be sourced. For ZEVs especially, very few estimates exist in literature due to the fact that ZEV HDVs are not yet mature and market penetration remains low. As a result, only a few estimates could be sourced, presenting a limitation which should be targeted as more of these vehicles are introduced and more studies are published, hopefully with better data availability.

Table 6-1 - Embodied vehicle emissions sourced in literature (limited availability).

Production Emissions (tCO$_2$e)	**Study Estimates:**			**Literature Estimates (GWP):**		
	ICEV	**BEV**	**FCEV**	**ICEV**	**BEV**	**FCEV**
Car	16.1	17.5	21.3	• Citroen C1: 6 tCO$_2$e • Ford Mondeo: 17 tCO$_2$e • L Rover [146]: 35 tCO$_2$e	• Tesla Model 3 [147]: 13.2 tCO$_2$e • Tesla Model S [148]: 14.9 tCO$_2$e • Mid-Sized BEV [149]: 20.4 tCO$_2$e	• No Availability.
City Bus	44.1	52.6	46.2	• [138]: 85 tCO$_2$e	• 12m Bus [170]: 100 tCO$_2$e [138]: 100 tCO$_2$e	• No Availability.
Long Haul	102	102	120	• Long Haul Truck Cab [171]: 21 tCO$_2$e • 16t Truck [268]: 19.2 tCO$_2$e	• 16t BEV Truck [268]: 51.2 tCO$_2$e	• No Availability.
Tipper	68.9	72.4	71.3			
RCV	72.2	76.5	76.8			
Forklift	78.2	79.8	80.1	• No Availability.	• No Availability.	• No Availability.

6.1.1. ICEV Production Emissions:

Figure 6-4 to Figure *6-6* give a breakdown of the total emissions associated with the production of a passenger car, a city bus, and a long haul truck respectively. Due to constraints of page limits, not all vehicles are presented in this section however breakdowns of all other vehicles can be found in Section 11.4 in Appendix 2 respectively.

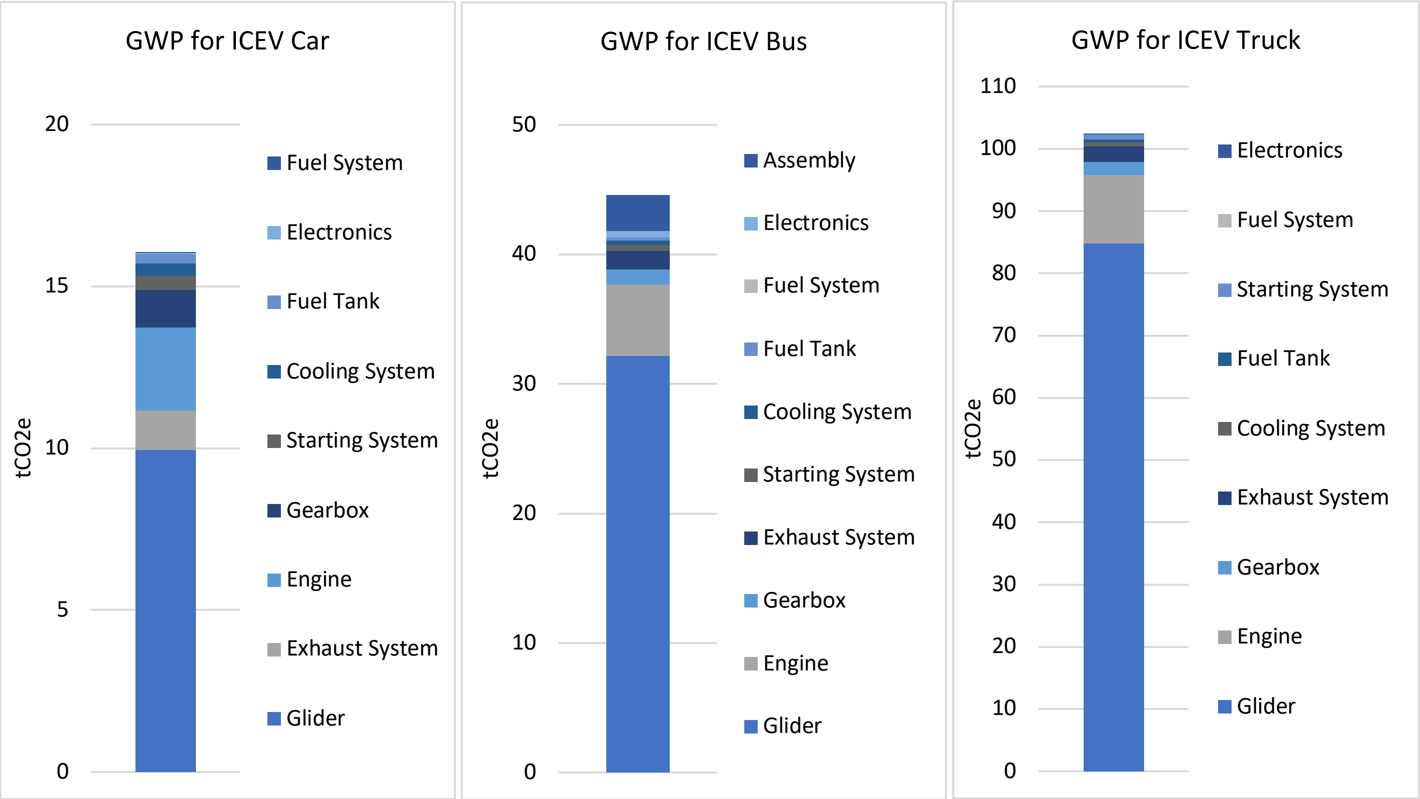


Figure 6-4 – Breakdown of ICEV production emissions for a car, bus, and truck (in terms of GWP).

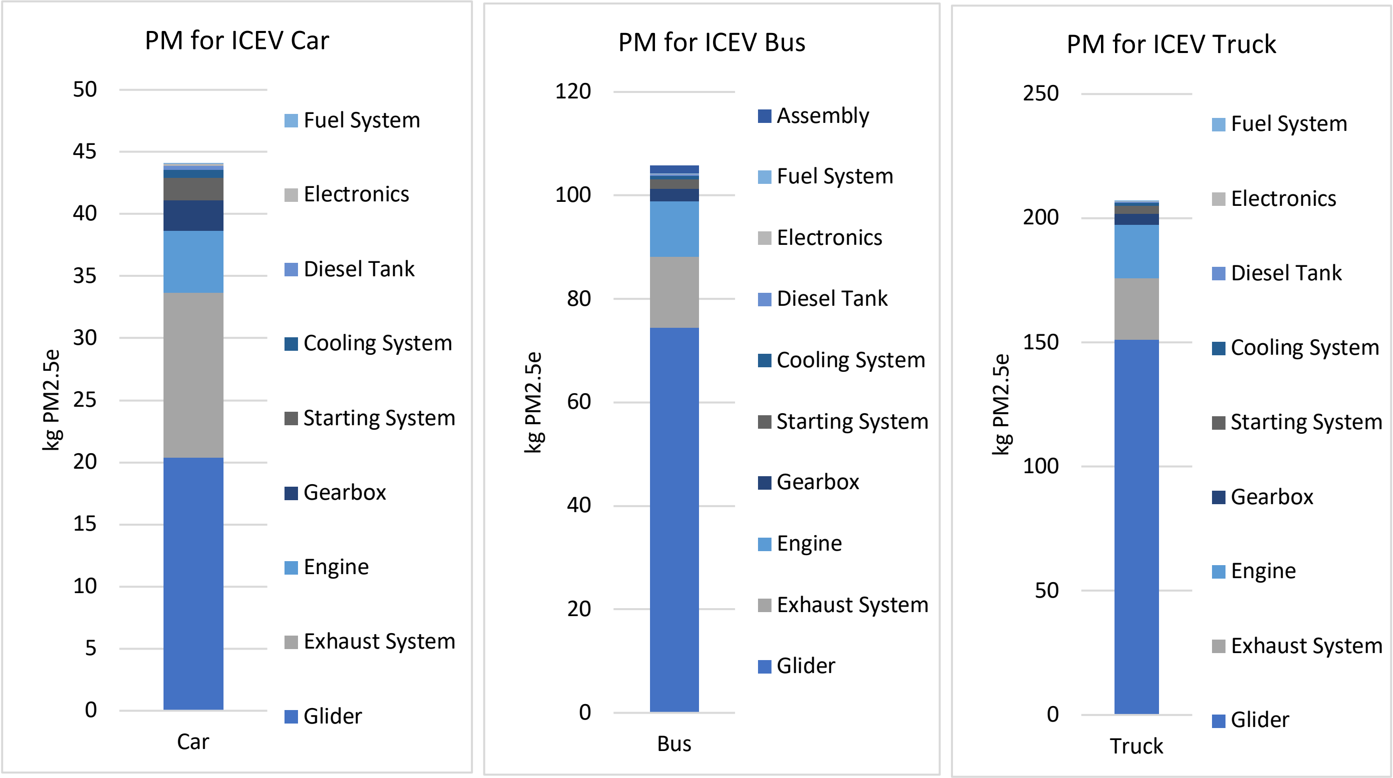


Figure 6-5 - Breakdown of ICEV production emissions for a car, bus, and truck (in terms of PM).

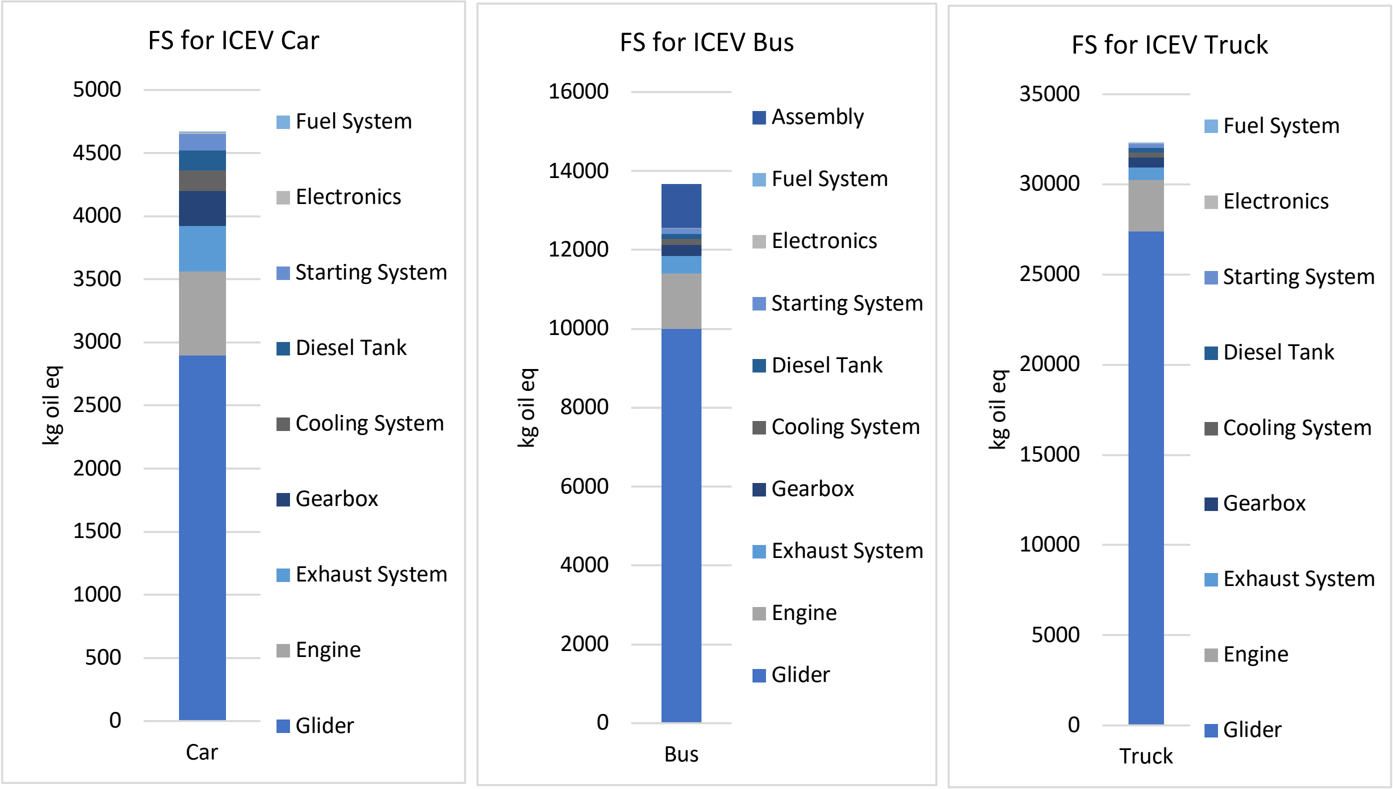


Figure 6-6 - Breakdown of ICEV production emissions for a car, bus, and truck (in terms of FS).

6.1.1.1. Vehicle Gliders:

For ICEVs (and most ZEVs), the component with the greatest share of total emissions across all impact categories is the glider. This finding is shared with other LCAs such as Evangelisti *et al.* [245]. From Figure 6-4, in terms of GWP, the glider of a passenger car is responsible for approximately 10 tCO_2e, whilst for a bus and a truck these emissions are ~32 tCO_2e and ~85tCO_2e. The composition of the gliders for each vehicle was covered in Chapter 5 and is inclusive of the vehicle frame, tires, steering, braking, and suspension system, among other components. Since cars, buses, and trucks all use different inventory for their gliders due to an absence of data in Ecoinvent, their material breakdowns are slightly different. This section will give an overview of the main materials in each vehicle glider respectively.

For passenger cars, the glider accounts for ~47-64% of the total GWP across ICEVs, BEVs, and FCEVs and is similar to Joshie *et al.* [252] who report 36-57%. In this work, the majority of the glider is composed of steel (reinforcing, low-alloyed, and chromium) which accounts for approximately 2.5 tCO_2e (25%) of the total GWP, either from its production or processing. This is common for many vehicles currently on the road which use large quantities of steel in their frames. In this work, the Ecoinvent process for reinforcing steel is composed of a mix of low alloyed steel and unalloyed steel with all steel production including the transport of hot metals, the production processes and casting, along with hot rolling. Unalloyed steel production is carried out using basic oxygen steelmaking (BOS) whilst alloyed steel is from a combination of both BOS and electric arc furnace (EAF) steelmaking. BOS involves the smelting of iron ore to produce molten iron which is then mixed with oxygen in a converter before impurities are removed and the iron is refined into steel. For EAF steelmaking, this involves the heating of scrap metal using electricity followed by refining processes. As a result of using scrap material, this route has a lower environmental impact. 1 kg of unalloyed steel produced from BOS incurs 2.23 $kgCO_2e$ compared to only 0.384 kg CO_2e from EAF steelmaking. Similar to GWP, the emissions from steel production are the largest contributor to glider PM and FS with 25% and 24% respectively. Emissions from electricity are the second largest contributor to glider emissions across all impact categories with roughly 23% (GWP), 24% (PM), and 22% (FS) respectively.

The glider for buses is dominated by low-alloyed steel and requires over 7.5t of the material, contributing 52% of its total GWP. The second largest contributor is aluminium with 23% respectively. Although the glider for passenger cars doesn't contain a large quantity of aluminium, more recently manufacturers are now using it in HDVs due to its light weight and high strength properties, despite higher production emissions. For the production of the ~1.1t of aluminium required for this glider, bauxite is mined and processed into aluminium oxide which is then broken down using an electrolytic process to produce molten aluminium before being heated in a furnace to 750°C. After, several alloying elements are added to improve its properties before casting. Polypropylene and electricity are the third and fourth biggest contributors to bus GWP with 8.8% and 4.8% respectively. In total, the GWP from the glider accounts for 73% of the total for ICEV, 61% for a BEV, and 70% for FCEV buses. Comparing these figures to Lie *et al.* [138] shows agreement as they report contributions of 90% for ICEV and 61% for BEVs respectively. In terms of air quality, steel and aluminium remain the first and second largest contributors to total glider PM. For FS, steel contributes the most with 37% but polypropylene production is second accounting for approximately 23% of the total glider emissions.

The inventory used to produce the glider of the long haul truck was described in Section 5.3.4 of Chapter 5. For this vehicle, the glider accounts for 83% of the total GWP due to the vast quantities of steel (>12t), cast iron (>1.5t) and aluminium (>0.5t) required. Steel makes up ~33% of the glider emissions, glass fibre makes up 19%, nylon makes up ~11%, and aluminium ~5% respectively. Other materials which contribute to a lesser extent include synthetic rubber, cast iron, and copper, along with electricity. PM and FS from glider production are also dominated by steel and glass fibre production, with PM also impacted by copper production contributing 7.5%.

6.1.1.2. Combustion Engine and Gearbox:

In general, the second largest contributor to total GWP and FS from ICEV production is the combustion engine. For PM the second largest contributor is the exhaust system which is covered in the next section. The engine however is responsible for 2.6 tCO_2e of a car's total GWP emissions, and 5.5 tCO_2e and 11 tCO_2e for a bus and truck. Since the material inventory for the engine is the same for all vehicles, the percentages contributions from each material making up the engine are the same. Emissions are largely from carbon fibre, aluminium, and low-alloyed steel. For cars, approximately 114 kg of low-alloyed steel is used in the production of its engine, 57 kg of aluminium, and 17 kg of carbon fibre. Although it doesn't demand the highest material quantities overall, across all impact categories, the emissions from carbon fibre production account for the largest portion of the engine emissions with over 59% in terms of GWP due to the process heat and electricity requirements. The gearbox demands large quantities of steel and aluminium, with 215 kg and 96 kg respectively. For the gearbox, production emissions are split fairly evenly between the two metals with ~42% (0.481 tCO_2e for car) from steel and 58% (0.68 tCO_2e for car) from aluminium. Overall for an ICEV car, total emissions associated with aluminium equate to over 1.2 tCO_2e which is in line with estimates from Hannon *et al.* [150] for an ICEV car (1.4 tCO_2e).

6.1.1.3. Exhaust System:

For cars, the exhaust system is the second largest contributor to PM, and third for GWP and FS. This component accounts for 30% (13.3 kg $PM_{2.5}e$) of the total PM and ~8% of the GWP (1.2 tCO_2e). For HDVs which generate much greater production emissions overall, the portion of total emissions from the exhaust system is much smaller with only a 3.3% and 2.4% contribution to the total for buses and trucks respectively. The composition of this system was discussed in Chapter 5 and consists of a diesel oxidation catalyst (DOC) followed by a particulate filter (DPF) and selective catalytic reduction (SCR) to minimise exhaust emissions as much as possible.

The three individual exhaust components are made up of a number of different materials, but the most impactful component is the DOC, which for a bus contributes 0.96 tCO_2e (~67%) of the total exhaust emissions. Within this DOC, platinum is the greatest contributor across all impact categories, followed by palladium in the case of PM emissions. These elements belong to the platinum group metals (PGMs) and face increasing pressures on their supply chains due to growing vehicle markets. They are also listed on the 2020 European

Critical Raw Materials (CRM) list and can only be found in select locations, generating significant emissions from their ore mining, beneficiation, smelting, separation, transport, and refining processes respectively. They are often extracted together from the same locations with reports highlighting that around 80% of global PGM mining takes place at the Bushveld complex in South Africa and at the Kola Peninsula in Russia [145]. The Ecoinvent process used to model the production of the catalyst components contains several palladium sources, but the vast majority of this palladium is sourced in Russia and South Africa respectively. For platinum (of which the quantity used in the DOC is triple that of palladium), the majority (~78%) is from South African underground and open pit mining at the Bushveld complex. This includes all associated concentration, smelting, and refining processes. Not surprisingly, roughly 80% of the rhodium used in the device also comes from the same complex.

The SCR and DPF have a much smaller contribution towards the total exhaust system emissions of each vehicle. In the case of buses, these components generate 234 kgCO$_2$e and 241 kgCO$_2$e from their production, equivalent to 16% and 17% respectively. The majority of SCR emissions originate from the steel production and electricity usage; all other components have a very minor impact in comparison.

All other materials and processes associated with ICEV car production, such as its assembly, electronics, and the fuel tank contribute less to the total global warming impact but still make up a combined total of ~1.5 tCO$_2$e.

6.1.2. BEV Production Emissions:

Since all the vehicle types in this study use the same glider with the same embodied emissions, the majority of the differences in production emissions are associated with the powertrain. The supply chains for these ZEV components are not as mature as those of ICEVs which have had sufficient time to develop. A number of these ZEV components also rely on precious metals which are difficult to source and require energy intensive upstream processing. These points will be discussed further throughout this section.

For all ZEVs, excluding the glider, emissions from production are dominated by the powertrain components. For BEVs, Figure 6-7 to Figure *6-9* show the GWP, PM, and FS breakdown for cars, buses, and trucks with the vast majority of emissions across all impact categories coming from the glider and battery. For BEV cars and buses the lithium-ion battery accounts for ~30% of GWP whilst for trucks this figure is ~13% due to the much larger glider. Studies focusing on buses and trucks are less prevalent in literature but for passenger cars this figure of 30% is in close agreement with work from Hung *et al.* [241] who report that the battery accounts for 33-44% of total BEV production emissions. Similarly, Joshie *et al.* [252] derives a figure of 37%, depending on the battery design and size. The electric motor contributes only ~8% to the total GWP for cars and 3% for buses and trucks, in line with estimates of 7-8% from [155] for cars respectively. The share of PM from the electric motor and power control unit is also small for HDVs. Here, the motor contributes 5.5% and 6% of total PM for a bus and truck. PM for cars and buses is dominated by the battery which is greater than the glider itself with 34.1 kg PM$_{2.5}$e (53%) and 100 kg PM$_{2.5}$e (53%) respectively. The breakdown of FS follows a similar pattern to GWP with the contribution from the battery decreasing as vehicle (and glider) weight increases, accounting for a greater portion.

Emissions from aluminium production, anode and cathode materials, printed wiring board, and cobalt account for high battery emissions as they are used for the production of its major components like the cells, battery management system (BMS), and pack respectively. It is well documented in literature that the battery production accounts for a very large portion of BEV emissions, with the individual cell production being a major contributor. A breakdown of battery production emissions is covered in the next section.

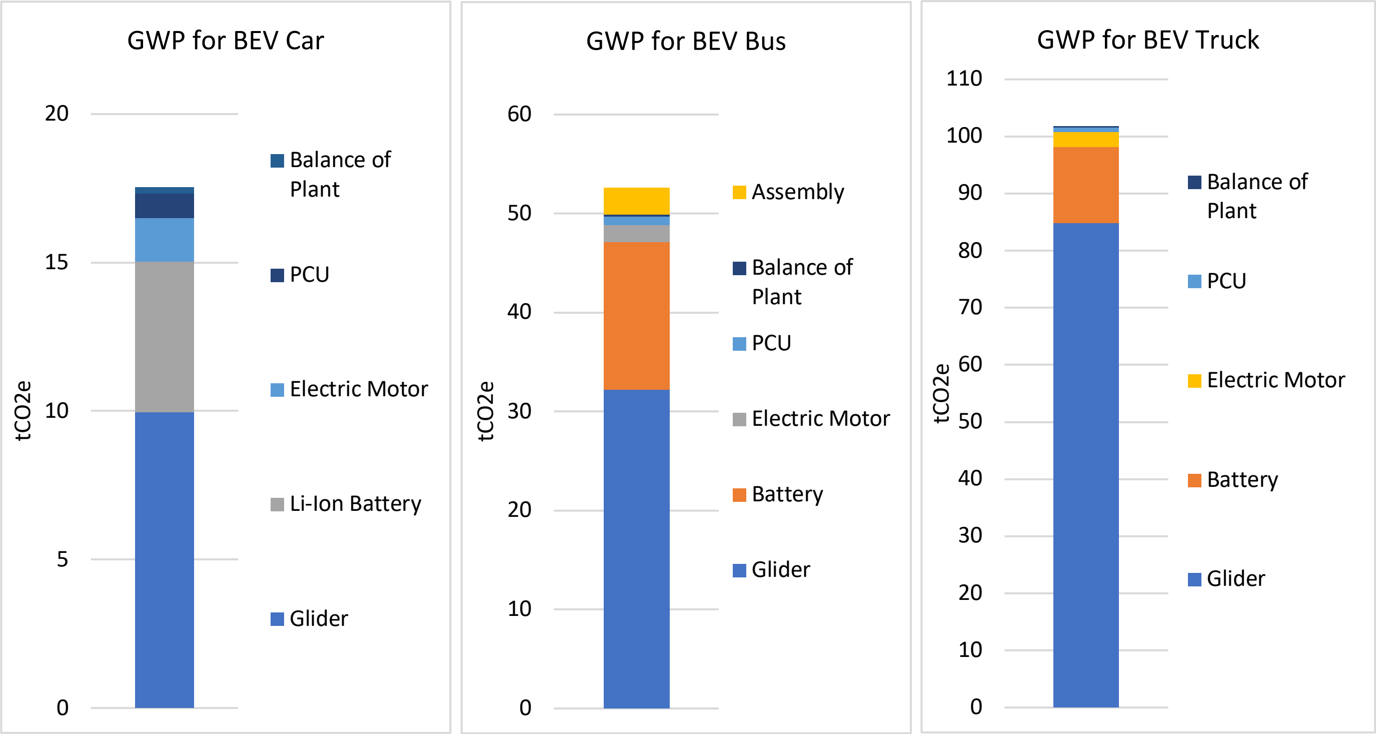


Figure 6-7 – Breakdown of production emissions for a BEV passenger car, bus, and truck (in terms of GWP).

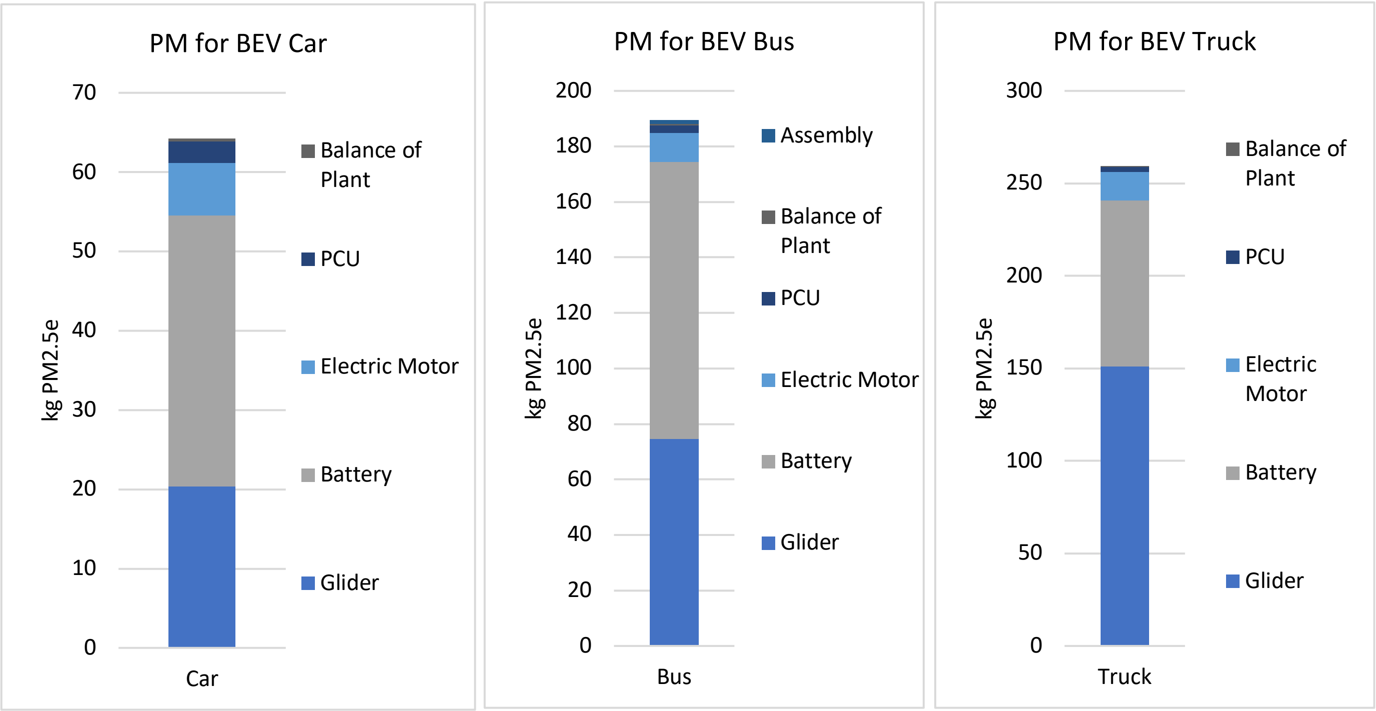


Figure 6-8 - Breakdown of production emissions for a BEV passenger car, bus, and truck (in terms of PM).

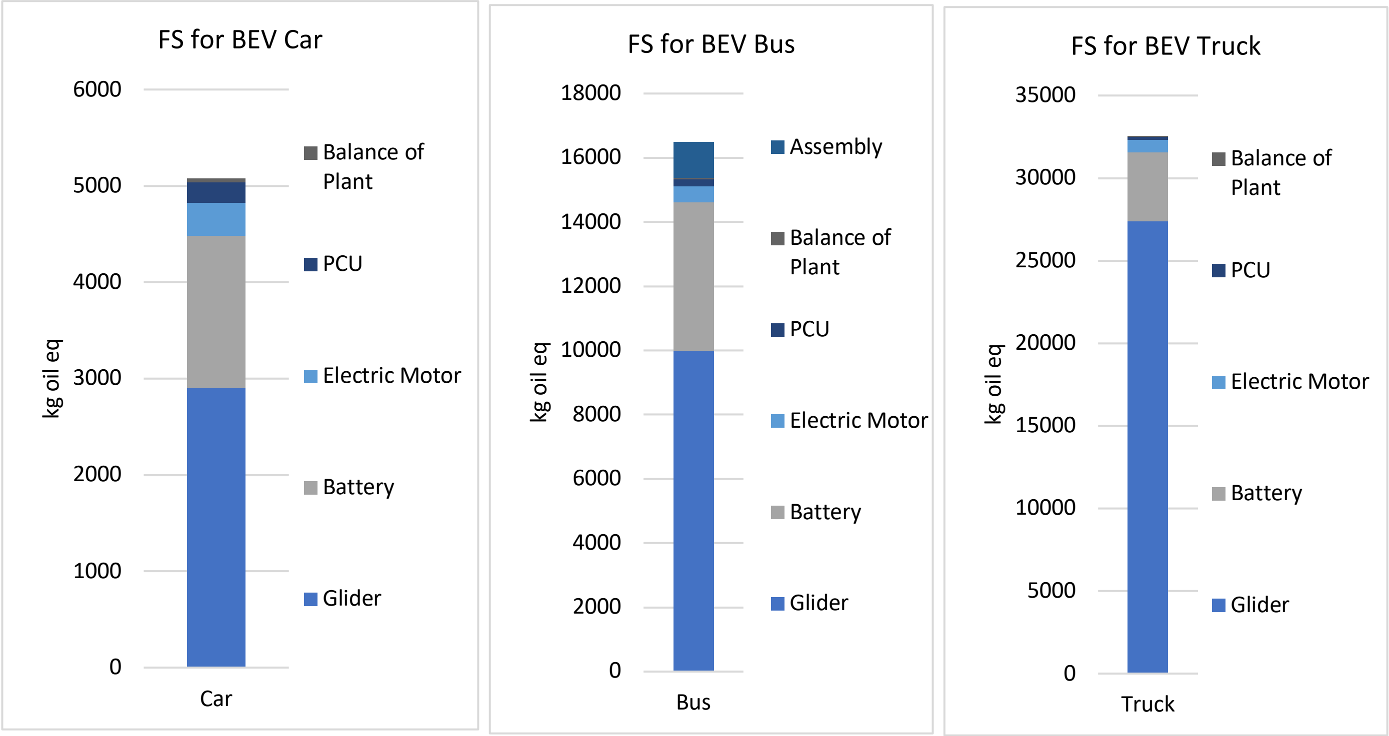


Figure 6-9 - Breakdown of production emissions for a BEV passenger car, bus, and truck (in terms of FS).

6.1.2.1. Lithium-Ion Battery:

Figure 6-10 (left) gives a breakdown of the GWP from the battery production in this study.

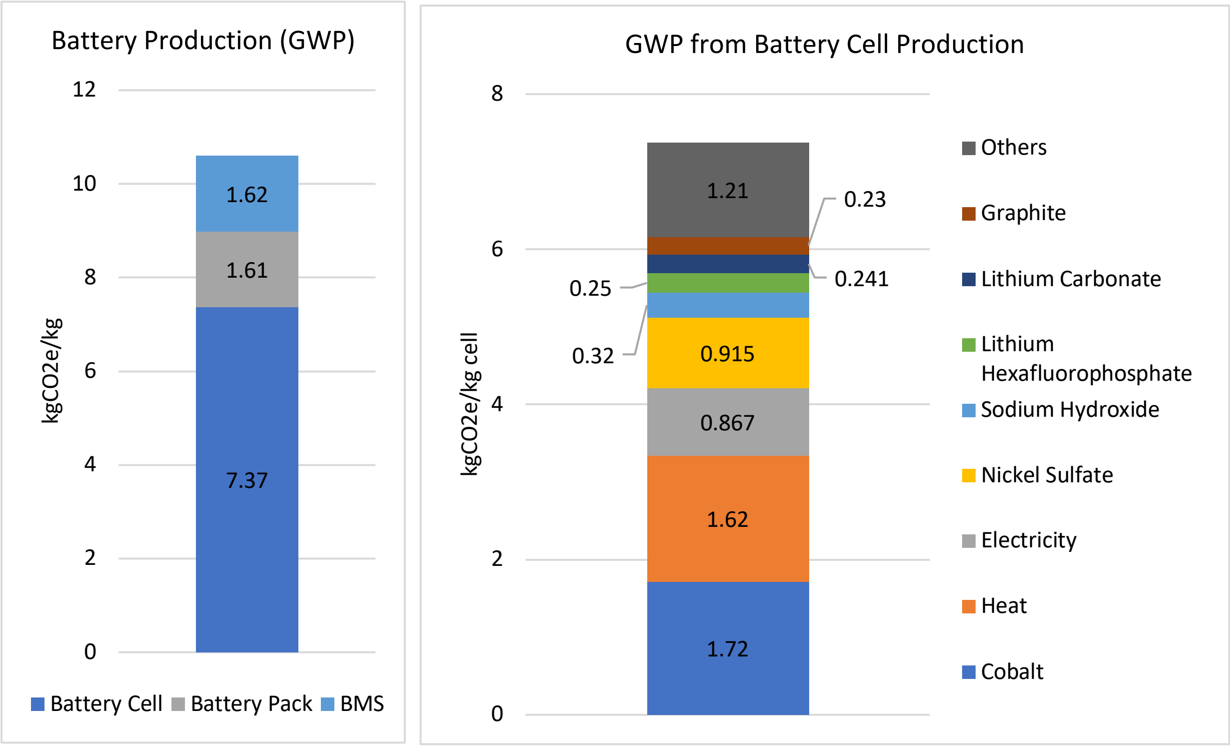


Figure 6-10 – GWP from total battery production (left), and battery cell production (right).

Total battery emissions are approximately 10.6 kgCO_2e per kg of battery, or ~43 kgCO_2e/kWh taking into account battery energy density. Inventory for the battery was covered in Chapter 5 and aimed to represent one of the most widely used battery technologies available (NMC chemistry). These production estimates are reasonable when compared to others published in literature. For example, Melin *et al.* [81] published a report on the energy consumption from an NMC111 lithium-ion battery and estimated emissions at 73 kgCO_2e/kWh. Emilsson *et al.* [151] also estimated emissions at 72.9 kgCO_2e/kWh but highlighted that the source of energy significantly influences results with a potential range of between 61-106 kgCO_2e/kWh based on clean or fossil-rich electricity sources. Ellingsen *et al.* [240] also gave estimates ranging more widely from 38-356 kgCO_2e/kWh, depending on battery chemistry and energy sources. It should also be noted that since manufacturers are not very transparent regarding the material composition of their batteries, many studies rely on assumptions to estimate these unknowns which may not be as accurate, leading to a wide range of results. These factors should be acknowledged as results will be influenced by the electricity mix used and study-specific assumptions. In this work, all electricity demands were satisfied using the UK grid mix but since the majority of lithium-ion battery production is carried out in countries like China with a fossil dominated electricity mix (where 35-50% of battery production emissions are attributed to electricity consumption), production emissions in this work may appear slightly lower compared to emissions in reality [155]. However, these studies provide some reassurance that estimates from this study are reasonable. For the other impact categories, battery production emits 0.29 kg

$PM_{2.5}$e/kWh (PM) and 13.2 kg oil eq/kWh (FS). The breakdown of these emissions is discussed in the next sections respectively.

Focusing on overall battery production shown in Figure 6-10 (left), approximately 70% of the GWP is attributed to the production of the cells, 15% for the pack, and 15% for the battery management system (BMS) respectively. Hung *et al.* [241] reported figures of roughly 50% of battery production emissions from cell manufacture and 20% from the cell materials themselves. As a result, if the GWP of battery production is to be reduced in the future, cell manufacture should be targeted. A breakdown of the battery cell production emissions per kg of cell is given in Figure 6-10 (right chart) highlighting the contributions more clearly. Since the battery cells largely dominate in terms of the total battery emissions, analysis will focus on these components. Emissions are dominated by the cathode production where cobalt, heat and electricity, and sulphates are used. A selection of these will be covered in greater depth in the following sections.

6.1.2.2. Battery Cells:

The majority of the battery cell emissions are associated with the cathode, and specifically the active material. The NMC oxide active material used by the cathode incurs the most significant emissions. As mentioned previously, this is produced through a multi-stage calcination process with an NMC hydroxide precursor and lithium carbonate. However, the NMC hydroxide must first be produced through a separate process in which sulphates of nickel, manganese, and cobalt are co-precipitated. The production of these sulphates leads to high emissions and energy consumption which can be seen in Figure 6-10 (right). Cobalt production is the highest contributor to total cathode GWP (33%) respectively. Nickel and manganese sulphate and lithium carbonate also contribute 25% of total cathode production emissions. In terms of air quality, for PM, nickel sulphate accounts for the vast majority with 85% followed by cobalt (9%) and copper, contributing significantly less.

The cathode component is responsible for the high cobalt production emissions and is an essential element and the largest contributor to the battery cell emissions. Here, cobalt accounts for 1.72 kg CO_2e/kg (~23%) of the total cell production emissions, with its demand expected to increase in the future as the BEV market continues to grow. Studies have predicted that in order to satisfy this rising demand from BEVs, a 3% annual growth rate is needed [156]. Cobalt belongs to the 2020 critical raw material list and incurs significant emissions through its extraction process (
Figure 6-11 6-11), with the majority of the GWP production emissions from electricity consumption (~35%). It is often produced as a by-product from nickel open pit or underground mining and includes ore mining, beneficiation, and metallurgical processing [157]. In the Ecoinvent process for cobalt production, it is based on nickel production and a mix of 50% grey cobalt oxide and 50% black cobalt oxide are reduced with a yield of 95%. Although no location is specified, 60% of global cobalt production comes from the Democratic Republic of Congo where political stability is considered weak, environmentally unsustainable practices are used, and several reports highlight human rights violations relating to the use of child labour. China is also responsible for

50% of global cobalt refining [156]. Since the supply of cobalt is concentrated in particular regions, this could lead to shortages and rising prices if mines become inaccessible, for example.

GWP emissions associated with graphite are roughly 3% of the total battery cell emissions and therefore relatively minor in comparison to the cathode. Graphite is the major material used for the production of the anode with the biggest contributors to anode GWP being the graphite (40%) and electricity (21%) respectively. Other materials contributing towards the cell emissions include aluminium, copper, and battery separator production respectively, though these all play a very minor role and are negligible in comparison.

GWP associated with energy consumption for battery cell production are approximately 1.62 $kgCO_2e$/kg battery from heat and 0.87 $kgCO_2e$/kg battery from electricity respectively (Figure 6-10, right). Electricity is required for the assembly of the cells and the battery pack as a whole. For heat roughly 26 MJ is required per kg of cathode. This electrode drying and the operation of the drying room facility are two of the major energy consumers in battery cell manufacturing [152]. It was reported from Emilsson *et al.* [151] that approximately 50% less heat is required for the drying of the anode, however this is still significant in terms of overall emissions.

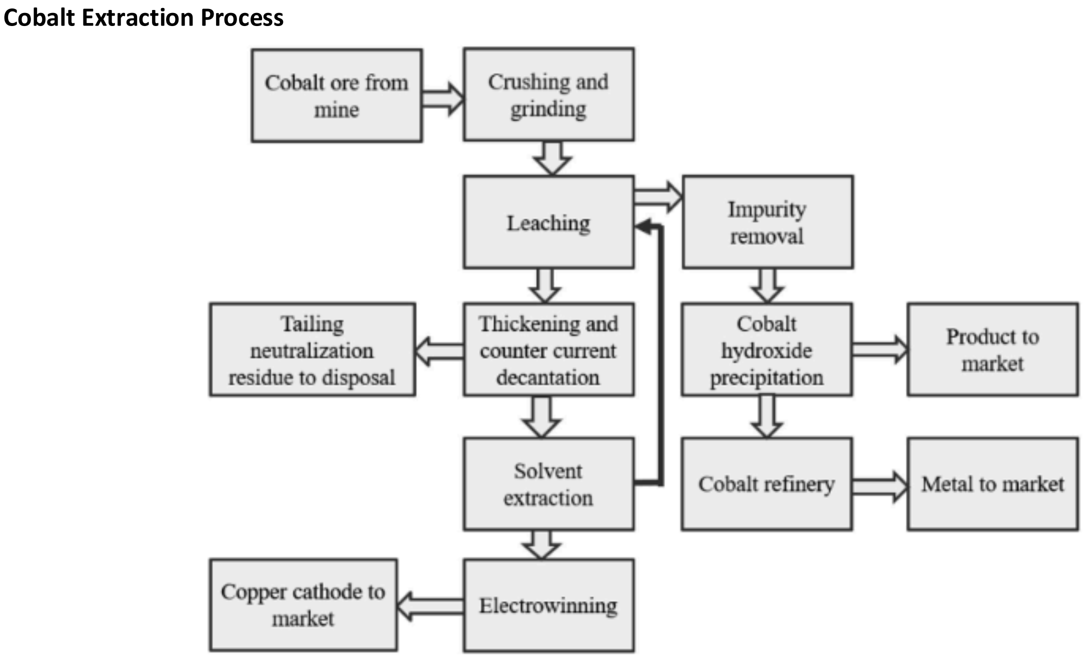


Figure 6-11 – Flow diagram outlining cobalt extraction process. [157]

6.1.2.3. Battery Management System and Pack:

The contribution from the BMS and battery pack to the total battery GWP is small in comparison to the cells, both at approximately 15%. However, improvements in the production process could help reduce emissions and when this change is magnified by volumes of scale it could be a significant step forward. Currently, the production emissions for 1 kg of BMS is ~67 $kgCO_2e$, with over 80% of this attributed to the printed wiring board. The electronic component factory is the second largest contributor at 16%. The battery pack emissions are dominated by aluminium production and processing respectively. PM and FS are also dominated by these two components respectively.

6.1.2.4. Electric Motor:

The electric motor for a BEV car generates ~1.5 tCO_2e during its production (8% of total GWP). This aligns well with existing LCA studies on BEV production as EEA [155] report the electric motor contributes 7-8% of total BEV production emissions. Here, 0.84 tCO_2e (56%) is from aluminium production. Copper also contributes ~0.3 tCO_2e (20%) with the remaining materials making up significantly less. In terms of PM, copper production accounts for a majority 71% of the total electric motor emissions, whilst for FS aluminium production generates 55% respectively. For BEV trucks with much higher total emissions the contribution of the electric motor is very minor in comparison, whilst for buses it accounts for ~3% respectively.

6.1.3. FCEV Production Emissions:

The GWP of all cars, long haul trucks, RCVs, and forklifts in the study are the highest from the FCEV versions and are estimated at 21.3 tCO_2e, 120 tCO_2e, 76.8 tCO_2e, and 80.1 tCO_2e respectively. This statement is also true for PM, with FCEV cars, trucks, tippers, refuse, and forklift vehicles all showing the highest emissions of all the powertrain types considered, shown earlier in Figure 6-1 to Figure *6-3*. For FCEV buses in Figure *6-12*, GWP is roughly 6.5 tCO_2e lower than BEV buses, largely due to the size of the lithium-ion battery required in the reference bus which incurs a significant portion of emissions. Here, the powertrain of the FCEV reference bus (fuel cell, electric motor, and battery) generates approximately 8.1 tCO_2e compared to 16.6 tCO_2e for the BEV reference bus powertrain (battery and electric motor). Unfortunately, no estimates for the production emissions for FCEVs could be sourced in literature since the current market is so small. Direct contact was made with Toyota to gain insight into the production emissions from the Mirai but no response was received and no estimates could be provided, leaving limited data to verify this estimate.

Similarly to BEVs, the powertrain components of FCEVs contributes significantly to the total PM and is in some cases greater than the glider for a number of vehicle types. From Figure 6-13, PM from the fuel cell production for cars and trucks outweighs the glider emissions contributing a majority 78% and 46% share respectively. For the other vehicles in the study the glider is the main cause of PM. For FS, the fuel cell production for cars accounts for the majority of emissions with 47% respectively, though for all other vehicles which have greater material quantities associated with their glider production, this share is much lower. Aside from the glider and fuel cell, the remaining components contribute a much smaller share of the total emissions across all impact categories. Generally, for HDVs the third and fourth highest emissions come from the battery and the hydrogen storage tank. These individual component breakdowns will be discussed in the next section similar to ICEVs and BEVs.

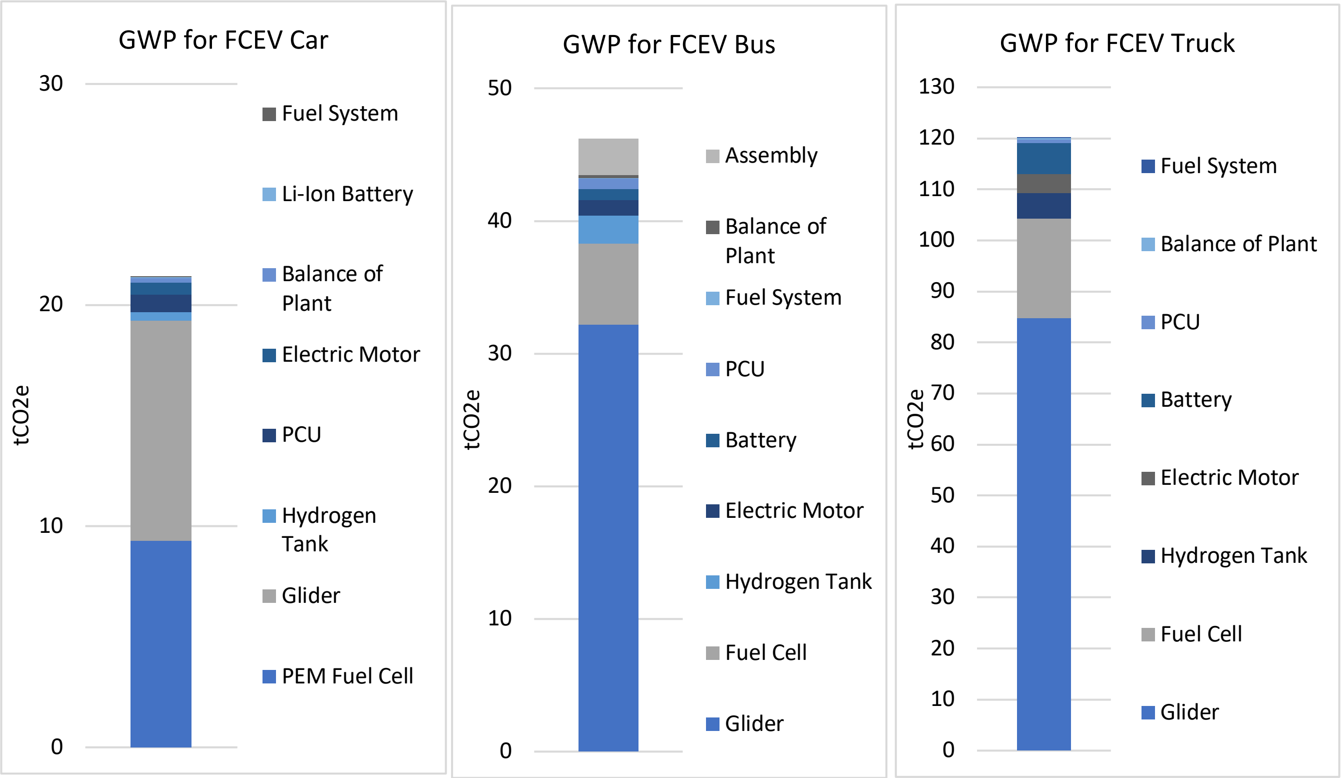


Figure 6-12 – Production emissions for a FCEV car, city bus, and long haul truck (in terms of GWP).

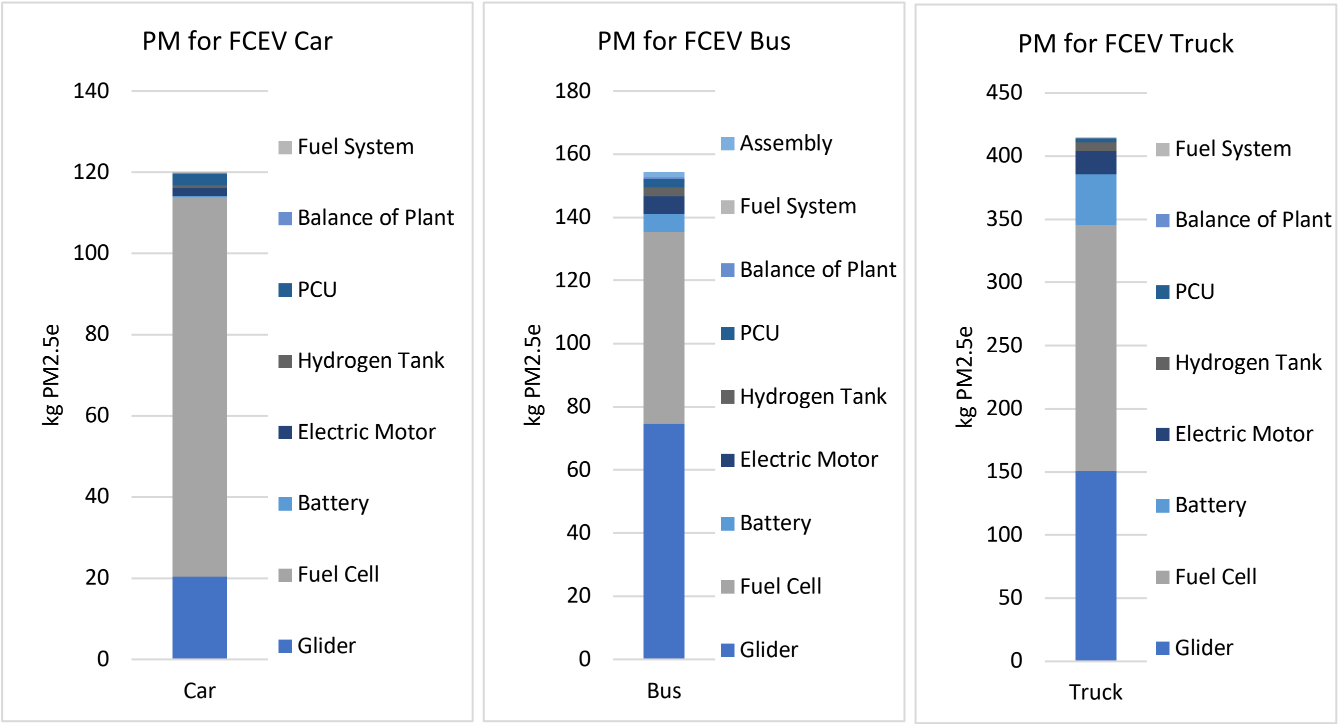


Figure 6-13 - Production emissions for a FCEV car, bus, and truck (in terms of PM).

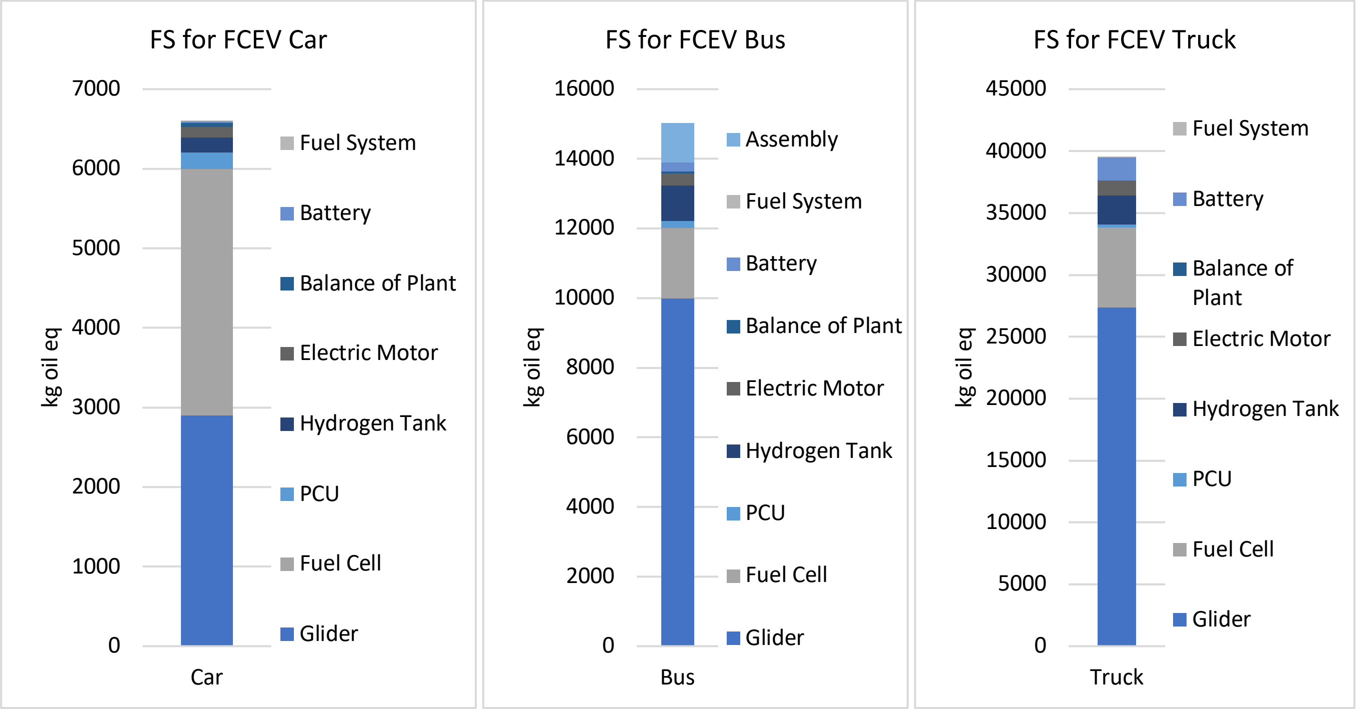


Figure 6-14 - Production emissions for a FCEV car, city bus, and long haul truck (in terms of FS).

6.1.3.1. PEM Fuel Cell:

From *Figure 6-12* 6-12, GWP from the manufacture of the 115 kW PEM fuel cell for a car is 9.3 tCO$_2$e. For the smaller 75 kW fuel cell in a bus emissions are 6.1 tCO$_2$e, and 19.5 tCO$_2$e for a 240 kW truck fuel cell. These figures are equivalent to ~81 kgCO$_2$e/kW and it is by far the most energy intensive powertrain component in these FCEVs. This estimate of fuel cell production emissions is close to Simons *et al.* [154], who derived a value of 89.3 kgCO$_2$e/kW for a PEM fuel cell, whilst Evangelisti *et al.* [245] reported figures slightly higher of 110 gCO$_2$e/kW, with several other study estimates ranging from 50 to 100 kgCO$_2$e/kW respectively. This range of estimates highlights the uncertainty in the studies and it should be noted that a lack of detail surrounding the primary data used will force different assumptions to be made in each case, leading to varying results. In addition, since studies were published at different time periods where the levels of technology development varied considerably, higher emission estimates were generally reported in earlier studies, such as the one by Evangelisti *et al.* [245]. Despite this, estimates from this work lay within this range and are considered reasonable in comparison.

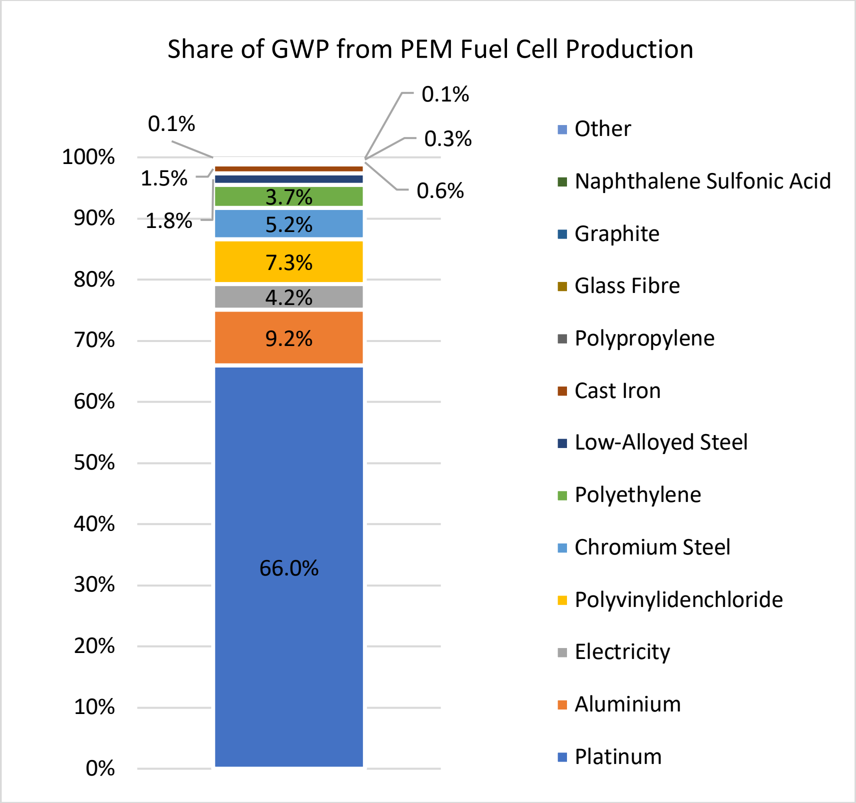


Figure 6-15 – Emissions breakdown for a PEM fuel cell (GWP).

The GWP from the fuel cell is broken down further in Figure 6-15 and shows the platinum content for the electrode catalyst is responsible for 66% of the total per kW (53 kgCO_2e/kW). In fact, platinum is the largest contributor to the fuel cell production emissions across all impact categories, with 94% for PM and 64% for FS respectively. Similar findings are shown in work by Simons *et al.* [154]. Platinum contributes over 28% (~6 tCO_2e) towards the entire FCEV car production GWP, ~9% (4 tCO_2e) for a bus, and ~10% (12.7 tCO_2e) for a truck. This CRM belongs to the platinum group metals (PGMs) and faces increasing pressure on its supply chain due to growing markets, similarly to cobalt in BEV and battery production. It can only be found in select locations and is often extracted together with other PGMs (such as palladium and rhodium) and minerals from the same location using energy intensive processes. Here, the extraction process includes physical separation of the minerals and PGMs to produce a mineral concentrate, drying, pyrometallurgical separation at 1500°C, leaching using high temperature and pressure, and refining [158]. Reports have highlighted that around 80% of global PGM mining takes place at the Bushveld complex in South Africa and at Kola Peninsula in Russia [145]. Since it is also very expensive, it accounts for a significant cost to FCEVs, leading to higher purchase prices compared to ICEVs, which is one of the factors contributing to its slow uptake. From this, it can be said that if emissions from stack production are to fall in the future, the platinum content must be targeted and either replaced by cheaper or less energy intensive alternatives, or its supply chain must be developed to incorporate more sustainable practices.

For GWP, aluminium is the second largest contributor towards fuel cell production emissions, though this is much less than platinum at only 9% (7.4 kgCO_2e/kW). Aluminium is the main material used for the housing of the stack, along with the bipolar plates, offering lightweight and easy forming properties respectively with its production process covered in ICEV production respectively. Approximately 4% of the fuel cell GWP originates from electricity used for its assembly and material processing and 7% from polyvinylidenchloride production which is for ancillary balance of plant. Chromium steel makes up 5% and is used for the housing. For PM, the second highest emissions during fuel cell production arise from steel production though only make up 2.2% whilst for FS this is associated with polyethylene production with 8.6%. These low figures help highlight the energy intensity of platinum extraction and usage on environmental emissions. Although some of the remaining items have relatively high production emissions on a per kg basis, since their quantities in the fuel cells are very low these all contribute <3% and have a very minor impact to overall fuel cell emissions.

6.1.3.2. Hydrogen Storage Tank:

The Type 4, 700 bar gaseous hydrogen storage tank on board the FCEV car is a vital component in the vehicle makeup and its emissions are shown in Figure 6-16 in terms of GWP respectively. Using the material inventory sources discussed in Chapter 5, approximately 380 kgCO$_2$e is generated from the production of each tank. Under these modelling conditions, the production of carbon fibre generates 235 kgCO$_2$e, equivalent to ~60% of the total GWP. Outside of carbon fibre, the remaining materials associated with the hydrogen tank include chromium steel, glass fibre, and polyethylene which contribute significantly less towards the total tank emissions. These results align with other LCA studies which report the carbon fibre production accounts for the majority of the total GWP from tank production, due to its intense manufacturing process which gives it the properties of high tensile strength and low thermal expansion [15] [248] [250]. In fact, Usai *et al.* [255] reported that roughly 75% of the emissions from carbon fibre production come from electricity, and the remainder from heat production respectively. This highlights the impact of electricity mix on tank emissions.

Benitez *et al.* [15] reports the high variability of emission figures across LCA studies due to the complex carbon fibre manufacturing process, highlighting that detailed inventory is often unavailable in literature due to fact this information is closely related to the intellectual property of the manufacturers. As a result, studies differ in their modelling of this process and are therefore prone to generating a wide array of results. For example, the carbon fibre production process in Ecoinvent generates 89 kgCO$_2$e per kg produced, Benitez *et al.* [15] reports 69 kgCO$_2$e/kg, Mutzel *et al.* [251] reports 55 kgCO$_2$e/kg, Joshie *et al.* [252] reports 23.5 kgCO$_2$e/kg, Miotti *et al.* [244] reports 20 kgCO$_2$e/kg, and Knop *et al.* [250] reports 14.6 kgCO$_2$e/kg respectively.

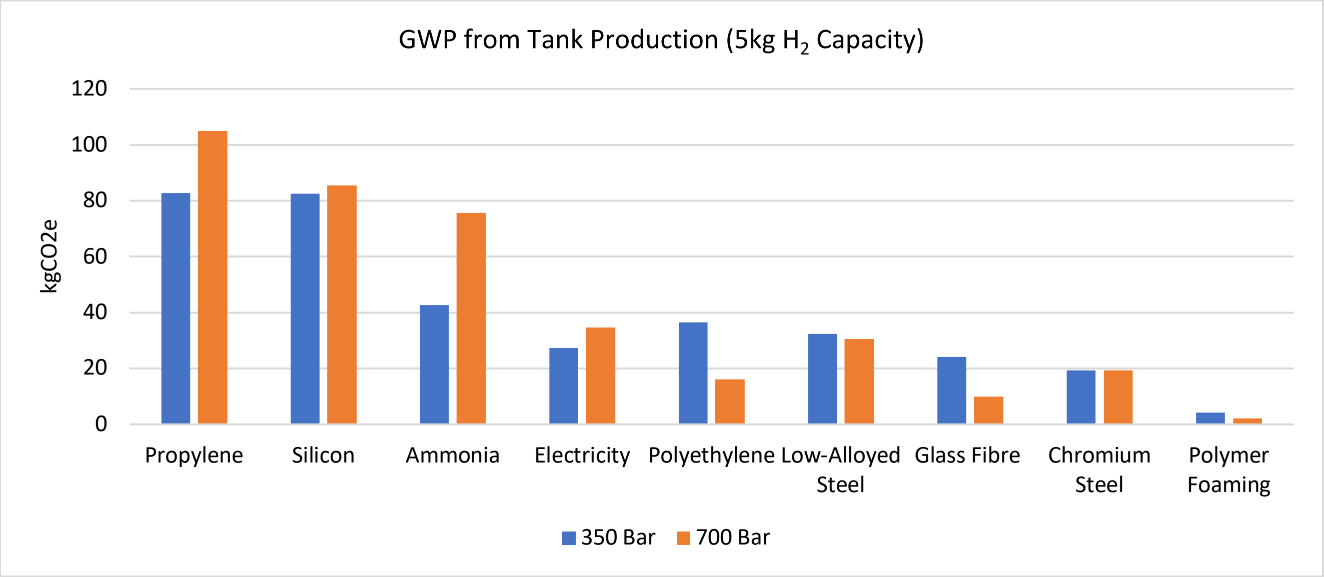


Figure 6-16 – Production emissions for 350 bar (Type 3) and 700 bar (Type 4) hydrogen tanks (5 kg capacity).

In addition to the lack of inventory data for carbon fibre production, variations in tank emissions are widened further when taking into account the modelling conditions different studies use. These include the electricity mix, energy intensity of heat generation, the year of the study, and other underlying assumptions, all of which have a significant impact on the emissions from its manufacture. This is showcased by the wide range of results reported in literature. For example, Benitez *et al.* [15] generated estimates of 5.6 tCO_2e from Type 4 tank production under a 2015 German electricity mix (carbon intensity of 460 gCO_2e/kWh), Miotti *et al.* [244] generated figures of 1.5 tCO_2e under a 2015 mix (carbon intensity of 594 gCO_2e/kWh), whilst Knop *et al.* [250] offered estimates of ~1.1 tCO_2e respectively [249]. As mentioned previously, the carbon fibre production has the largest impact on tank emissions. In this study, since the UK electricity grid has a much lower GWP of 243 gCO_2e/kWh and a low production energy intensity for carbon fibre manufacture, emissions in this case are expected to be significantly lower.

For HDVs which store and utilise hydrogen at lower pressures of 350 bar using Type 3 tanks, the tanks are manufactured using the same material mix as Type 4 700 bar tanks but in slightly different quantities. In this case, since the pressure is reduced less carbon fibre is required which is reflected in lower production emissions of 352 $kgCO_2e$, with the majority of the GWP coming from carbon fibre related components such as propylene (~24%) and ammonia (~12%), as well as electricity (10%), and silicon (~23%). This silicon production is responsible for the majority of the PM emissions from tank production at 25% respectively. For a FCEV bus containing seven 5 kg tanks (35 kg total capacity), and a FCEV truck containing 14 tanks (70 kg total capacity), the total emissions associated with hydrogen storage are approximately 2 tCO_2e and 5 tCO_2e, equivalent to ~4% of the total production GWP in both cases. Unfortunately, very few LCA studies available focus on the HDV sector, which means that there are fewer estimates on the storage tanks of these vehicles reducing the comparisons which can be made. However, since many of these HDVs currently in operation use multiple smaller tanks, it is expected that these emissions will rise proportionally.

6.1.3.3. Battery:

Since the size of the lithium ion batteries used in the FCEVs are much smaller compared to those used in the BEVs, emissions from this component are negligible compared to others like the glider, fuel cell, and storage tank. For a car, the battery production emits only ~53 kgCO_2e in the FCEV manufacture, a minor contribution of 0.3%. For HDV buses and trucks which utilise larger batteries these emissions are ~1 tCO_2e and 6 tCO_2e respectively, which also only makes up a minor portion of the total.

These results highlight that since FCEVs are not yet mature and still limited in numbers with their market small in comparison to ICEVs and BEVs, the supply chains for many of their component materials (particularly platinum), have not yet had enough time to develop and be established with sustainability in mind. As a result, as the government continues to urge consumers to switch to ZEVs, these supply chains will need to improve and more sustainable materials should be introduced to reduce shortages and minimise upstream emissions.

6.1.4. Emissions from Component Replacement:

GWP associated with the replacement of batteries and fuel cells in ZEVs is summarised in Figure 6-17 and is significant over the course of their 15 year lifetime. The frequency of replacements was highlighted in Chapter 5 and has been multiplied by the production emissions of each component to generate a total additional emission for lifetime replacements. From the graph the emissions associated with truck replacements are the highest of all vehicle types with 174 tCO_2e (BEVs) and 331 tCO_2e (FCEVs) generated over their 15 year lifetime, with 13 replacements needed; equivalent to almost one per year under the mileage conditions. Although the total accumulated emissions associated with the production of new batteries and fuel cells overrides the vehicle production emissions in some cases, when taking into account the emissions recovered during fuel cell EOL recycling, as well as the distribution of these emissions over the mileage covered by the vehicles, they become much lower, especially for trucks which have the highest mileage requirements of all fleet vehicles. In this case, on a per tkm basis, component replacement emissions for BEV and FCEV trucks becomes only 1.5 gCO_2e/tkm and 0.66 gCO_2e/tkm respectively. Nevertheless, Figure 6-17 still helps to highlight the importance of developing these technologies further and reducing their production emissions.

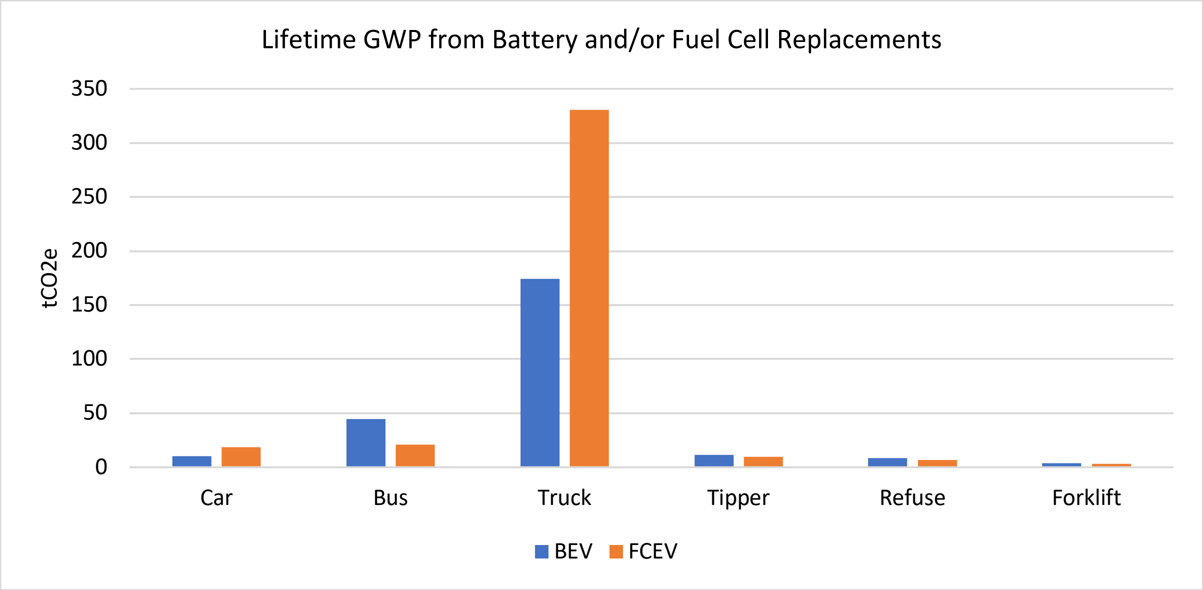


Figure 6-17 - Emissions from ZEV component replacement over 15-year lifetime.

6.1.5. Emissions from Component Transport:

GWP associated with the transport of the glider and powertrain from their places of production to their place of assembly is shown in Figure 6-18. The approach used to model this was covered in Chapter 5 and the highest emission calculated is ~0.7 tCO_2e for the transport of ICEV forklift components. Since these estimates are highly dependent on component weight, HDVs incur the greatest emissions during transit, with cars only creating ~50 $kgCO_2e$. 16-32t diesel trucks are used for transport but emissions have potential to be reduced by using ZEV transport modes. It should also be reminded that these emissions are UK-based, with emissions from overseas transport excluded. If these emissions were considered, ZEVs would have more significant emissions during their transport which may impact their carbon footprints. However in the future as supply chains develop and markets grow, and knowledge and expertise improves, more manufacturing will take place locally in the UK and these emissions will likely fall.

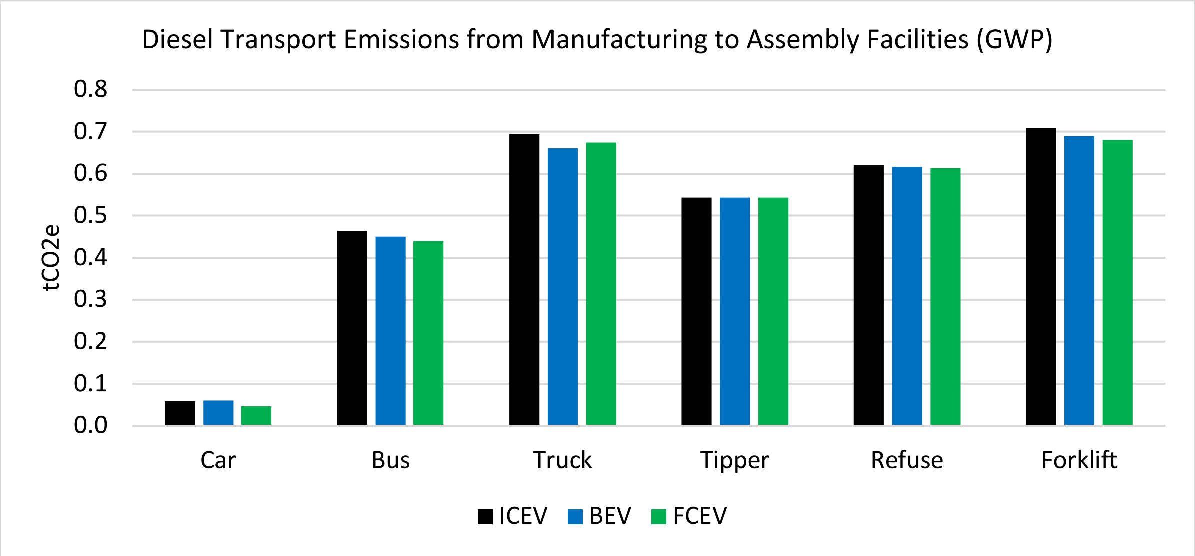


Figure 6-18 – Emissions from the transport of vehicle components using diesel transport.

6.2. Emissions from Fuel Production:

This section outlines emissions generated from the production of the fuels prior to their distribution and delivery. Similarly to vehicle production, analysis is focused towards the climate change impact category though also considers PM and FS respectively. All emissions are given per kWh of fuel respectively.

Table 6-2 – Production emissions for each of the fuels in terms of GWP, PM, and FS impact categories.

	Emissions/kWh Fuel										
	ICEV	**FCEV**						**BEV**			
	Diesel	SMR	SMR w/ CCS	225 kW	100% RES	100% Grid	50/50 Split	225 kW	100% RES	Rapid Charger	50/50 Split
GWP (gCO2e)	46	220	78	348	22	447	234.5	12	12	243	127.5
PM (gPM2.5e)	0.13	-0.05	0.00	0.17	0.06	0.20	0.1	0.03	0.03	0.11	0.1
FS (g oil eq)	104	75.6	88.2	129.6	5.7	167	86.6	3.1	3.1	90.7	46.9

Table 6-2 shows the production emissions per kWh of each transport fuel in this study. Unsurprisingly, the lowest emissions arise from fuels which utilise renewable energy sources, with electricity and hydrogen from 100% RES generating only 12 and 22 gCO_2e/kWh in terms of GWP. Emissions are also lowest in terms of FS with only 3.1 and 5.7 g oil eq/kWh. Here, hydrogen incurs slightly higher emissions due to the deionised water required for electrolysis. The highest GWP, PM, and FS comes from electrolytic hydrogen powered using 100% grid electricity, with 447 gCO_2e/kWh, 0.2 $gPM_{2.5}e/kWh$, and 167 g oil eq/kWh. Comparing these estimates to literature is challenging since emissions from grid-powered electrolysis strongly depends on the carbon intensity per kWh in each country. However, Blank *et al.* [239] provides some estimates of GWP from a number of countries which can be used to validate the 447 gCO_2e/kWh (14.9 $kgCO_2e/kg\ H_2$) estimate in Table 6-2. Production from electrolysis using US grid power generates 21 $kgCO_2e/kg\ H_2$, whilst the Rest of World generates 26 $kgCO_2e/kg\ H_2$. Some lower estimates were made by countries having an advantage of high renewable resources which meant their electricity grid had a very low intensity per kWh, closer to a UK scenario. For PM from this route, this may be highest due to incomplete combustion reactions taking place during the electricity generation process since the grid still relies on some fossil fuels. For rapid chargers also utilising grid power, these have the highest production emissions of all BEV production scenarios across all impact categories.

For hydrogen and electricity production using a 225 kW turbine, emissions are fleet specific in this case. This is because the total production emissions are impacted by the fleet size, which affects the total energy required for fuel production, and influences the demand for grid electricity. 348 gCO_2e/kWh (or 11.6 $kgCO_2e/kg$) is emitted from hydrogen production, as opposed to only 12 gCO_2e/kWh from electricity. This is due to the fact that the daily energy production from this turbine (1350 kWh) is not enough to produce the total daily hydrogen demand for the fleet. As a result, the remaining energy is sourced from the UK grid which accounts for these higher emissions. For BEVs which require less energy to operate the fleet each day, the 225 kW turbine provides the entire daily demand of electricity and therefore incurs significantly lower emissions as no energy is taken from the grid. This is a limitation of FCEVs powered by electrolysis as they show no environmental benefits over BEVs under these conditions. If the fleet was larger however, BEVs would likely also require grid electricity to make up any difference in energy demand, but total production emissions would still remain lower than FCEVs.

For grey hydrogen from conventional SMR, emissions are not fleet specific and remain the same per kWh regardless of the fleet demand. In terms of GWP, 220 gCO_2e/kWh (equivalent to 7.3 kgCO_2e/kg H_2) are emitted from production which is a reasonable estimate aligning closely with existing literature. Pettersen *et al.* [238] offers a range of 8-9 kgCO_2e/kg H_2 from conventional SMR whilst Blank *et al.* [239] extends this range to 8-12 kgCO_2e/kg H_2. For blue hydrogen with CCS technology these emissions fall to 78 gCO_2e/kWh (or 2.6 kgCO_2e/kg H_2) respectively. This estimate is very similar to those reported by Pettersen *et al.* [238], who provide a compilation of emission estimates from 25 individual blue hydrogen studies between 2011 and 2022, 24 of which showed production emissions ranging between 1-4 kgCO_2e/kg H_2.

In terms of PM, the lowest emissions arise from grey hydrogen via SMR at -0.05 g$PM_{2.5}$e/kWh since this process includes avoided emissions associated with the export of steam to other processes, avoiding virgin steam generation which relies on a variety of fuels including coal and natural gas which generates PM, covered previously in Chapter 5. The production of the 6.4 kg of steam required to produce 1 kg of hydrogen from SMR generates 2.16 kgCO_2e (GWP), 2.11 g$PM_{2.5}$e (PM), and 0.613 g oil eq (FS) respectively. By recovering this steam, these emissions are taken away from the process leading to emissions falling significantly as a result and negative emissions in terms of PM. Here, PM emissions from steam generation exceed those from natural gas production so when avoiding them by exporting the steam, the PM emissions are negative overall. The study by Imran *et al.* [233] also highlighted these higher PM emissions associated with steam production respectively. In terms of GWP and FS, the impact of this credit is less severe with emissions of CO_2e and oil eq still reaching 7.3 kgCO_2e/kg and 2.52 kg oil eq/kg respectively. Inventory for SMR with CCS incurs lower quantities of avoided steam and therefore PM is close to zero g$PM_{2.5}$e/kWh.

Although a low sulphur blend is used in this work, PM generation from fossil combustion associated with diesel fuel may contribute to its emissions of 0.13 g$PM_{2.5}$e/kWh. For GWP, 46 gCO_2e/kWh (or 0.46 kgCO_2e/L) is emitted which is lower than 5 out of 6 of the hydrogen production routes. This is partly due to the fact that the diesel production is a mature and efficient process, having had years of development through learning by doing. Although its production emissions are lower than most of the ZEV fuels, its consumption emissions offset this. This will be covered later in Section 6.5.

6.3. Emissions from Fuel Distribution and Delivery:

This section provides a breakdown of the emissions associated with the distribution of all transport fuels (per kWh of fuel), from their point of production to the point of use. Diesel delivery emissions include only road transport using tanker trucks. For hydrogen, an overview of the emissions associated with the 3 delivery modes (compressed gas pipelines, tube trailers, and liquid tankers) is given, along with required conditioning processes. Since electricity is generated locally on site, there are no conditioning or distribution emissions to consider.

Due to constraints on page limits, the graphs in this section show distribution and delivery emissions for climate change only. Graphs showing PM and FS are given in Appendix 2 with reference made to them in this section.

6.3.1. Diesel:

Diesel delivery employs a tanker truck to transport the fuel from the production point at Teesside to the fleet at Leeds. As a result, GWP from distribution is approximately 5.5 gCO_2e/kWh (shown in Figure 6-19). To satisfy the daily diesel consumption of the fleet (164L), this equates to 9 $kgCO_2e/day$ and if the tanker operates at full load and transports a total capacity of 20,000L for long-term storage on site, the emissions are ~1 tCO_2e.

6.3.2. Hydrogen:

Figure 6-19 compares the GWP from each of the 3 hydrogen distribution routes along with the conditioning processes required to deliver hydrogen at 350 bar for HDVs. For pipeline transport, zero emissions are generated since the hydrogen is injected into the pipeline network directly after its production at 20 bar with no compression stage necessary. Also, since leakage is assumed zero and recompression is not required for short distances of under 250 km, no emissions are generated [309]. For diesel-powered tube trailers and liquid tankers however, the conditioning of the hydrogen is responsible for the vast majority of these emissions.

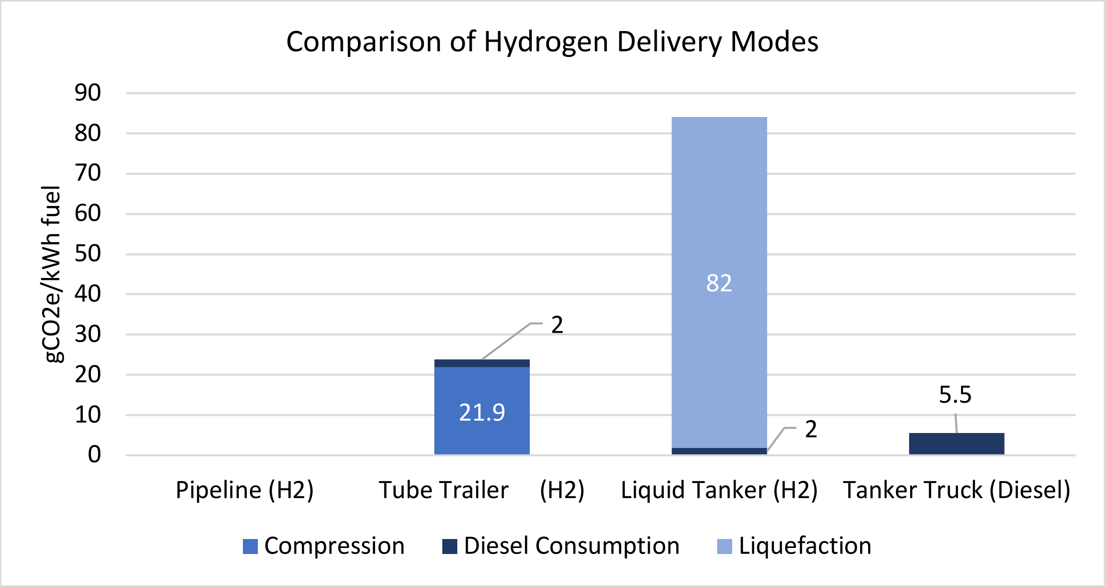


Figure 6-19 – GWP from the 3 hydrogen delivery modes (for 350 bar dispensing), and diesel.

For tube trailers, 21.9 gCO_2e/kWh is required for compression from 20 to 350 bar prior to transport, with only a small portion of the total (~6%) coming from diesel consumption for the transportation of the fuel. This is also true for PM and FS which have the same breakdown proportions. Since liquid tankers are modelled using the same 16-32t diesel vehicles as tube trailers, their diesel consumption emissions remain the same and accounts for an even smaller percentage of total delivery emissions equal now to only ~2%. This is because the energy for liquefaction and the cryopump is almost four times that of 350 bar compression, generating 82 gCO_2e/kWh respectively. Although liquid hydrogen transport generates higher emissions from the liquefaction process, these tankers can carry much larger volumes of hydrogen (up to 4000 kg) compared to tube trailers (~500 kg) which means they save emissions from diesel consumption by carrying out less trips. Also, several studies indicate that the liquefaction process could be improved, and its energy requirements could fall from 10 to ~6 kWh/kg H_2 in the future [173]. This would have a significant impact on liquid hydrogen supply chain emissions and is investigated later in this work in Chapter 7.

In the future however, the demand for diesel transport is likely to shrink as the transition towards low carbon transport progresses. As a result, these tube trailers and liquid tankers are more likely to be powered by hydrogen instead of diesel, leading to emissions savings from the 400 km (round trip) road transport. If FCEVs were used (assuming a FCEV long haul), the emissions would fall from 2 gCO_2e/kWh to 0.67 gCO_2e/kWh; a reduction of ~67%. Across the entire fleet which has a hydrogen demand of ~74 kg/day, this equates to a saving of 3.28 $kgCO_2e$ per day, or 1.15 tCO_2e per year.

6.3.2.1. Hydrogen Supply Chain:

Figure 6-20 gives the total GWP from hydrogen distribution, delivery, and conditioning from the point of production to the point of refuelling. Compared to Figure 6-19, the pipeline and tube trailer delivery modes have increased total conditioning emissions of 24.8 and 26.8 gCO_2e/kWh. This rise is a result of the precooling energy required to lower the temperature of the hydrogen to -40°C prior to dispensing in a HRS, as well as the compression of the hydrogen after pipeline delivery to 350 bar. Similarly, for liquefied hydrogen the total conditioning emissions are 109 gCO_2e/kWh which has increased due to the energy requirements for the compression to 350 bar after evaporation, as well as precooling. For hydrogen distributed using these liquid tankers, this liquefaction process accounts for the majority (75%) of distribution emissions when powered using grid electricity and is supported by work from [173].

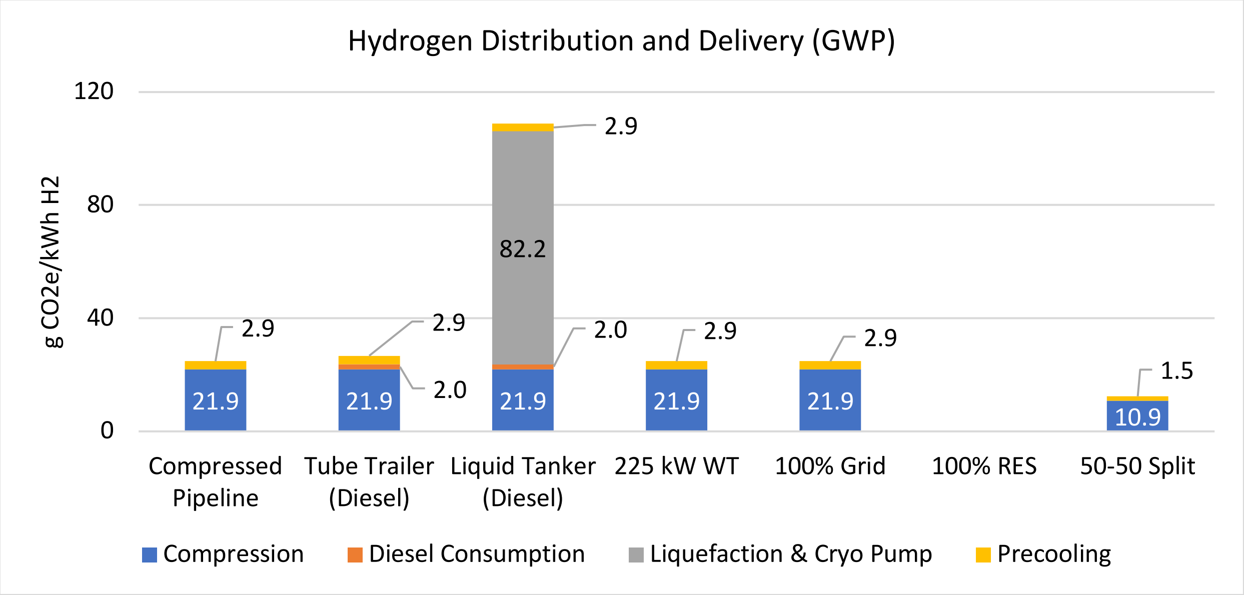


Figure 6-20 – GWP from the hydrogen supply chain (for 350 bar dispensing).

In terms of PM and FS from hydrogen distribution and delivery, these are given in Appendix 2 and have very similar percentage contributions to the GWP emissions in Figure 6-20 from each process. The reason for this is because SimaPro assumes PM emissions are directly linked to fuel consumption in the same way as CO_2 emissions. However, in reality these emissions are much more closely linked to the working conditions of the engine and the travel conditions. As a result, the emissions of CO_2 generated in SimaPro are likely to be much closer to their true values in reality compared to PM which has much more uncertainty. This highlights a limitation of SimaPro software. Across all impact categories, emissions associated with 100% RES hydrogen remain zero whilst for hydrogen distributed using liquid tankers emissions are highest with 0.05 $gPM_{2.5}e$ (PM) and 40 g oil eq (FS) per kWh of hydrogen respectively.

6.4. Total Fuel Supply Chain Emissions:

Figure 6-21 to summarise the total fuel production and supply chain emissions data given in the previous sections in terms of GWP, PM, and FS respectively. Focusing more closely on GWP, Figure 6-24 reports the contribution of these individual processes as a percentage of the total emissions.

The use of grid electricity for hydrogen production has a significant contribution to emissions under all impact categories. This can be seen clearly in the case for 100% grid hydrogen which has a GWP of 472 gCO_2e/kWh, with 95% of these emissions coming from its production (Figure 6-24), making it the most energy intensive route not only for FCEVs but overall in the study. This route also shows the highest total emissions under both PM and FS categories with 0.21 $gPM_{2.5}e/kWh$ and 178 g oil eq/kWh respectively, due to the combustion and consumption of fossil fuels which are associated with intensive use of grid power. Similarly, for BEVs the use of grid electricity for rapid chargers gives the highest emissions overall across all impact categories with 243 gCO_2e/kWh for its GWP, with the total emissions attributed to production since BEVs generate their fuel on site and do not incur emissions from conditioning or distribution. For pipeline and tube trailer transport, this majority contribution from the production stage on overall fuel supply emissions was also highlighted in the work by [173], unless zero carbon production routes are used.

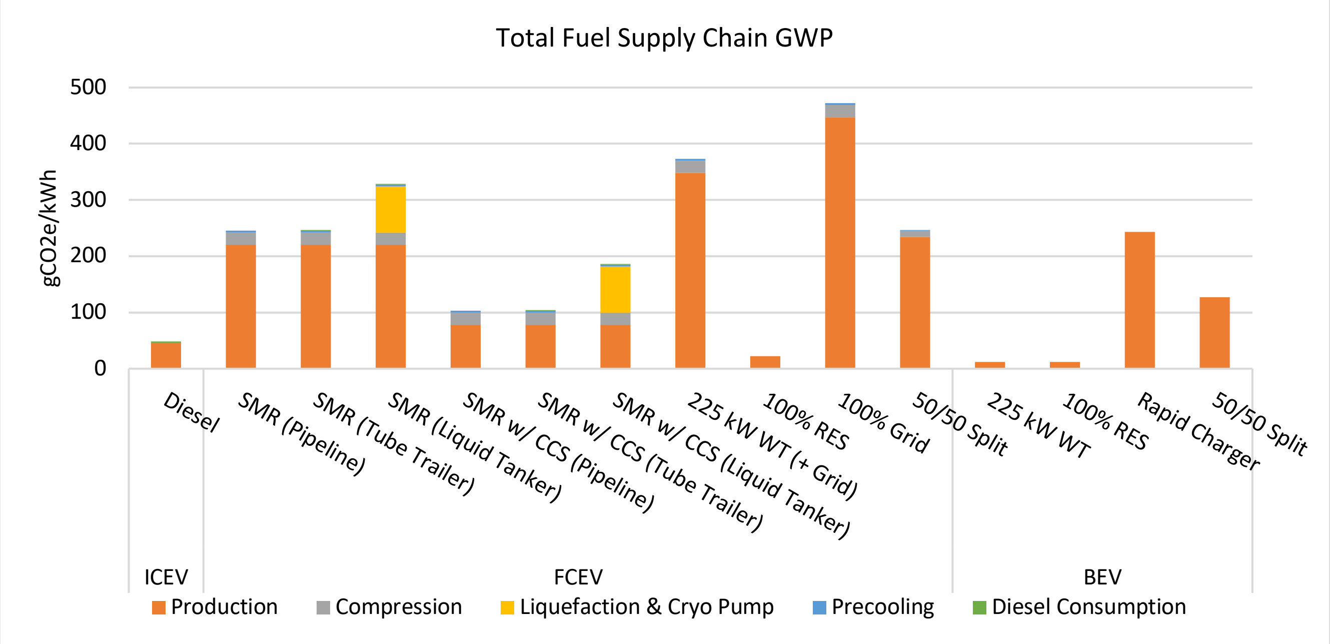


Figure 6-21 – GWP from fuel production, distribution, and conditioning processes.

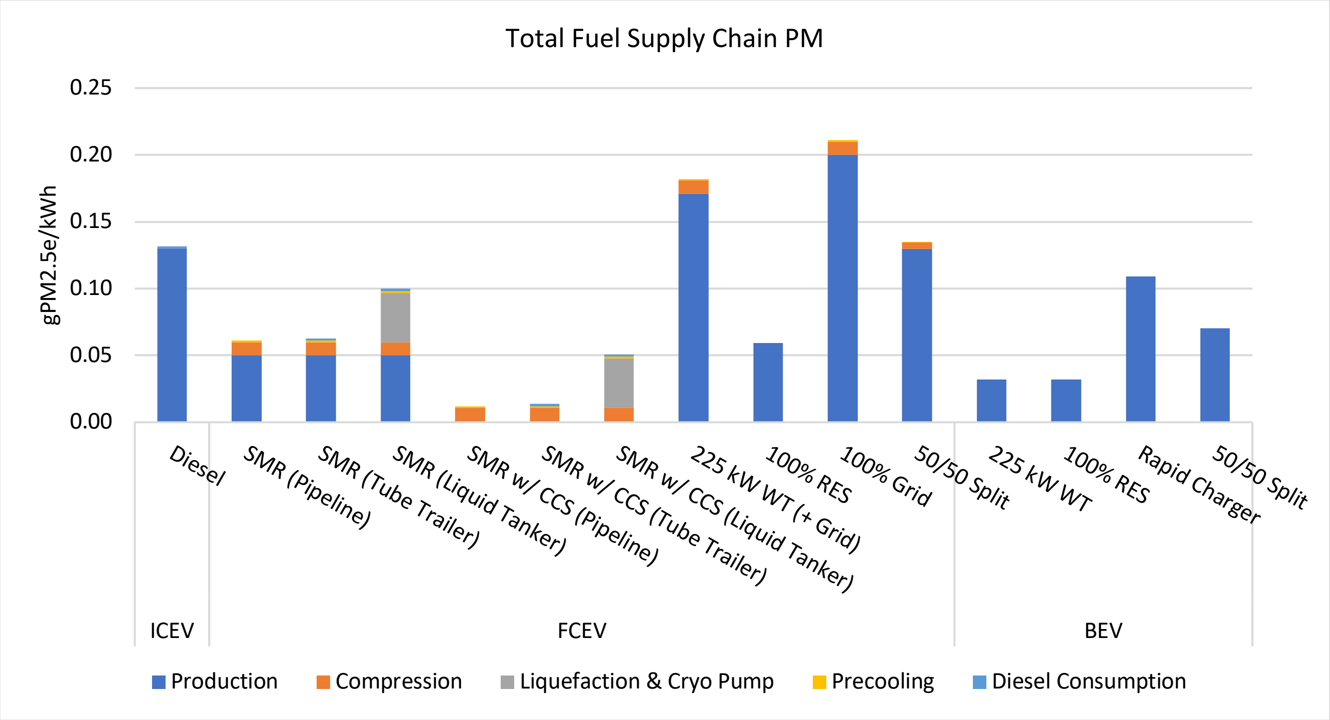


Figure 6-22 - PM from fuel production, distribution, and conditioning processes.

Out of the 3 distribution scenarios for SMR and SMR with CCS hydrogen, the highest emissions come from distribution using liquid tankers, primarily due to the greater energy requirements associated with liquefaction. Here, an additional 82 gCO_2e/kWh (equivalent to ~25% and 44% of the total GWP for SMR and SMR & CCS) is generated from liquefaction giving overall figures of 329 and 187 gCO_2e/kWh in Figure 6-21. This is a very significant portion of the total emissions coming solely from the liquefaction process. If this process was made more efficient in the future, these emissions have the potential to fall dramatically. As mentioned previously, several studies suggest the energy for the liquefaction process could fall from 10 to ~6 kWh/kg H_2. For PM, the emissions from hydrogen production using SMR are negative due to the steam credits incurred, mentioned previously in Chapter 5.

The compression of hydrogen also accounts for a sizeable portion of total emissions in some hydrogen scenarios. For hydrogen from SMR distributed via pipeline and tube trailer, this compression from 20 bar to 440 bar prior to dispensing in a HDV accounts for 9% of the total GWP, and 21% when using hydrogen from SMR with CCS (Figure 6-24). Similarly, when looking at PM under these conditions, since the production of hydrogen from SMR results in emission savings, the majority of the emissions incurred come from this compression process. Since hydrogen fuel incurs more processing stages than electricity, it is harder to reduce its total fuel emissions. Since emissions from electricity for BEVs includes only production, shown in Figure 6-24, reducing the total emissions can be achieved just by targeting the production process respectively. Hydrogen precooling and diesel consumption from trailers and tankers accounts for a minor portion of the emissions across all hydrogen fuel scenarios and impact categories respectively.

For diesel fuel, only ~50 gCO_2e are emitted from its supply chain and similar to electricity, the majority of these emissions arise from its production since this does not require any conditioning processes prior to delivery. As a result, only a small portion (4%) is associated with its transport to the point of use.

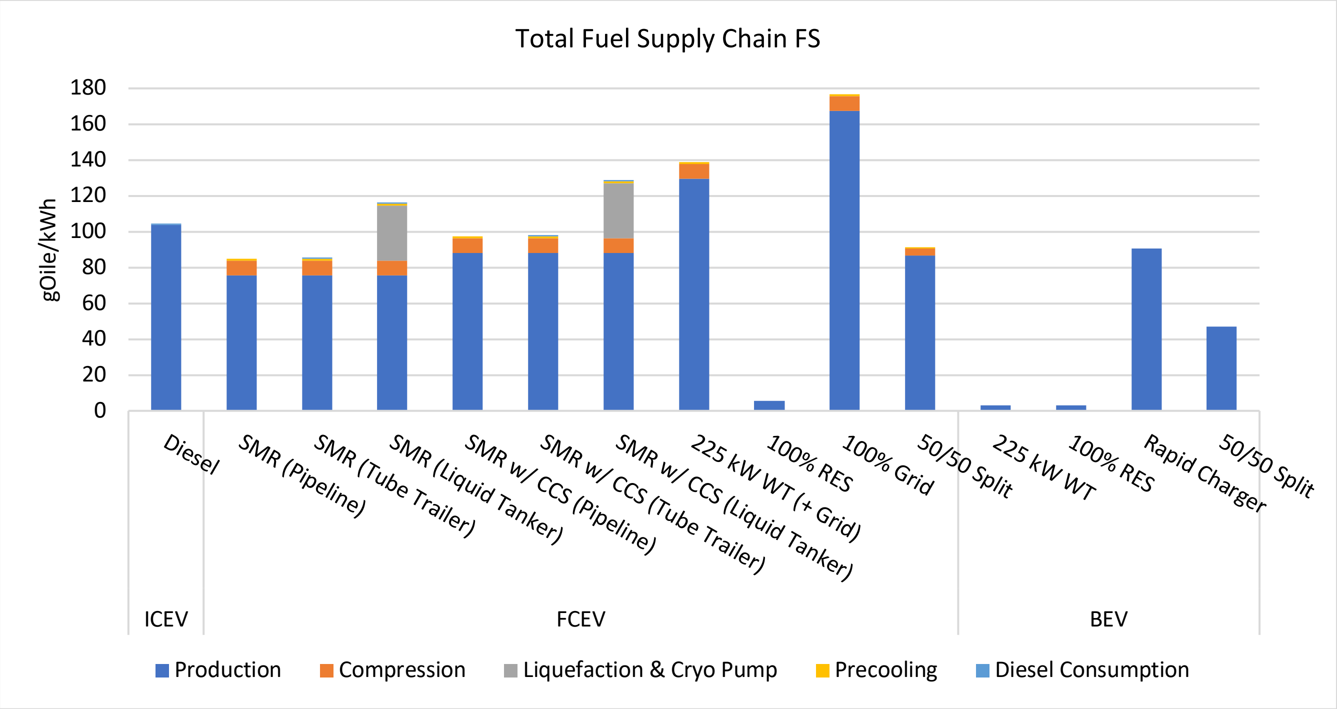


Figure 6-23 - FS from fuel production, distribution, and conditioning processes.

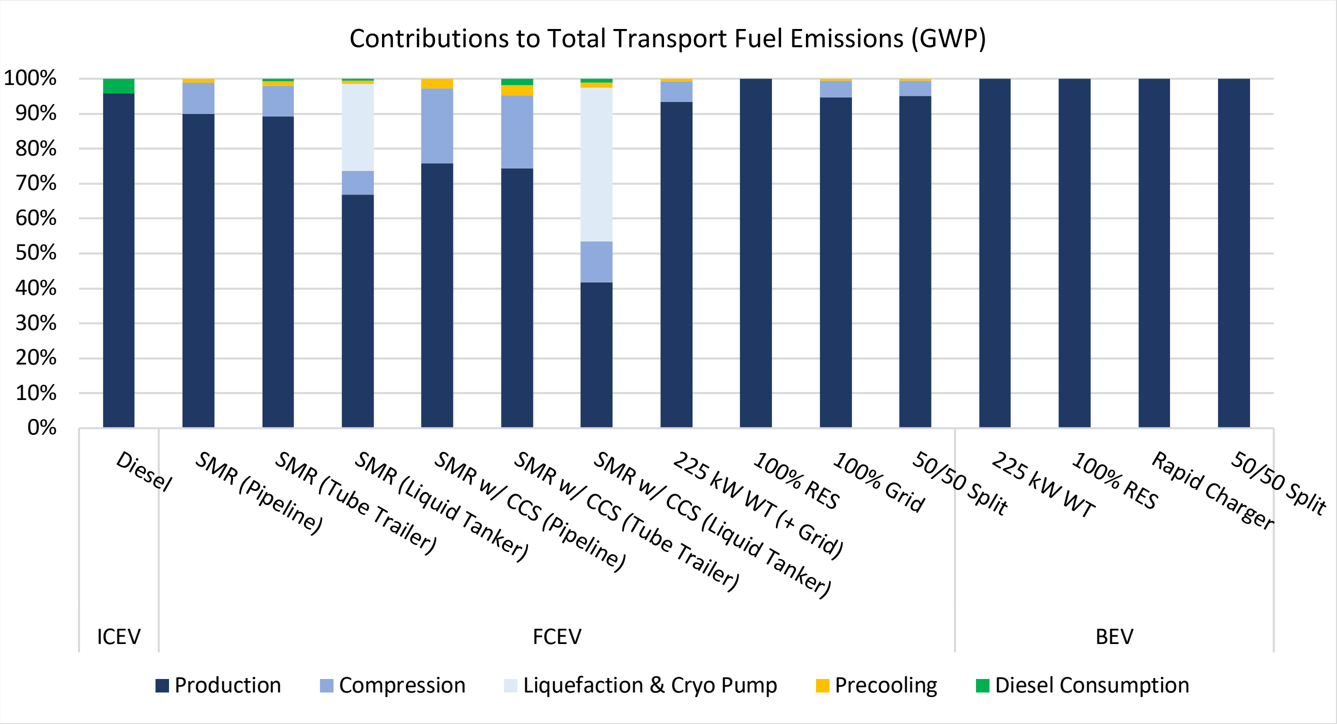


Figure 6-24 – Breakdown of total fuel emissions.

6.5. Emissions from Fuel and Vehicle Use:

This section covers both the exhaust and non-exhaust emissions from all vehicles and powertrains respectively. As a reminder to the reader, the term ‘unit-km’ refers to all per km, passenger-km, and tonne-kilometre units respectively, depending on the vehicle being discussed.

6.5.1. Tailpipe Emissions:

6.5.1.1. Diesel Vehicles:

Although the production emissions of diesel fuel per kWh are low in comparison to some of the ZEV fuels considered in this study, the emissions from its combustion in the use phase are expected to offset this. This section reports the tailpipe emissions from each of the vehicles in the study per unit-km, generated using COPERT software. As mentioned in Chapter 5, this software was used instead of Ecoinvent as it is designed specifically for transport emissions modelling and provides a more comprehensive overview of the emissions from vehicle use. All emissions presented correspond to the input conditions used in COPERT respectively.

Calibration Test:

Prior to the analysis of the use phase emissions, it should be made clear that exhaust emissions generated using COPERT do not refer to a specific driving cycle. Instead, it simply offers an insight into the emissions associated with the operating conditions for this fleet study, which were given in Table 5-19. Although there are official driving cycles such as the worldwide harmonised light vehicle test procedure (WLTP) which are used to compare and certify emissions from different vehicles fairly under like for like conditions, these are for LDVs only. COPERT was chosen as it can also support the modelling of emissions from HDVs.

In order to test COPERT as a suitable emissions modelling tool, results should first be compared to an official legislated procedure for driving emissions like WLTP. In this test, if the emissions from COPERT are in alignment with those from the WLTP cycle, it will suggest the software is suitable for accurate modelling and supports the justification for the selection of COPERT as the emissions tool of choice. Since the WLTP cycle is comprised of four sub-parts (urban, suburban, rural, and highway driving) which are aimed to test the vehicle under different speeds, the input conditions used in COPERT must also take this into account. Table 6-3 outlines all of the operating parameters used in the WLTP cycle which were also used in COPERT for this initial reliability test. These conditions have been replicated in COPERT to generate emissions on a comparable level.

Table 6-3 – Operating parameters of the WLTP cycle (for vehicles with a max speed > 120 km/h).

Parameter:	**Urban:**	**Suburban:**	**Rural:**	**Highway:**	**Total:**
Duration (s):	589	433	455	323	1800
Distance (m):	3095	4756	7162	8254	23267
Average Speed without Stops (km/h):	25.7	44.5	60.8	94	-
Average Speed with Stops (km/h):	18.9	39.5	56.7	92	-
Max Vehicle Speed (km/h):	56.5	76.6	97.4	131.3	-
Stopping Percentage (%)	26.5	11.1	6.8	2.2	-

Table 6-4 shows the emissions generated from COPERT under these WLTP cycle input conditions. Alongside these, the total GHG emissions are reported in terms of their 100-year GWP in CO_2e respectively, with CH_4 and N_2O having values of 25 and 298 respectively. Air pollutant emissions are also given, including PM, NOx and CO which originate from incomplete combustion and the oxidation of nitrogen present in the combustion chamber. Across all emissions, PM refers to $PM_{2.5}$ since coarse PM greater than 2.5µm in diameter is assumed to be negligible by COPERT [178].

Table 6-4 – COPERT emissions results under the WLTP cycle conditions.

	Greenhouse Gas Emissions:				
g/km:	Urban	Suburban	Rural	Highway	Combined
CH_4	2.3E-05	1.5E-05	0.0E+00	0.0E+00	3.74E-05
CO_2	43.9	35.5	53.6	50.9	183.8
N_2O	2.7E-03	1.8E-03	6.3E-04	1.4E-03	6.6E-03
CO_2e	44.7	36.0	53.8	51.3	185.8
	Air Pollutant Emissions:				
g/km:	Urban	Suburban	Rural	Highway	Combined
CO	6.55E-03	4.87E-03	6.96E-03	4.69E-03	2.31E-02
NOx	1.23E-02	1.03E-02	1.49E-02	1.47E-02	5.21E-02
NO_2	2.47E-03	2.06E-03	2.97E-03	2.93E-03	1.04E-02
VOC	6.34E-04	4.89E-04	6.29E-04	2.60E-03	4.35E-03
NMVOC	6.11E-04	4.74E-04	6.29E-04	2.60E-03	4.32E-03
PM	3.23E-03	2.10E-03	4.19E-03	3.32E-03	1.28E-02

The modelled emissions from COPERT can be compared to the published emissions under the WLTP cycle for the reference passenger car used in this work; the Mercedes E400d. For the combined CO_2 emissions across the entire WLTP cycle, taking into account all road types, data was taken from the latest vehicle certification agency (VCA) emissions database for comparison (September 2021 at the time of this work). This database consists of emissions data relating to the WLTP (2017+) and New European Driving Cycle (NEDC, Pre-2017) [179]. For CO_2, this figure was 175 gCO_2/km. From Table 6-4, the emissions generated from COPERT are 184 gCO_2/km, which is only a 5% deviation, meaning the prediction of fuel consumption made by COPERT is closely matched to the WLTP cycle. For emissions of NOx, these were published at 60 mg/km, with COPERT generating figures of 52 mg/km, which is also close to WLTP, highlighting its suitability as an accurate emissions tool. Unfortunately, only limited emissions data was given in the VCA database with emissions of CH_4, N_2O and VOC absent. However, based on the CO_2 and NOx results generated by COPERT, it was assumed for the sake of this work that it can also accurately estimate the remaining emissions respectively.

Since the exhaust emissions from the operation of the Mercedes E400d reference car generated from COPERT are in good alignment with those published by Mercedes under the WLTP driving cycle, the software is considered accurate enough to model the emissions for the other vehicles in this study. Although the other vehicles are HDVs and do not perform under the WLTP cycle, this trial was simply an effort made aimed to validate COPERT as a reliable emissions tool.

Exhaust Emissions from ICEVs:

Now, similar to Table 6-4, Table 6-5 summarises the tailpipe emissions generated from COPERT for the majority of the HDVs, this time whilst operating under the input conditions of this study, given earlier in Table 5-19.

Table 6-5 – Exhaust emissions from ICEVs.

Vehicle:	**Greenhouse Gases:**				**Air Pollutant Emissions:**					
	CH_4	CO_2	N_2O	CO_2e	CO	NOx	NO_2	VOC	NMVOC	PM
Car (g/km)	7.5E-05	170.3	1.04E-02	1.7E+02	2.1E-02	5.1E-02	1.0E-02	1.5E-03	1.4E-03	5.10E-04
Bus (g/pkm)	8.7E-05	10.6	6.92E-04	1.1E+01	2.1E-03	3.7E-03	3.7E-04	4.0E-04	3.1E-04	9.42E-05
Truck (g/tkm)	1.1E-04	25.2	1.26E-03	2.6E+01	2.9E-03	4.5E-03	4.5E-04	7.5E-04	6.4E-04	1.23E-04
Tipper (g/tkm)	1.9E-04	35.8	1.36E-03	3.6E+01	6.7E-03	1.1E-02	1.1E-03	1.4E-03	1.2E-03	2.09E-04
Refuse (g/tkm)	2.0E-04	37.8	1.42E-03	3.8E+01	7.4E-03	1.3E-02	1.3E-03	1.5E-03	1.3E-03	2.35E-04

From

Table *6-5*, CO_2 emissions account for over 98% of the total GHG emissions for each vehicle in the study. For the passenger car, GHG emissions from the use phase equate to 173 gCO_2e/km, with 170 gCO_2/km; higher than the emissions from the average diesel car in 2019 (pre-Covid-19) at only 127 gCO_2e/km respectively [177]. The reason for this is due to the driving conditions set out in COPERT as it is assumed LDVs travel a daily mileage of 64 km with all journeys taking place around urban roads which are typically more congested and characterised by a higher frequency of vehicle starts, contributing towards a lower engine temperature and a less efficient journey with higher average emissions, reflected by the results. NOx emissions from cars are only 51 mg/km which is ~36% lower than the 80 mg/km limit mandated by Euro 6 emissions standard, partly due to the inclusion of SCR systems targeting NOx reduction after fuel combustion, but also due to the low vehicle speeds in urban road shares which lead to lower combustion temperatures and a reduced NOx formation [223]. Similarly, CO emissions from cars are only 0.02 g/km which is well below the Euro 6 standard of 0.5 g/km. This is because CO is formed primarily from incomplete combustion under fuel rich conditions. However, since diesels are lean combustion engines there is often excess air available, so they do not generate high quantities of CO. For PM in the exhaust gas, this is also largely generated during incomplete combustion and is formed from the agglomeration of fine particles resulting from partly burned fuel, ash content, and cylinder oil [229]. From Table *6-5*, PM emissions are also significantly lower than the 5 mg/km Euro 6 limits and show emissions of 0.51 mg $PM_{2.5}$/km, partly due to the use of particulate filters in COPERT modelling [223]. As a result, the majority of the PM generated during the use phase originates from non-exhaust emissions, covered later in the next section. No specific CH_4 emissions standard is set for LDVs, so it is instead controlled indirectly through HC limits. However, since diesel fuel typically generates low HC emissions, CH_4 from partial or incomplete combustion is negligible, though can be increased by cold starts [184] [229]. The generation of hydrocarbons like CH_4 can be influenced by several factors including the fuel composition, the combustion conditions, and the control technologies, for example.

GHG emissions from the diesel bus are 10.9 gCO_2e/pkm, whilst for the other HDVs emissions are 25.7 gCO_2e/tkm for long haul trucks, 36.3 gCO_2e/tkm for tippers, and 38.3 gCO_2e/tkm for refuse collection vehicles, all shown in Table *6-5*. Refuse vehicles generate greater GHG emissions per tkm because they are used exclusively in urban environments, similarly to passenger cars with a 50/50 split of their operation carried out in urban peak and urban off-peak conditions, leading to a lower engine temperature which increases the likelihood of incomplete combustion of the diesel fuel, also contributing to higher air pollutant emissions, such as PM and CO at 0.235 mg/tkm and 7.4 mg/tkm. The opposite is true for NOx emissions though, where there is a trade-off between combustion temperature and the efficiency of exhaust aftertreatment technology. The slower speeds of refuse vehicles minimise NOx formation as N2 oxidation is promoted by high engine temperatures. However, under the low exhaust temperatures achieved by driving at low speed, low load, and high frequency cold start driving, the efficiency of NOx reduction technologies is reduced because the urea used in the SCR systems will not work below 200°C (it cannot be vaporised into NH_3). As a result, in addition to the catalyst activity falling sharply, the NH3 is unable to react with NOx to form N2. This leads to NOx emissions being the highest for refuse vehicles. The efficiency can be seen by a vehicle's SCR temperature profile, highlighting the portion of the vehicles operation that has an exhaust temperature <200°C (and where SCR is not effective for NOx control). Temperature profiles for the vehicles in this study are not available but the study by Su *et al.* [235] shows that exhaust temperatures for HDVs fall below the optimum for SCR efficiency (200°C) most frequently under urban conditions leading to significantly higher NOx emissions, which supports the findings of this work.

In contrast to refuse vehicles, trucks operate the largest portion of their journeys (50%) on motorways, which are typically characterised by less frequent braking and accelerating which allows the engine (and exhaust) to reach higher temperatures, increasing the efficiency of combustion. In addition, the fact that trucks have a much greater load than refuse vehicles (with a 44t GVW) also promotes NOx formation further through increased combustion duration and temperatures. As a result, it would be reasonable to expect NOx emissions of trucks to exceed refuse vehicles. However, this high-speed operation helps to achieve the minimum urea decomposition exhaust temperature of ~200°C for the SCR aftertreatment system, which leads to fewer air pollutant emissions in comparison [234]. Although it can influence emissions, all vehicles in the study are assumed to operate at zero gradient (i.e. flat road surfaces). Also, it should be made clear that only DPF and SCR aftertreatment systems are included by COPERT in the emission estimates of these vehicles. Other technologies such as lean NOx traps (LNTs) are not practical for HDVs from an economical perspective due to the expensive catalyst materials required [227]. LNTs are also less mature and limited by the narrower temperature range under which they can operate, and are unable to solely provide the desired NOx reduction required to achieve levels of NOx within emission standards, unlike SCR.

Not only are NOx emissions a precursor to acid rain and a contributor of human lung disease, but they are also an important source of oxidant which facilitates tropospheric ozone formation. As briefly mentioned, the vast majority of the NOx emissions arise in the combustion chamber in the form of NO, where N2 is oxidised to NO under high temperatures and high oxygen concentrations. In addition to NO, significant emissions of NO_2 are also released which are influenced by the exhaust aftertreatment technology used. N_2O emissions can also be formed during fuel combustion in a reaction between NO and intermediates, and also as a by-product of catalyst operation. If this temperature is too high its formation will be reduced. Research has shown N_2O emissions are highest when the catalyst warms up after cold starts to ~360°C. As a result of slower speeds in urban conditions, refuse vehicles show higher N_2O emissions compared to trucks and tippers which have greater catalyst temperatures that may exceed this optimal range [185] [180].

Air pollutant emissions in Table 6-5 are dominated by CO and NOx, accounting for 25-31% and 48-60% of the total across all vehicle types, whilst PM emissions account for a smaller share of only 0.6-1.3%. Emissions in COPERT were not generated in terms of oil equivalent therefore the impact category FS shows no results across the use phase.

Comparison of Exhaust Emissions to Euro 6 Limits:

For passenger cars, Euro 6 emission limits are reported under the WLTP driving cycle using vehicle/chassis dynamometer tests, with emissions reported per unit of distance (g/km); the same units as the exhaust emissions given in Table 6-5, allowing comparisons to be made easily. For HDVs, Euro VI emission standards are based on the worldwide harmonised stationary cycle (WHSC) and worldwide harmonised transient cycle (WHTC) which target the engines, not the vehicles, and reported using engine dynamometers. This is because the same engine could be configured to different vehicle chassis, changing emissions greatly as a result. HDV emissions are therefore reported per unit of energy delivered by the engine (g/kWh). As the units generated in COPERT differ, the emissions in Table 6-5 must be converted before comparisons are made. This conversion can be done using the vehicles fuel consumption under the driving conditions used in COPERT. First, the fuel consumption of each HDV was calculated using the energy consumption figures generated in COPERT for each vehicle under each mode share (i.e. urban, rural, high speed). COPERT reported via email that this energy consumption takes into account the engine efficiency and is based on both literature and measured fuel rate data, though the specific details of this are unknown. Using the energy content and density of diesel along with the mileage of each vehicle allowed the individual fuel consumption to be calculated in each mode share (L/100km) using Equation 41. Once these figures were known, the combined fuel consumption was estimated using Equation 42.

$$\text{Fuel Consumption}\left(\frac{\text{L}}{100\text{km}}\right) = \frac{\text{Energy Consumption (TJ)} \times 10^{11}}{\text{Total Mileage (km)} \times \text{ Diesel Energy Content}\left({}^{\text{MJ}}/_{\text{kg}}\right) \times \text{Diesel Density }\left({}^{\text{kg}}/_{\text{m}^3}\right)} \qquad \text{Equation 41}$$

Table 6-6 - Data used to calculate HDV fuel consumption.

Vehicle Type:	Energy Consumption [TJ/year]				Road Share (%)				Fuel Consumption (L/100km)			
	Urban Off-P	Urban Peak	Rural	High Speed Roads	Urban Off-P	Urban Peak	Rural	High Speed Roads	Urban Off-P	Urban Peak	Rural	High Speed Roads
Truck	0.294	0.364	0.772	1.171	10%	10%	30%	50%	47.2	58.3	41.2	37.5
Tipper	0.056	0.067	0	0	40%	40%	0%	20%	33.4	40.4	-	27.1
Refuse	0.115	0.139	0	0	50%	50%	0%	0%	33.4	40.4	-	-
Bus	0.137	0.162	0	0	50%	50%	0%	0%	22.0	26.0	-	-

$$\begin{aligned}&\text{Combined Fuel Consumption} =\\ &(\text{Urban Peak FC} \times \text{Urban Peak Share})\\ &+ (\text{Urban Off Peak FC} \times \text{Urban Off Peak Share})\\ &+ (\text{Rural FC} \times \text{Rural Share})\\ &+ (\text{Highway FC} \times \text{Highway Share})\end{aligned} \qquad \text{Equation 42}$$

Table 6-7 - Final fuel consumption figures, based on COPERT driving conditions and manufacturer estimates.

COPERT Combined Fuel Consumption				
Bus	Long Haul	Tipper	Refuse	
0.040	0.093	0.134	0.142	(kWh fuel/unit-km)
24.0	41.7	35.0	36.9	(L/100km)
Manufacturer Fuel Consumption (L/100km)				
Bus	**Long Haul**	**Tipper**	**Refuse**	
24.0	19.4	21.1	21.1	(L/100km)

Table 6-7 shows the fuel consumption for HDVs based on the driving conditions used in COPERT, as well as figures reported directly from manufacturers of the reference vehicles given previously in Chapter 3. As city buses have similar driving cycles, typically characterised by a majority share of urban driving at slower speeds with frequent stop/starts, they show the same fuel consumption of 24 L/100km. However, these figures are not expected to be the same for other HDVs since they differ largely in their duty cycles, since heavy duty vehicle do not have a specific driving cycle when recording fuel consumption figures, unlike passenger cars and the WLTP cycle, for example. For the HDVs, fuel consumption figures from the manufacturer estimates are all significantly lower than those calculated under conditions used in COPERT. This is because these vehicles can vary more widely in their driving conditions, and also because manufacturers often report the best-case fuel consumption figures for their vehicles, which are recorded under ideal driving conditions to increase the attractiveness of the vehicle performance, increasing sales. These are therefore not often accurate representations of typical fuel consumption figures. This is evidenced by refuse vehicles which have a much lower fuel consumption of 21.1 L/100km reported by manufacturers compared to the figure calculated from COPERT of 36.9 L/100km. In this case, manufacturers may not record data under 100% urban driving which were the conditions used in COPERT for this vehicle. It should be made clear that the driving conditions used to derive these figures are likely not to be the same. This comparison is simply aimed to highlight the variations in fuel consumption figures respectively.

After calculating fuel consumption (in kWh/unit-km, in Table 6-7), the emissions from COPERT (in g/unit-km), are then divided by this figure to give emissions in terms of g/kWh which can now be compared to Euro VI exhaust emission standards for HDVs. This is shown in Table 6-8. Since the driving conditions simulated in COPERT are simpler and less intense than the WHSC and WHTC HDV cycles, all exhaust emissions comfortably conform to the Euro VI standards (shown in green). Since trucks only have a 20% share of urban driving, they easily fall within these limits. For buses, tippers and refuse vehicles their NOx and PM emissions more closely approach the limits since a greater portion of their total operation takes place on urban roads (100%, 80%, and 100%). In all vehicle cases, total hydrocarbon (THC) and CO emissions remain well below these limits due to the advantages of lean combustion.

Table 6-8 – COPERT exhaust emissions and the Euro VI limits for diesel HDVs in g/kWh.

Euro VI Limits (g/kWh):				**COPERT Exhaust Emissions (g/kWh)**				
THC	CO	NOx	PM	Vehicle:	THC	CO	NOx	PM
0.16	4.0	0.46	0.01	Bus	0.010	0.053	0.093	0.002
				Truck	0.008	0.031	0.049	0.001
				Tipper	0.010	0.050	0.082	0.002
				Refuse	0.011	0.052	0.092	0.002

Forklift Vehicles:

As mentioned in Chapter 5, COPERT does not include forklift vehicles in its stock list so the exhaust emissions from ICEV forklifts in this work are based on literature using forklifts with similar performance characteristics and scaled based on engine power. Table 6-9 highlights the air pollutant and GHG emissions from the reference diesel forklift respectively.

Table 6-9 – Exhaust emissions from ICEV reference forklift.

Tech Specs:	**Reference Forklift:**
Model	Kalmar FLT12
Fuel Consumption (kWh fuel/100km)	694.6 (69.6L)
Engine Power (kW)	99
Exhaust Emissions (g/tkm):	
CO	0.83
VOC	0.26
NOx	2.52
$PM_{2.5}$	0.16
$*CO_2$	205.22
$*CH_4$	0.023
$*N_2O$	2.86
$*CO_2e$	208.1

**These emissions were not based on the literature study as they were omitted. Instead, they were estimated using the fuel consumption and 2021 GHG conversion factors, taken from BEIS [183] respectively.*

Similar to the other ICEVs in Table 6-5, CO_2 emissions dominate the ICEV forklift GHG emissions with 205.2 gCO_2/tkm. All GHG and air pollutant emissions from forklifts exceed those from any of the other ICEV HDVs in Table 6-5 per tkm, primarily because of its high energy consumption, consuming large quantities of fuel whilst operating either at low speeds or stationary (evidenced in the conditions of the VDI cycle, which is characterised by short distances and frequent lifting operations). These exhaust emissions were divided by fuel consumption similar to the other HDVs in Table 6-8 and converted to units of g/kWh, shown in Table 6-10. Here, forklifts are seen breaching some of the Stage 5 emission limits for diesel off-road vehicles. In this case, PM emissions from forklift exhausts are 0.7 g/kWh; significantly higher than the other HDVs reported and the 0.015 g/kWh limit. Quantities of NOx and THC are also higher than the other HDVs and the Stage 5 limits at 10.96 g/kWh and 1.13 g/kWh respectively, which could be a result of the low speeds experienced by forklifts which lead to lower engine temperatures and incomplete combustion, similar to refuse vehicles discussed previously. All of these pollutant emissions could be avoided with the transition to ZEV fuels.

Table 6-10 - ICEV forklift exhaust emissions and Stage 5 off-road emission limits.

Stage 5 Limits (g/kWh):				**Exhaust Emissions (g/kWh)**			
THC	CO	NOx	PM	THC	CO	NOx	PM
0.19	5.0	0.40	0.015	1.13	3.61	10.96	0.70

Impacts of ICEVs on Ozone Formation:

Tropospheric ozone formation potential (OFP) is another environmental impact category included in SimaPro software which estimates the contribution of specific processes to ozone formation. Tropospheric ozone formation is caused by the influence of sunlight in the presence of NOx under Equation 43 and Equation 44. After ozone is formed, it then reacts with NO to form NO_2 and oxygen under Equation 45. However, if volatile organic compounds (VOCs) are present, highly reactive and toxic peroxy radicals are formed from their oxidation which can increase the concentration of ozone further. In this case, these radicals can either consume NO or convert it to NO_2, thus competing with ozone in Equation 45. As a result, less ozone is consumed which causes its concentration to increase as a direct impact. The OFP from the use phase of vehicles is estimated by calculating the individual OFP from all ozone precursors respectively.

$$\mathrm{NO_2 + hv\ (sunlight) \rightarrow NO + O} \qquad \text{Equation 43}$$

$$\mathrm{O + O_2 \rightarrow O_3} \qquad \text{Equation 44}$$

$$\mathrm{NO + O_3 \rightarrow NO_2 + O_2} \qquad \text{Equation 45}$$

Since CH_4 is non-toxic in air quality contexts it is excluded from VOCs so non-methane VOCs (NMVOCs) are considered instead. To understand fully the impact of these precursors on ozone formation, it is also necessary to consider the speciation of the NMVOC emissions. Typically, emission inventories report only the total emissions of all these NMVOCs which is required by reporting guidelines. However, each of the NMVOC compounds has a different rate of reaction with NOx when forming ozone. As a result, these individual NMVOCs differ in their contribution to total ozone formation. In order to calculate the OFP of each NMVOC compound, the maximum incremental reactivity (MIR) of each species was taken from Li *et al.* [222] and multiplied by the mass of each NMVOC emitted during vehicle operation, generated from COPERT, using Equation 46 to give ozone formation in terms of grams of ozone. The Air Quality Directive 2008/50/EC recommends 31 NMVOC ozone precursors to be measured to support the understanding and estimation of OFP [221]. However, some of these precursors are not listed in COPERT software, highlighting a limitation. As a result, only 25 out of 31 NMVOCs were considered. The results of these calculations are given in Table 6-11 respectively.

$$\mathrm{OFP_i\ (g\ O_3) = MIR_i\ (\frac{g\ O_3}{g\ NMVOC_i}) \times NMVOC_i\ (g)} \qquad \text{Equation 46}$$

The OFP from the use of each vehicle is shown in Table 6-11. Unfortunately however, this impact category has not been included in this work due to complications regarding the units the figures are reported in. There are a wide variety of research papers available which use the MIR method, highlighting it as a reliable and accurate method to estimate OFP from vehicle operation, reporting results in of grams of ozone. However, none of these studies report OFP in terms of NOxe, which is the default unit used in SimaPro LCA software. As a result, there is no way to convert between these units to generate one single figure for the OFP over the entire vehicle life cycle. Contact was made with model developers from SimaPro, Ecoinvent, and COPERT to remedy this, along with several authors publishing studies around the topic of OFP, however a conversion between these units is not possible. For this reason, the OFP impact category is not considered a focus of the study and will not be explored further. Despite this limitation, these results are still presented and are aimed to highlight the avoided emissions upon switching from diesel to renewable or low carbon transport fuels, such as hydrogen and electricity.

The table shows the total ozone formation potential across all individual NMVOCs totals 0.7 mgO_3/pkm for ICEV buses and reaches a maximum of 2.95 mgO_3/tkm in the case of refuse vehicles. For all vehicle types, ethylene has the highest contribution towards the total OFP, largely due to its high MIR of 9.07 which gives it a contribution of 19.5% to the total OFP for cars, and 28% for trucks, for example. Although other compounds such as 1,2,3-trimethylbenzene and 2-Pentene have higher MIRs, these are emitted in much smaller quantities, so their overall contributions remain lower. For cars, alkanes contribute only a small percentage of the total OFP from NMVOCs whilst alkenes and aromatics account for the vast majority with roughly 42% and 47% respectively. For all HDVs, contributions from alkanes and alkenes are fairly even with ~33% and 36%, whilst aromatics have only an ~11% share.

Table 6-11 – Contribution of each individual NMVOC ozone precursor to total OFP.

		OFP				
	MIR ($gO_3/gNMVOC$):	gO_3/km	gO_3/pkm	gO_3/tkm		
NMVOC:		**Car**	**Bus**	**Truck**	**Tipper**	**Refuse**
Ethane	0.31	7.13E-06	2.88E-08	5.91E-08	1.10E-07	1.20E-07
Ethylene	9.07	1.10E-03	1.97E-04	4.04E-04	7.49E-04	8.23E-04
Acetylene	1.24	9.51E-05	4.03E-06	8.28E-06	1.53E-05	1.68E-05
Propane	0.56	3.67E-06	1.73E-07	3.56E-07	6.60E-07	7.25E-07
Propene	11.57	7.86E-04	4.73E-05	9.71E-05	1.80E-04	1.98E-04
n-Butane	1.32	5.34E-05	6.13E-07	1.26E-06	2.33E-06	2.56E-06
i-Butane	1.34	2.41E-05	5.81E-07	1.19E-06	2.21E-06	2.43E-06
1-Butene	10.22	7.13E-05	-	-	-	-
trans-2-butene	13.9	2.46E-04	-	-	-	-
1,3-butadiene	13.47	2.67E-04	1.38E-04	2.83E-04	5.24E-04	5.75E-04
n-Pentane	1.53	3.80E-05	2.84E-07	5.84E-07	1.08E-06	1.19E-06
1-Pentene	7.73	9.70E-06	-	-	-	-
2-Pentene	10.23	3.28E-05	-	-	-	-
n-Hexane	1.43	2.57E-05	-	-	-	-
n-Heptane	1.26	6.33E-06	1.17E-06	2.40E-06	4.45E-06	4.89E-06
n-Octane	1.09	8.51E-06	-	-	-	-
Benzene	0.81	2.24E-05	1.76E-07	3.60E-07	6.68E-07	7.34E-07
Toluene	3.97	7.11E-04	1.23E-07	2.52E-07	4.68E-07	5.14E-07
Ethyl Benzene	2.79	1.86E-04	-	-	-	-
m+p-Xylene	7.43	6.90E-04	2.25E-05	4.63E-05	8.58E-05	9.42E-05
o-Xylene	7.48	4.71E-04	9.26E-06	1.90E-05	3.52E-05	3.87E-05
1,2,4-trimethylbenzene	7.18	2.53E-04	1.91E-05	3.93E-05	7.27E-05	2.79E-05
1,2,3-trimethylbenzene	11.25	9.26E-05	1.04E-05	2.15E-05	3.98E-05	1.25E-04
1,2,5-trimethylbenzene	11.22	1.74E-04	1.56E-05	3.21E-05	5.95E-05	6.53E-05
Formaldehyde	8.96	2.60E-04	2.33E-04	4.78E-04	8.86E-04	9.74E-04
Total:	-	**5.64E-03**	**6.99E-04**	**1.44E-03**	**2.66E-03**	**2.95E-03**

The OFP from forklifts has not been estimated here because COPERT software does not include forklifts. As a result, a breakdown of individual NMVOC compounds and their contributions to total OFP could not be generated in the same way using the MIR method. However this is not considered to be a limitation since, as stated earlier, this calculation was simply aimed to bring attention to the additional emission savings that can be seen when switching to low carbon fuels.

The emissions from the Mercedes E400d when operating under just the urban portion of the WLTP cycle (Table 6-3) are compared to the simulated results from this study (Table 6-5) and highlighted below. This test shows the similarities between the emissions from both driving cycles, both sharing the same order of magnitude due to the similar driving cycle input conditions. This again highlights COPERT as a reliable emissions tool.

Table 6-12 – Emissions from the urban portion of the WLTP cycle and study conditions for a passenger car.

	GHG Emissions:				**Air Pollutant Emissions:**					
	g/km			gCO_2e/km	g/km					
	CH_4	CO_2	N_2O	CO_2e	CO	NOx	NO_2	VOC	NMVOC	PM
WLTP (Urban)	7.27E-05	2.36E+02	1.00E-02	2.39E+02	2.95E-02	7.09E-02	1.42E-02	2.71E-03	2.63E-03	0.0157
Study Conditions	7.50E-05	170.37	1.04E-02	1.73E+02	2.11E-02	5.08E-02	1.02E-02	1.47E-03	1.39E-03	0.0157

6.5.1.2. Zero Emission Vehicles:

ZEVs do not emit any greenhouse gases from their tailpipe and as a result their exhaust emissions are zero, contributing nothing to global warming over their use phase. This highlights a huge advantage of these vehicles in the transport sector. In addition to global warming emission savings, the use phase of these vehicles also benefits air quality massively since no PM, NOx, HC, or CO emissions are released from their exhaust. As mentioned previously, the SCR exhaust aftertreatment technologies of ICEVs only reduces NOx emissions effectively at high temperatures, and in urban environments where these conditions are not met, high emissions are seen as a result. Even for alternative fuels like biodiesel, NOx emissions from their operation have been reported to increase and still contribute towards poor air quality. However, all of these issues are completely eliminated with the use of ZEVs. Here, the only emissions generated from ZEVs are non-exhaust emissions, covered in the next section respectively.

6.5.2. Non-Exhaust Emissions:

As emissions regulations become stricter and exhaust emissions continue to fall thanks to improved emission control technologies, non-exhaust emissions contribute a larger portion of the total usage emissions and are becoming more significant. The inputs used in Ecoinvent to generate non-exhaust emissions were outlined in Chapter 5 respectively and all brake, road, and tyre wear emissions are reported in terms of the PM impact category respectively. Non-exhaust emissions are not given in terms of GWP or FS because emissions of CO_2 and oil eq are either negligible or zero.

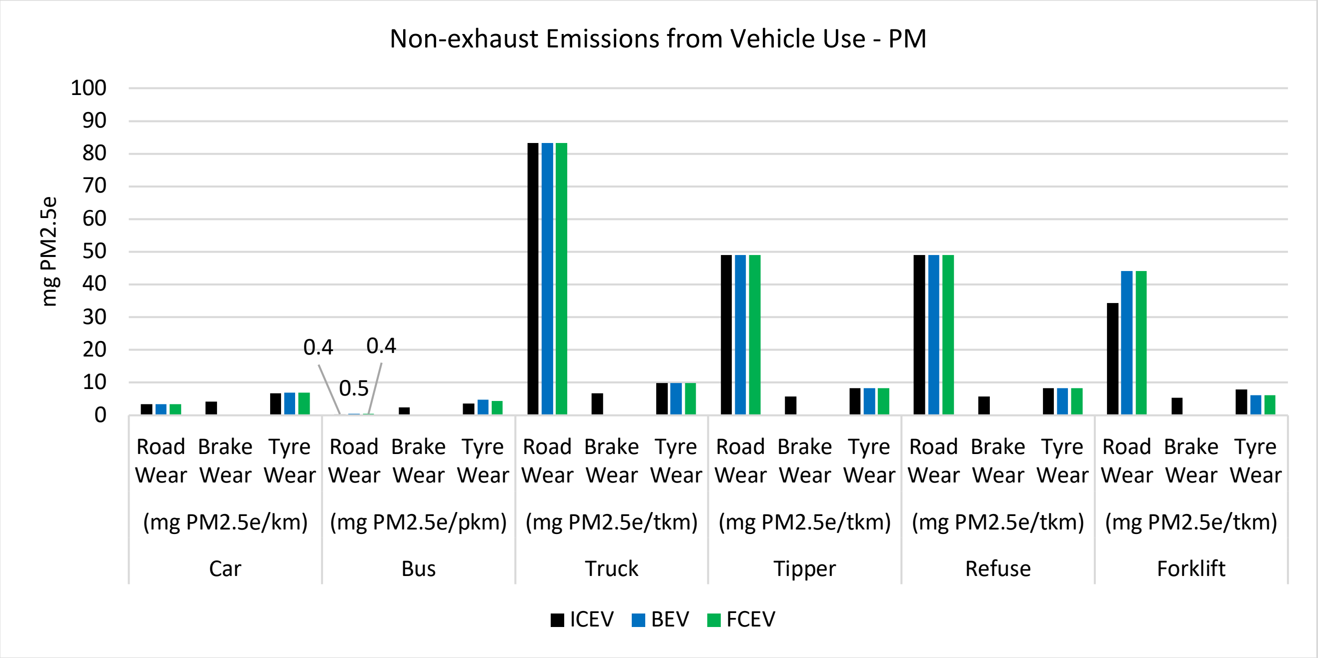


Figure 6-25 – Non-exhaust emissions from the operation of the fleet vehicles (in terms of PM).

Figure 6-25 gives the non-exhaust emissions for each of the vehicles in the study in terms of PM from one unit-km of vehicle operation. There are four major sources of non-exhaust emissions from transport. Three of these sources are abrasive processes and are brake, road, and tyre wear, whilst the fourth is particle resuspension which is associated with dust particles being lifted into the air as vehicles pass by. Ecoinvent does not estimate emissions from particle resuspension since the wear rate of asphalt is difficult to quantify, largely due to the varying compositions of bitumen. On top of this, the road particles combine with dust and other material which makes emission rates highly uncertain, as well as the fact that this is not considered a primary emission source. Therefore resuspension is not included in this analysis [196]. Emissions of VOC may also be released during vehicle operation from the use of screen wash and other liquids, however these are not considered in this analysis since their contribution is often considered negligible [219].

Brake wear emissions result from the frictional contact between the discs and pad and can potentially contribute up to 55% by mass to overall traffic-related non-exhaust emissions in high frequency braking scenarios [174]. Tyre wear emissions are generated from the constant interaction between the road and the tyres and have been shown to increase with vehicle weight and the number of tyres. Finally, road wear emissions originate from degradation of the road surface as the vehicle passes over it which can lead to particulate formation. From Figure 6-25, across powertrains there is no significant variation in the total non-exhaust PM emissions. Despite ZEVs incurring lower brake wear PM than ICEVs, because the vast majority of PM comes from road and tyre wear, their total PM is similar from this life cycle stage. This finding was also seen by Timmers *et al.* [176] who concluded that road and tyre wear made up ~80% of total PM emissions, and due to the greater weight of ZEVs, road wear increased. This can also be seen in Figure 6-25 for forklifts which vary in GVW unlike the other HDVs considered.

Since non-exhaust emissions from road wear are correlated to GVW, the highest emissions arise from those vehicles weighing the most. Here, road wear emissions are the highest of all the HDV non-exhaust PM emissions. For each truck, tipper, and RCV, the GVW remains the same regardless of which powertrain they use, so they each share the same road wear emissions as a result, with the highest at 83 mg $PM_{2.5}e$/tkm coming from long haul trucks which travel the furthest distance of all the vehicles in the fleet and having the highest GVW of 44t. For these long hauls, the road wear emissions account for the majority of the non-exhaust emissions at 83% for ICEVs and 90% for ZEVs respectively. For tippers and RCVs which weigh less at 26t, road wear emissions are lower at 49 mg $PM_{2.5}e$/tkm. Because bus emissions are reported in terms of pkm, their values are much smaller in comparison to the other HDVs. Since the capacity of the ICEV bus (60) is higher than FCEV (49) and BEV (45) buses, the total emissions are spread out across more passengers. In this case, road wear emissions are 0.4, 0.5, and 0.4 mg $PM_{2.5}e$/pkm for ICEV, BEV, and FCEV respectively, which accounts for only 6-10% of the total non-exhaust emissions.

Focusing on tyre wear, similarly to road wear, since each version of truck, tipper, and RCV has the same GVW and number of tyres, they each have the same emissions per tkm regardless of powertrain. Long hauls show the highest PM from tyre wear with 10 mg $PM_{2.5}e$/tkm primarily due to the fact these vehicles use 12 tyres, as opposed to only 8 for tippers and RCVs, giving them lower emissions of 8.4 mg $PM_{2.5}e$/tkm. The only major differences in tyre wear emissions can be seen from forklifts which vary more widely in their GVW and therefore have emissions ranging from 6-8 mg $PM_{2.5}e$/tkm.

ICEV long hauls emit approximately 7 mg $PM_{2.5}e$/tkm (PM) and have the highest emissions from brake wear across all vehicle types. This is because heavy duty trucks have 12 tyres each and are characterised by high mileage. For ZEVs however, all brake wear emissions were assumed to be zero since they utilise regenerative braking and the use demand for the brake discs is much lower, resulting in minimal brake pad wear compared to ICEVs over the course of the vehicles use. Although brake wear emissions for trucks are the highest on a per tkm basis compared to the other HDVs in the study, it only contributes 7% to their total non-exhaust PM emissions, compared to 39% for ICEV buses, for example. This is because trucks typically operate on motorway routes where braking frequency is low, unlike buses which operate in urban areas and are characterised by stop and start operating patterns.

When comparing non-exhaust PM emissions in Figure 6-25 to the PM emissions from vehicle exhausts in Table 6-5 it can be seen that non-exhaust emissions from all 3 categories of road, brake, and tyre wear show significantly higher PM emissions. Since diesel vehicles are a major source of PM emissions, new vehicles have now adopted technologies designed to control them, such as DPFs for example. As a result, their emissions have declined rapidly which has led to non-exhaust emissions now exceeding exhaust emissions [219]. For example, total PM emissions from ICEV passenger car exhausts are approximately 0.51 mg $PM_{2.5}$/km compared to 3.4, 4.2, and 6.8 mg $PM_{2.5}$e/km from all road, brake, and tyre wear respectively. The situation is worsened in the case of HDVs where the PM emissions of trucks from the exhaust are only 0.12 mg $PM_{2.5}$e/tkm, whilst total non-exhaust PM emissions reach 100 mg $PM_{2.5}$e/tkm; which is over 800 times greater. This finding has been highlighted extensively in literature with studies concluding that non-exhaust emissions can reach as much as 1000 times the level as exhaust emissions [228]. It has therefore led to increased attention being placed on non-exhaust emissions with regards to the transport sector.

6.6. Well-to-Wheel Emissions:

to Figure 6-28 show the total well to wheel (WTW) emissions from each fuel under the GWP, PM and FS impact categories. WTW emissions include all fuel production, conditioning, distribution stages, as well as vehicle use. Since the emissions from each of these stages have already been discussed individually in the previous sections, this section provides a brief summary of the combined emissions.

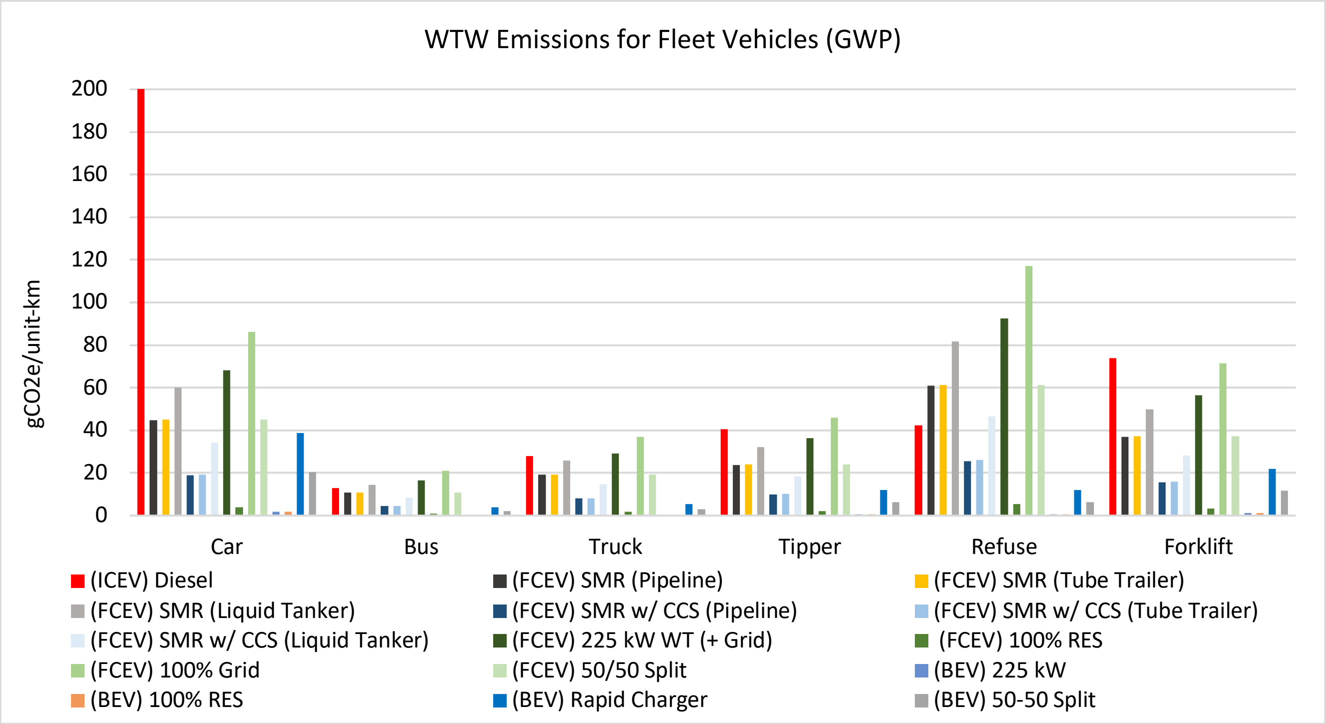


Figure 6-26 – WTW emissions in terms of GWP.

In all graphs shown, ICEVs are shown in red. In terms of GWP in , diesel is one of the most highly polluting fuels across all vehicle types. The high WTW GWP from ICEVs highlights the severity of its combustion in the use phase since its production, conditioning, and delivery emissions are lower than 11 of the 14 ZEV fuel scenarios per kWh, shown previously in *Figure 6-21*. For cars in , the WTW GWP from diesel is 204 gCO_2e/km which far exceeds any of the ZEV fuel scenarios. In this case, 84% of these WTW emissions are attributed to the fuel combustion in the use phase. These results are in agreement with work by Hung *et al.* [241] who report roughly 80% of total WTW emissions are from the use phase of petrol and diesel vehicles. It should be noted that efforts to compare both these WTW and cradle to grave estimates to others in literature is challenging since all studies vary in their modelling conditions and underlying assumptions. This point was also raised by EEA [155], highlighting both the methodological differences in LCA studies, as well as differences associated with the vehicles and systems being investigated. Examples of these differences include vehicle type, annual mileage, powertrain type/requirements, electricity mix, and energy efficiency, among others.

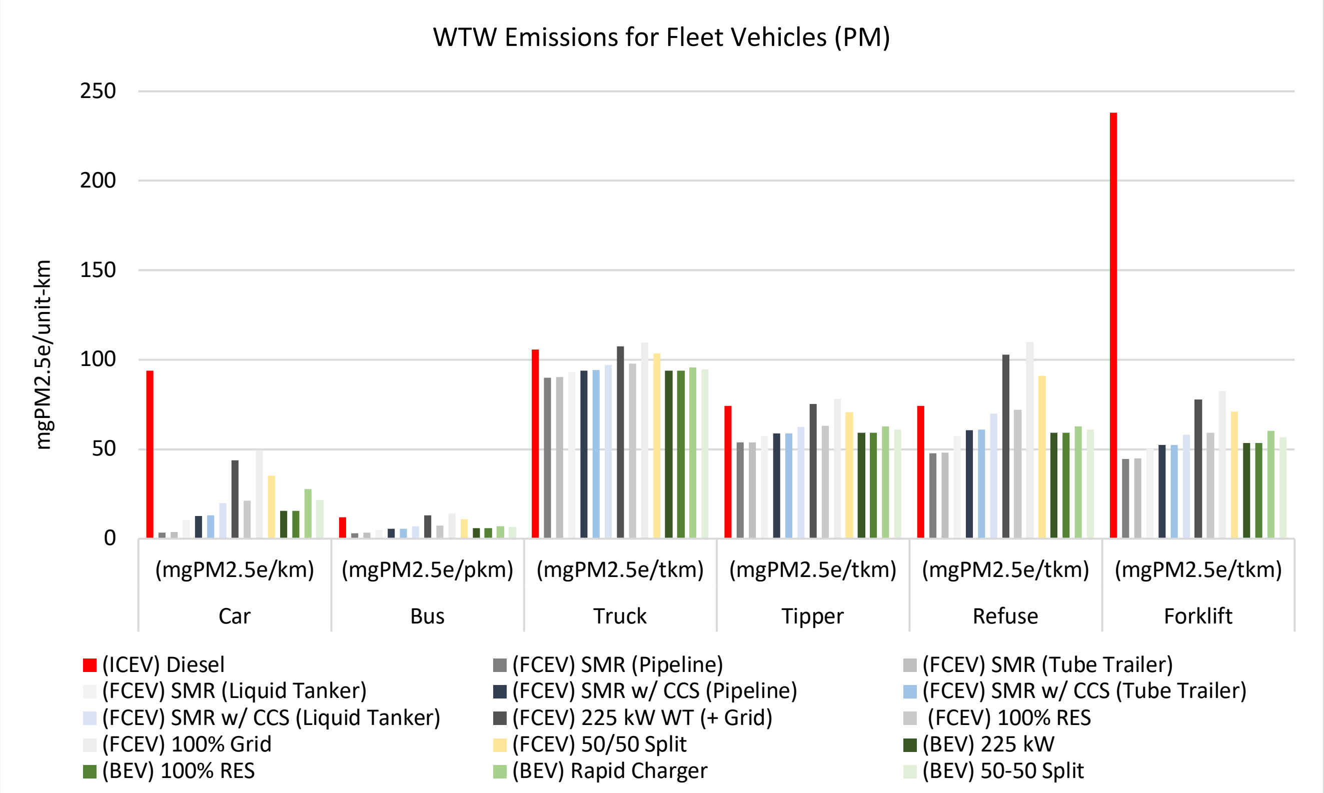


Figure 6-27 - WTW emissions in terms of PM.

After diesel, the next highest car WTW emission is 58% lower, from 100% grid hydrogen at 86.3 gCO_2e/km. This order is also the same for FS in Figure 6-28 where diesel cars approach 63 g oil eq/km, 49% higher than the next fuel scenario (also 100% grid hydrogen). The high FS from diesel is associated almost entirely (99%) from its production process which is dominated by the use of non-renewable resources, unlike many of the ZEV fuels which incur low FS due to their use of renewable energy. Diesel cars also have a higher energy consumption per km compared with ZEV cars so require more fuel to travel the same distance, furthering their environmental damage. For both GWP and FS, from a WTW perspective, using any other fuel would lead to significantly lower emissions per km than diesel. The diesel car WTW GWP estimated in this work aligns closely to other studies published in literature. Marmiroli *et al.* [80] estimates WTW emissions for a diesel car with an energy consumption of 55 kWh fuel/100 km at ~160 gCO_2e/km. When taking into account the increased energy consumption of the reference diesel car in this study (at 60 kWh fuel/100km) as well as study-specific assumptions, results are very similar.

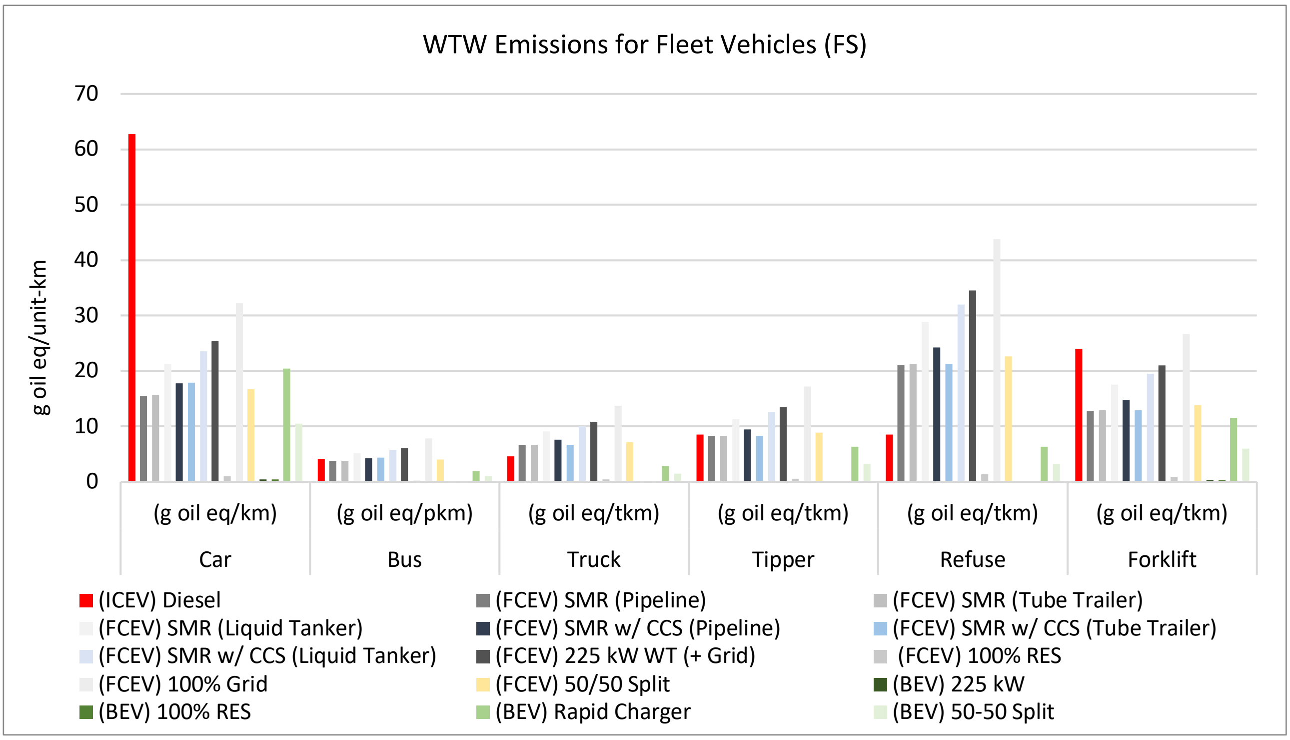


Figure 6-28 - WTW emissions in terms of FS.

For HDVs, the fuel that offered the highest WTW GWP and FS was electrolytic hydrogen powered using 100% grid electricity, except for diesel forklifts which had the highest GWP. Since the grid mix still relies on a significant share of non-renewable sources, it has a significant GWP and FS of 0.243 $kgCO_2e/kWh$ and 91g oil eq/kWh, which contributes greatly to the WTW emissions. Refuse vehicles have the highest emissions of all HDVs at 117 gCO_2e/tkm and 44 g oil eq/tkm when running on this 100% grid hydrogen respectively. This is partly because refuse vehicles have the highest energy consumption of all FCEV HDVs at 646 kWh/100km. In contrast, if hydrogen is produced using electrolysis powered by 100% renewable wind power, the WTW GWP and FS becomes the lowest of all hydrogen scenarios across all HDV types. In this case, the WTW GWP and FS emissions for a FCEV refuse vehicle fall 95% and 97%. Since no emissions are generated from the on-site fuel production, delivery, or use, and no fossil resources are consumed, 100% of the emissions are attributed to the electricity required for conditioning, prior to storage and dispensing at 350 bar. The next most sustainable hydrogen scenarios come from non-electrolytic hydrogen from SMR with CCS distributed in gaseous form using pipelines and tube trailers. A portion of the production emissions from SMR are recovered by CCS, whilst for its conditioning and distribution the electricity demand for compression is much lower compared to liquefaction required for liquid tanker transport. Despite diesel production incurring high FS, for many of the HDVs in Figure 6-28 the WTW FS of ICEVs is relatively low. This is because aside from the production process which relies on fossil fuels, there is little additional resource consumption since diesel does not require these intensive conditioning and delivery processes which hydrogen fuels do. As a result, from a purely FS standpoint, diesel offers a competitive option against many hydrogen scenarios across the WTW cycle for buses, trucks, and refuse vehicles respectively.

Despite low WTW GWP and FS from both 100% RES and SMR with CCS hydrogen, the lowest emissions recorded for each vehicle type come from electric fuel scenarios. This is in part due to the fact that electricity does not require any conditioning or distribution and many BEVs have a lower energy consumption than ICEVs or FCEVs. For 100% RES (and also 225 kW) electricity, the WTW GWP in ranges from only 0.19-1.92 gCO_2e/unit-km, making BEVs by far the best option for achieving low carbon sustainable transport, as long as the electricity is not sourced from rapid chargers powered by grid electricity. For cars using rapid chargers, WTW emissions are 39 gCO_2e/km in and close to estimates of 60-76 gCO_2e/km made by EEA [155] for mid-sized BEVs. These estimates are based on the 2015 EU grid mix though, so figures are expected to be much closer to this work when considering a cleaner grid mix, validating the estimates in this study somewhat. When rapid chargers are used, BEVs show higher WTW emissions ranging from 4-39 gCO_2e/unit-km and lose environmental competitiveness against several hydrogen scenarios. For example, under these conditions, a number of FCEVs (cars, tippers and forklifts) powered by SMR with CCS and 100% RES electrolytic hydrogen would now be a more sustainable option. In terms of WTW FS of BEVs, this follows a similar pattern to GWP since a lower reliance is placed on fossil fuel resources. Here, the majority of electric fuel scenarios have WTW FS below FCEVs, except for those FCEVs using 100% RES hydrogen.

Moving on to air quality indicators, WTW PM is shown in Figure 6-27. This shows many of the ZEV fuels have a similar WTW PM and are more closely competitive across all HDV types. In terms of diesel, PM emissions are generally quite high for all vehicle types, but especially for forklifts where it dominates and reaches a peak of 238 mg $PM_{2.5}e$/tkm. These emissions are dominated by the use phase where 77% is attributed to the exhaust from diesel combustion and 23% to the non-exhaust emissions. The reason for these high PM emissions is largely due to the high fuel consumption associated with forklifts, since a large portion of their operation takes place at low speeds or stationary during lifting. For other HDVs like trucks which have a lower fuel consumption and are characterised by more transient operation, PM is dominated by non-exhaust emissions largely from road wear, shown in the previous section. As a result, ICEV trucks are the third largest emitter of PM in Figure 6-27 and are less harmful than FCEV trucks using electrolytic 225 kW and 100% grid hydrogen respectively. 50-50 split hydrogen is also very similar to diesel in terms of WTW PM. In fact, these hydrogen fuels have the highest ZEV emissions for all of the HDVs in this study. The production of these 3 hydrogen routes (225 kW, 100% grid, 50-50 split) is particularly harmful in terms of PM per kWh, ranging from 130-200 mg $PM_{2.5}e$/kWh, despite being on-site and not requiring distribution. In contrast, for those hydrogen fuels which require intense conditioning and distribution like SMR hydrogen transported by liquid tanker, despite the high PM emissions from liquefaction of 37 mg $PM_{2.5}e$/kWh (due to high electricity consumption), the negative PM emissions associated with the production at -50 mg $PM_{2.5}e$/kWh reduces total PM and leads to emissions that are competitive with electric fuels. In terms of BEVs, WTW PM emissions are significant across all vehicle types and electric fuel scenarios. Here, despite renewable electricity (i.e. 100% RES and 225 kW scenarios) production generating minimal PM per kWh, the non-exhaust emissions still remain high and account for the vast majority of the total.

6.7. End of Life Emissions:

Figure 6-29 shows the EOL emissions for each vehicle and powertrain type in the study in terms of CO_2e under the GWP impact category. Results of PM and FS are provided in Section 11.6 in Appendix 2 and follow the same pattern as this figure respectively.

In general, all EOL emissions are small in comparison to vehicle production, component replacement, and WTW stages, regardless of powertrain type. These emissions are inclusive of diesel consumption, associated with the collection of the vehicles from their fleet base in Leeds and their delivery to the treatment facility in Bradford (approximately 32km away) using a 16-32t diesel truck. The emissions generated from this EOL stage (in red) are influenced by the vehicle weight (since this determines the payload of the collection vehicle) and range from 8 kgCO_2e for a FCEV car to 94 kgCO_2e for a long haul truck. Across all impact categories, the emissions associated with vehicle collection account for the smallest contribution to the total EOL emissions. Once delivered to the facility, vehicles are dismantled and shredded prior to material sorting. Emissions from these processes (in blue) are also impacted by vehicle weight as dismantling and shredding for HDVs requires approximately 139 kWh/tonne material, mentioned previously in Chapter 5. For cars, the shredding process is taken directly from the Ecoinvent database per kg of vehicle and scaled to the values required in this work. For ICEVs and BEVs, this stage accounts for the majority of their total EOL emissions across all impact categories.

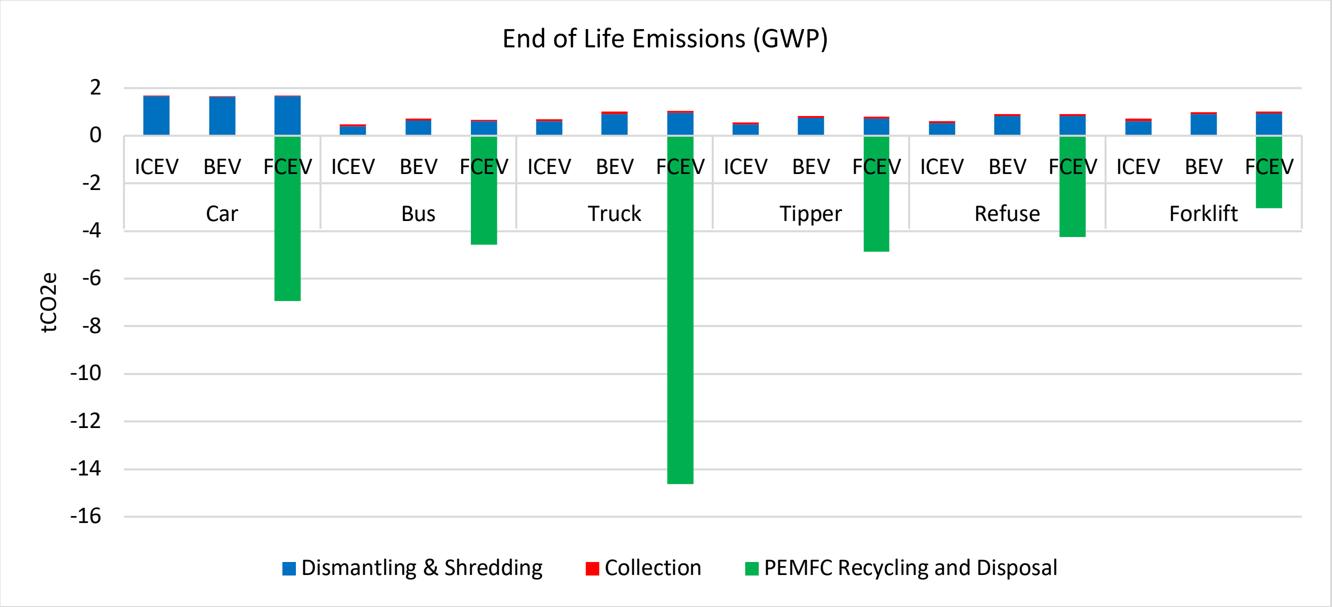


Figure 6-29 – Vehicle end of life emissions breakdown.

For FCEVs, since the boundaries of this work consider only the recycling of the fuel cells and not battery second use, the EOL of FCEVs incurs emissions savings, shown by the green bars. However, these do not represent the total EOL emissions from all fuel cells that are replaced during the vehicle lifetime. Since these are taken out and treated whilst the vehicle is still in operation they are not shown. However, the emissions recovered from the final fuel cell can be used to estimate the total across all used fuel cells by simply multiplying by the total number used, from Chapter 5. As a result of recycling, 73% of GWP, 77% of PM, and 73% of FS is recovered from the production emissions of each fuel cell by the emissions savings from avoided products (i.e. virgin material production). On a per kW basis, approximately 83.4 $kgCO_2e$ (GWP) is generated from PEM fuel cell production, whilst 60.9 $kgCO_2e$ is recovered from material recycling and the avoidance of virgin material production, giving net emissions for the PEM fuel cell of only 22.5 $kgCO_2e/kW$. As a result, FCEVs show the lowest EOL emissions of all the powertrains in the study, ranging from -2 tCO_2e for a FCEV forklift to -14 tCO_2e for a FCEV long haul truck. Since BEVs and their lithium-ion batteries in this work are not recycled, the EOL emissions are much higher and range from 710 $kgCO_2e$ for a bus to 1.6 tCO_2e for a car. If the recycling process was more mature and could be accurately modelled, these emissions would be lower and it would also help minimise the extent of material consumption, ensuring better availability in the future. As discussed in Section 5.3.4.4, the emission savings from the repurposing of these batteries are considered outside the scope of this work and are therefore excluded due to the unknowns associated with the second use cases.

6.8. Total Life Cycle Emissions:

Total life cycle emissions account for all individual life cycle stages, including vehicle and fuel production, distribution and delivery, use, and vehicle EOL. These total life cycle emissions allow fair comparisons to be made across different powertrain types and the most sustainable transport fuels to be identified more easily. Figure 6-30 to Figure 6-32 highlight the cradle to grave emissions under all impact categories for each vehicle type and fuel scenario over their 15 year lifespan. These graphs won't be discussed extensively since the individual life cycle stages and WTW emissions have already been analysed separately in the previous sections. The key differences between the cradle to grave emissions in this section and the WTW emissions in Section 6.6 is now vehicle production, EOL, and component replacements are also included. As a result, all differences can be attributed to one or more of these three stages. In addition to the cradle to grave emissions, Table 6-13 and Figure 6-33 show the breakdown of cradle to grave emissions for trucks in terms of GWP from each life cycle stage. Full emission breakdowns for all vehicles under all impact categories can be found in Section 11.2 of Appendix 2. Discussion later in this section will focus on the contribution of these individual life cycle stages to the total life cycle emissions respectively.

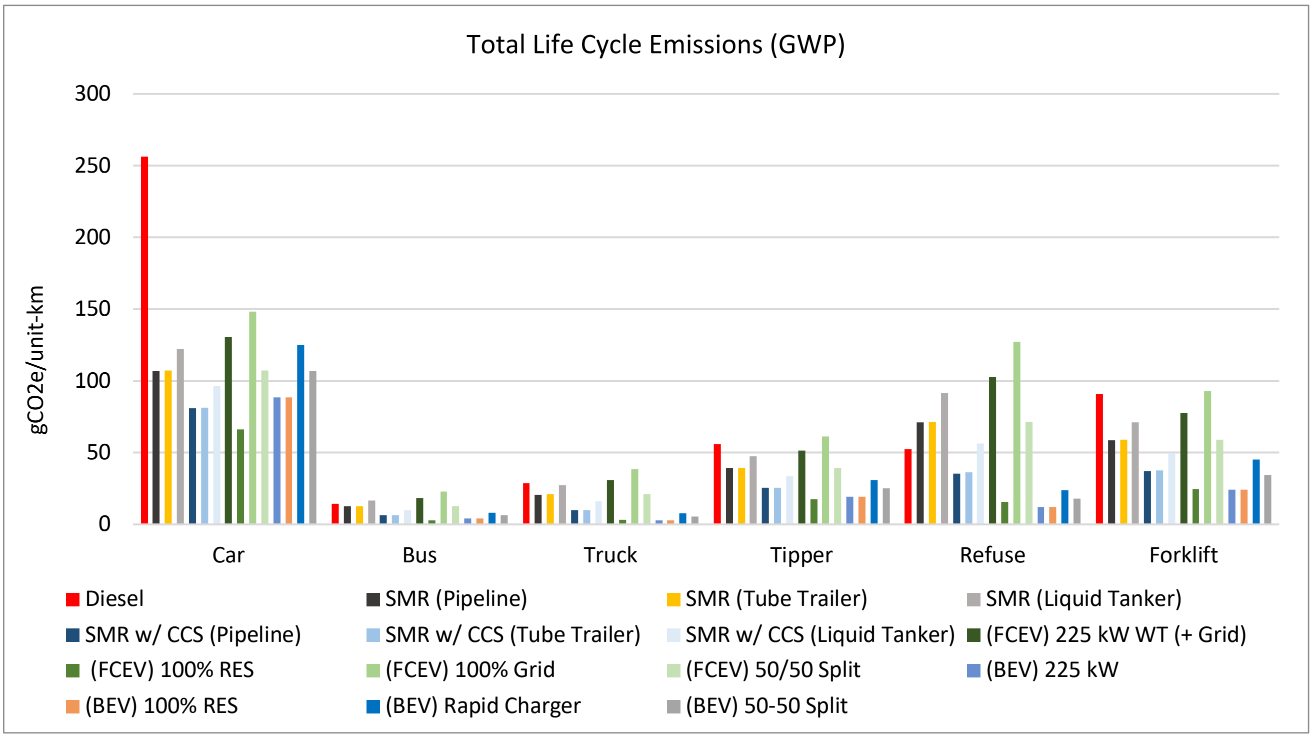


Figure 6-30 – Cradle to grave life cycle emissions (vehicle production, WTW, and EOL) in terms of GWP.

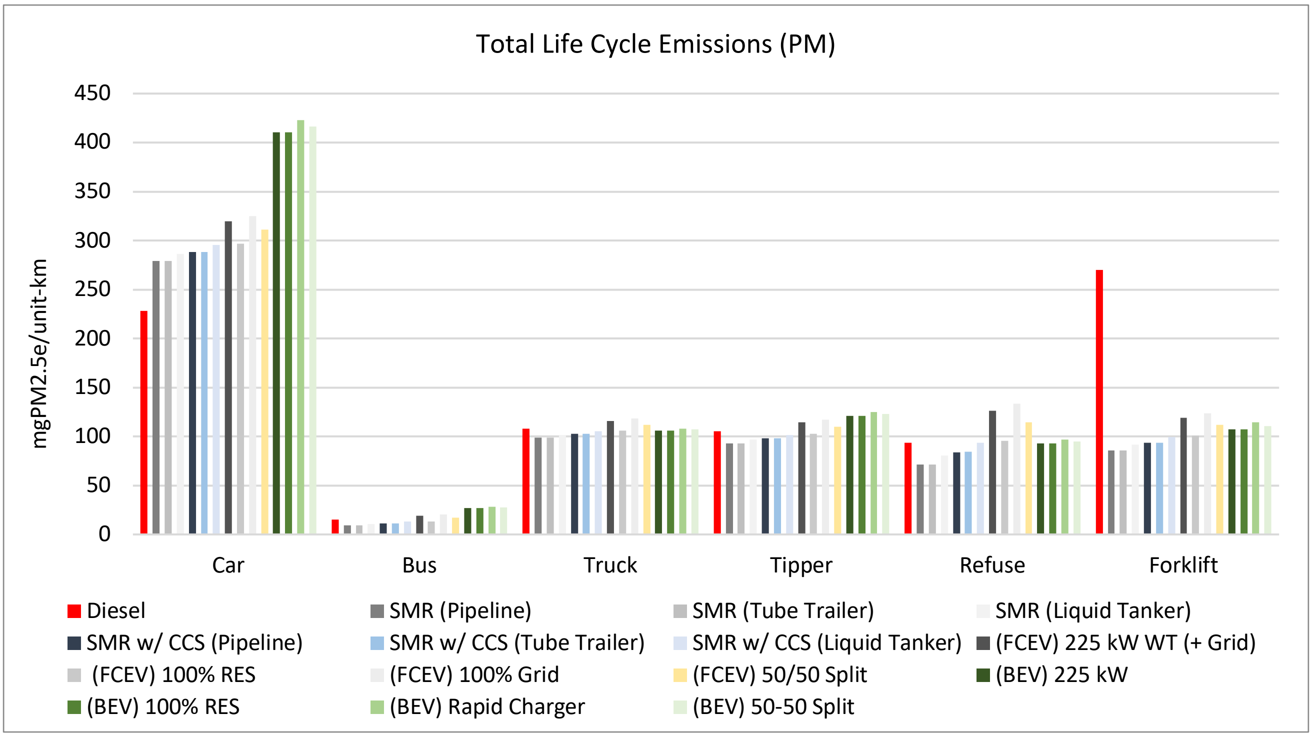


Figure 6-31 - Cradle to grave life cycle emissions (vehicle production, WTW, and EOL) in terms of PM.

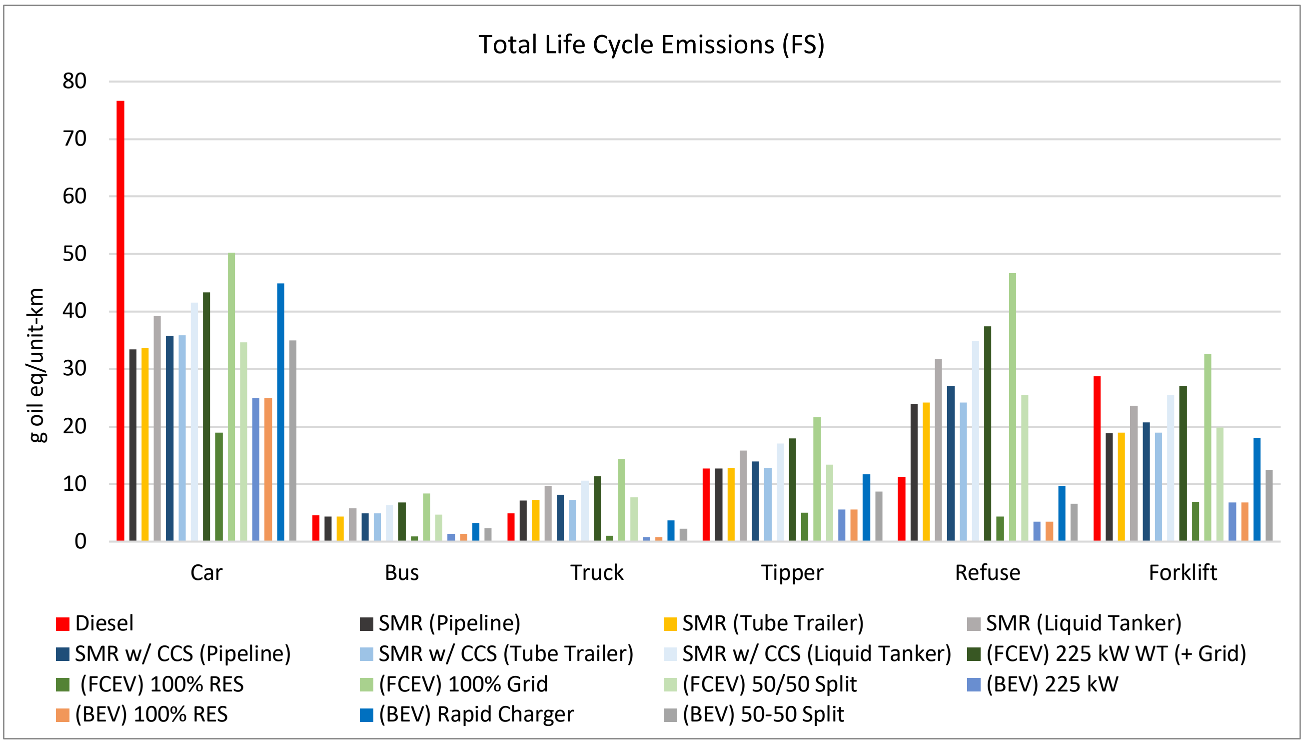


Figure 6-32 - Cradle to grave life cycle emissions (vehicle production, WTW, and EOL) in terms of FS.

From Figure 6-30 and Figure 6-32 for cars, ICEVs running on diesel are by far the most energy intensive transport options considered in term of GWP and FS, with total life cycle emissions of 257 gCO_2e/km and 77 g oil eq/km; roughly 42% and 35% higher than the next most harmful option which is FCEVs utilising electrolytic hydrogen from 100% grid power, at 149 gCO_2e/km and 50 g oil eq/km. Despite higher production emissions from FCEV cars, their zero exhaust emissions are significantly lower than diesel, and because the fuel cells are recycled at their EOL they recover some of the production and component replacement emissions which gives them an advantage on a life cycle basis over both ICEVs and BEVs. This advantage is seen clearly in the 100% RES FCEV scenario which has the lowest cradle to grave GWP and FS of all the cars considered in the study, with only 66 gCO_2e/km and 19 g oil eq/km, lower than any of the BEV fuel scenarios, despite two BEV fuel scenarios having a lower WTW GWP and FS, shown previously in and Figure 6-28 respectively.

For all BEVs which make use of this renewable-based electricity and have low use phase emissions, over 90% of the cradle to grave emissions are from vehicle production and component replacement, with similar findings also highlighted in work by EEA [155]. This is largely due to the energy intensity of battery production, outlined earlier in Section 6.1.2. For BEV cars using rapid chargers in Figure 6-30, cradle to grave emissions are 125 gCO_2e/km. When comparing this to the work by [54], emissions appear higher as they report figures of only ~85 gCO_2e/km for a medium sized BEV car powered by EU27 average grid electricity. However, since emissions are highly dependent on the source of grid power, a change in the electricity grid leads to drastic changes in emissions which can account for these differences. For example, [54] also estimated cradle to grave emissions if Polish grid power was used, and in this case emissions are much higher with ~160 gCO_2e/km respectively.

For the GWP and FS of all HDVs, although diesel is still a harmful transport fuel on a cradle to grave basis, its environmental impacts are not as severe as some of the other fuels. Now, unlike the cradle to grave emissions for passenger cars, a range of fuels now share similar or even higher life cycle emissions when compared to diesel. For example, a long haul truck running on diesel has a GWP of 29 gCO_2e/tkm which is lower than FCEV trucks utilising electrolytic hydrogen from both 225 kW and 100% grid power respectively. The high fuel consumption for these HDVs leads to increased emissions over the fuel cycle, and FCEV trucks also incur higher vehicle production emissions compared to ICEVs and BEVs (see Figure 6-1). The lowest cradle to grave emissions for trucks come from electric scenarios, specifically those utilising 225 kW and 100% RES electricity since these vehicles generate less emissions from their manufacture and their fuels do not utilise grid power or require any conditioning or distribution, despite their EOL boundaries excluding emission savings from battery re-use. The same patterns are seen for BEV refuse collection vehicles and forklifts which have lowest cradle to grave emissions when operating on these electric fuels.

Both FCEV refuse vehicles and forklifts utilising 100% grid power show very high cradle to grave GWP at 127 gCO_2e/tkm and 93 gCO_2e/tkm. Previously from Figure 6-1, all refuse and forklift vehicles have similar production emissions, so the major disparities do not originate from this phase. Instead, it is because the fuel consumption of these FCEV reference vehicles is higher in comparison to the BEVs, increasing the WTW emissions, which is the major contributor to these emissions.

In terms of PM in Figure 6-31, the cradle to grave emissions of cars increase dramatically from their WTW emissions. For example, FCEV cars running on hydrogen from SMR with tube trailer transport are 280 mg $PM_{2.5}e$/km compared to just 4 mg $PM_{2.5}e$/km in terms of its WTW emissions; an increase of 276 mg $PM_{2.5}e$/km. These dramatic increases can be seen for all ZEV cars and are primarily due to car production and component replacement emissions. It is these two stages which account for a large portion of the variation in cradle to grave emissions between fuel/powertrain types of cars. For example, the production emissions for an ICEV car in terms of PM are 130 mg $PM_{2.5}e$/km compared to 190 mg $PM_{2.5}e$/km for a BEV and 354 mg $PM_{2.5}e$/km for the FCEV model (see Figure 6-2). For component replacement PM emissions, diesel cars are exempt as they don’t require replacements, whereas BEVs and FCEVs incur an additional 201 and 127 mg $PM_{2.5}e$/km, which ultimately leads to ICEV cars having the lowest cradle to grave PM emissions of all fuels in Figure 6-31. As a result of recycling savings, the cradle to grave PM emissions of all BEV cars are higher compared to FCEVs. Under WTW conditions, BEV cars using 100% RES electricity had PM emissions of 16 mg $PM_{2.5}e$/km and were one of the cleanest fuel scenarios. However in Figure 6-31, these are now one of the highest with 410 mg $PM_{2.5}e$/km. Under these conditions, all FCEV cars are more environmentally competitive than their BEV equivalents.

Looking at HDVs in Figure 6-31, the PM emissions follow a similar pattern to cars but do not increase as dramatically from their WTW emissions because some of these vehicles have a greater lifetime mileage, as well as all vehicles having a greater weight, which lowers the emissions on a per unit-km basis compared to cars, making the increase in emissions from WTW to cradle to grave less noticeable as a result. Here, BEV and FCEV production emissions in this case are fairly similar and do not deviate as widely, though still remain higher than ICEVs. For ZEVs the largest deviations from WTW to cradle to grave emissions of HDVs are from this vehicle production stage. PM generated from component replacement is greater from BEVs compared to FCEVs due to the emission savings from the recycling of each spent fuel cell; an advantage BEVs do not receive. These savings are also extended to the FCEV EOL, increasing the disparity further and making FCEVs more competitive. For example, for a tipper the EOL emissions for BEVs are 0.1 mg $PM_{2.5}$e/tkm compared to -11 mg $PM_{2.5}$e/tkm for FCEVs. Similarly for replacements, BEVs incur 17 mg $PM_{2.5}$e/tkm compared to just 4.3 mg $PM_{2.5}$e/tkm for FCEVs.

For the majority of the ZEV scenarios, the dominant life cycle stage from the emission breakdown tables in Appendix 2 in terms of GWP and FS is fuel production. In terms of FS, this is also true for all ICEVs with the contribution from fuel production ranging from 66-94%. However from Table 6-13 and the others in Appendix 2, the GWP of ICEVs is dominated by the use phase, and ranges from 65-89%. For an ICEV truck, Table 6-13 and Figure 6-33 show vehicle and fuel production emissions generate 3.1% and 7% of total GWP, fuel conditioning and distribution contributes 0.8%, and the use phase accounts for a massive 89%. This highlights the importance of vehicle operation in the case of ICEVs since this phase has the biggest impact on total life cycle emissions. As a result, it is here where ZEVs offer advantages since their operation emits no exhaust gases, which over long periods of time and high mileage applications, can offset their higher vehicle production and component replacement emissions.

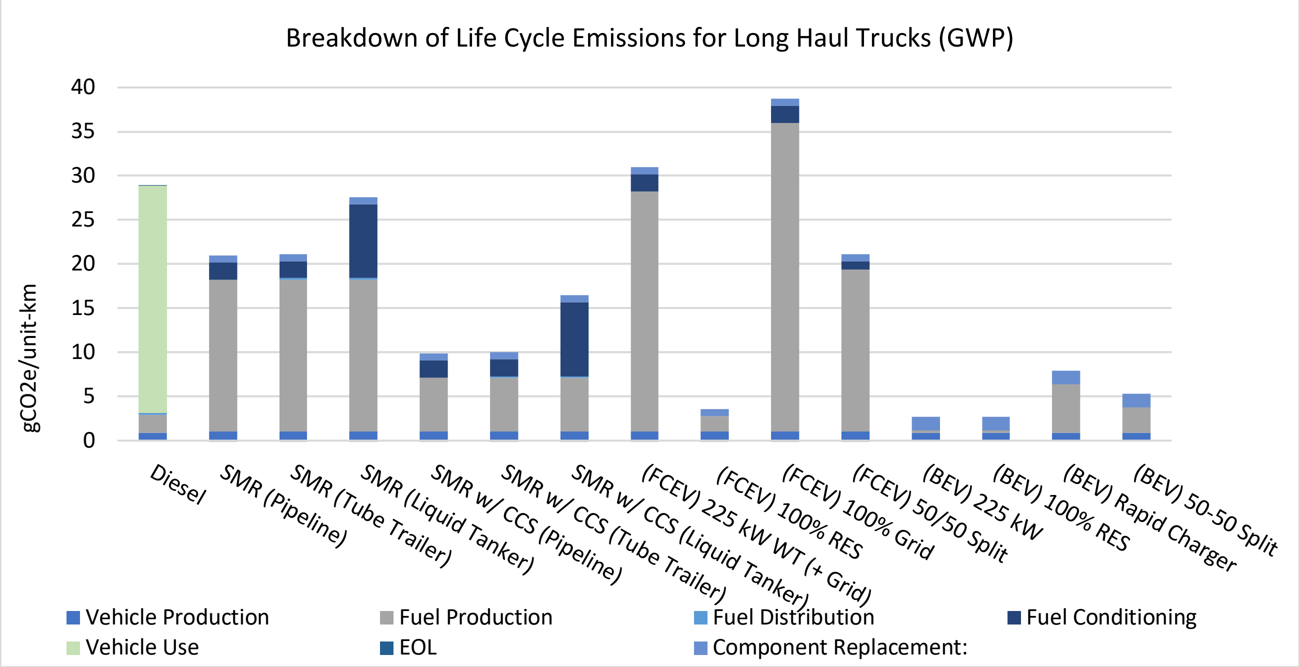


Figure 6-33 - Breakdown of life cycle emissions for long haul trucks.

Table 6-13 - Breakdown of life cycle emissions for trucks in terms of GWP.

	Trucks - Percentage Contribution							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement:	Total:
Diesel	3.1%	7.0%	0.8%	0.0%	89.0%	0.0%	0.0%	100%
SMR (Pipeline)	5.0%	82.5%	0.0%	9.3%	0.0%	-0.6%	3.7%	100%
SMR (Tube Trailer)	5.0%	81.9%	0.7%	9.2%	0.0%	-0.6%	3.7%	100%
SMR (Liquid Tanker)	3.8%	62.7%	0.6%	30.5%	0.0%	-0.4%	2.8%	100%
SMR w/ CCS (Pipeline)	10.7%	62.6%	0.0%	19.9%	0.0%	-1.2%	8.0%	100%
SMR w/ CCS (Tube Trailer)	10.6%	61.6%	1.6%	19.6%	0.0%	-1.2%	7.9%	100%
SMR w/ CCS (Liquid Tanker)	6.4%	37.3%	1.0%	51.2%	0.0%	-0.7%	4.8%	100%
(FCEV) 225 kW WT (+ Grid)	3.4%	88.2%	0.0%	6.3%	0.0%	-0.4%	2.5%	100%
(FCEV) 100% RES	30.5%	50.2%	0.0%	0.0%	0.0%	-3.5%	22.7%	100%
(FCEV) 100% Grid	2.7%	90.6%	0.0%	5.0%	0.0%	-0.3%	2.0%	100%
(FCEV) 50/50 Split	5.0%	87.3%	0.0%	4.6%	0.0%	-0.6%	3.7%	100%
(BEV) 225 kW	33.1%	10.1%	0.0%	0.0%	0.0%	0.3%	56.5%	100%
(BEV) 100% RES	33.1%	10.1%	0.0%	0.0%	0.0%	0.3%	56.5%	100%
(BEV) Rapid Charger	11.2%	69.6%	0.0%	0.0%	0.0%	0.1%	19.1%	100%
(BEV) 50-50 Split	16.7%	54.5%	0.0%	0.0%	0.0%	0.2%	28.6%	100%

The contribution from fuel production to total GWP and FS is the highest in the case of electrolytic hydrogen using 100% grid power and reaches a high of 91% for FCEV trucks respectively. As for FCEV trucks using hydrogen transported with liquid tankers, the conditioning stage is the second highest contributor to a trucks total emissions with 31% (GWP and FS) for SMR with LT and 51% and 29% (GWP and FS) for SMR & CCS with LT. In this case, it is the liquefaction energy that is a major contributor to these overall emissions. As for BEVs, since their electricity does not require conditioning this stage has a contribution of zero under all impact categories. For those ZEV fuel scenarios utilising renewable power which don't generate high fuel production emissions, such as 100% RES hydrogen and electricity, the contribution from this stage is lower so other stages contribute more, such as vehicle production and component replacement emissions. Component replacements contribute the most to those vehicle applications with a high mileage (since a greater number of replacements are needed at higher mileage) and those scenarios with low fuel production emissions. For example, for ZEV trucks the percentage contribution to total GWP and FS from component replacements is the highest of all the vehicle types and reaches a maximum of 57% (for GWP and FS) for BEVs using 100% RES which have very low WTW emissions. In the case of FCEVs which have their fuel cells recycled, in general for the HDVs the portion of total FS and GWP from replacements is much lower compared to BEVs since their component replacement emissions only include the portion of fuel cell production emissions not recovered from recycling. Since a large portion of the fuel cell replacement emissions are recovered during EOL, the total emissions from component replacement per unit-km for FCEVs are lower compared to BEVs for all vehicle types as they do not include this benefit. The advantage of this helps improve FCEV competitiveness overall in terms of cradle to grave emissions.

When switching focus to the PM impact category, the biggest contributor to total life cycle PM for the majority of HDVs is vehicle use. This is partly because the PM emissions from the production of most ZEV fuels are very low, with SMR generating negative PM emissions and renewable energy sources also generating negligible quantities. Here, only hydrogen and electricity production using grid power generates a high portion of the total PM since this utilises fossil fuel sources. For example, in the 100% grid hydrogen fuel scenario, production makes up 11-44% of the total PM across all vehicles respectively. The majority of the PM emissions attributed to the operation of the vehicles are generated from road, brake, and tyre wear, and are independent of the powertrain type, covered earlier in Section 6.5.2. Here, these PM emissions are dependent on factors such as vehicle weight and tyre/brake numbers, for example. As a result, the contribution from vehicle use to total PM is highest for trucks, since these vehicles have a high energy consumption and mileage, meaning they generate larger quantities of PM from road wear and their emissions from other life cycle stages are spread out over a greater number of kilometres and therefore contribute less in terms of total emissions per tkm. In addition, they also have a greater number of tyres which generates higher tyre and brake wear PM. For lighter vehicles which don’t generate as much PM during the use phase, the vehicle production phase accounts for a greater portion of the total. For example, for trucks the contribution from vehicle production ranged from 1.7-3.7%, whereas for forklifts with lower use phase PM, this range was 12-56% respectively. Fuel distribution has a negligible contribution to total PM for all vehicle types and fuel scenarios, whilst fuel conditioning contributes zero for all BEVs, FCEVs using 100% RES, and ICEVs respectively.

The last point to make is when switching from a diesel fleet to some hydrogen or electric fleets, although a reduction in one impact category may be seen, the transition can potentially lead to a rise in emissions under other impact categories. This is known as burden shifting and can be seen when examining Figure 6-30 to Figure *6-32*. For example, GWP is reduced across all vehicle types in Figure 6-30 when switching from diesel to hydrogen from SMR with CCS with liquid tankers. However, although this change is positive for GWP, looking at Figure 6-31 and Figure 6-32 in terms of PM and FS shows that using this hydrogen can actually lead to increased emissions compared to diesel for the majority of vehicle types. When looking at trucks for example, GWP falls 44% per tkm compared to diesel, but FS increases 116%. Burden shifting was also identified in the LCA by Miotti *et al.* [244] who also acknowledge the high uncertainty surrounding environmental impacts of categories other than GWP, stating that emissions in some categories can be highly impacted by a single process, for example.

6.9. Chapter Summary:

This chapter presented a cradle to grave life cycle assessment of passenger cars and heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel fuels, accounting for emissions from all stages including fuel and vehicle production, fuel distribution and conditioning, vehicle use, component replacement, and vehicle EOL, respectively. For the vast majority of fuel scenarios and vehicles considered, fuel production and conditioning, vehicle production, and component replacement life cycle stages showed the largest contributions to total emissions.

Key findings derived from Chapter 6 are:

- Fuel cycle emissions per unit-km are largely impacted by the fuel/energy consumption of the individual vehicles. This was evidenced in the production emissions of hydrogen in the 225 kW scenario which varies depending on the fleets hydrogen demand since this impacts the quantity of grid electricity required, impacting the total production emissions as a result.

- Mileage figures were shown to impact emissions from component replacements as vehicles carrying out high volumes of travel required more battery and fuel cell replacements over their lifetimes.

- The location of fuel production influenced conditioning and distribution emissions within the fuel cycle, whilst the system boundaries and cut-off points applied to the vehicles also impacted their EOL emissions.

- BEVs powered solely from renewable energy (100% RES) in general show the lowest life cycle emissions across all vehicle types and are therefore the most environmentally competitive transport solutions identified in this study.

- For RES-based BEVs, despite their emissions being the lowest, other factors not considered in this work and which are likely to impact and/or offset these results should be acknowledged. These factors include the performance of BEVs in cold weather conditions, which can lead to a 50% reduction in efficiency (and an increased fuel consumption as a direct consequence), increasing their fuel cycle emissions significantly. BEVs are also susceptible to payload losses if larger batteries are required to offset these efficiency drops. This loss in payload can have a negative impact on vehicle productivity and could result in more miles being driven (i.e. more trips), so should also be acknowledged. The omissions of these factors are limitations to this study and present an interesting area for future work. In terms of FCEVs, despite their higher emissions, they do not suffer from any of the shortcomings highlighted for BEVs and this may prove them to be more environmentally friendly solutions in the long-term.

- Although RES-based BEVs show the lowest emissions, FCEVs still offer competitive solutions if using green hydrogen from 100% renewable power. Results show that for several of the vehicles considered (cars, buses, and tippers), this fuel scenario offers lower life cycle emissions than their RES-based BEV equivalents. Further, if BEVs are powered using rapid chargers with a high reliance on grid power, more FCEVs become environmentally competitive.

- Finally, for ICEVs, although not the worst fuel scenario for all vehicles, diesel still remains very damaging in terms of its cradle to grave emissions, largely due to its high use phase emissions which account for the vast majority. Its harmful impacts on global warming and air quality make it unsuitable as a future transport fuel and is one reason why these vehicles are due to be phased out after 2030 (LDVs) and 2040 (HDVs).

7. Chapter 7 - Future Outlook on FCEV Emissions

The results of an LCA depend to some extent on the underlying assumptions and modelling conditions used, which may be subject to change and which may have a significant impact on the results and overall conclusions. Conditions which are reasonable to assume today may not be reasonable to assume in future years, so this section investigates the impacts of changing specific input conditions on the life cycle emissions of each of the vehicles and powertrains in the study.

Based on the breakdown of life cycle emissions shown in Figure 6-33 and Table 6-13 in Chapter 6, as well as Appendix 2, parameters that are expected to have a significant influence on life cycle emissions and which are selected for further investigation are listed below. Each of these parameters will be examined throughout this section respectively.

1. Electricity Mix
2. Hydrogen Production by Electrolysis
3. Vehicle Fuel Consumption
4. Hydrogen Liquefaction Energy
5. SMR Steam Credit

7.1. Electricity Mix:

This section examines the impact of a future electricity mix for the year 2050 on life cycle emissions of FCEVs. Studies have shown that electricity's share of global final energy consumption will rise from its current 21% to 50% by 2050 so in order for the UK to meet net zero targets, the electricity grid must rapidly decarbonise. As a result, the electricity mix outlined previously in Figure 5-3 (in Chapter 5) is now expected to be more heavily dominated by renewables which are predicted to see their annual growth rate increase eight-fold by 2050 as net zero commitments and the impacts of Russia's invasion of Ukraine encourage the reduction of fossil fuel dependency and use [208].

7.1.1. Electricity Scenario:

The UK electricity forecast considered in this future outlook is based on data published by National Grid [132]. This mix was chosen for investigation as it represents the fastest scenario to grid decarbonisation with a focus on the 2050 net zero target. This forecast was used for modelling in SimaPro to examine the impact of different grid mixes on life cycle emissions. The mix considered is:

- A 'Leading the Way' scenario – Hydrogen and electricity use in industry to heat homes. Hydrogen is imported and exported to offer high system flexibility. Minimum levels of electricity curtailment. Direct air capture and storage is used for negative emissions.

Although the estimates from National Grid [132] were made prior to the Russia and Ukraine conflict which has now highlighted the risks of relying on other countries for energy, it is impossible to accurately predict what portion of energy will be imported in the year 2050 and where it will come from, so these predictions have been kept in this case.

A full source breakdown of the 2050 mix is shown in Figure 7-1. In this scenario natural gas usage falls to only 6.3%, with wind and bioenergy accounting for the largest proportions, making up 52% and 16% of the total mix. The mix also contains a small share of electricity generated from 'other fuels' which was not specified by National Grid [132]. As a result, this work assumes the category 'other fuels' is pumped storage hydro since energy storage is a huge challenge globally and this route offers some potential to help alleviate the issues surrounding the intermittency of renewable power. The geography of the UK is not well suited to natural hydropower, however pumped hydropower offers a more logical and economical option. Excess electricity generated at off-peak times where demand is low can be used to pump water to upper reservoirs using reversible turbines where it is stored until electricity demand is high. At this point the water is released downhill to drive turbines and generate electricity.

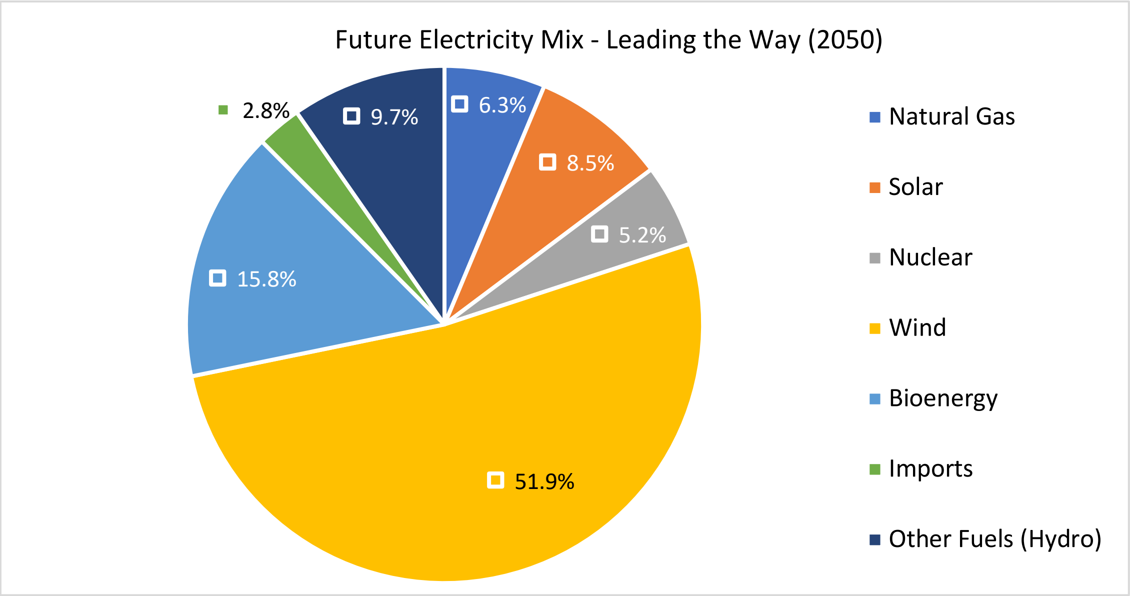


Figure 7-1 - 2050 future electricity mix under the Leading the Way scenario.

Figure 7-2 shows the emissions per kWh from the base case and future mix. From the graph, emissions per kWh across GWP and FS impact categories fall when using the 2050 mix compared to the base case mix. However, PM remains lower under the base case mix with 0.109 compared to 0.137 gPM$_{2.5}$e/kWh respectively. Emissions of CO$_2$ fall by 48% when using the Leading the Way mix compared to the base mix due to the increased use of renewables over natural gas, and for the FS impact category the emissions also drop by 54% respectively.

The higher PM emissions in the Leading the Way mix is partly due to the increased use of bioenergy which makes up 16% of the total mix and contributes a majority 42% of the total PM emissions per kWh. In addition, the use of hydro pumped storage also accounts for a larger portion of the total mix in the Leading the Way scenario, with 10% compared to 1.8% in the base case mix. This is also a significant source of PM emissions due to the additional electricity required and contributes over 30% to the total in the Leading the Way scenario.

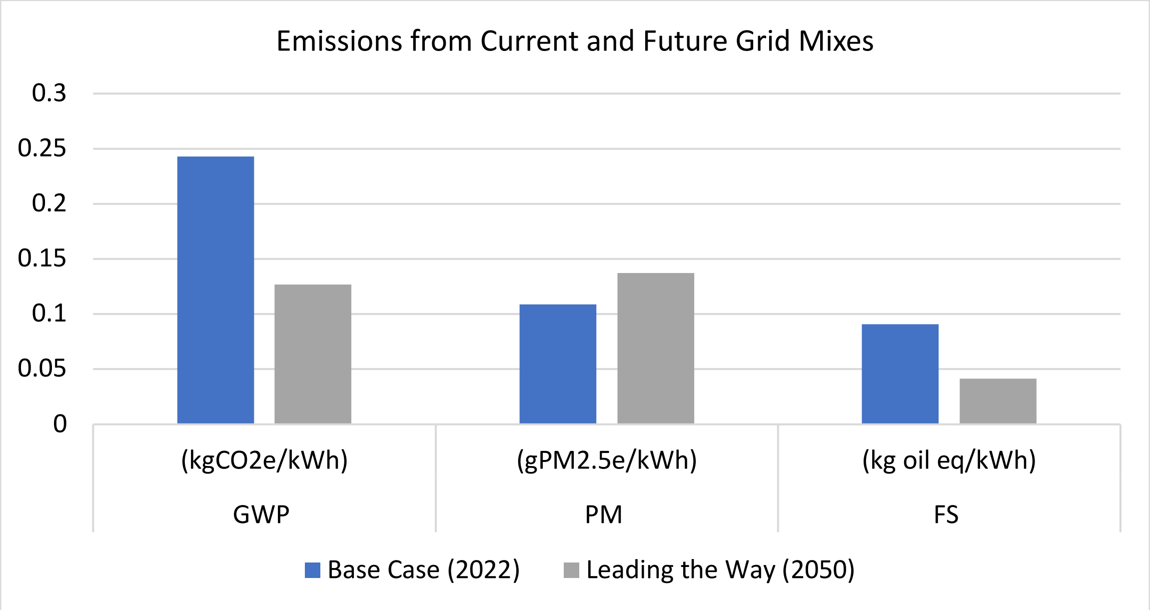


Figure 7-2 - Emissions from the production of 1 kWh electricity under each electricity mix.

7.1.2. Impacts of a 2050 Mix:

Figure 7-3 shows the GWP savings across the vehicle life cycle under the 2050 grid mix scenario, whilst the figures in Section 11.7.1 in Appendix 2 show these savings in terms of PM and FS respectively. This section aims to highlight the impacts of a decarbonised 2050 grid mix on cradle to grave emissions.

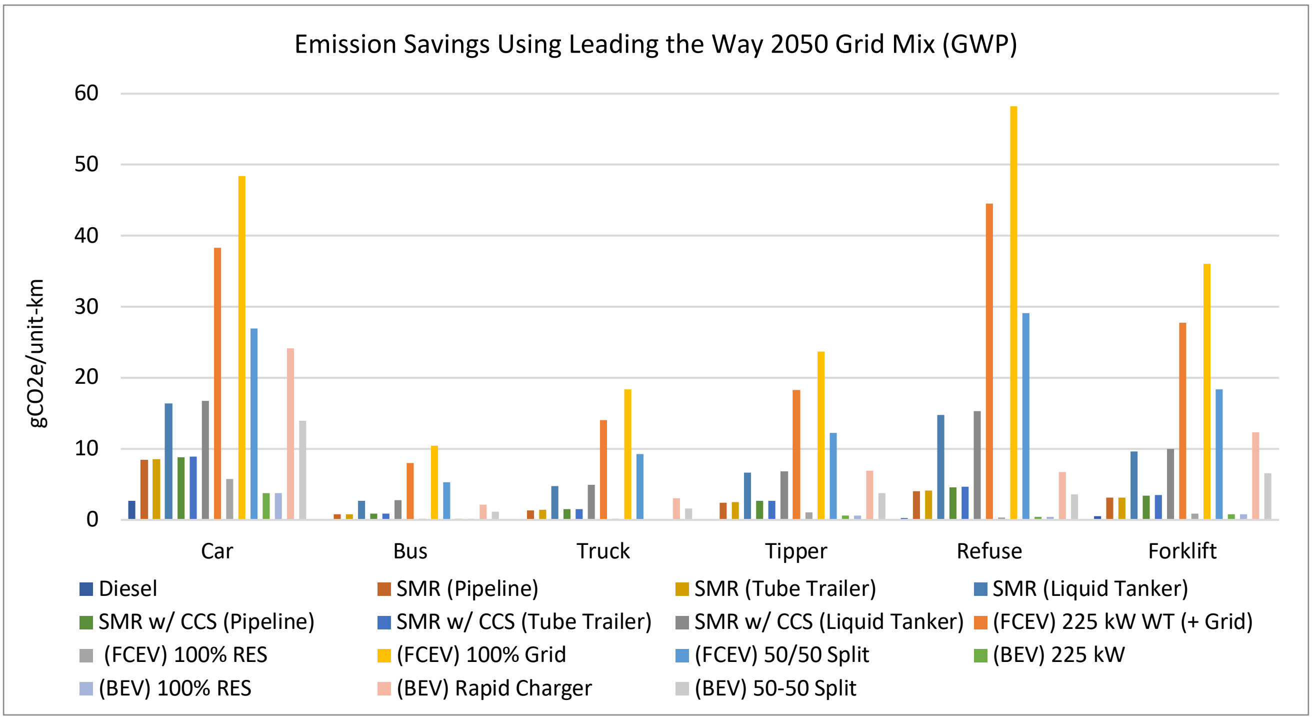


Figure 7-3 – Emission savings when using the 2050 Leading the Way electricity mix (GWP).

Across all impact categories, ICEV cradle to grave emissions do not noticeably change after switching to the 2050 mix. In fact, the emission savings from doing so are negligible in the majority of cases. For example, for ICEV trucks in the base case, GWP and PM was 28.9 gCO_2e/tkm and 107.6 $mgPM_{2.5}e/tkm$ and after switching to the Leading the Way 2050 grid mix, GWP falls less than 1% (Figure 7-3) whilst PM remains the same (Figure 11-19). These negligible savings in emissions are because the life cycle stages of ICEVs are less dependent on electricity in comparison to ZEVs. In this case, ICEVs don't use electricity for diesel production, fuel conditioning or distribution stages, and they don't require electricity from component replacements like ZEVs as these are not required. As a result, the competitiveness of diesel vehicles against ZEVs does not improve with the use of the 2050 grid mix as the emission savings from ZEVs outweigh those from ICEVs. As a result, ZEV fuels become more competitive and more attractive in terms of emissions compared to diesel when this decarbonised mix is used.

Despite negligible emission savings for ICEVs over the entire life cycle, more significant savings are made across the vehicle production stage when switching grid mix. In terms of GWP, ICEV cars save approximately 6% (1 tCO_2e) when using the Leading the Way 2050 scenario, whilst buses and trucks save ~5% (2 tCO_2e) and ~6% (6 tCO_2e) compared to base case production. However, these savings are much smaller for PM and FS. ICEVs also see savings in the dismantling and shredding EOL stages. The 2050 grid mix leads to a 52% decrease in GWP from the dismantling and shredding of an ICEV truck compared to the base case value of 0.61 tCO_2e. Total emission savings from this EOL stage are higher for those vehicles with a greater GVW since they demand more electricity overall. Despite these savings, even under this 2050 grid scenario, diesel still shows the highest GWP for 5 of the 6 vehicle types in the study respectively.

Unlike ICEVs, the impacts of using the 2050 grid mix on cradle to grave emissions is high for all ZEVs. For GWP and FS impact categories, cradle to grave emissions are lowest when using this mix, since this incurs fewer emissions. However for PM, emissions are generally lowest under the base case mix due to the sources of energy used, as it generates 25% less PM than the 2050 mix, shown in Figure 7-2. For most FCEV HDVs under the base case mix (shown previously in Figure 6-30 to Figure *6-32*), cradle to grave PM and FS is highest when using 100% grid hydrogen. Since PM is greater per kWh in the 2050 mix, upon switching to it, the emission savings are negative (shown in Figure 11-19), so the order of competitiveness of the fuels is largely unchanged, with 100% grid hydrogen remaining the most damaging fuel for the majority of HDVs. For FS though (Figure 11-20), which falls under a future mix, this leads to a significant change and alters the environmental competitiveness of the fuels. Now, all HDV FCEVs fuelled by non-electrolytic hydrogen show higher life cycle emissions.

As mentioned, the most positive impacts are seen by ZEV fuels which have the highest dependency on grid electricity (such as 100% grid hydrogen and electricity from rapid chargers). For example, GWP for the production of hydrogen from 100% grid was 447 gCO_2e/kWh in the base case and now falls ~50% to 226 gCO_2e/kWh under the 2050 mix. These savings lower total life cycle emissions compared to the base case and contribute to changing the order of environmental competitiveness for some of the scenarios. FCEV tippers utilising 100% grid power showed higher life cycle emissions than ICEV tippers in the base case (Figure 6-30) with 61 gCO_2e/tkm compared to 56 gCO_2e/tkm. However, under a 2050 grid mix scenario this FCEV tipper now becomes more competitive as a result of emission savings of 24 gCO_2e/tkm, shown in Figure 7-3. This change in competitiveness can actually be seen for FCEV buses, trucks, tippers, and forklifts utilising 100% grid hydrogen, which have higher emissions than ICEVs in the base case but now fall lower under this 2050 mix. In terms of BEVs, fuel production emissions are unchanged for 100% RES and 225 kW electricity scenarios as they don't rely on grid power for their production. The largest savings are from rapid charger electricity which shows GWP falls 48% from 243 gCO_2e/kWh in the base case to only 127 gCO_2e/kWh in 2050 under the 2050 mix. Due to fuel production being such a big contributor to life cycle emissions of ZEVs, BEVs using rapid chargers show the biggest reductions in emissions across the BEV fuel scenarios. Emissions from BEV forklifts using rapid chargers fell by 12 gCO_2e/tkm (27%) when using the Leading the Way mix, compared to reductions of only 3.4% when using 100% RES electricity, for example.

Alongside fuel production savings, some energy intensive hydrogen fuel conditioning processes, such as liquefaction and compression, also contribute to the savings in cradle to grave emissions. For example, GWP emissions from the conditioning and distribution of liquid hydrogen is 109 gCO_2e/kWh in the base case which falls 51% to just 53 g CO_2e/kWh under the Leading the Way scenario. Since diesel and electric fuels don't require conditioning, this also accounts for the lower emission reductions seen by ICEVs and BEVs. Both FCEVs and BEVs also generate larger savings across the cradle to grave using this 2050 grid mix due to the additional electricity demands associated with the production of their powertrain components, as well as component replacements which ICEVs omit. In terms of the vehicle EOL, the impact of this Leading the Way mix led to a reduction in production GWP per kW of PEM fuel cell; now at 79 $kgCO_2e/kW$ compared to 83.4 $kgCO_2e/kW$. This means that the emissions recovered from the recycling of the fuel cell account for a larger portion of its total production emissions, now rising from 73% to 77% respectively. However, overall the majority of the emission savings are associated with the fuel cycle, which is generally the largest contributor to life cycle emissions of ZEVs respectively, shown previously for trucks in Table 6-13.

In terms of PM, the base case mix has the lowest PM emissions per kWh, therefore the lowest cradle to grave PM for all vehicles is seen using this mix in Figure 6-31. As previously mentioned, for all ICEVs the GWP, PM, and FS does not change noticeably when switching electricity mixes. Similarly, for PM from FCEVs specifically, in general, for all vehicle types using non-electrolytic hydrogen, the 2050 grid mix does not lead to a dramatic change in the cradle to grave PM. This is evidenced by vehicles using liquefied hydrogen from SMR which is one of the most electricity-demanding non-electrolytic hydrogen scenarios, due to the intense liquefaction process. For FCEV trucks using this fuel, cradle to grave PM rose only 0.8% when switching from the base case mix to the mix in 2050 (Figure 11-19). Similar changes are seen across all FCEV types using non-electrolytic hydrogen and are even lower for those fuels not requiring liquefaction.

For those electrolytic hydrogen scenarios which rely more heavily on grid power such as 100% grid and 225 kW, total PM rises are greater. For example, FCEV refuse vehicles using 100% grid hydrogen have PM emissions of 134 mg $PM_{2.5}e/tkm$ under the base mix which increases by ~17 mg $PM_{2.5}e/tkm$ (~10.5%) under the 2050 mix (Figure 11-19); a larger rise compared to the 0.8% from liquefied hydrogen mentioned previously. Although these emissions are higher, the cradle to grave PM of FCEVs using these electrolytic hydrogen fuels are the highest of all the ZEV HDVs in the base case anyway. Since electric fuels do not require conditioning or distribution, their overall PM changes are lower than FCEVs when using a 2050 grid mix since fewer life cycle stages are impacted. As a result, cradle to grave emissions inclusive of savings from Figure 11-19 show similar patterns to the base case with several hydrogen fuels offering lower cradle to grave PM compared to electric fuels across all HDV applications.

Fossil scarcity shows a similar pattern to PM as the largest emission savings are seen by electrolytic hydrogen fuels with high grid electricity demand. Across all vehicle types using 100% grid and 225 kW hydrogen, the impact of the 2050 grid mix in Figure 11-20 shows a large saving in cradle to grave FS. For all HDVs in particular, these fuels showed the highest FS in the base case and now fall below the majority of the non-electrolytic hydrogen fuels after decarbonising the grid. However, across all vehicle types BEVs still show generally lower cradle to grave FS compared to FCEVs. The only hydrogen fuel scenario that competes with BEVs is 100% RES respectively.

7.2. Electrolyser Efficiency:

Some of the hydrogen production routes used in this study have the potential to significantly increase in efficiency in the future. The electrolysis process is one example since it is a relatively new production route which currently accounts for only ~4% of global hydrogen production. As a result of increasing offshore wind projects in the UK and its green credentials, electrolysis is at the centre of hydrogen research and development and is receiving significant investment from both public and private sectors. This means it has great potential to grow in the future as renewable energy generation increases and electrolyser technology is predicted to develop further.

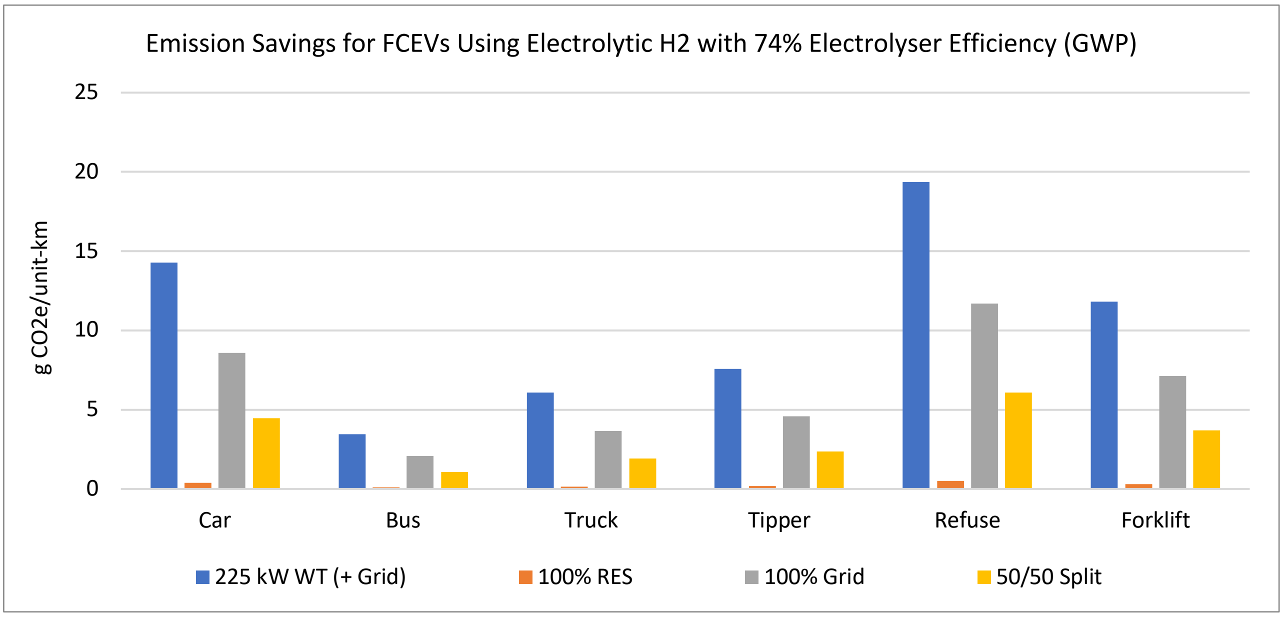


Figure 7-4 – Life cycle emission savings of FCEVs from an increased electrolyser efficiency of 74%.

For other hydrogen production routes like SMR which currently accounts for 75% of global production, the process is already mature having been in use for several decades. Although SMR can be carried out with other fuels, traditionally it involves the use of fossil fuels which are now trying to be minimised. As a result, many industry experts oppose the use of SMR technology and view it as a way to lock in the continued use of fossil fuels. Furthermore, the use of SMR alone is not enough to produce the quantities of hydrogen required to reach future demands predicted. When considering these factors, the efficiency of the SMR process is not expected to improve significantly in the future. Also, it is uncertain as to whether this technology will even be in operation in the future since the success of achieving net zero targets will likely be influenced by its use. Similarly, for blue hydrogen using SMR with CCS, this route also faces worldwide scrutiny over its place in the hydrogen mix since CCS technology has yet to be proven on the large scale with limited demonstration plants in use, along with uncertainty regarding the security of carbon sequestration. SMR with CCS is unlikely to be the option selected for new plants built in the coming years as other technologies show better efficiency and economics; one being autothermal reforming with CCS. For these reasons the SMR production process is not considered here and focus will lie solely on electrolytic hydrogen.

Current electrical efficiencies for PEM electrolysers for hydrogen production are estimated at 65%, outlined previously in Chapter 5. However, several sources including the IEA and ICCT predict this efficiency to increase in the future, with exact figures varying depending on economies of scale, technological breakthroughs, and general operating conditions. In this work, a modest future efficiency of 74% is assumed, based on the work by Christensen *et al.* [55] and predictions by the IEA [17] respectively. As a result, this section investigates the impact of an efficiency rise in PEM electrolysers. Now, only 54.1 kWh of electrical power is required for the production of 1 kg of hydrogen instead of 61.5 kWh. The impacts of this change in terms of life cycle GWP for the electrolytic hydrogen scenarios are shown in Figure 7-4. For other impact categories of PM and FS, the new life cycle emissions are shown in Figure 11-21 and Figure 11-22 in Section 11.7.2 in Appendix 2 respectively.

In the 225 kW hydrogen scenario, 1350 kWh of renewable electricity is generated each day from the 225 kW which is used to produce the hydrogen required for the vehicles. However, since the hydrogen demand in this work is 74 kg/day, and now 54.1 kWh of electrical energy is required for the production of each kilogram of hydrogen, this turbine only provides 34% of the demand and is still not enough to provide the total 4000 kWh required each day. As a result, the remaining 2650 kWh of electricity is sourced from the grid. For each kilogram of hydrogen produced using electrolysis, out of the 54.1 kWh required, 18.4 kWh comes from the 225 kW turbine whilst 35.7 kWh comes from the grid.

Since the electrolyser efficiency is only one variable in one of the life cycle stages for FCEVs, the impact of this relatively small efficiency increase is still quite noticeable for several of the vehicle types in terms of their cradle to grave GWP and FS. In terms of PM however, the impact is lower and only shows noticeable improvements in the cradle to grave emissions of refuse vehicles since they have the highest fuel consumption. For example, Figure 11-21 shows tippers running on 100% grid hydrogen have emission savings from increased electrolyser efficiency of only 1.1 mgPM$_{2.5}$e/tkm (1%) compared to refuse vehicles with 21.2 mgPM$_{2.5}$e/tkm (16%) respectively. Since hydrogen from 100% grid power incurs the highest PM emissions of all production routes, the increase in electrolyser efficiency leads to the biggest savings in PM under this route. As a result, all vehicles running on hydrogen from other production routes will show fewer PM savings across their cradle to grave. For hydrogen from 100% RES and 50-50 Split, since either no or a low amount of grid electricity is used to produce hydrogen this way, increasing the electrolyser efficiency shows a very minor benefit in terms of PM, and the cradle to grave emissions remain either the same or very marginally lower for all vehicle types. For example, PM from 100% RES hydrogen production in the base case is 59 mg $PM_{2.5}$e/kWh and falls to 52 mg$PM_{2.5}$e/kWh after the efficiency rise, equivalent to a 12% reduction. In addition, Figure 11-21 shows the cradle to grave PM of refuse vehicles using 100% RES hydrogen falls only 1.7 mg$PM_{2.5}$e/tkm (~2%), highlighting the fact that this efficiency increase only shows a significant benefit for those fuels with high grid dependence. This observation is in fact true for all impact categories, with GWP and FS also showing negligible changes in the cradle to grave emissions of all vehicle types using 100% RES hydrogen.

For the other impact categories of GWP and FS, cradle to grave emissions for all vehicle types using 100% grid and 225 kW hydrogen fall more significantly than PM as a result of the electrolyser efficiency rise. As mentioned earlier, and similar to PM, savings are high for vehicles with high fuel consumption, such as refuse vehicles and forklifts. Figure 7-4 shows the savings in cradle to grave GWP for forklifts using 100% grid, with 7.1 gCO_2e/tkm (8%). Similar results are shown in Figure 11-22 in terms of FS, also with an 8% decrease.

Aside from 100% RES hydrogen which already showed cradle to grave emissions similar to and below some BEV fuel scenarios under all impact categories, the efficiency rise does not alter the competitiveness of the fuels as none of the other electrolytic hydrogen scenarios become less energy intensive than electricity per unit-km. Although the emissions from fuel production fall significantly in those electrolysis scenarios utilising grid power, when combining this with emissions from fuel conditioning and delivery, vehicle production, component replacement, and EOL, savings are less noticeable. For example, for 225 kW hydrogen, production GWP in the base case is 348 gCO_2e/kWh H_2, compared to only 270 gCO_2e/kWh H_2 after an efficiency increase, equivalent to a 22% reduction. However, the cradle to grave emission savings are much lower than this for all vehicle types.

7.3. Fuel/Energy Consumption:

Alongside the electricity mix and technology efficiency, fuel consumption is another parameter likely to change in the future that will impact the life cycle emissions. For ICEVs, despite potential developments in weight saving and refinements to ICE technology, the fuel consumption is not expected to change significantly in the future as this technology is already mature and their use is due to be phased out from 2030. As a result, this section considers improvements in vehicle fuel consumption for ZEVs only. Predicting the change in fuel consumption can be a difficult task since the future of ZEVs is unknown in these early stages. It is uncertain which ZEVs will dominate the transport sector and in which applications they will be most frequently used. Both of these factors impact the level of development that will be seen in battery and fuel cell technology.

In order to help estimate the rate of improvement in the fuel consumption of FCEVs, the study by Benitez *et al.* [15] was used which employed the first-generation Toyota Mirai (first manufactured in 2014) as the reference vehicle of interest. In the study, its current-day fuel consumption (in 2020) was reported at 0.76 kg H_2/100km whilst the future value was predicted to fall to 0.58 kg H_2/100km, largely due to developments in PEM fuel cell technology along with weight reductions associated with hydrogen storage tanks. This equates to a reduction in fuel consumption of 23.7%. In this work, which uses the second-generation Toyota Mirai as the reference vehicle of interest, the same reduction is applied which gives a future consumption of 0.42 kg H_2/100km respectively. Since estimates for the future fuel consumption of FCEV HDVs are not yet available due to their current market size, the same rate of improvement was applied to all the FCEVs in this work respectively.

For BEVs, the method used was similar and is based on future estimates made by [246]**.** The energy consumption of BEV regional delivery trucks was predicted to fall from 1.44 kWh/km in 2020 to 1.15 kWh/km in 2030, equivalent to a 20% decrease, largely due to developments in battery energy density, reducing vehicle weight. These estimates of energy consumption have been used for all the BEVs in this work, since few BEV HDVs are currently available leaving no historical data available to base estimates on, similar to FCEVs. Table 7-1 summarises the changes in energy consumption for each powertrain and vehicle type.

Table 7-1 – Current and future energy consumption for FCEVs and BEVs.

		Energy Consumption (kWh Fuel/100km)					
	Powertrain:	**Car:**	**Bus:**	**Truck:**	**Tipper:**	**Refuse:**	**Forklift:**
23.7% Drop	FCEV (Current)	18.3	217	344	253	646	354
	FCEV (Future)	14	165.3	261.9	193	493.3	270
20% Drop	BEV (Current)	16.0	70.0	100.0	130.0	130.0	212.4
	BEV (Future)	12.8	56.0	80.0	104.0	104.0	169.9

The impact of these changes in fuel consumption directly affects the WTW emissions since this is the phase associated with fuel use. For the vehicle production, component replacement, and EOL stages, a change in fuel consumption has no impact on their emissions. Figure 7-5 for FCEVs and Figure 7-6 for BEVs shows the impact of these changes in fuel/energy consumption on GWP by reporting emission savings when using the future values compared to the current base case energy consumption in 2021. For the other impact categories, similar graphs are presented in Section 11.7.3 in Appendix 2 respectively.

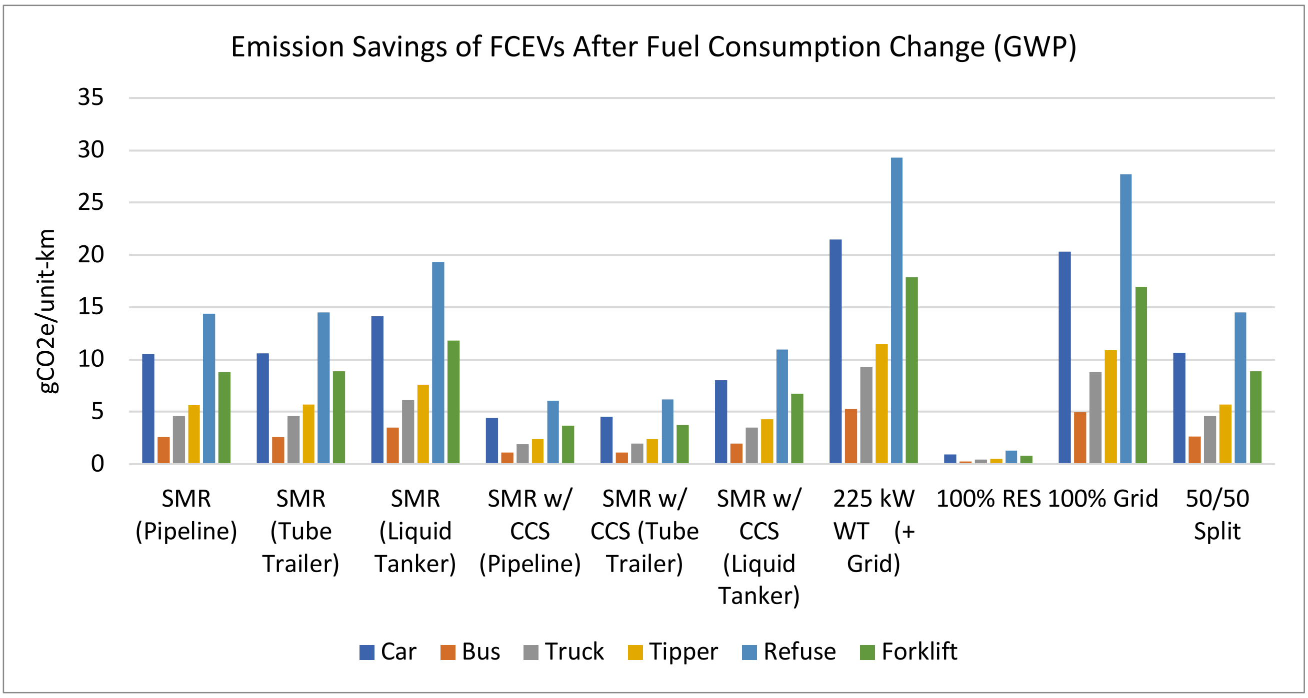


Figure 7-5 - Life cycle emissions of FCEVs under future fuel consumption.

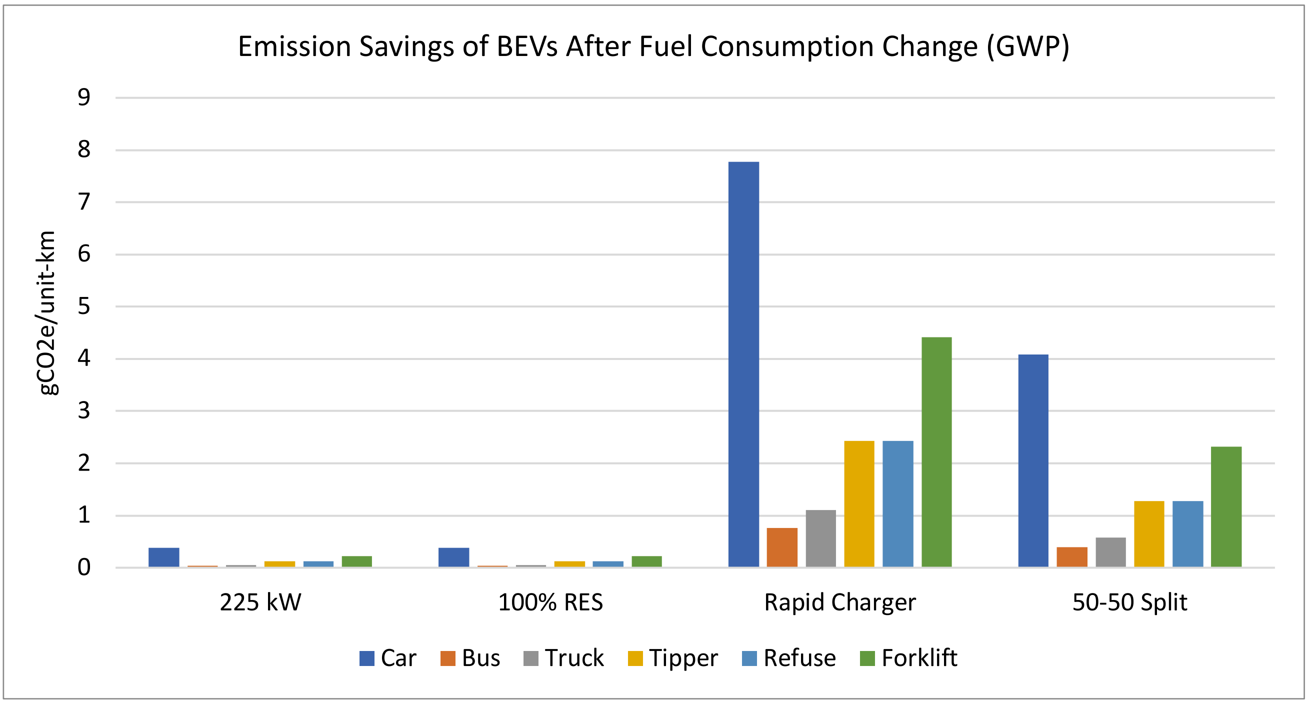


Figure 7-6 - Life cycle emissions of BEVs under future fuel consumption.

Improvements to the vehicle fuel/energy consumption positively impacts the cradle to grave emissions across all impact categories since less fuel needs to be produced per kilometre of travel. However, since PM emissions from SMR and SMR with CCS hydrogen production routes are negative, a reduction in fuel consumption leads to negative emission savings in this case, as shown in Figure 11-23.

Fuels that incur high emissions during their production processes will show the greatest savings. In addition to production, less conditioning and distribution is required, increasing savings further, though the impacts of this are much lower. For BEVs, electricity production from rapid chargers powered by grid electricity has the highest energy intensity per kWh under all impact categories, so the impact of a 20% decrease in energy consumption is higher when compared to BEVs using electricity from other routes, like 100% RES for example, which generates lower production emissions. This is evidenced in Figure 7-6, Figure *11-24*, and Figure 11-26 which show the savings in cradle to grave emissions for BEVs under all categories is greatest using rapid chargers. These savings are amplified for HDVs with a high fuel consumption, such as forklifts. In this case, BEV forklifts using rapid charger electricity show cradle to grave GWP savings of 4.4 gCO_2e/tkm in Figure 7-6, compared to only 0.2 gCO_2e/tkm using 100% RES electricity. For all other electric fuel scenarios and vehicles, the impact of this energy consumption change is smaller, with savings across the cradle to grave of only a few percent.

In terms of FCEVs, the response of an energy consumption drop on cradle to grave emissions is similar to BEVs, though the severity of the savings is greater. For example, in terms of cradle to grave GWP, the savings from refuse vehicles running on 100% grid hydrogen are 28 gCO_2e/tkm (22%) respectively, significantly higher than any of the BEV scenarios. As mentioned previously, the largest savings are seen by vehicles with the highest fuel consumption and fuels with the highest production emissions. In this case, electrolytic hydrogen using 100% grid power incurs the highest production emissions per kWh across all impact categories, whilst refuse vehicles have the greatest fuel consumption. As a result, these show large savings across all impact categories, shown in Figure 7-5, Figure 11-23, and Figure *11-25* respectively.

However, for vehicles using 225 kW hydrogen, emission savings are the highest of all the fuels considered in the study. This is due to the decrease in energy consumption per km which shows a significant impact on cradle to grave emissions since the production emissions generated from this route are dependent on the fleet's hydrogen demand. In this case, since the daily hydrogen consumption under these new conditions is lower than the base case (now 56.6 kg compared to 74 kg H_2), less energy needs to be generated to produce the total hydrogen needed. As a result, the 225 kW turbine provides a greater portion of the total energy required for this hydrogen production compared to the base case, now increasing from 28% to 37%. This means less grid electricity is required, significantly reducing emissions across all impact categories as a result. For example, GWP from hydrogen produced this way falls from 348 gCO_2e/kWh in the base case to 309 gCO_2e/kWh respectively, equivalent to an 11% decrease. Here, in Figure 7-5 refuse vehicles running on 225 kW hydrogen show cradle to grave emission reductions of 29 gCO_2e/tkm (29%) in terms of GWP, which is the highest reduction of any vehicle/fuel scenario considered. Despite these greater savings across all impact categories, no FCEVs running on 225 kW hydrogen in this future scenario show cradle to grave emissions that are competitive with BEVs.

In addition to fuel production savings, FCEVs incur additional savings from the reduced fuel distribution and conditioning required, since hydrogen fuels require these stages, unlike electric fuels. These savings are highest for liquefied hydrogen, with vehicles using this distribution route showing more significant reductions across the cradle to grave compared to the other routes. However, the total emission savings are still dominated from fuel production, with these distribution and conditioning savings only accounting for a minority share. For example, from Figure 7-5 for FCEV refuse vehicles using hydrogen from SMR with tube trailers, cradle to grave GWP falls approximately 14.5 gCO_2e/tkm. Of this, only ~11% is attributed to the fuel conditioning and distribution. For refuse vehicles using hydrogen from SMR but transported using more energy intensive liquid tankers, savings are 19.3 gCO_2e/tkm, with 24% of this associated with conditioning and distribution, highlighting the increased savings from these fuel cycle stages.

From Table 7-1, it is clear that the energy consumption of all BEVs is significantly lower than FCEVs, despite FCEVs having a larger decrease in energy consumption. As a result, the environmental competitiveness of all BEV fuels per unit-km in terms of their cradle to grave emissions remains higher than FCEV fuels under all impact categories. Life cycle emissions from some of the FCEVs now approach their BEV equivalents more closely, but these savings are not large enough to become the most sustainable fuel solution. Although FCEVs still cannot compete with BEVs, they can against ICEVs in certain applications. Some FCEVs now become less energy intensive per unit-km and would be the better transport option in terms of global warming impact. One example of this is trucks running on electrolytic hydrogen from 225 kW, which have a cradle to grave GWP of 30.9 gCO_2e/unit-km in the base case, which was 7% higher than diesel at 29 gCO_2e/unit-km. However, after fuel consumption savings, FCEV trucks become more sustainable with emissions dropping by 30% to only 22 gCO_2e/unit-km.

7.4. Liquefaction Energy:

From the life cycle emissions in the base case shown earlier in Figure 6-30 to Figure 6-32, it can be seen that for all vehicle types and under all impact categories, when excluding electrolytic hydrogen, the FCEV fuel scenario which gives the highest cradle to grave emissions comes from hydrogen transported in liquid form. As a result, the parameter to be changed in this section is the electricity requirement for the liquefaction of hydrogen.

The theoretical minimum energy requirement for hydrogen liquefaction is 2.7 kWh/kg. However, due to the inefficiencies in reality this process typically requires around 10 kWh/kg H_2, which is the figure used in the base case. Liquefaction is over 3x more energy intensive compared to compression to 350 bar, but several studies have suggested that due to process improvements expected in the future, this energy requirement will drop to around 6 kWh/kg H_2 [209] [210]. Taking this into account, this section aims to examine the impact of this change on the cradle to grave emissions of FCEVs using liquefied hydrogen. Figure 7-7 shows the GWP, PM, and FS emission savings across the cradle to grave under this lower liquefaction energy requirement respectively.

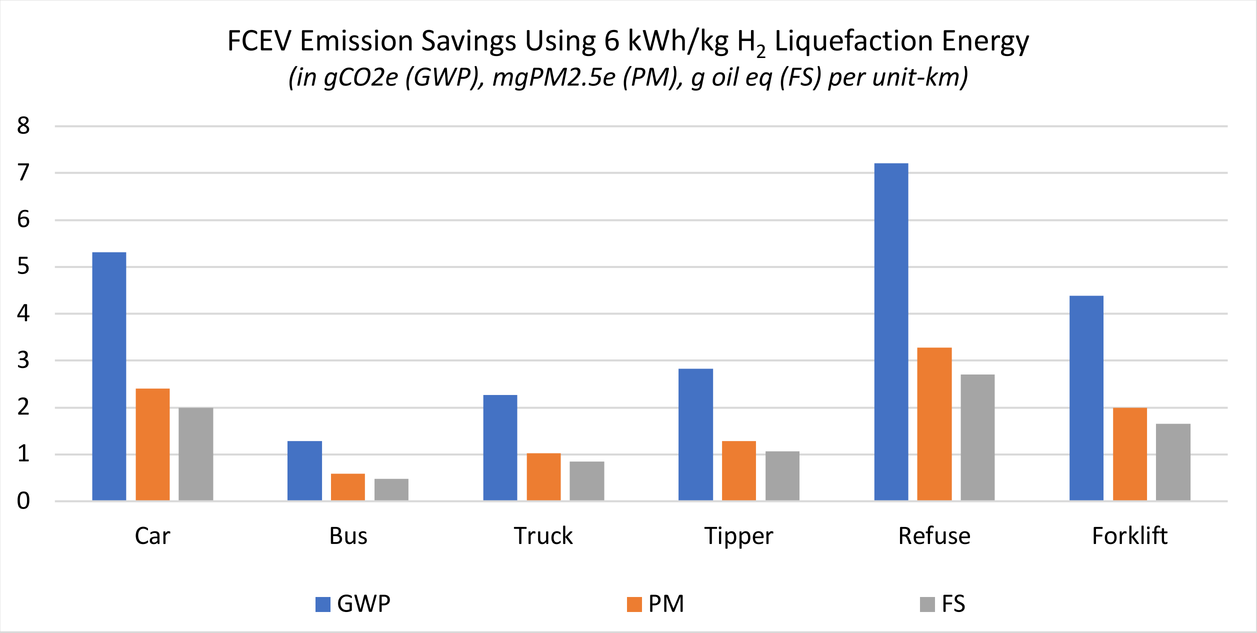


Figure 7-7 – Emission savings when using a reduced liquefaction energy of 6 kWh/kg H_2.

From Figure 7-7, in general for the majority of vehicles the savings in cradle to grave emissions under all categories is relatively minor, reaching a maximum of only 7.2 gCO_2e/tkm (GWP) in the case of refuse vehicles. The extent of these savings is largely influenced by the vehicle fuel consumption, similar to the other sensitivities covered. As more hydrogen is required per km, the demand for liquefaction is higher which incurs greater emissions. As a result, those FCEVs with high fuel consumption (in this case refuse and forklift HDVs) show more noticeable savings across their cradle to grave per km. Since refuse vehicles have the highest consumption of all FCEVs in the study at 19.4 kg/100km, they show the largest savings across all impact categories. Here, when using hydrogen from SMR with CCS, the cradle to grave GWP falls 7.2 gCO_2e/tkm (or ~13%) from 56.5 gCO_2e/unit-km to 49.3 gCO_2e/unit-km respectively, which is a significant reduction compared to some other FCEVs under the same fuel conditions. For PM and FS impact categories, cradle to grave savings for all vehicles are lower in comparison as the liquefaction conditioning stage contributes a smaller portion of the life cycle emissions. From the emission breakdown tables covered previously and shown in Section 11.2 in Appendix 2, fuel conditioning accounts for a maximum of 20% and 32% of the CTG emissions for PM and FS impact categories, whereas this figure is higher for GWP at 51% respectively.

Comparing the cradle to grave emissions under this lower liquefaction energy to the other (unchanged) fuel scenarios in the base case (i.e. ICEV, BEV, and the remaining FCEV fuels) doesn't show any change in the order of the life cycle emissions of the fuels. However, forklifts using hydrogen from SMR & CCS with liquid tankers now reach parity with BEV forklifts using rapid chargers in terms of GWP. Here, emissions from the FCEV in the base case were 65 gCO_2e/unit-km and were higher than BEV forklifts using rapid chargers at 58 gCO_2e/unit-km, however after the reduction in energy demand for liquefaction these FCEV emissions fall to 58 gCO_2e/unit-km making the hydrogen scenario an equally sustainable option.

7.5. Steam Methane Reforming Steam Credits:

In the base case in Chapters 5 and 6, the production of hydrogen using steam methane reforming (SMR) technology included the use of steam credits as excess steam produced throughout the process was used in secondary applications, saving emissions associated with virgin steam generation. Now, this section aims to highlight the life cycle emissions when this credit is excluded and 100% of the emissions from steam generation are attributed to the SMR process for hydrogen production. In the case of conventional SMR, 6.4 kg of steam is now listed as an input from the technosphere, not as an avoided product, whilst for SMR with CCS 0.8 kg steam is required per kg of hydrogen production.

Table 7-2 below shows the hydrogen production emissions from SMR and SMR with CCS both with and without the steam credit applied. The impact of this credit is high across both production routes and all impact categories but is greatest for conventional SMR where the steam requirement is highest. The most significant changes are in terms of PM where emissions are now 53 mg $PM_{2.5}e/kWh\ H_2$, significantly higher than the previous value of -50 mg $PM_{2.5}e/kWh\ H_2$ respectively.

Table 7-2 - Emissions from SMR and SMR with CCS with and without steam credit (per kWh H_2 produced).

	SMR			SMR with CCS		
	GWP (gCO_2e)	PM (mg $PM_{2.5}e$)	FS (g oil eq)	GWP (gCO_2e)	PM (mg $PM_{2.5}e$)	FS (g oil eq)
With Credit	220	-50	76	78	1	88
Without Credit	339	53	113	93	19	93

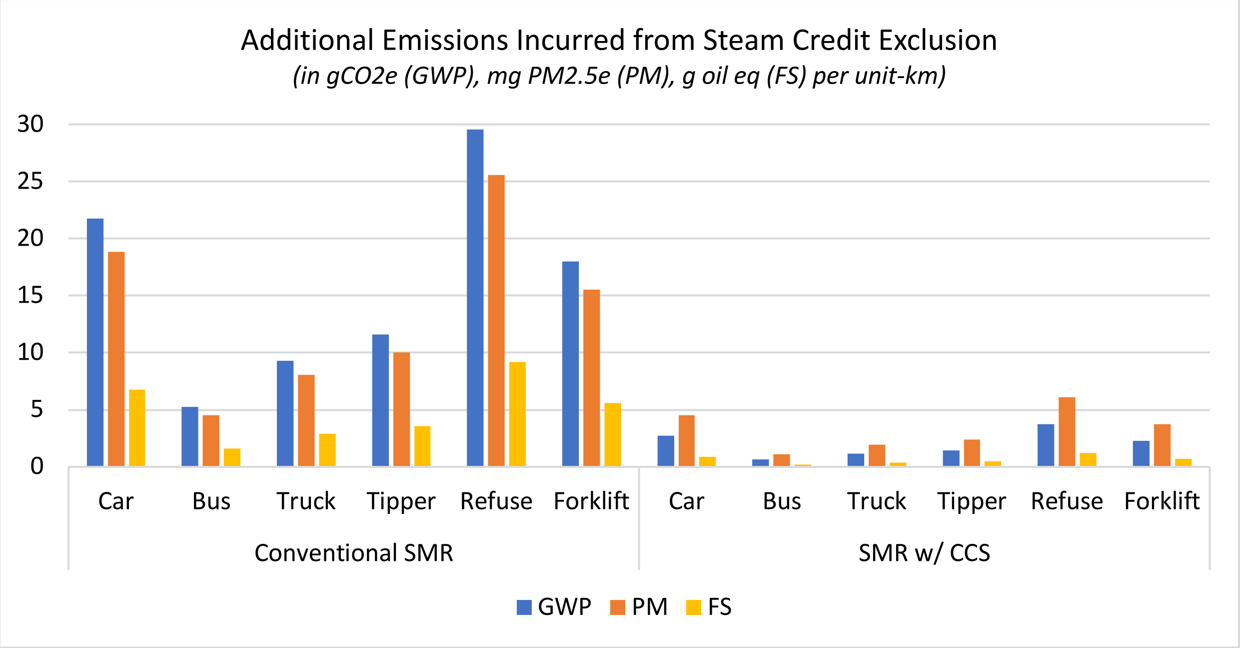


Figure 7-8 – Additional emissions associated with steam generation for hydrogen production.

The impact of this steam credit on the life cycle emissions of all impact categories is shown in Figure 7-8. This graph shows that if the credit is not applied and the emissions from steam generation are included in the hydrogen production life cycle stage, cradle to grave GWP can increase from 5.3-29.6 gCO_2e/unit-km in the case of SMR, and from 0.7-3.7 gCO_2e/unit-km for SMR with CCS, depending on the vehicle type. For FS, the additional emissions are much lower however, reaching a peak of only 9.2 g oil eq/unit-km respectively. Also, the increase in emissions from hydrogen produced by SMR with CCS is much lower under all impact categories, reaching a peak of only 6.1 mg $PM_{2.5}e$/tkm for refuse vehicles. These additional emissions reduce the environmental competitiveness of FCEVs using SMR-based fuels compared to those using electrolytic hydrogen, as well as BEVs, all of which remain unchanged, making them more attractive options now compared to the base case where the credit was active. These credit exclusions can also make diesel powered vehicles appear more attractive in comparison, encouraging their continued use in transport which is undesired if net zero is to be achieved. For example, ICEV buses and trucks show lower cradle to grave GWP compared to FCEVs versions running on hydrogen from SMR when the credit is excluded.

Figure 7-8 shows that the largest increases in emissions for all impact categories as a result of the credit exclusion are seen for refuse vehicles. This is because these vehicles have the highest fuel consumption of all FCEVs and therefore incur higher emissions per km from the fuel production phase of the life cycle. This is supported by the emission breakdown tables covered earlier in the report (and given in Section 11.2 in Appendix 2), which show fuel production accounts for the largest share of life cycle emissions for a number of FCEV scenarios.

In terms of GWP, refuse vehicles incur an additional 29.6 gCO_2e/tkm (SMR) and 3.7 gCO_2e/tkm (SMR with CCS) when the credit is excluded. For PM, these values are 25.5 mg $PM_{2.5}e$/tkm (SMR) and 6.1 mg $PM_{2.5}e$/tkm (SMR with CCS) respectively. As a result, the impact of this credit is most significant for FCEVs using pure SMR hydrogen compared to the base case cradle to grave emissions. FCEV refuse vehicles using SMR with pipeline transport show an increase in cradle to grave GWP of over 21%, rising from 71 gCO_2e/tkm to 96.7 gCO_2e/tkm respectively. Although this GWP rise does not change fuel competitiveness for refuse vehicles, it does for other vehicles. For trucks running on SMR hydrogen, they now show higher cradle to grave GWP compared to those running on diesel, which was not the case when the credit was active. Under these conditions, it is more environmentally friendly (in terms of GWP) to continue using diesel powered trucks as opposed to FCEVs powered with this hydrogen fuel. ICEV trucks have a GWP of 28.9 gCO_2e/tkm compared to ~31 gCO_2e/tkm for FCEVs powered by SMR with pipeline or tube trailer transport. This change in fuel competitiveness can also be seen in terms of PM for trucks, tippers, and refuse vehicles. For FS however, as previously stated, the additional emissions from the credit exclusion are much lower compared to PM and GWP so changes are less severe. Despite this, buses using SMR and SMR with CCS with pipeline and tube trailer transport now become more harmful compared to their diesel equivalent.

7.6. Chapter 7 Summary:

The results presented in Chapter 6 depend on the underlying assumptions and modelling conditions used and because these may be subject to change, they can have a significant impact on the results. As a result, this chapter expanded upon the earlier findings and provided a future outlook by varying specific conditions.

Five parameters were varied in this chapter to examine their impact on the environmental competitiveness of FCEVs. Parameters included the electricity mix, electrolyser efficiency, vehicle fuel/energy consumption, liquefaction energy, and the steam credit included in the SMR production process. The bullet points below highlight key findings from each of the varied parameters:

- The use of a decarbonised grid mix reduces the life cycle emissions of FCEVs and sees several hydrogen fuel scenarios fall below ICEVs and BEVs per unit-km.

- Increasing electrolyser efficiency shows emission reductions from fuel production, especially for 225 kW hydrogen which is fleet-specific. However, aside from 100% RES hydrogen which showed emissions similar to and below some BEV fuel scenarios, the efficiency rise does not alter the competitiveness of the fuels compared to Chapter 6. Although emissions from fuel production fall significantly in those electrolysis scenarios utilising grid power, when combining this with emissions from all other stages, savings are less noticeable.

- A lower vehicle fuel/energy consumption is expected due to developments in PEM fuel cell technology, weight reductions associated with hydrogen storage tanks, and increased battery energy density. The largest savings are seen by vehicles with the highest fuel consumption and fuels with the highest production emissions. However, the environmental competitiveness of all BEV fuels per unit-km remains higher than FCEV fuels under all impact categories. Life cycle emissions from some of the FCEVs now approach their BEV equivalents, but savings are too small to become the most sustainable solution.

- Reductions in hydrogen liquefaction energy from 10 kWh/kg H_2 to 6 kWh/kg H_2 show the savings in cradle to grave emissions under all categories are relatively minor for the majority of vehicles. The extent of the savings are largely influenced by the vehicle fuel consumption. Here, results don’t show any change to the order of the life cycle emissions of the fuels when comparted to Chapter 6.

- The exclusion of the steam credit in the SMR hydrogen production process leads to increased fuel production emissions and can significantly alter the competitiveness of several fuel scenarios, but this depends on a number of factors including the vehicles fuel consumption.

8. Chapter 8 - Total Emissions of Ownership

All results presented in Chapters 6 and 7 related to the entire life cycle of the vehicles, from their production to end of life (i.e. their cradle to grave emissions) and considered a 15-year lifespan under a generic vehicle mileage. This chapter is an extension of that assessment and focuses solely on the emissions associated with operating the vehicles in council fleet applications for a fraction of their useful life; more specifically, a fleet centered around the North of the UK. Throughout this section, this approach is going to be referred to as the Total Emissions of Ownership (TEO). Since the TEO considers only vehicle procurement and its use in the specific fleet, EOL is excluded as vehicles are expected to enter a new fleet after their service in the first one. As a result, the EOL is attributed to the next life cycle and is outside of the new system boundaries.

This chapter first starts by highlighting the sources of council data which form the basis of these emission estimates, and then investigates the corresponding TEO under two ownership periods within the fleet using scenario analysis. This aims to examine the environmental feasibility of combined mixed fleets of FCEVs from the perspective of a fleet owner and compares to BEVs and ICEVs respectively.

8.1. Sources of Fleet-Specific Mileage Data:

Unlike the generic mileage scenario presented in Chapter 3 which draws mileage data from a range of different fleets and locations, the TEO is based largely on mileage data recorded from Leeds City Council (LCC). This data is taken from the same sources as those outlined in Chapter 4. Additional mileage data was collected from a number of other Northern UK council fleets including Newcastle, Manchester, and Sheffield using Freedom of Information (FOI) requests but was not used for a variety of reasons. In this case, some data was only provided for 2021 which was not considered an accurate reflection of typical mileage as the impacts of Covid-19 were still active, whilst other data was severely limited with large gaps in the entries and only total lifetime mileage provided, not annual figures. In addition to these limitations, average annual mileage figures that were sourced successfully were significantly lower compared to LCC, partly because these fleets had more vehicles available which reduced their individual usage. A number of other factors also have influence such as the size of the region, the number of fleet bases, and the vehicle duty cycles, for example. As a result, instead of taking an average of the mileage figures from all these fleets combined, which would not give an accurate representation of any of the fleets, it was decided that only data from LCC is to be used in the TEO analysis. Final mileages used in this chapter were shown previously in Table 4-15 and Table 4-17 of Section 4.4.3 in Chapter 4 respectively.

8.2. TEO Scenarios:

Unlike Chapters 6 and 7 which estimated emissions across the 15-year lifespan, this chapter estimates emissions from the vehicle service life whilst in its specific fleet and is therefore from the perspective of a fleet owner. As a result, the TEO considers two ownership scenarios: a 6 and 10 year service period. The 6-year scenario is based on LCC who operate all of their vehicles on a rolling replacement scheme, keeping vehicles in operation for 5-7 years before replacing them where they enter service again in other fleets [61]. The 10-year scenario is based on the economics of fleets transitioning from ICEVs to ZEVs. In many cases the higher purchase costs of ZEVs can only be offset by using them for periods of 10+ years due to low running costs. Energy Savings Trust [62] calculated that the replacement of diesel RCVs with electric ones could be made affordable when using a 10-year replacement cycle. This 10-year ownership is also in line with typical battery manufacturer warranties.

To calculate the TEO, vehicle production emissions must be distributed fairly among each of the users over its active lifetime. This is because it is unreasonable for one fleet to incur the entire burden of all production emissions when the vehicles are also used by other fleets. To do this, production emissions are divided based on the mileage share from each user. This requires some assumptions to be made regarding the next users of the vehicles after use in this fleet. Firstly, all vehicles are assumed to have a 15-year lifespan, which is consistent with the base case assumption. After the 6-year service scenario, vehicles are assumed to enter other fleets where the remaining 9 years of service takes place (totalling a 15-year lifespan). Likewise, for the 10-year service scenario vehicles are assumed to enter other fleets where 5 years of remaining service is carried out before they are taken out of operation. Alongside the remaining service in other fleets, the mileage is also uncertain as different fleets have different duty cycles. As a result, in both scenarios, the annual mileage achieved by the vehicles throughout the remaining service years is based on the generic mileage figures covered in Chapter 3. These figures are used to derive the total lifetime mileage for each of the vehicles, which is then used to calculate the mileage share from the fleet being investigated in this study. Once this is known, vehicle production emissions are divided by this share, so each owner is responsible for its portion of total production emissions. This is shown more clearly in Table 8-1 and Table 8-2 and by Equation 47 respectively.

Table 8-1 – Calculation of mileage share for vehicles under a 6-year TEO scenario.

Vehicle:	**LCC Annual Mileage (km/year):**	**LCC Service Life (years):**	**LCC Total Mileage (km):**	**Generic Annual Mileage (km/year):**	**Remaining Service Life (years):**	**Remaining Total Mileage (km):**	**Lifetime Mileage (km):**	**LCC Mileage Share:**
Car	18,524	6	111,144	22,530	9	202,860	314,004	35.4%
Bus	28,759		172,554	34,685		312,165	484,719	35.6%
Truck	134,532		807,192	173,740		1,563,660	2,370,852	34.0%
Tipper	11,464		68,784	11,620		104,580	173,364	39.7%
Refuse	19,141		114,846	19,145		172,305	287,151	40.0%
Forklift	6,939		41,634	10,430		93,870	135,504	30.7%

Table 8-2 – Calculation of mileage share for vehicles under a 10-year TEO scenario.

Vehicle:	**LCC Annual Mileage (km/year):**	**LCC Service Life (years):**	**LCC Total Mileage (km):**	**Generic Annual Mileage (km/year):**	**Remaining Service Life (years):**	**Remaining Total Mileage (km):**	**Lifetime Mileage (km):**	**LCC Mileage Share:**
Car	18,524	10	185,240	22,530	5	112,700	297,940	62.2%
Bus	28,759		287,590	34,685		173,425	461,015	62.4%
Truck	134,532		1,345,320	173,740		868,700	2,214,020	60.8%
Tipper	11,464		114,640	11,620		58,100	172,740	66.4%
Refuse	19,141		191,410	19,145		95,725	287,135	66.7%
Forklift	6,939		69,390	10,430		52,150	121,540	57.1%

$$\text{Fleet 1 Share Vehicle Prod Emissions} = \text{Vehicle Prod Emissions} \times \text{Fleet 1 Mileage Share} \qquad \text{Equation 47}$$

8.3. Results and Discussion:

The following subsections summarise the changes in emissions generated when considering a 6 and 10 year TEO as opposed to the 15-year base case scenario in Chapters 5 and 6. To avoid repeating analysis, only final reductions are reported in Figure 8-1 to Figure 8-4, in terms of GWP, PM, and FS. Figures showing the absolute TEO results are listed in Figure 12-1 to Figure 12-6 in Appendix 3. This section examines HDVs only since they are the main focus of the study, however results for passenger cars can also be found in the Appendix respectively.

When considering a service period of either 6 or 10 years and annual mileage figures which are either the same (tippers and refuse vehicles) or lower (cars, buses, trucks, forklifts) than those in the base case, the changes in emissions per unit-km are attributed to four areas. These are bulleted and discussed individually below.

1. Fuel Production (specifically the 225 kW hydrogen scenario)
2. Vehicle Production
3. Vehicle EOL
4. Battery and/or Fuel Cell Replacements

Fuel Production - Since the fuel consumption of the vehicles is constant, the emissions from all other life cycle stages (i.e. the fuel cycle) remain the same per unit-km to the base case, since a change in ownership duration and annual mileage has no bearing on their emissions. The only fuels potentially affected by these changing conditions are hydrogen and electricity produced by the 225 kW turbine since their production is fleet-specific and dependent on the requirement for additional grid electricity. In this case, under the TEO conditions, the 225 kW turbine still provides 100% of the energy needed for BEVs to operate, so production emissions remain the same as the base case. However, for FCEVs despite the daily hydrogen demand being lower due to the reduced vehicle mileage, the turbine is still unable to provide 100% of the energy needed for hydrogen production. Now, the turbine accounts for approximately 34% of the total, with the remaining 66% sourced from the grid. Although grid power is still required, production emissions for the hydrogen fall from 348 gCO_2e/kWh in the base case to 321 gCO_2e/kWh, equivalent to an 8% decrease in GWP. In terms of PM and FS, these production emissions fall by 6% and 10% respectively.

Vehicle Production - The second stage which sees a change in emissions is the vehicle production. This was covered earlier in Section 8.1 with the total vehicle production emissions divided among the different fleets based on their mileage shares. Since the annual mileage of tippers and refuse vehicles in the TEO is the same as the base case (shown in Table 3-7 and Table 4-15), their production emissions remain unchanged per unit-km in both 6 and 10 year scenarios. However, for the other vehicles, because their annual mileage in the LCC fleet is lower than the generic base case (shown in Table 8-1), the longer these vehicles are kept in this fleet the lower the total lifetime mileage will be compared to the base case. As a result, production emissions will increase per km since they are spread out over fewer kilometres. The severity of this rise depends on the mileage of each individual vehicle in the LCC fleet. Table 8-1 and Table 8-2 show that that lifetime mileage falls with increasing service in the LCC fleet, and therefore vehicle production emissions per km are highest under the 10 year TEO.

Vehicle End-of-Life (EOL) - As mentioned in the introduction to this chapter, vehicle EOL is excluded in the TEO as the vehicles enter a new fleet after their service in the first one. EOL emissions are attributed to the fleet disposing of the vehicles and are considered outside of these system boundaries. As a result, ICEVs and BEVs incur emission reductions compared to the base case as their EOL generated emissions from vehicle collection, dismantling, and shredding. However, for FCEVs, the exclusion of this EOL stage leads to an increase in emissions because they no longer receive any credits from the recycling of their fuel cells. This factor reduces their environmental competitiveness and increases the gap between life cycle emissions of FCEVs and BEVs.

Replacements - Since the mileage of the vehicles either stays the same (tippers and refuse vehicles) or is reduced (cars, buses, trucks, forklifts) when compared to the base case, the frequency that they exceed 200,000 km is reduced so fewer component replacements are required. Under a 6-year TEO, trucks (which have the highest lifetime mileage) now only require four replacements during their service, less than the 15-year base case. Similarly, under the 10-year TEO, trucks require seven replacements and buses now require one (with buses needing 3 replacements in the base case). For all other vehicle types, no replacements are required under a 6 or 10 year TEO, showing reductions compared to the base case.

The emission reductions for each vehicle and fuel scenario are shown in Figure 8-1 to Figure 8-4 for GWP, FS, and PM. As previously mentioned, the fuel cycle incurs no changes to emissions so this will not be focused on in the discussions. Instead, focus will centre around one or more of the four factors outlined at the start of this section.

8.3.1. Global Warming Potential and Fossil Scarcity:

Since there is a strong relationship between FS and GWP, their results mirror each other closely and for this reason these two indicators are discussed together in this section. From the results, the largest and most significant emission reductions for each vehicle arise from FCEVs using 225 kW hydrogen, however these reductions are still very low with only a minor impact on the environmental competitiveness of the fuels. All other fuel scenarios show even fewer reductions across all vehicle types. As a result, Figure 8-1 (for GWP) and Figure 8-2 (for FS) focus solely on this 225 kW hydrogen scenario respectively, though TEO results for all fuel scenarios can be found in Figure 12-1 to Figure 12-4 in Appendix 3 respectively.

The results shown are primarily due to reductions in hydrogen production emissions as a result of reducing the demand for grid electricity, as all other hydrogen fuel scenarios show negligible changes in emissions, with the impacts of vehicle production, EOL, and component replacement stages negligible in comparison. For example, refuse vehicles in Figure 8-1 saved approximately 6.5 gCO_2e/tkm when under both a 6 and 10-year TEO. In this case, because the annual mileage is the same in the TEO as the base case, vehicle production emissions remain unchanged, so the changes are from only 3 life cycle stages. Here, the impact of replacements accounted for 0.3 gCO_2e/tkm whilst EOL accounted for only -0.39 gCO_2e/tkm. These show a negligible impact compared to fuel production which accounted for the majority of this saving at 6.4 gCO_2e/tkm. This trend is the same for all FCEVs using 225 kW hydrogen, though reductions fluctuate depending on their fuel consumption. Vehicles that consume more hydrogen per unit-km will see a greater saving as a result of the reduced production emissions under TEO conditions. For vehicles with a lower annual mileage under TEO conditions compared to the base case and therefore see an increase in vehicle production emissions per unit-km (i.e. buses, trucks, and forklifts), impacts are still low when compared to fuel production. For example, for FCEV trucks in Figure 8-1, emission reductions fell only ~0.1 gCO_2e/tkm which is a negligible drop overshadowed by fuel production savings, amounting to 1.8 gCO_2e/tkm respectively.

Since vehicle production, EOL, and component replacement emissions contribute so little towards the total reductions of FCEVs using 225 kW hydrogen, the changes when extending this service period from a 6-year to a 10-year TEO are very small. Although after 10 years of service both ZEV buses and trucks require more replacements, these emissions become very small when spread out over the total mileage and reported per unit-km. This is seen in the FS reductions of FCEV buses and trucks using 225 kW hydrogen in Figure 8-2 which fall by only 0.19 g oil eq/unit-km and 0.03 g oil eq/unit-km. It should also be noted that these reductions in emissions are also inclusive of increased vehicle production emissions and the omission of the fuel cell recycling credit, highlighting their minor impact. Under a longer TEO period of 10 years, these vehicles accumulate fewer lifetime miles as a larger portion of their life is spent operating under lower LCC mileage figures, so vehicle production emissions are spread out less. Since forklifts show the most significant difference between TEO mileage and base case mileage figures, these vehicles lose their reductions after 10 years of ownership.

Many of the findings for GWP are mirrored in Figure 8-2 in terms of FS as it shows very small changes in emissions per unit-km when extending the TEO from 6 to 10 years. FCEV buses using 225 kW hydrogen in Figure 8-2 show very minor reductions of 0.46 g oil eq/unit-km under a 6-year TEO, which changes to 0.27 g oil eq/unit-km after an extension to 10 years. Trucks, tippers, and refuse vehicles show either no or negligible changes in emissions over a 6 and 10 year TEO, similar to the GWP of refuse vehicles in Figure 8-1.

For all ICEVs (shown in Appendix 3), the changes in emissions per unit-km are negligible, staying almost identical to the base case. Since the fuel cycle is unaffected and ICEVs do not incur replacements, the only reductions originate from the absence of EOL emissions, whilst emissions rise from vehicle production per unit-km. Since the impact of these is very low and they also counteract each other, the reductions for ICEVs are negligible for the majority of vehicles. For ICEV forklifts which see the greatest change, because their mileage in the LCC fleet is much lower compared to base case than any other vehicle (at ~35% less), the increase in vehicle production emissions is greater, leading to additional emissions of 2.4 gCO_2e/unit-km under a 6 year TEO. This increases further to 4.5 gCO_2e/unit-km after a 10 year TEO as total emissions are spread over much fewer lifetime kilometres. A similar response is also seen by BEV and FCEV forklifts respectively.

Although not the focus of this section, in general the response of all BEVs to 6 or 10 year TEO is minor, with the largest saving being 2.6 gCO_2e/unit-km (for tippers) and the highest emission increase being 4.9 gCO_2e/unit-km (for forklifts). These results are given in Figure 12-1 and Figure 12-2 in Appendix 3 respectively. The response to a 6 year TEO is positive for buses, tippers, and refuse vehicles. This is because the reductions generated from fewer replacements and the exclusion of the EOL stage outweigh the increase in vehicle production emissions for these vehicles. After a 10 year TEO however, the reductions for buses disappears as vehicle production emissions become greater per unit-km, whereas for tippers and refuse vehicles these emissions do not change as the mileage in the LCC fleet is equal to that of the original base case. This is a similar pattern to the figures below for FCEV forklifts. As for BEV trucks, the response to the changes in conditions is negligible under both TEO scenarios.

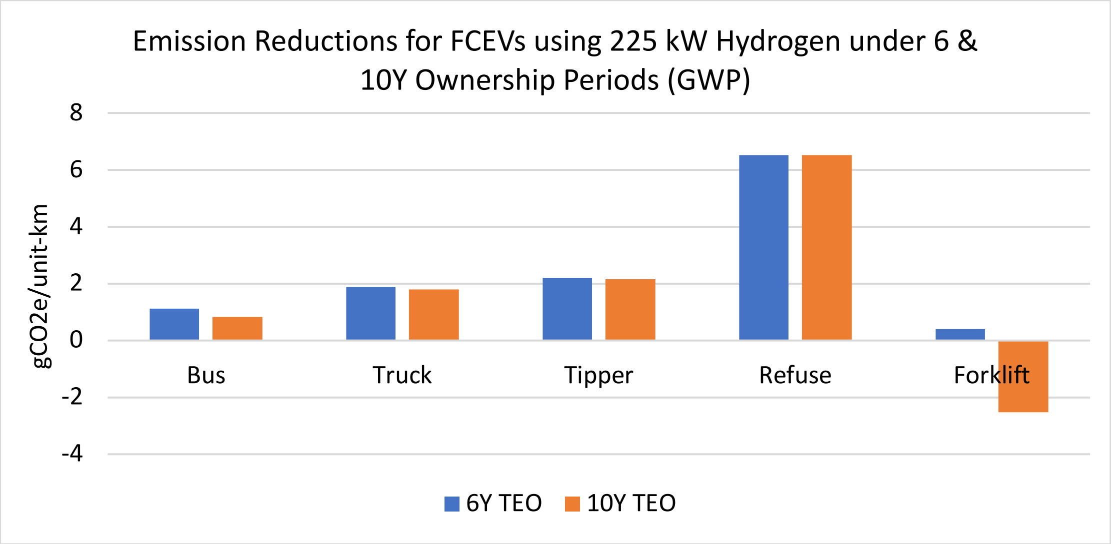


Figure 8-1 - Reductions for 225 kW H_2 under a 6 and 10-year TEO (compared to 15-year base case) (GWP).

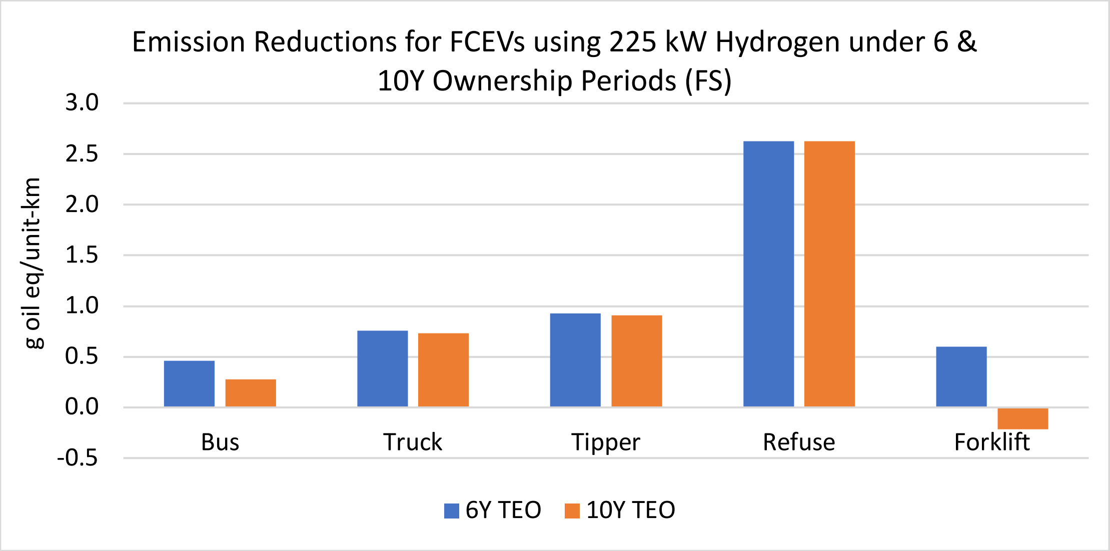


Figure 8-2 - Reductions for 225 kW H_2 under a 6 and 10-year TEO (compared to 15-year base case) (FS).

8.3.2. Particulate Matter:

The emission saved under a 6 and 10 year TEO compared to the 15 year base case are shown in Figure 8-3 and Figure 8-4 in terms of PM. In this case, many of the impacts are similar to those covered for GWP and FS, so this section aims to minimise repeating discussions where possible.

Firstly, the impact of a reduced lifetime mileage in both TEO scenarios has the same impact on PM as GWP and FS. As stated in the previous section, the reduced mileage means vehicle production emissions are spread out less so emissions increase per unit-km for those vehicle types which have lower annual mileages in the LCC fleet; namely buses, trucks, and forklifts. For tippers and refuse vehicles the vehicle production emissions remain the same, so the impact is zero.

From Figure 8-3 and Figure 8-4 the vast majority of vehicles using hydrogen fuels incur no reductions when operating in the fleet for 6 or 10 years. This is primarily because EOL emissions are excluded which were negative for FCEVs due to the recycling of the fuel cells, now leading to a significant loss in reductions. These emission reductions ranged from 2 to 11 mg$PM_{2.5}$e/unit-km and are now excluded, contributing towards a rise in emissions. Despite this, FCEVs using 225 kW hydrogen show lower emission rises in the two TEO scenarios compared to the other hydrogen fuels. This is for the same reason as GWP and FS covered previously; the fuel production emissions associated with this route are lower due to the reduction in grid demand. As a result, PM emissions fall by 10 mg $PM_{2.5}$e per kWh hydrogen production, equivalent to a 6% reduction from the base case.

When comparing Figure 8-3 and Figure 8-4 it is clear that emission reductions for buses, trucks, and forklifts fall when increasing the TEO from 6 to 10 years. This is for the same reasons as those mentioned in the previous section; the fewer lifetime kilometres that are accrued, the greater the vehicle production emissions are on a per km basis. For example, FCEV forklifts using 225 kW hydrogen under a 6 year TEO have reductions of -12.5

mg $PM_{2.5}$e/unit-km in Figure 8-3 and gradually fall even further to -20.3 mg $PM_{2.5}$e/unit-km after 10 years of service in Figure 8-4. This rise in emissions is most severe for forklifts as their mileage falls the most in the LCC fleet.

For BEV buses, tippers, and refuse vehicles, reductions are positive and range from 8-17 mg $PM_{2.5}$e/unit-km under a 6 year TEO. Since the annual mileage of buses in the LCC fleet is lower than the base case, these reductions are eliminated after a 10 year TEO and emissions rise by 7.8 mg $PM_{2.5}$e/unit-km respectively. Also, for these BEV buses, battery replacements are not required under a 6 year TEO as 200,000 km have not been accrued, resulting in a saving of 12 mg $PM_{2.5}$e/unit-km. However, after 10 years one replacement is needed which adds 13 mg $PM_{2.5}$e/unit-km, accounting for the majority of their emissions rise across a 6 and 10 year TEO. In this case, the increase from vehicle production accounts for only 1 mg $PM_{2.5}$e/unit-km.

For ZEV trucks, although they also benefit from fewer replacements, decreasing from 13 in the base case to just four in the 6 year TEO and seven in the 10 year TEO, their emission reductions do not change significantly from a 6 to a 10 year TEO. The reason for this is because their mileage decreases significantly in the LCC fleet and the contribution of emissions from the vehicle production stage counteracts this saving, so net changes are small.

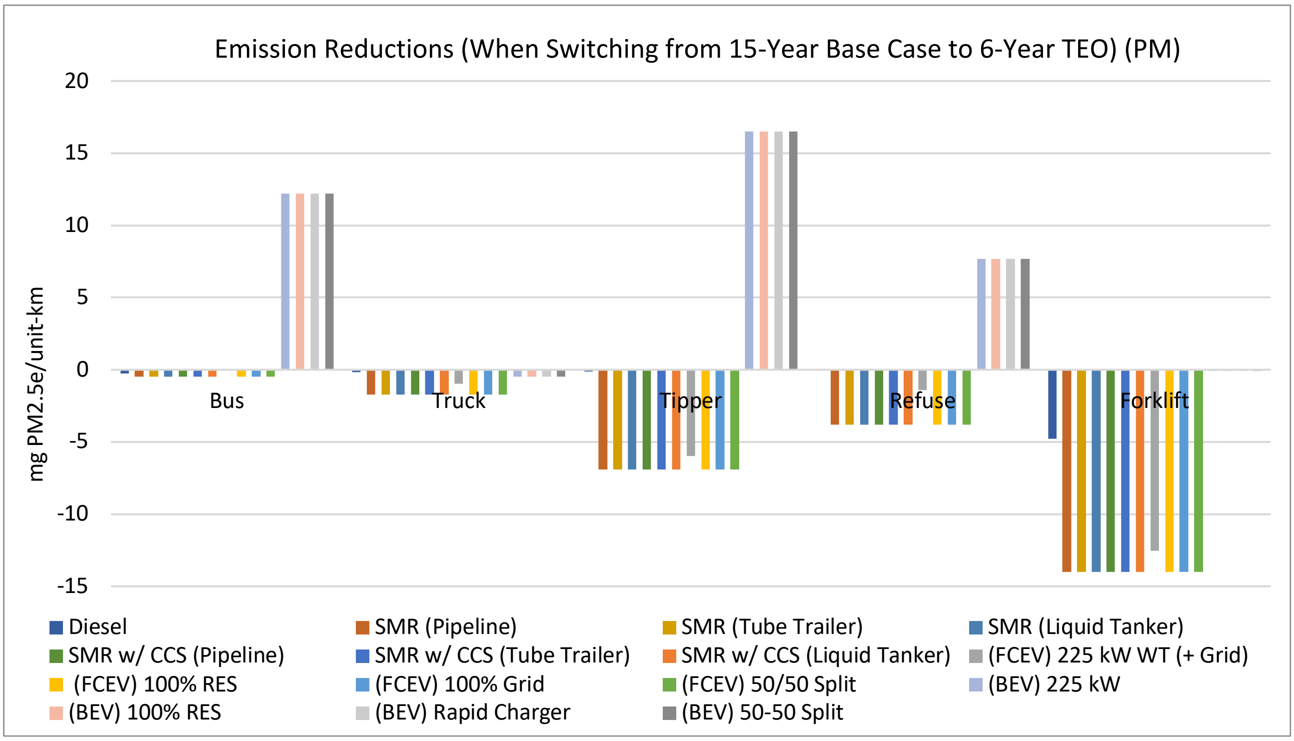


Figure 8-3 - Emission reductions generated under a 6-year TEO (compared to 15-year base case) (PM).

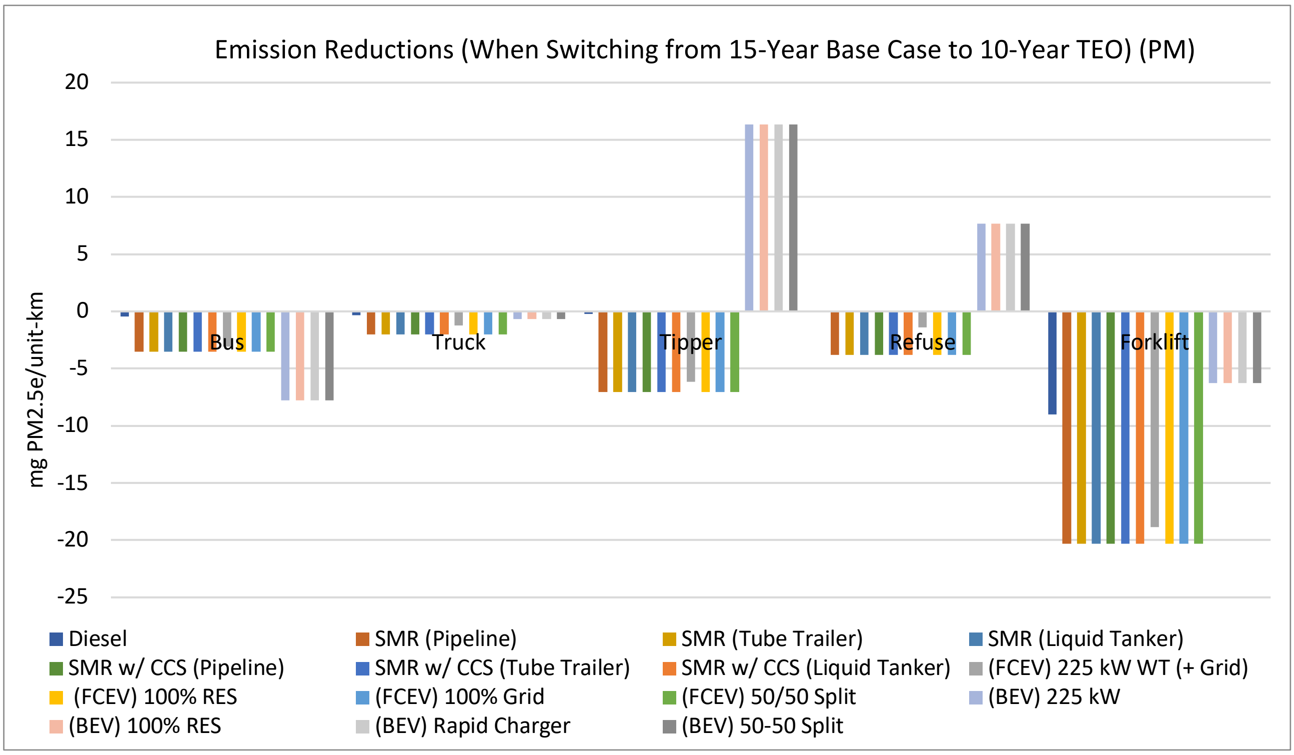


Figure 8-4 - Emission reductions generated under a 6-year TEO (compared to 15-year base case) (PM).

8.4. Chapter Summary:

This chapter presented the global warming and air pollutant emissions of vehicles operating for a fraction of their useful life in one specific fleet, using real mileage data recorded from UK councils. Results were presented from the perspective of a fleet owner and reported under two service period scenarios of 6 and 10 years respectively, with the vehicle EOL stage omitted. Analysis showed that for both the 6 and 10-year service period scenarios considered, all emission reductions when compared to the 15-year vehicle ownership period in Chapter 6 were attributed to up to four life cycle stages; fuel production, vehicle production, vehicle EOL, and component replacement.

Results showed that for the vast majority of the fuel scenarios, the emissions per unit-km under both the GWP and FS impact categories showed minimal changes across a 6 or 10-year service period when compared to the 15-year scenario in Chapter 6. The only fuel scenario to show a noticeable saving was 225 kW hydrogen. These reductions are attributed predominantly to the fuel production life cycle stage as the production emissions from this fuel are fleet-specific. As a result of using real council data from LCC, the annual mileage of the vehicles fell, therefore less hydrogen is consumed by the fleet which means the 225 kW turbine provides a greater portion of the total electricity needed for hydrogen production, and therefore less additional electricity is needed from the grid, lowering production emissions as a result. For PM, a greater number of fuel scenarios showed emission reductions compared to GWP and FS, though reductions associated with 225 kW hydrogen were now negative. For this impact category, the exclusion of the vehicle EOL stage meant FCEVs no longer benefitted from the recycling credits given to their fuel cells, so reductions were negative for the majority of hydrogen fuel scenarios.

9. Chapter 9 - Conclusions and Future Work

This chapter concludes the study by highlighting the key findings in relation to the research questions, aims, and objectives from Chapter 2. It also outlines the value and contributions of this study to the wider context of transport decarbonisation before reviewing limitations and providing recommendations for future work.

9.1. Research Findings:

Despite improvements in the carbon footprints of many sectors, transport still remains the largest emitter of carbon dioxide in the UK. Even with the help of a rapidly growing market of BEVs with zero tailpipe emissions, this sector has been stubborn in its efforts to decarbonise, showing consistently high emissions over several decades. As a result of this and the net zero targets which need to be achieved by 2050, the sector is facing increasing pressure to decarbonise. This is especially true in the heavy-duty sector where carbon emissions are disproportionately large and where diesel usage dominates due to current battery technology lacking suitability. To support the goal of reducing transport emissions, this work examines the potential of hydrogen FCEVs as a low carbon solution. Using both economical TCO and environmental LCA tools, FCEVs are compared to BEVs and ICEVs in on-road and off-road HDV applications from a general viewpoint as well as the perspective of a fleet owner to determine conditions under which hydrogen is most competitive. To support the conclusions and to remind the reader of the study's aims, the research questions are:

1. *Which parameters have the biggest influence on FCEV costs and emissions, and how does varying them alter FCEV competitiveness?*

2. *Can hydrogen offer a cost competitive solution to conventional fossil-based transport and how does it compare to electric vehicles?*

3. *Under what conditions will FCEVs become the most cost competitive transport solution, and how might their economics change between now and 2050?*

4. *Do FCEVs offer a significant benefit in terms of life cycle emissions compared to conventional diesel vehicles, and do they compete with electric vehicles both now and in the future?*

5. *How do the emissions from FCEVs compare when considering vehicle usage in one specific fleet?*

A selection of the key findings of the study are bulleted, with sub-level bullets providing additional details. The research question(s) that each statement addresses is given in brackets and the chapter that each sub-bullet relates to is also given. Following this, more topical findings from each individual chapter are given, respectively. Please note that these lists are not exhaustive.

- ***TCO is dominated by depreciation and fuel costs, whilst life cycle emissions are dominated by vehicle production, fuel production and conditioning, and component replacements. (RQ 1)***
  - Fuel costs contribute anywhere between 0-65% of the TCO, whilst depreciation accounts for 13-78%. Depreciation accounts for a lower portion of the TCO for vehicles with high annual mileage because their purchase costs are spread out over more kilometres. As a result, all other costs make up a larger portion of their TCO, with fuel being the largest in most cases. This finding is also true for the portion of life cycle emissions attributed to vehicle production, which is smaller for vehicles with high mileages. (Chapters 4 and 6)
  - Costs and emissions from component replacements (i.e. batteries and/or fuel cells) make up a significant portion of the total for ZEVs with high mileages, like long haul trucks. This is because these vehicles accrue 200,000 km the quickest, and this is the limit before replacements are needed. (Chapters 4 and 6)
  - Emissions from the fuel production stage account for a larger portion of the total emissions if the fuel in question is heavily reliant on (2022 UK mix) grid electricity, which has a high energy intensity (such as electricity from rapid chargers or 100% grid hydrogen). Other fuels generated from renewable sources have a lower contribution, therefore the impact of other stages becomes greater. (Chapter 6)

- ***The majority of FCEVs do not show cost competitiveness with ICEVs or BEVs in 2021. However, many FCEVs show environmental competitiveness against ICEVs and even a number of BEVs. (RQs 2 & 4)***
  - The only FCEVs which show cost competitiveness with ICEVs in 2021 are forklifts. Forklifts operating on any of the hydrogen fuel scenarios have lower costs than diesel, with the lowest TCO recorded at £0.52/km under 100% RES hydrogen, compared to £1.53/km using diesel. Despite this, TCO is lowest for BEV forklifts which reach costs of only £0.46/km (using 100% RES electricity). (Chapter 4)
  - FCEV cars are more sustainable than ICEV cars. Cars running on any hydrogen fuel show lower life cycle GWP and FS compared to diesel. Further, several of these hydrogen fuels offer lower GWP and FS than BEV cars, with the lowest figures coming from 100% RES hydrogen at just 66.2 gCO_2e/km and 19 g oil eq/km. (Chapter 6)
  - Several hydrogen fuels give a lower GWP for all the HDVs in this study compared to diesel. Fuels include 100% RES, SMR & CCS with pipelines, and SMR & CCS with tube trailers. (see Chapter 6)
  - FCEV cars, buses, and tippers using 100% RES hydrogen show the lowest GWP of all the fuels considered in the study with 66.2, 2.9, and 17.5 gCO_2e/unit-km respectively. These FCEVs are more sustainable than their ICEV and BEV counterparts. However, for trucks, refuse vehicles, and forklifts, the lowest GWP is seen when using battery electric powertrains (100% RES electricity). (Chapter 6)

- ***The use of hydrogen incentives and/or diesel deterrents improves the cost competitiveness of FCEVs, but generally BEVs still remain the lowest cost solutions overall. (RQs 2 & 3)*** (Chapter 4)
  - Implementing a fossil tax on ICEVs increases their TCO and indirectly makes FCEVs a more attractive solution. For example, under base case conditions with no fossil tax, no hydrogen buses show cost

competitiveness with diesel buses between 2021-2050. However, with a low fossil tax rate, FCEV buses operating on 100% RES hydrogen achieve parity in 2037. A high fossil tax rate now sees parity in 2027, along with two other hydrogen fuels (SMR with pipelines and SMR & CCS with pipelines) becoming cost competitive.

  - For most fuel scenarios, purchase grants do not significantly improve FCEV cost competitiveness. The only vehicles that show a significant change in the order of fuel competitiveness are cars and buses. The impact of either grant on the remaining FCEVs does not lead to any new fuel scenarios achieving parity with ICEVs in 2021. However, a high grant does cause the TCO of FCEV trucks using SMR hydrogen with pipelines to fall below BEV trucks using rapid chargers.

- ***For most fuels, 6 or 10-year vehicle service shows a negligible change in GWP and FS per unit-km compared to a 15-year lifetime. Only 225 kW hydrogen shows noticeable reductions. (RQ 5)*** (Chapter 8)
  - Since only hydrogen produced from a 225 kW turbine is 'fleet specific', its production emissions are influenced by the fleets hydrogen consumption and the demand for additional grid electricity. Therefore, when using annual mileage data from LCC in 6 or 10-year service periods, it leads to a reduction in total fleet mileage and lower hydrogen consumption compared to the 15-year base case, which used generic mileage figures. As a result, the turbine can provide a larger portion of the total hydrogen demand, reducing additional grid electricity required, leading to significant emission reductions.

In addition to these overall conclusions, some other findings from the economic analysis in Chapter 4 are:

- ***In 2021, the only FCEV that had a TCO competitive with diesel ICEVs was forklifts, whilst BEV buses, trucks, and forklifts had the lowest costs per km overall.***
- ***A low hydrogen price and a high purchase grant give all vehicles using 100% RES hydrogen a TCO below diesel. These tools give more vehicles and hydrogen fuels a TCO below their ICEV and BEV counterparts.***
- ***By 2050, the majority of hydrogen fuels will give FCEVs a lower TCO than diesel, but for most vehicle types, BEVs still remain the cheapest unless hydrogen-favourable conditions are implemented.***

Similarly, some other findings from the environmental analysis in Chapters 6 and 7 are:

- ***BEV trucks, refuse vehicles, and forklifts show the lowest life cycle GWP and FS when powered by 100% RES electricity, whilst cars, buses, and tippers show the lowest with 100% RES hydrogen.*** (Chapter 6)
- ***The lowest life cycle PM recorded for all HDV types comes from FCEVs.*** (Chapter 6)
- ***A future decarbonised grid mix noticeably reduces the life cycle emissions of FCEVs and leads to several vehicles having a lower GWP than their ICEV and BEV equivalents.*** (Chapter 7)

9.2. Contributions to Knowledge and Project Impact:

This work contributes to knowledge firstly by building upon and advancing existing research surrounding the wider area of transport decarbonisation, whilst simultaneously providing a detailed methodology that enables both fleet owners and policymakers to generate their own estimations of the costs and emissions of hydrogen solutions, offering a tool which could accelerate a transition to FCEVs.

This work is of high importance and is needed in the context of transport because both its slow rate of decarbonisation over the past several decades and the net zero target are now calling for new low carbon fuels to be introduced in replace of conventional ones. This is especially important for the HDV sector which currently operates almost exclusively with diesel fuel and does not show suitability with battery technology today, making it an area of particular concern. As a result, not only is it vital that studies are conducted to assess the effectiveness of solutions like hydrogen in reducing emissions, but they also need to be economically feasible otherwise they are unlikely to be adopted in time. Considering the ban on diesel vehicles which will begin in 2030 for LDVs and predicted for 2040 for HDVs, the potential of hydrogen as a solution needs to be researched quickly and extensively to support this transition and to prove to fleet owners and policymakers that the switch is a logical and worthy investment.

After conducting a literature review on the existing work focused on FCEV transport, much of the focus to date surrounds the on-road light duty sector, primarily because these vehicles are responsible for the majority of transport emissions. Although studies are available which focus on HDVs, these mostly consider on-road buses or trucks, with other HDVs and off-road vehicles often excluded. In addition, most studies examine the impacts of hydrogen on one vehicle type only and fail to consider a combination. Other limitations found in literature and gaps that this research targets includes the omission of vehicle production and EOL stages in many emission assessments, the use of data recorded from real working fleets, and the inclusion of a future outlook, for example. These are targeted to provide a new foundation which can be built upon in future studies. To the authors knowledge, the comparison and analysis of the economics and life cycle emissions of both on-road and off-road vehicles, 6 vehicle types, 3 powertrains, and 14 fuel scenarios offers a unique and novel contribution to the existing literature. This will provide a useful insight into the use of FCEVs in fleet applications, offering more information to fleet owners in the process which can be used as a basis for purchasing FCEVs. Further, policymakers may also gain a better understanding on the impacts that various financial tools can have on manipulating the economics of FCEVs and can use this to help encourage their uptake.

This work provides a thorough step-by-step description and breakdown of each individual cost element and emission stage and provides a detailed insight into the feasibility of hydrogen in HDV transport. Data can be easily adapted to give results which target other geographical locations or correspond to different fleet requirements for example, offering advantages over other works which omit specific details and lack flexibility, making them harder to replicate. As a result, this work could be used globally to provide the foundations of modelling a FCEV transition and then refined and expanded further to offer more tailored results based on the user requirements. In December 2022, the economic analysis in Chapter 4 was published in a research paper entitled *"A comparative total cost of ownership analysis of heavy duty on-road and off-road vehicles powered by hydrogen, electricity, and diesel"*. Despite this publication focusing on a UK scenario, it has been positively received in other countries as readers have contacted to offer their feedback, with a number of them highlighting their interest in the study and discussing the findings further. In addition, snippets of work have been published in university alumni magazines and posters have been presented to audiences with no hydrogen or transport related background, increasing the awareness of hydrogens potential in transport further. The feedback and conversations suggest that the work offers a strong contribution to the topic of transport decarbonisation and is not useful to just the UK but can in fact trigger discussion and influence the thoughts of industry experts and policymakers from all countries, supporting the movement of transport towards zero and low carbon solutions, which was one of the main goals of the study.

9.3. Limitations and Recommendations for Future Work:

This section begins by first bulleting several limitations that could be targeted to improve this work further. In addition to these, one of the advantages of this study lies in the fact that many of the conditions can be expanded and broadened further as more resources and information becomes available, offering more detailed insights, for example. As a result, some further recommendations are proposed which could present other areas of investigation and form the basis of new projects in the future. All suggestions may be directed towards the study as a whole or focused on one chapter in particular, targeting either the economic or environmental assessments of FCEVs, the sensitivity analysis of results, or the comparison of hydrogen with other low carbon fuel solutions.

Limitations identified include:

- **Vehicle Fuel/Energy Consumption:** Due to limited market availability, fuel consumption data for some ZEVs was estimated and therefore may not be an accurate representation of actual figures. These figures should be updated as new vehicles are brought to market. In addition, fuel consumption will vary constantly with dynamic driving conditions and vehicle payload, for example. Therefore, a variable fuel consumption could be used to take these into account and ensure more accurate estimates are calculated which more closely represent real world driving.

- **Sensitivity Analysis:** This could be expanded to explore the impacts of more variables on vehicle TCO and/or life cycle emissions. Chapters 4 and 7 examined five parameters but more could be added to improve their level of detail. For example, different battery chemistries, other diesel deterrents or FCEV grants, variable depreciation rates, SMR production efficiency, vehicle mileage, and on-site vs off-site fuel production.

- **Study Location:** This study is focused on a UK scenario but also provides a solid foundation for the estimation of vehicle costs and emissions in other geographical regions with methodologies that can be easily expanded and adapted. This would increase the accuracy of the results and make them more applicable to a wider audience. The inclusion of country-specific government grants and electricity grids for example, could add a new level of detail to both the analysis and discussions.

- **Non-Financial Costs:** Although TCO focuses on financial costs associated with owning and operating a vehicle or fleet, the work could be improved by making more effort to quantify wider non-financial costs and highlight their impacts. These may include payload losses from batteries, productivity losses due to charging times for BEVs, and changes to operating routes (and therefore mileage) based on the location of refuelling stations/charging points, for example.

- **Inventory and Vehicle Fleet Data:** For several ZEV types, since their market penetration is so low there are only a few vehicle models available which can be used as a reference for emissions assessment. Some ZEVs are not yet in operation, so their inventory data was not available in Ecoinvent and impossible to source in literature, and therefore had to be based on other vehicles with a similar performance. This impacts the accuracy of the results and if available in the future, more representative inventory data should be used. Other inventory databases could also be used which may have better availability. Similar to inventory data, the mileage data recorded from LCC and used was sourced for the 2018/2019 year to bypass any impacts of Covid-19 on fleet activity. The use of more recent data after 2020 would have given a less accurate representation of real fleet activity. As a result, it is recommended that the annual mileage data includes more recent figures not affected by the pandemic. In addition to the timeframe of the data, some mileage figures had to be sourced from other council fleets due to a lack of available information from LCC. Data for both long haul trucks and forklifts was sourced from Moray Council to overcome this issue. Therefore, it is recommended in the future that all mileage data is sourced from the same fleet as to minimise any inconsistencies.

- **BEV Payload Losses and Temperature Effects:** Currently, many HDV BEVs suffer from a loss in payload capacity as a result of their heavy batteries. This can negatively impact their productivity when operating in a fleet as more trips are required to transport the same amount of goods. Although not considered in the scope of this work, the LCA could be expanded further to consider the impact of these losses on emissions. This could be done by changing the functional unit to include the transport of goods. For example, "the transport of 1,000 bricks, each weighing 10 kg, over a distance of 100 km". Additionally, studies have shown that the efficiency of BEV batteries in cold weather can drop by as much as 50% [69]. As a result, it would be both interesting and valuable to consider this impact on the life cycle of BEVs since more electricity would be required to carry out the same functions and this could dramatically impact their competitiveness against FCEVs.

Areas for further investigation include:

- **Hydrogen Combustion as a Transport Solution:** This fuel scenario was not considered in this work due to a lack of evidence surrounding its performance and costs, largely due to current low maturity. However, as more research is conducted, the technology matures, and new data becomes available, the assessment of hydrogen combustion as a transport solution could be investigated.

- **Inclusion of Battery Recycling:** To date, only ~5% of batteries are recycled and so there are very few published studies which consider battery recycling in their system boundaries. This is largely due to a lack of available data as a result of the limited number of ZEVs being sent to scrappage today. Instead of recycling, batteries are often repurposed and used in other applications outside of transport, though this approach also presents issues surrounding safety as batteries are likely to require upgrading and refurbishment processes before being re-introduced into working life. Despite this, as a larger volume of ZEVs approach their EOL in the coming years, experience with treating used batteries will increase. Further, the recycling processes are expected to mature in the future due to the increased demand for cobalt recovery, which is the primary motivator for battery recycling. This presents an opportunity for further expansion as more information becomes available.

- **Additional Real-World Case Studies:** This work used data from LCC to estimate the costs and emissions associated with a mixed fleet of vehicles. However other fleets could be used to expand on these findings. For example, Liverpool recently introduced a new fleet of FCEV buses to their existing operations, whilst Aberdeen have a growing collection of FCEVs operating around the city which can provide a good foundation for further research. Recommendations in this case are made focusing on the HDV sector and long-distance freight applications which cannot currently operate to the same productivity or intensity using battery technology.

- **Expansion of TCO Using Policy Tools:** The TCO in Chapter 4 could be expanded further to consider the impacts of other tools on the cost competitiveness of both LDVs and HDVs in business fleets and their policy implications. The tools may include other grants and financial incentives or carbon taxes on ICEVs, for example. These tools vary from country to country so a range of conditions could be applied in this case to develop the analysis further and build on the insight provided in this study.

- **Creation of a Modelling Toolkit for Policymakers:** This work could provide the foundation for creating a modelling toolkit that could be used by policymakers and/or fleet owners to estimate their own costs and emissions based on their specific operating conditions. As further research is conducted and more data becomes available in the future, the development of a model could integrate COPERT, SimaPro, and Excel tools to simulate the economic and environmental position of different vehicle combinations under specific geographical locations and driving patterns entered by the user, based on their fleet requirements. This could be improved further by using sensitivity parameters and future predictions to generate suggestions on how to optimise fleet costs and improve the position of FCEVs further, increasing their uptake.

10. Appendix 1 – Total Cost of Ownership

10.1. Cost Component Breakdown:

Table 10-1 – TCO cost component breakdown for vehicles operating on diesel fuel.

	Diesel ICEV					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.11	£0.72	£0.12	£0.55	£0.68	£0.25
Fuel Cost	£0.11	£0.39	£0.31	£0.34	£0.34	£1.12
Maintenance	£0.06	£0.46	£0.05	£0.70	£0.26	£0.12
Component Replacement	£0.00	£0.00	£0.00	£0.00	£0.00	£0.00
Tax and Insurance	£0.03	£0.14	£0.03	£0.15	£0.15	£0.04
Total	£0.302	£1.701	£0.514	£1.739	£1.435	£1.525
%						
Depreciation	37.7%	42.1%	24.0%	31.8%	47.6%	16.2%
Fuel Cost	35.0%	22.7%	60.7%	19.5%	23.6%	73.2%
Maintenance	18.3%	27.1%	9.8%	40.1%	18.2%	7.9%
Component Replacement	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Tax and Insurance	8.9%	8.1%	5.5%	8.6%	10.6%	2.8%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-2 – TCO cost component breakdown for vehicles operating on hydrogen from SMR with TT.

	SMR with Tube Trailer (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.04	£0.42	£0.66	£0.49	£1.24	£0.68
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.412	£2.222	£1.072	£2.280	£3.531	£1.201
%						
Depreciation	52.4%	55.4%	15.2%	48.8%	50.8%	31.0%
Fuel Cost	8.5%	18.8%	61.6%	21.3%	35.1%	56.7%
Maintenance	9.4%	14.5%	3.3%	21.4%	5.2%	7.0%
Component Replacement	19.9%	1.6%	16.7%	0.0%	0.0%	0.0%

Tax and Insurance	9.7%	9.7%	3.2%	8.5%	8.9%	5.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-3 – TCO cost component breakdown for vehicles operating on hydrogen from SMR with LT.

	SMR with Liquid Tanker (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.04	£0.46	£0.72	£0.53	£1.35	£0.74
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.415	£2.260	£1.132	£2.324	£3.645	£1.263
%						
Depreciation	52.0%	54.4%	14.4%	47.8%	49.2%	29.4%
Fuel Cost	9.3%	20.1%	63.7%	22.8%	37.2%	58.8%
Maintenance	9.4%	14.3%	3.1%	21.0%	5.0%	6.6%
Component Replacement	19.7%	1.6%	15.8%	0.0%	0.0%	0.0%
Tax and Insurance	9.6%	9.6%	3.1%	8.3%	8.6%	5.1%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-4 - TCO cost component breakdown for vehicles operating on hydrogen from SMR with pipeline.

	SMR with Pipeline (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.01	£0.14	£0.23	£0.17	£0.42	£0.23
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.389	£1.947	£0.637	£1.959	£2.713	£0.752
%						
Depreciation	55.6%	63.2%	25.6%	56.8%	66.1%	49.4%
Fuel Cost	3.1%	7.3%	35.4%	8.5%	15.6%	30.8%
Maintenance	10.0%	16.6%	5.5%	24.9%	6.7%	11.1%
Component Replacement	21.1%	1.8%	28.1%	0.0%	0.0%	0.0%
Tax and Insurance	10.3%	11.1%	5.4%	9.9%	11.6%	8.6%

Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-5 – TCO cost component breakdown for vehicles operating on hydrogen from SMR & CCS with TT.

	SMR & CCS with Tube Trailer (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.04	£0.43	£0.68	£0.50	£1.27	£0.70
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.413	£2.231	£1.087	£2.291	£3.560	£1.217
%						
Depreciation	52.3%	55.1%	15.0%	48.5%	50.4%	30.6%
Fuel Cost	8.7%	19.1%	62.2%	21.7%	35.7%	57.2%
Maintenance	9.4%	14.5%	3.2%	21.3%	5.1%	6.9%
Component Replacement	19.9%	1.6%	16.5%	0.0%	0.0%	0.0%
Tax and Insurance	9.7%	9.7%	3.2%	8.5%	8.8%	5.3%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-6 – TCO cost component breakdown for vehicles operating on hydrogen from SMR & CCS with LT.

	SMR & CCS with Liquid Tanker (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.04	£0.47	£0.74	£0.54	£1.38	£0.76
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.416	£2.270	£1.148	£2.336	£3.674	£1.279
%						
Depreciation	51.9%	54.2%	14.2%	47.6%	48.8%	29.1%
Fuel Cost	9.4%	20.5%	64.2%	23.2%	37.7%	59.3%
Maintenance	9.3%	14.2%	3.1%	20.9%	5.0%	6.6%
Component Replacement	19.7%	1.5%	15.6%	0.0%	0.0%	0.0%
Tax and Insurance	9.6%	9.5%	3.0%	8.3%	8.5%	5.1%

Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-7 – TCO cost component breakdown for vehicles operating on hydrogen from CCS with pipeline.

	SMR & CCS with Pipeline (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.01	£0.15	£0.24	£0.18	£0.45	£0.25
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.389	£1.957	£0.652	£1.971	£2.742	£0.768
%						
Depreciation	55.4%	62.9%	24.9%	56.4%	65.4%	48.4%
Fuel Cost	3.3%	7.8%	36.9%	9.0%	16.5%	32.3%
Maintenance	10.0%	16.5%	5.4%	24.8%	6.7%	10.9%
Component Replacement	21.0%	1.8%	27.5%	0.0%	0.0%	0.0%
Tax and Insurance	10.3%	11.1%	5.3%	9.8%	11.4%	8.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-8 – TCO cost component breakdown for vehicles operating on hydrogen from 225 kW electrolysis.

	Electrolysis - 225 kW Turbine (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.04	£0.49	£0.77	£0.57	£1.46	£0.80
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.418	£2.294	£1.186	£2.364	£3.746	£1.319
%						
Depreciation	51.7%	53.6%	13.7%	47.0%	47.9%	28.2%
Fuel Cost	9.9%	21.3%	65.3%	24.1%	38.9%	60.5%
Maintenance	9.3%	14.1%	3.0%	20.6%	4.9%	6.4%
Component Replacement	19.6%	1.5%	15.1%	0.0%	0.0%	0.0%
Tax and Insurance	9.6%	9.4%	2.9%	8.2%	8.4%	4.9%

Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-9 – TCO cost component breakdown for vehicles operating on hydrogen from 50-50 split.

	Electrolysis - 50-50 Split (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.03	£0.38	£0.60	£0.44	£1.13	£0.62
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.409	£2.186	£1.015	£2.238	£3.425	£1.142
%						
Depreciation	52.8%	56.3%	16.0%	49.7%	52.4%	32.5%
Fuel Cost	7.9%	17.4%	59.5%	19.9%	33.1%	54.4%
Maintenance	9.5%	14.8%	3.5%	21.8%	5.3%	7.3%
Component Replacement	20.0%	1.6%	17.6%	0.0%	0.0%	0.0%
Tax and Insurance	9.8%	9.9%	3.4%	8.7%	9.2%	5.7%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-10 – TCO cost component breakdown for vehicles operating on hydrogen from 100% RES.

	Electrolysis - 100% RES (FCEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.22	£1.23	£0.16	£1.11	£1.79	£0.37
Fuel Cost	£0.01	£0.15	£0.23	£0.17	£0.44	£0.24
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.08	£0.04	£0.18	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.22	£0.03	£0.19	£0.31	£0.06
Total	£0.389	£1.952	£0.644	£1.965	£2.728	£0.760
%						
Depreciation	55.5%	63.0%	25.2%	56.6%	65.8%	48.9%
Fuel Cost	3.2%	7.5%	36.2%	8.7%	16.0%	31.6%
Maintenance	10.0%	16.5%	5.4%	24.8%	6.7%	11.0%
Component Replacement	21.1%	1.8%	27.8%	0.0%	0.0%	0.0%
Tax and Insurance	10.3%	11.1%	5.4%	9.9%	11.5%	8.5%

Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-11 – TCO cost component breakdown for vehicles operating on electricity from 225 kW turbine.

	Electricity - 225 kW Turbine (BEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.21	£0.82	£0.09	£1.09	£1.59	£0.32
Fuel Cost	£0.00	£0.00	£0.00	£0.00	£0.00	£0.00
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.05	£0.14	£0.20	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.15	£0.03	£0.19	£0.28	£0.06
Total	£0.339	£1.431	£0.349	£1.772	£2.054	£0.464
%						
Depreciation	62.2%	57.0%	24.6%	61.5%	77.5%	69.5%
Fuel Cost	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Maintenance	11.4%	22.6%	10.0%	27.5%	8.9%	18.1%
Component Replacement	14.6%	9.8%	57.9%	0.0%	0.0%	0.0%
Tax and Insurance	11.8%	10.6%	7.4%	10.9%	13.6%	12.4%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-12 – TCO cost component breakdown for vehicles operating on electricity from 50-50 split.

	Electricity - 50-50 Split (BEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.21	£0.82	£0.09	£1.09	£1.59	£0.32
Fuel Cost	£0.01	£0.06	£0.08	£0.10	£0.10	£0.17
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.05	£0.14	£0.20	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.15	£0.03	£0.19	£0.28	£0.06
Total	£0.352	£1.487	£0.429	£1.876	£2.157	£0.634
%						
Depreciation	59.9%	54.9%	20.0%	58.1%	73.7%	50.9%
Fuel Cost	3.6%	3.8%	18.6%	5.5%	4.8%	26.8%
Maintenance	11.0%	21.7%	8.2%	26.0%	8.5%	13.2%
Component Replacement	14.1%	9.5%	47.1%	0.0%	0.0%	0.0%
Tax and Insurance	11.3%	10.2%	6.0%	10.3%	13.0%	9.1%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-13 – TCO cost component breakdown for vehicles operating on electricity from 100% RES.

	Electricity - 100% RES (BEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.21	£0.82	£0.09	£1.09	£1.59	£0.32
Fuel Cost	£0.00	£0.01	£0.02	£0.02	£0.02	£0.03
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.05	£0.14	£0.20	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.15	£0.03	£0.19	£0.28	£0.06
Total	£0.342	£1.442	£0.365	£1.793	£2.075	£0.498
%						
Depreciation	61.7%	56.6%	23.5%	60.8%	76.7%	64.7%
Fuel Cost	0.8%	0.8%	4.4%	1.2%	1.0%	6.9%
Maintenance	11.4%	22.4%	9.6%	27.2%	8.8%	16.8%
Component Replacement	14.5%	9.8%	55.4%	0.0%	0.0%	0.0%
Tax and Insurance	11.7%	10.5%	7.1%	10.8%	13.5%	11.5%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 10-14 – TCO cost component breakdown for vehicles operating on electricity from a rapid charger.

	Electricity - Rapid Charger (BEV)					
(£/km)	Car	Bus	Truck	Tipper	Refuse	Forklift
Depreciation	£0.21	£0.82	£0.09	£1.09	£1.59	£0.32
Fuel Cost	£0.04	£0.17	£0.24	£0.31	£0.31	£0.51
Maintenance	£0.04	£0.32	£0.04	£0.49	£0.18	£0.08
Component Replacement	£0.05	£0.14	£0.20	£0.00	£0.00	£0.00
Tax and Insurance	£0.04	£0.15	£0.03	£0.19	£0.28	£0.06
Total	£0.377	£1.599	£0.589	£2.084	£2.366	£0.974
%						
Depreciation	55.9%	51.0%	14.6%	52.3%	67.3%	33.1%
Fuel Cost	10.2%	10.5%	40.7%	15.0%	13.2%	52.3%
Maintenance	10.3%	20.2%	5.9%	23.4%	7.7%	8.6%
Component Replacement	13.1%	8.8%	34.3%	0.0%	0.0%	0.0%
Tax and Insurance	10.6%	9.5%	4.4%	9.3%	11.8%	5.9%
Total	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

10.2. Sensitivity Analysis Common Parameters (£/km):

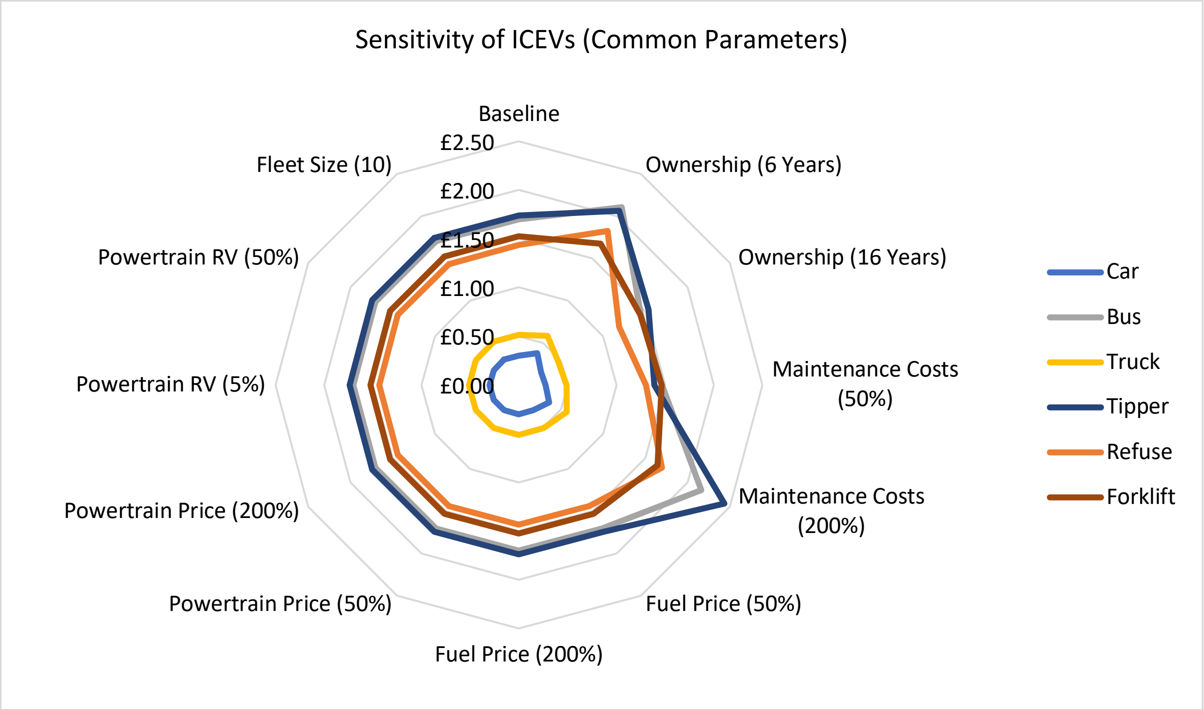


Figure 10-1 - Sensitivity of ICEVs to changes in common parameters.

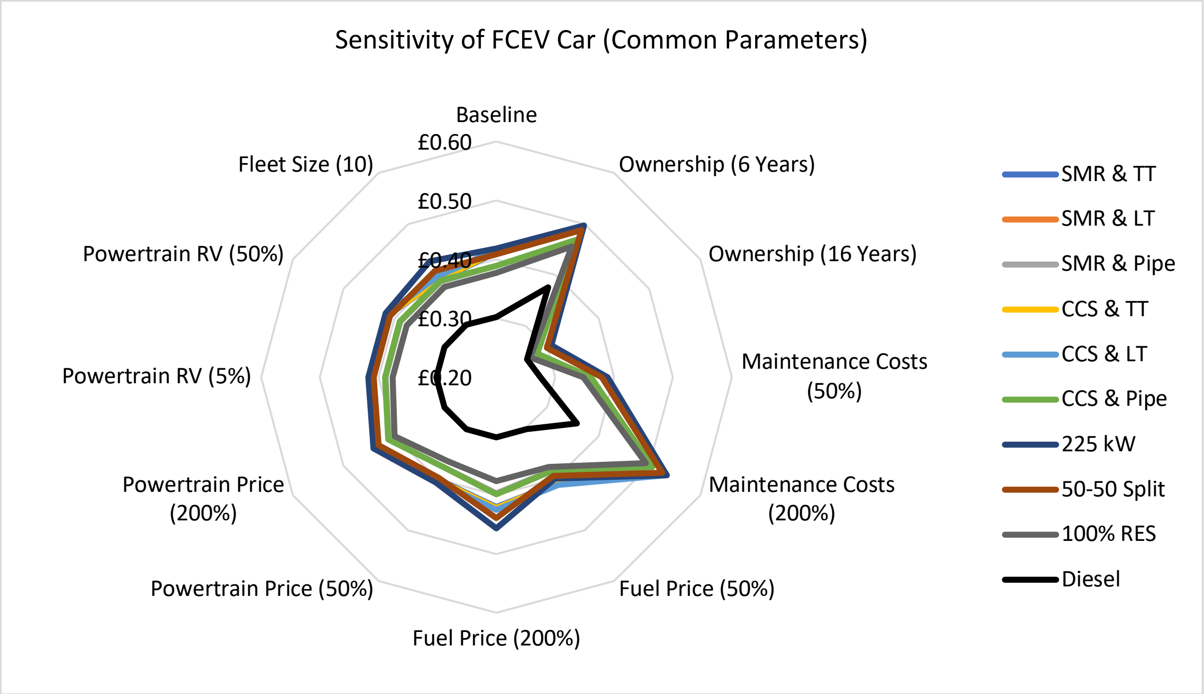


Figure 10-2 – Sensitivity of FCEV car TCO to changes in common parameters.

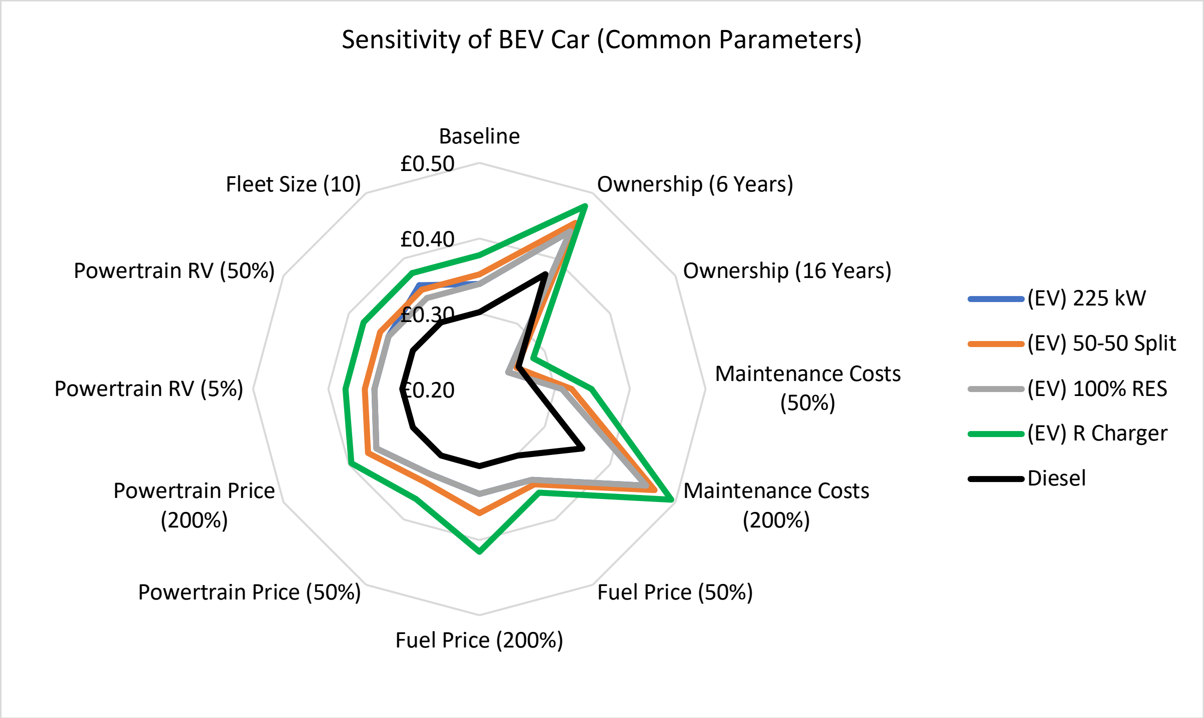


Figure 10-3 – Sensitivity of BEV car TCO to changes in common parameters.

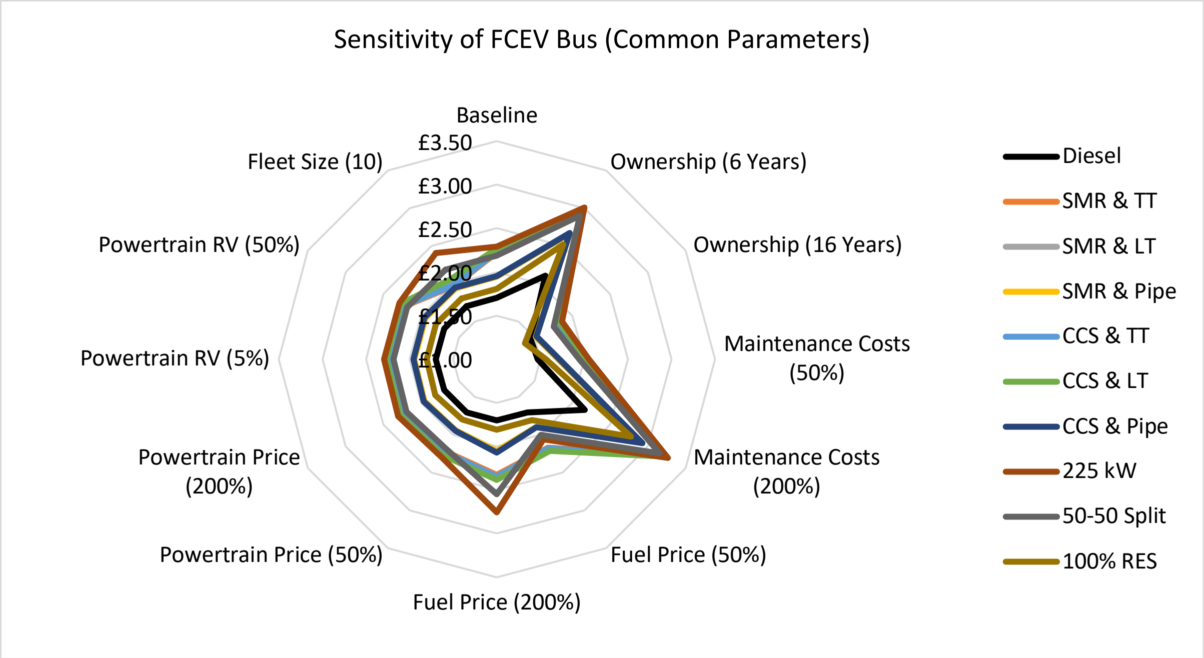


Figure 10-4 – Sensitivity of FCEV bus TCO to changes in common parameters.

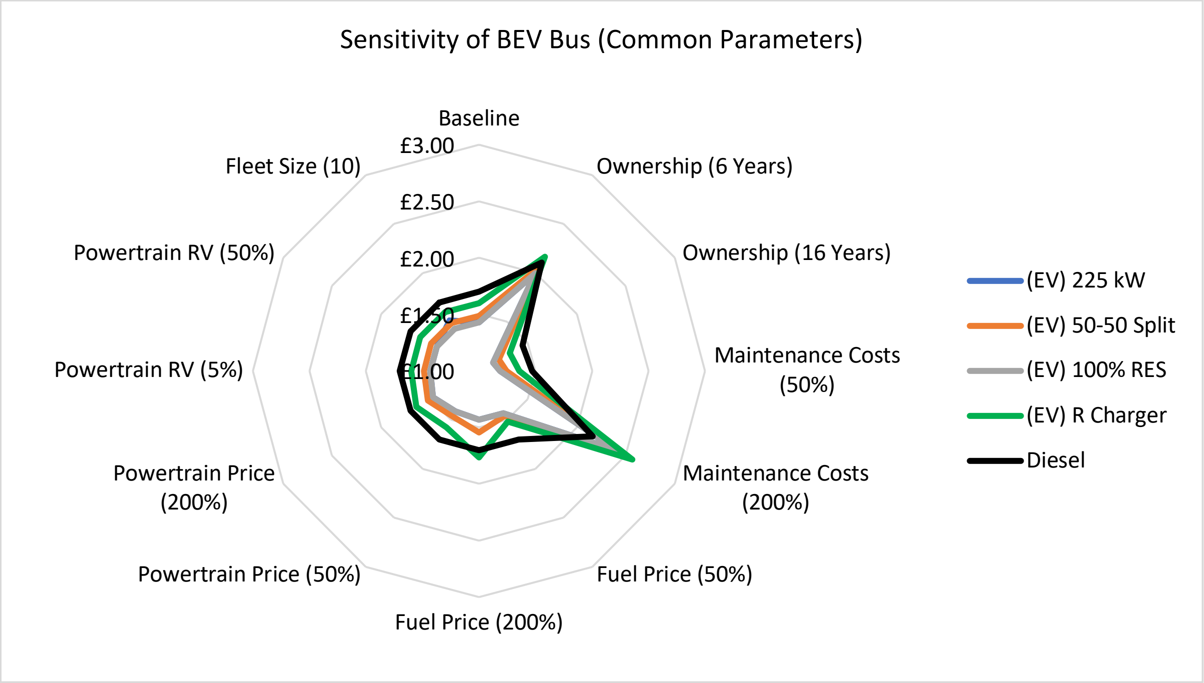


Figure 10-5 – Sensitivity of BEV bus TCO to changes in common parameters.

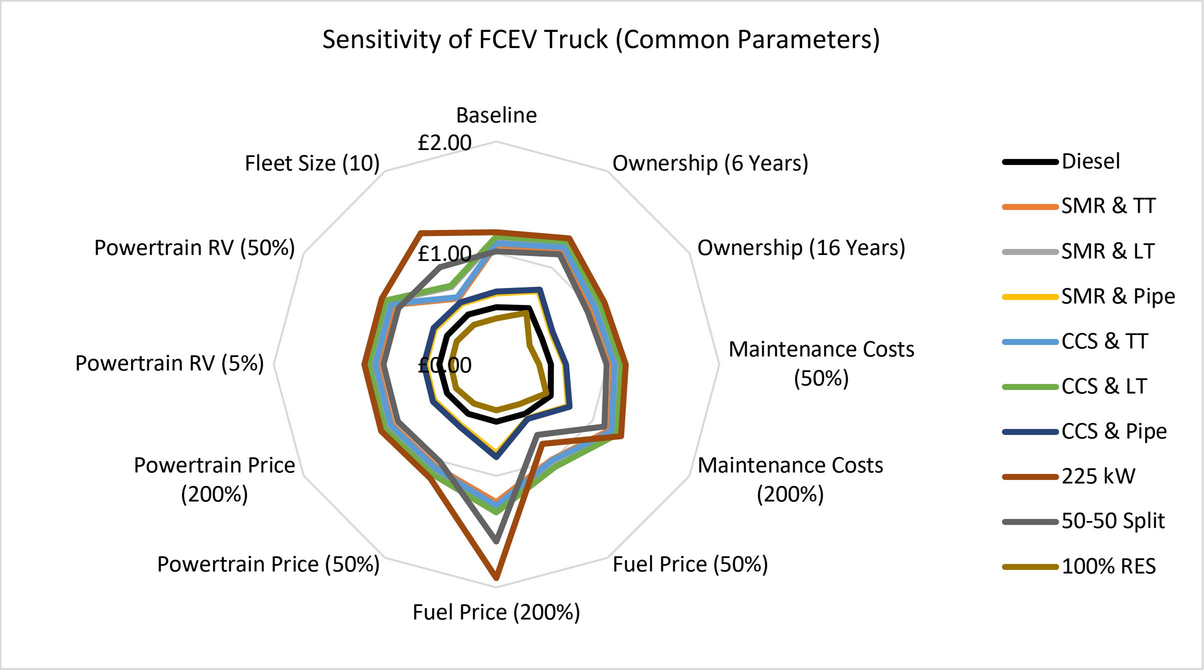


Figure 10-6 – Sensitivity of FCEV truck TCO to changes in common parameters.

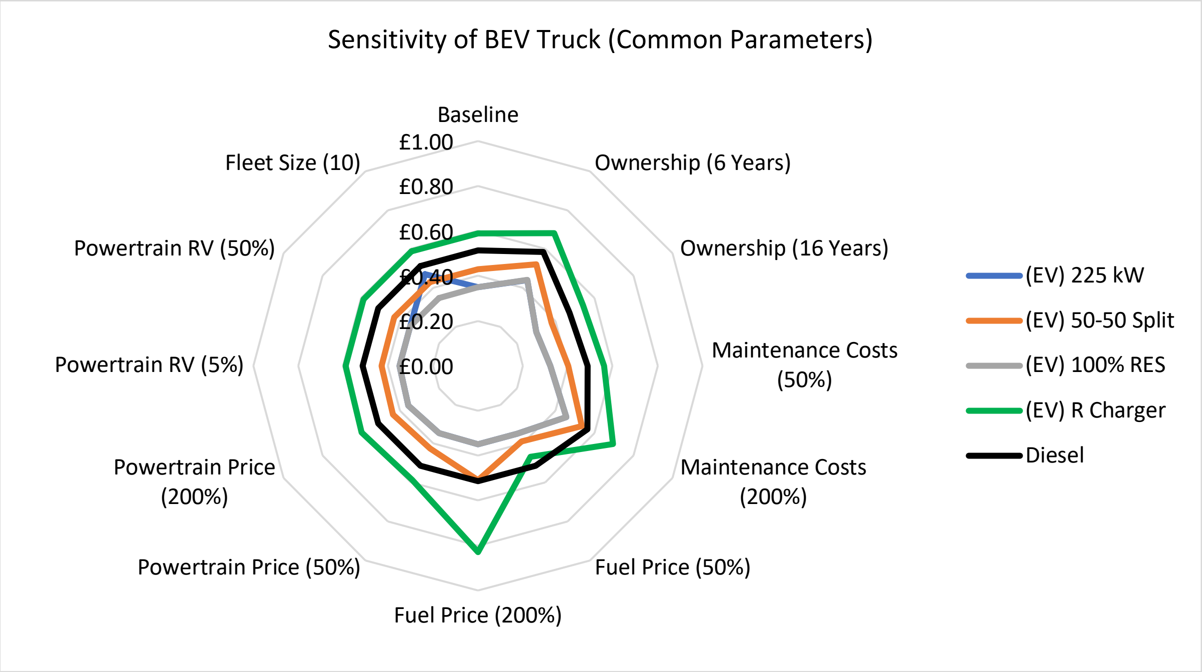


Figure 10-7 – Sensitivity of BEV truck TCO to changes in common parameters.

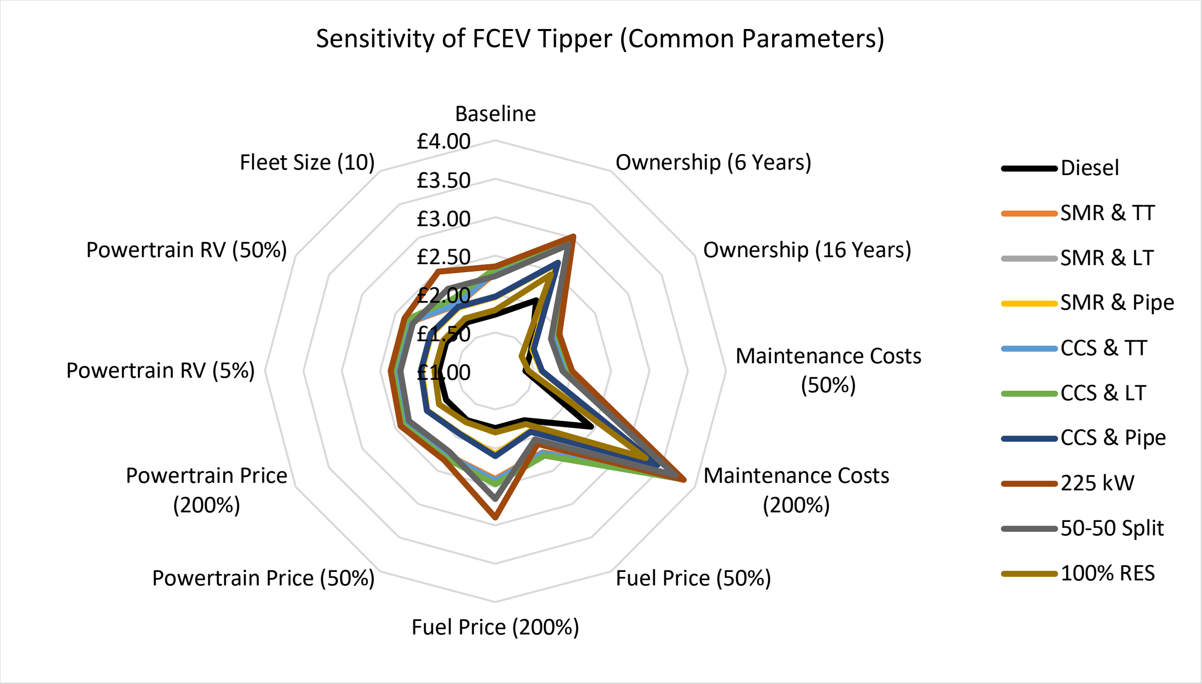


Figure 10-8 – Sensitivity of FCEV tipper TCO to changes in common parameters.

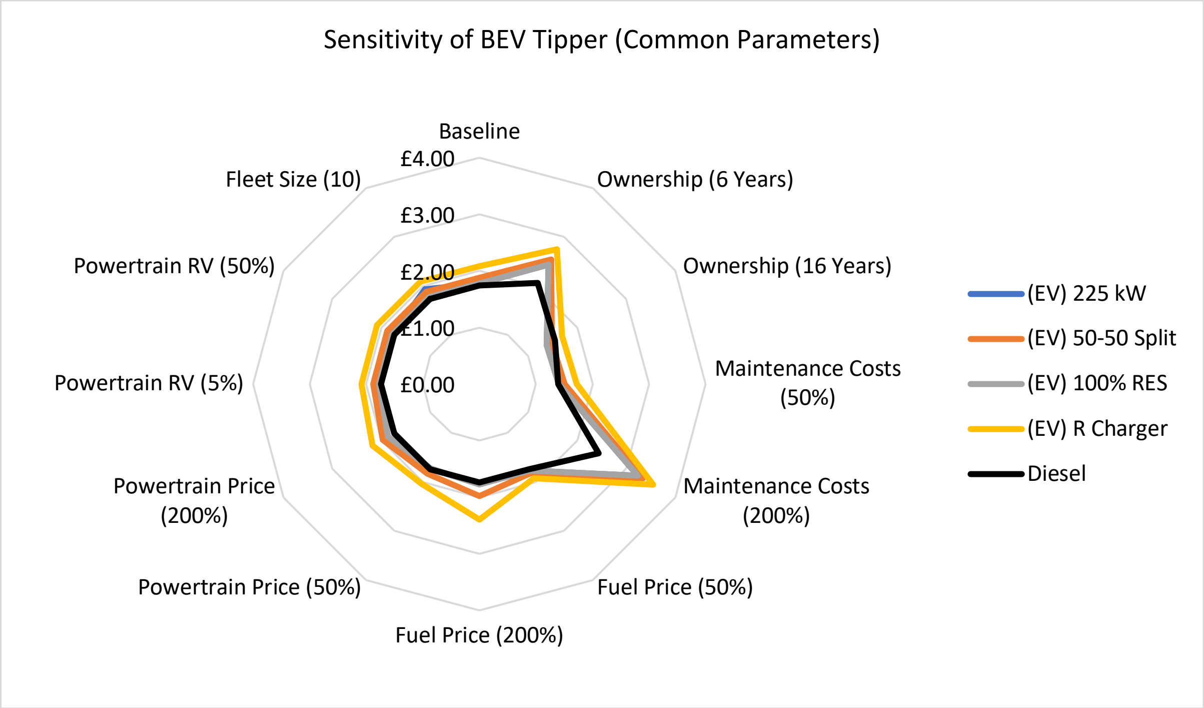


Figure 10-9 – Sensitivity of BEV tipper TCO to changes in common parameters.

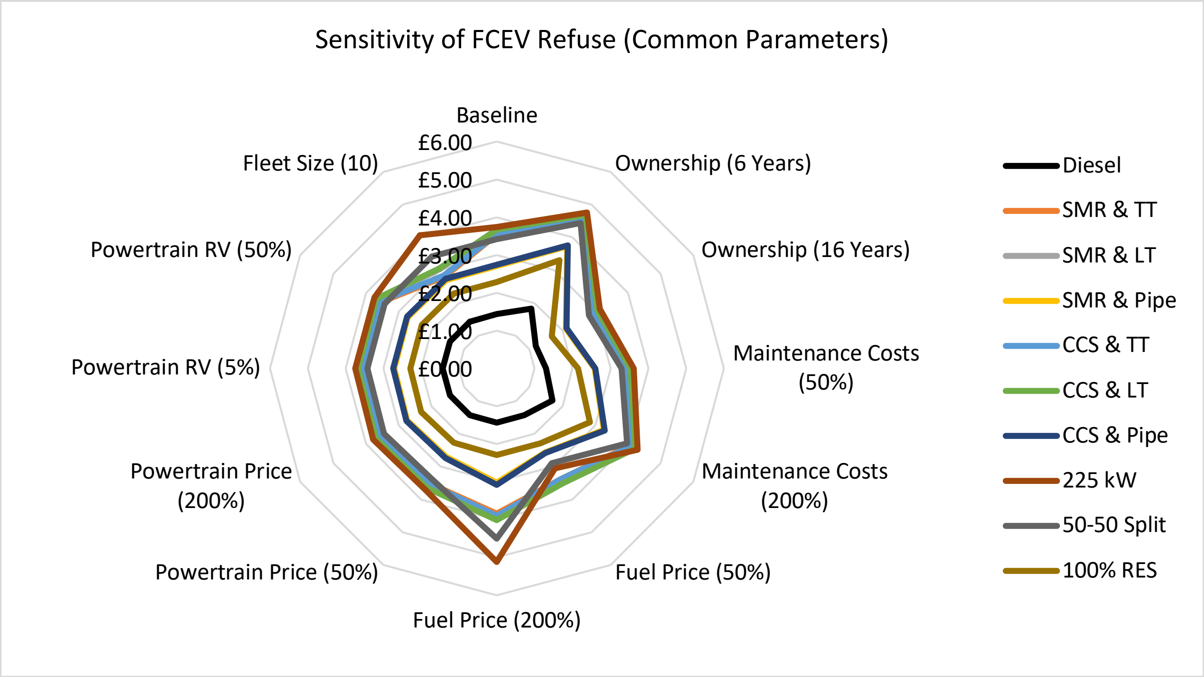


Figure 10-10 – Sensitivity of FCEV refuse TCO to changes in common parameters.

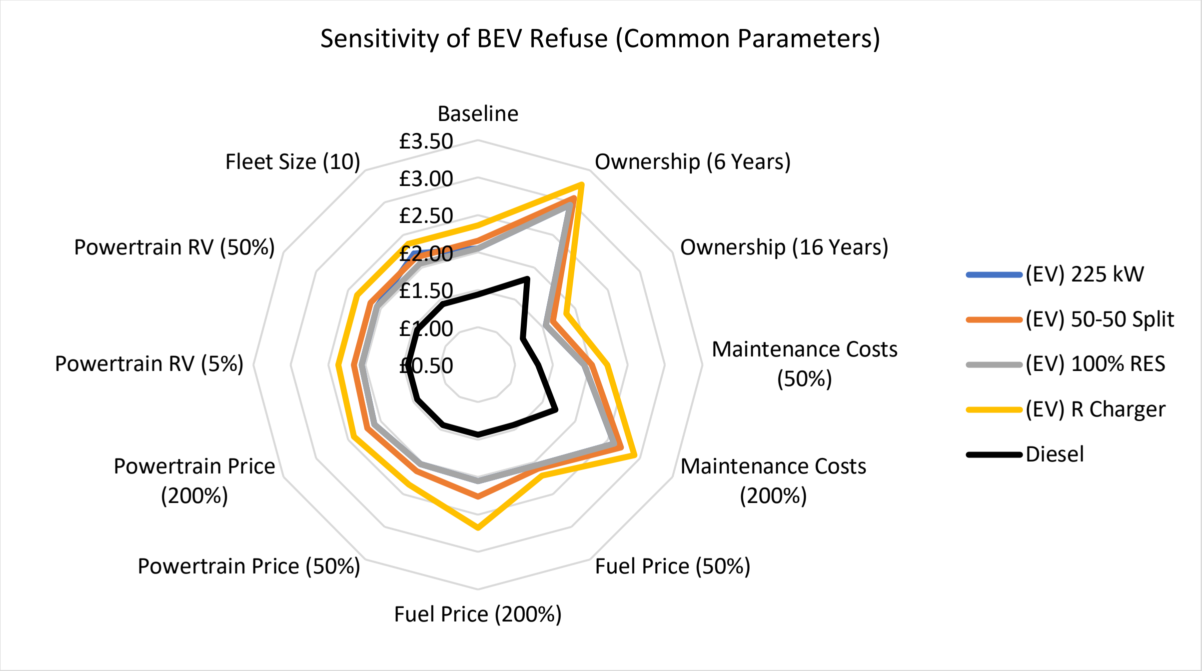


Figure 10-11 – Sensitivity of BEV refuse TCO to changes in common parameters.

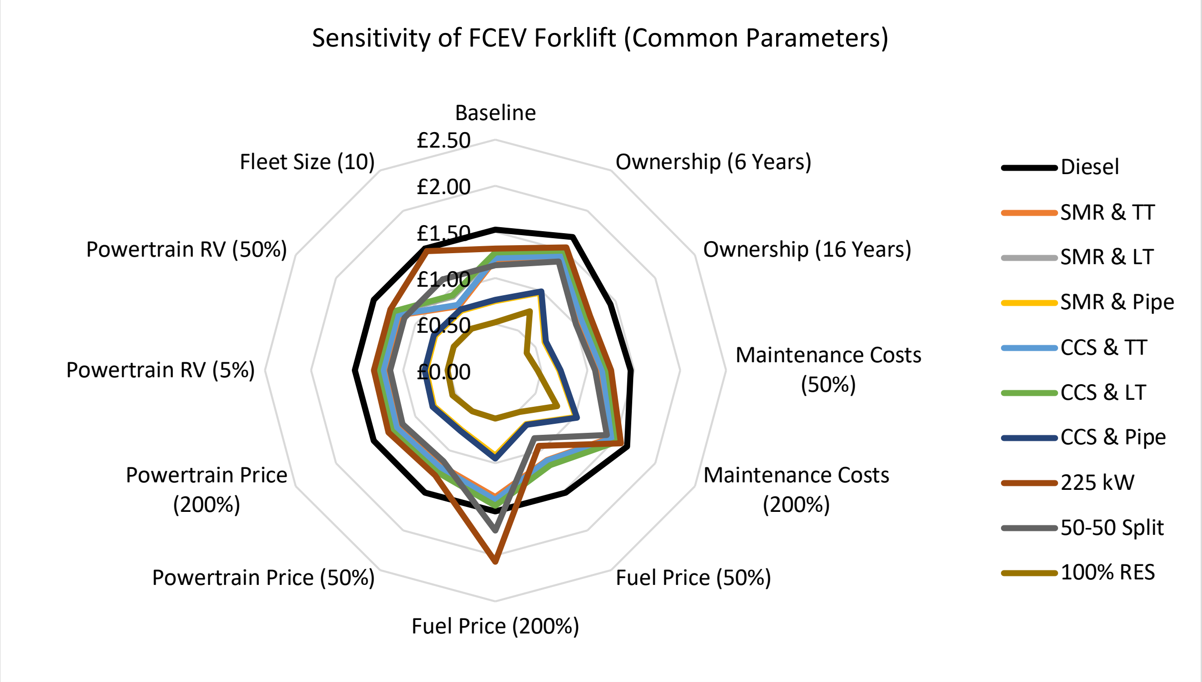


Figure 10-12 - Sensitivity of FCEV forklift TCO to changes in common parameters.

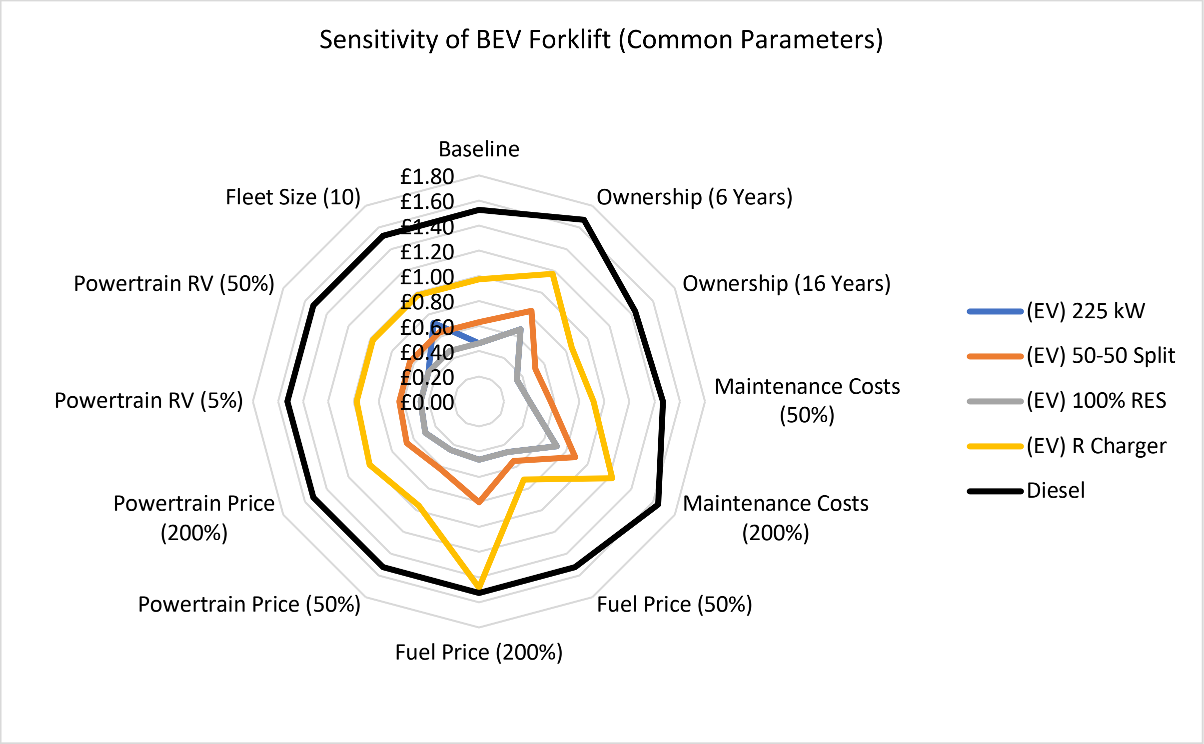


Figure 10-13 - Sensitivity of BEV forklift TCO to changes in common parameters.

10.3. Sensitivity Analysis Fuel-Specific Parameters (£/km):

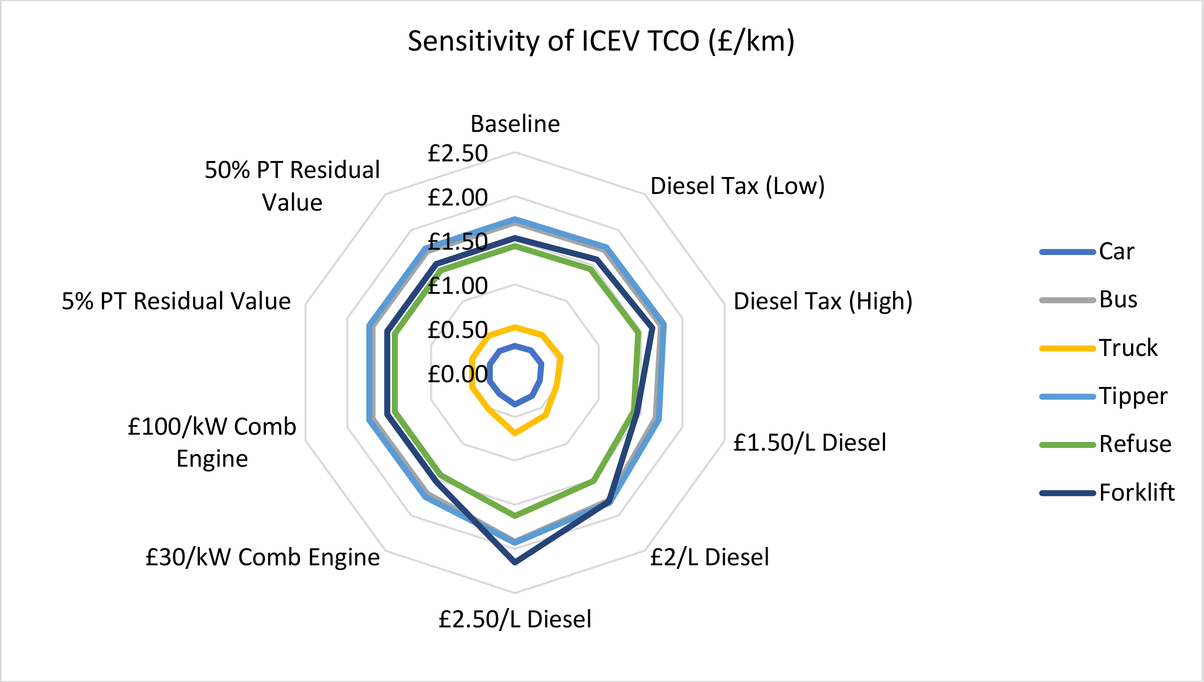


Figure 10-14 - Sensitivity of ICEV TCO to changes in fuel specific parameters.

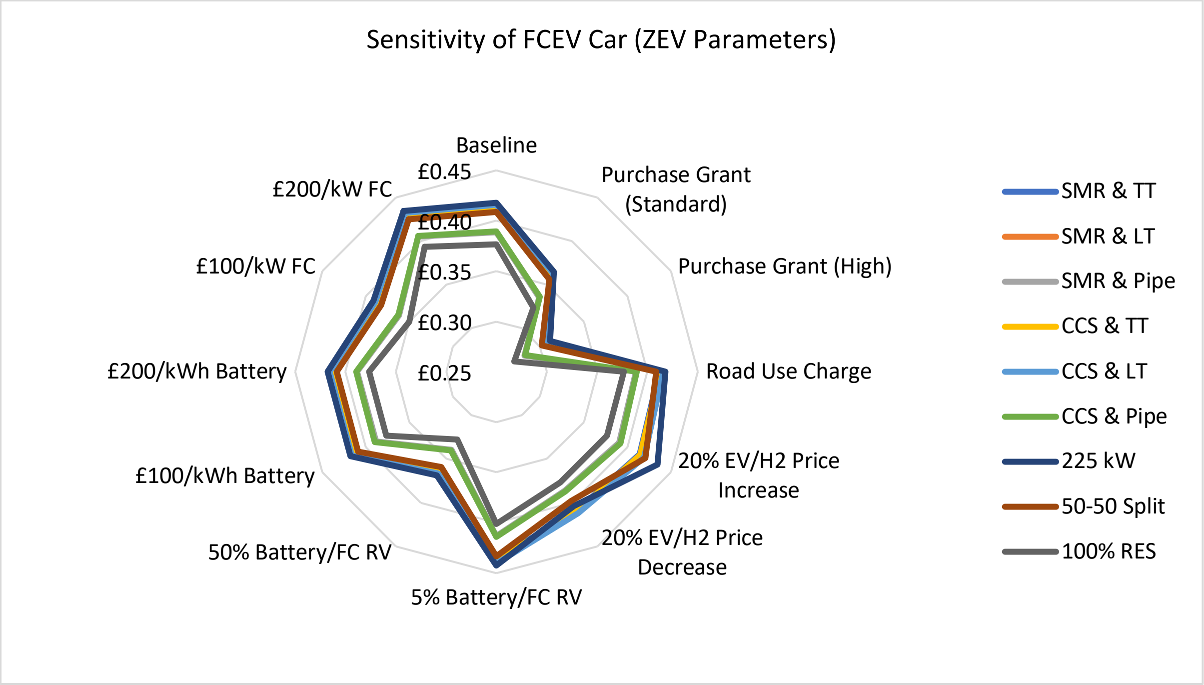


Figure 10-15 – Sensitivity of FCEV car TCO to fuel-specific parameters.

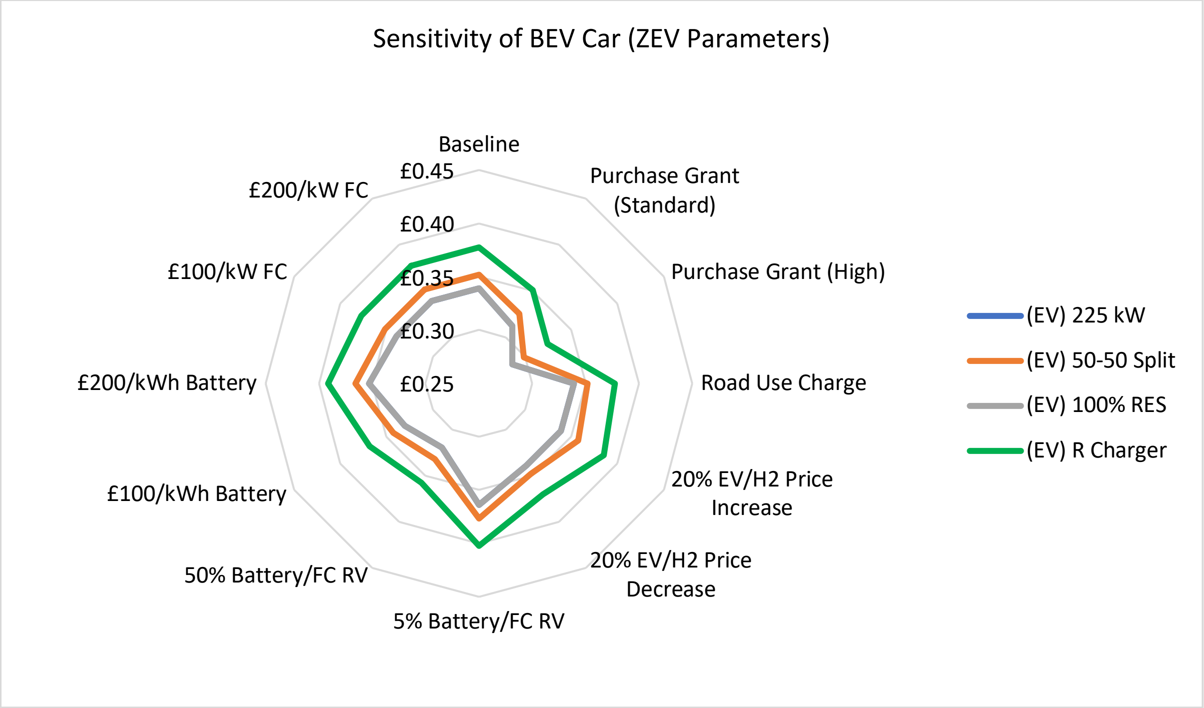


Figure 10-16 – Sensitivity of BEV car TCO to fuel-specific parameters (225 kW same as 100% RES).

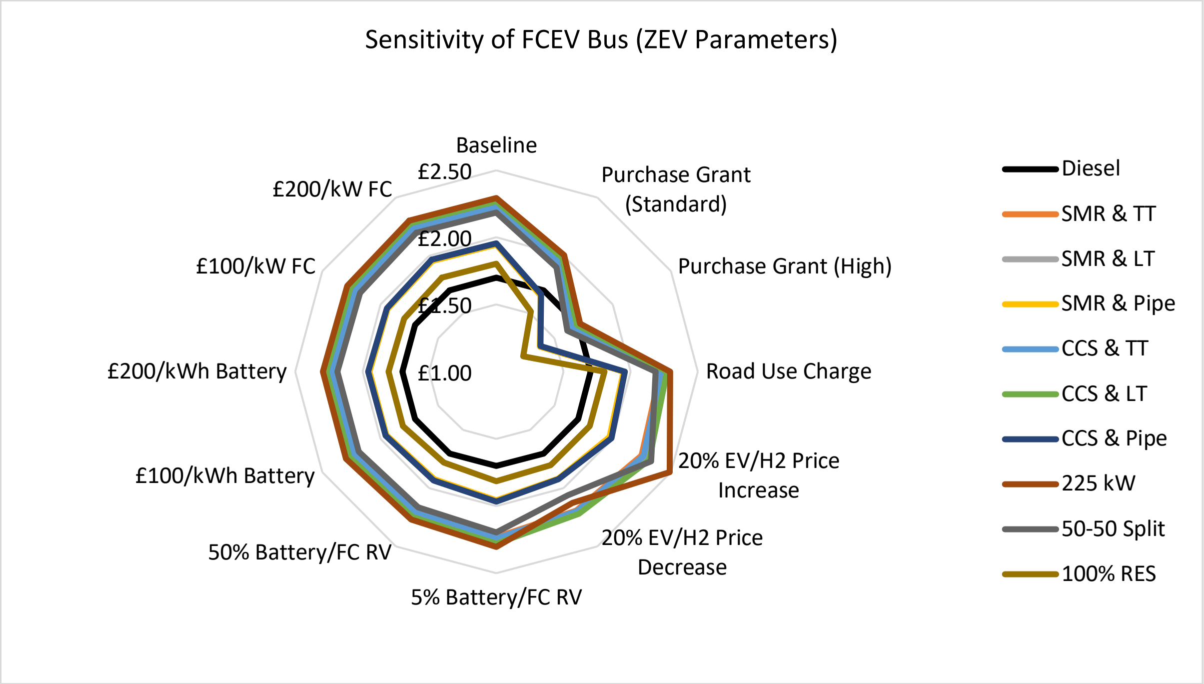


Figure 10-17 – Sensitivity of FCEV bus TCO to fuel-specific parameters.

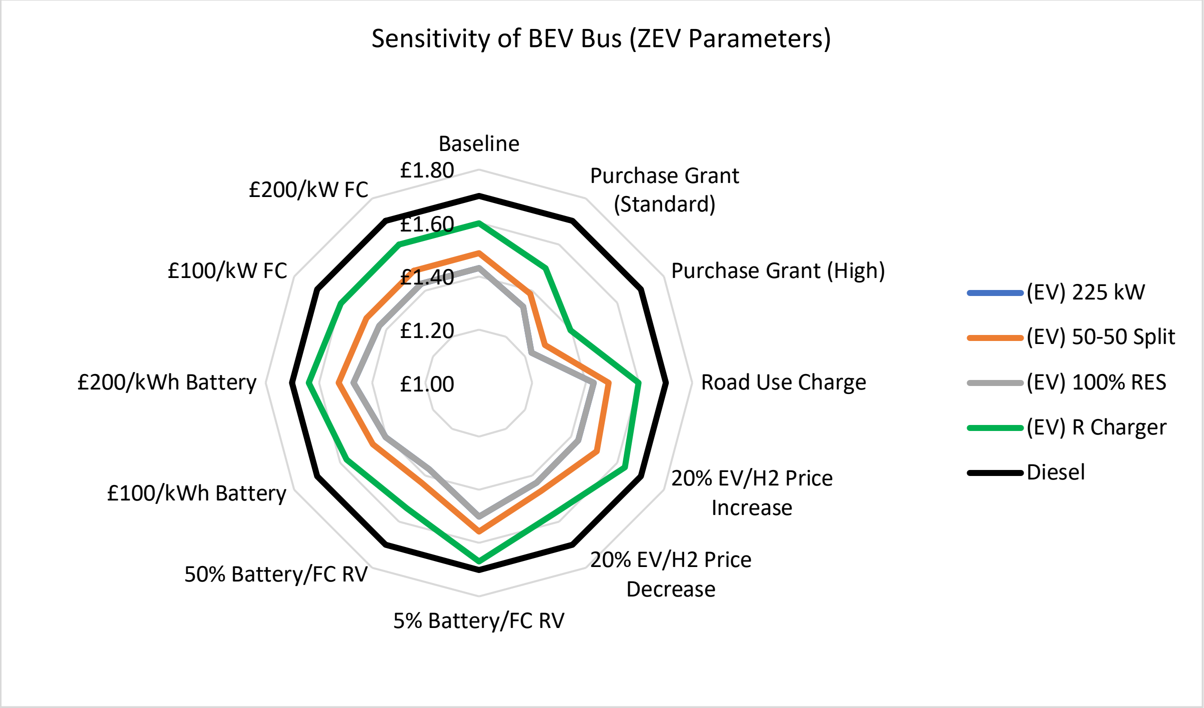


Figure 10-18 – Sensitivity of BEV bus TCO to fuel-specific parameters.

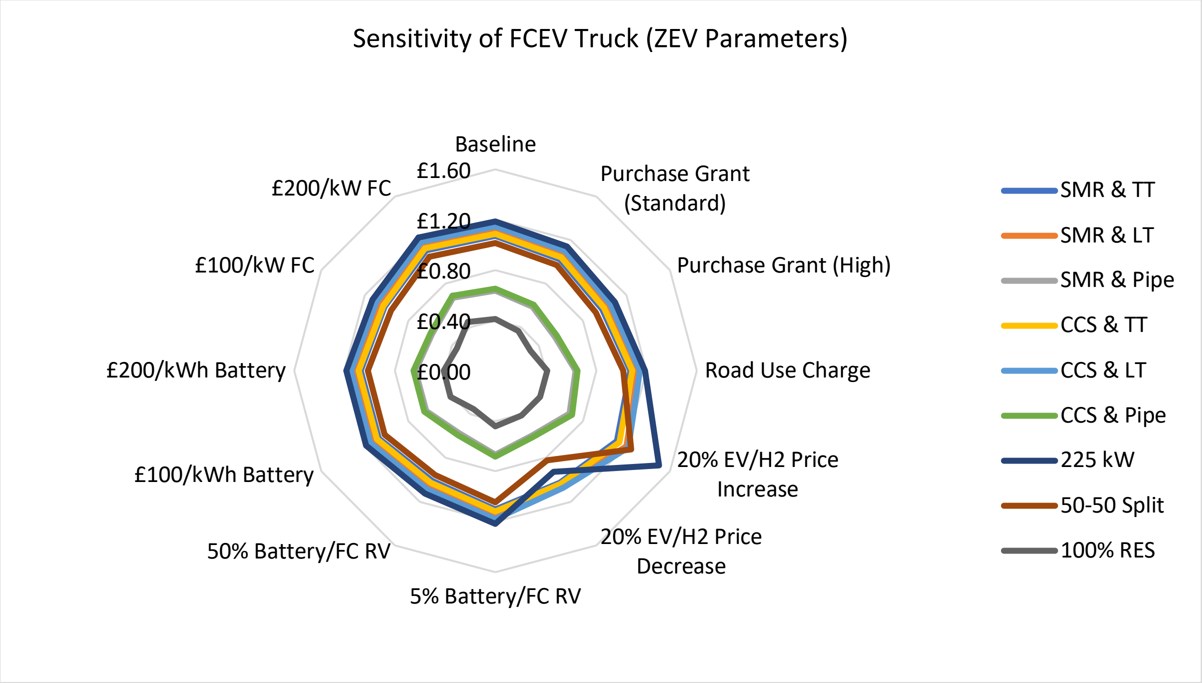


Figure 10-19 – Sensitivity of FCEV truck TCO to fuel-specific parameters.

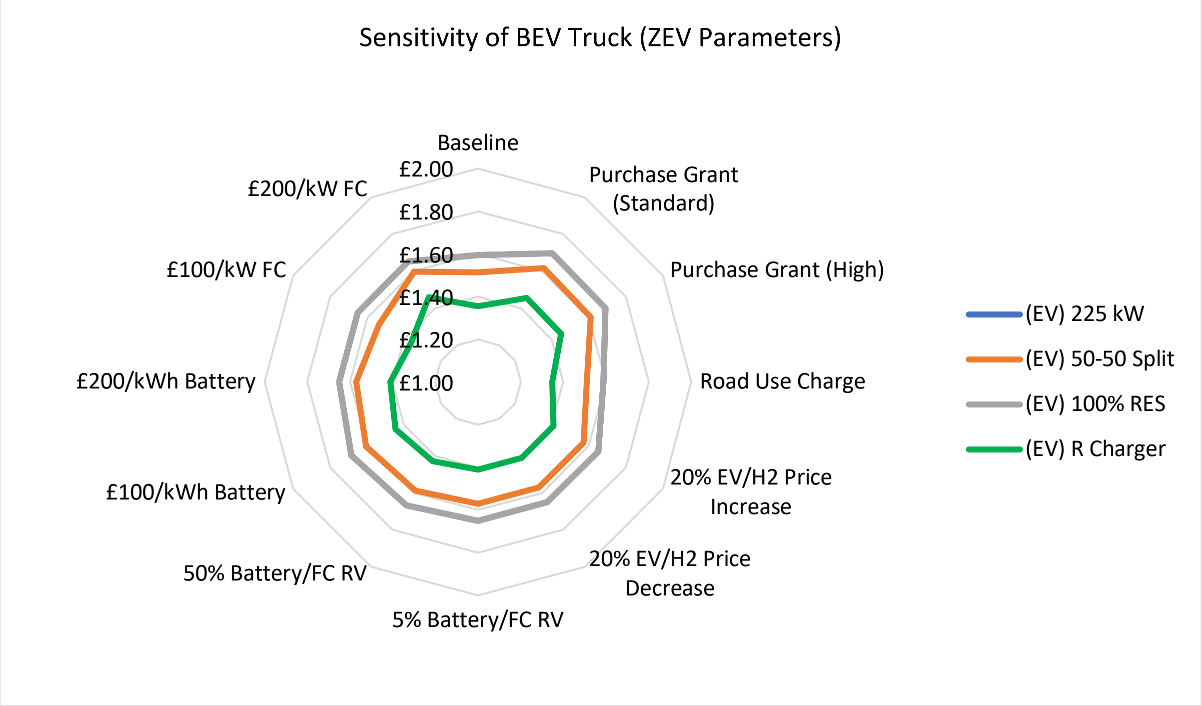


Figure 10-20 – Sensitivity of BEV truck TCO to fuel-specific parameters.

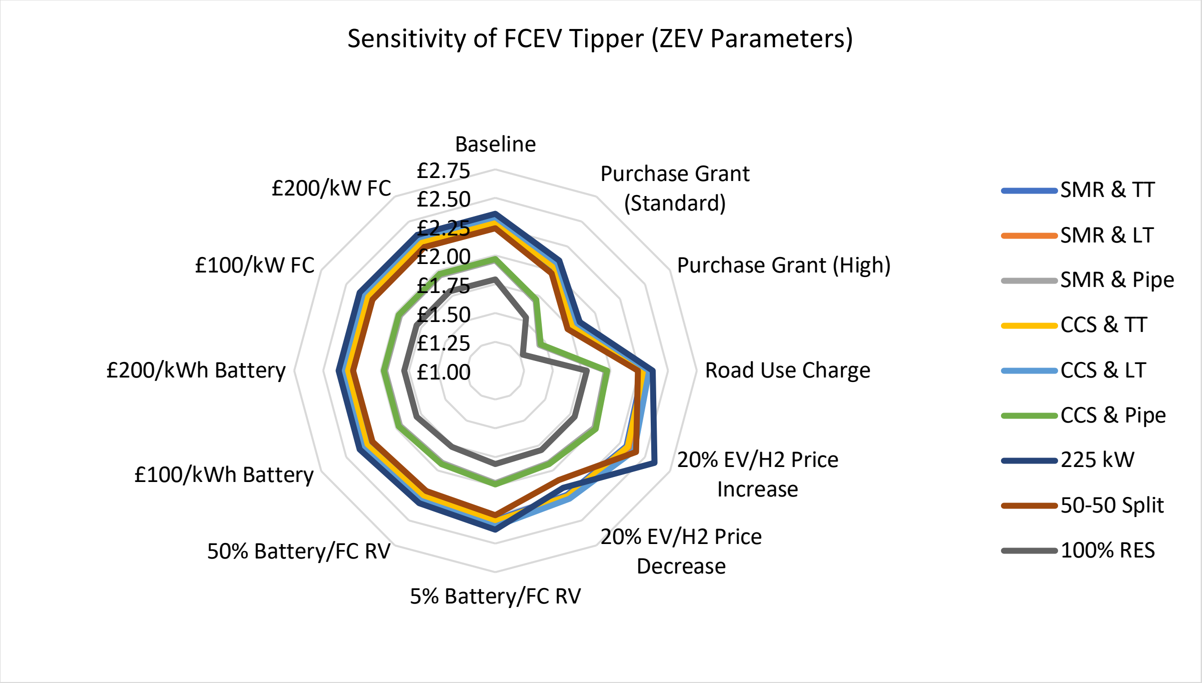


Figure 10-21 – Sensitivity of FCEV tipper TCO to fuel-specific parameters.

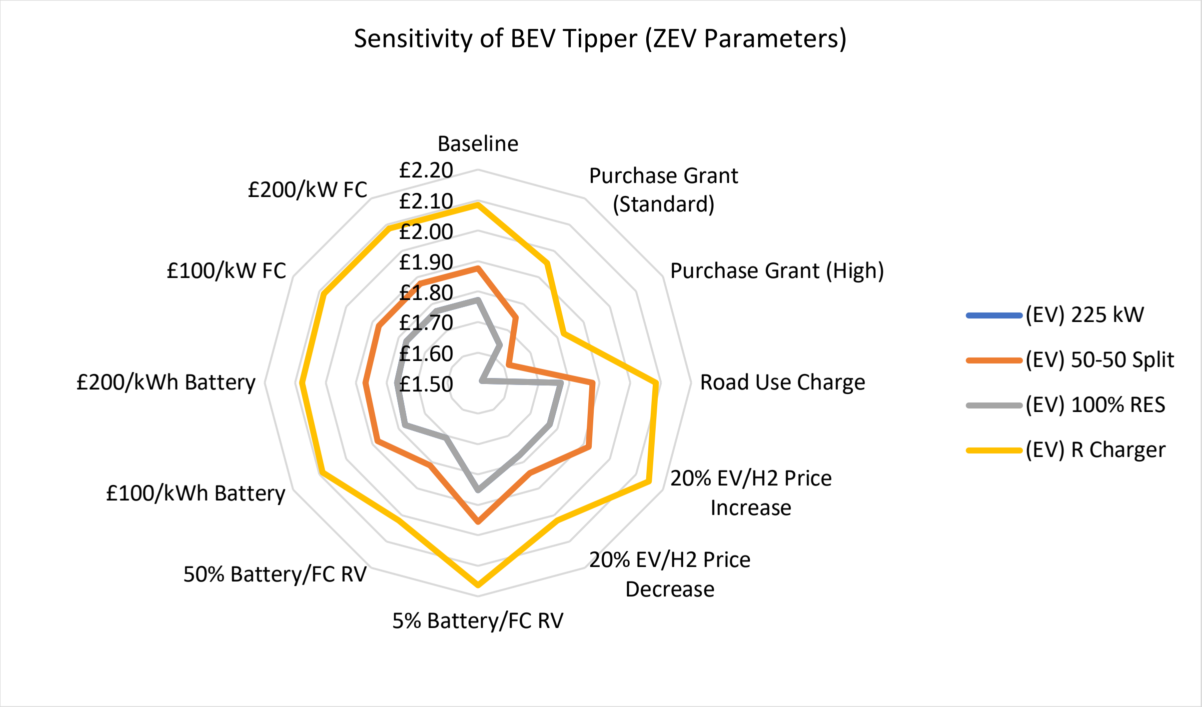


Figure 10-22 – Sensitivity of BEV tipper TCO to fuel-specific parameters.

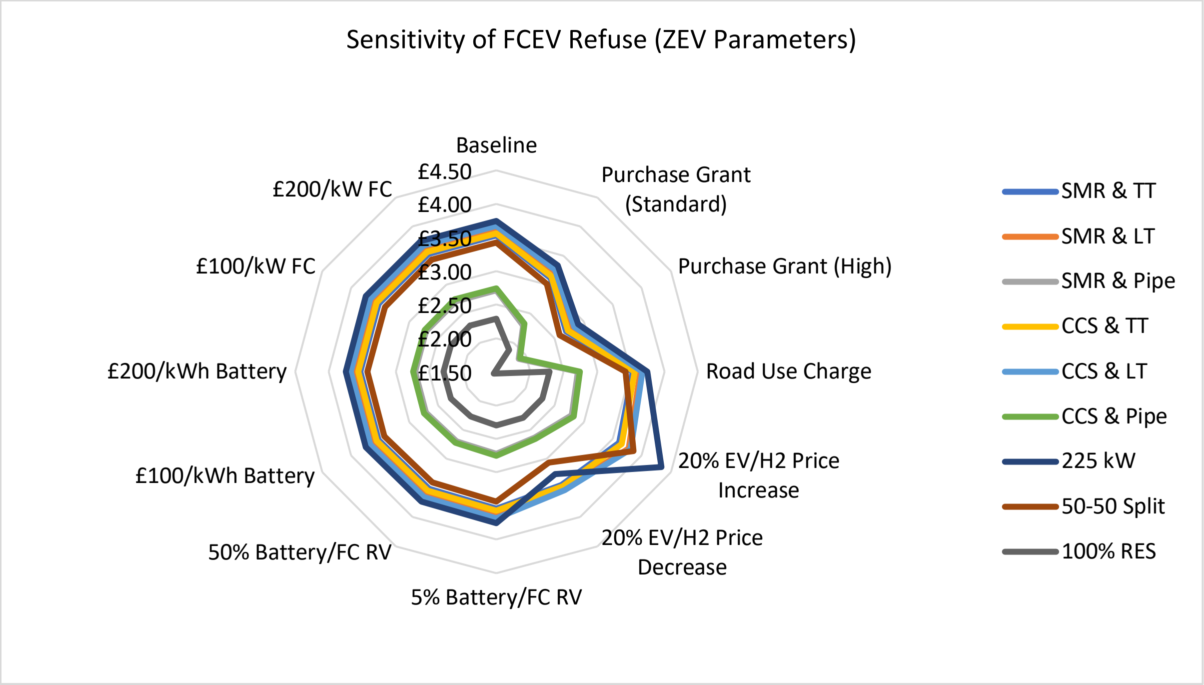


Figure 10-23 – Sensitivity of FCEV refuse TCO to fuel-specific parameters.

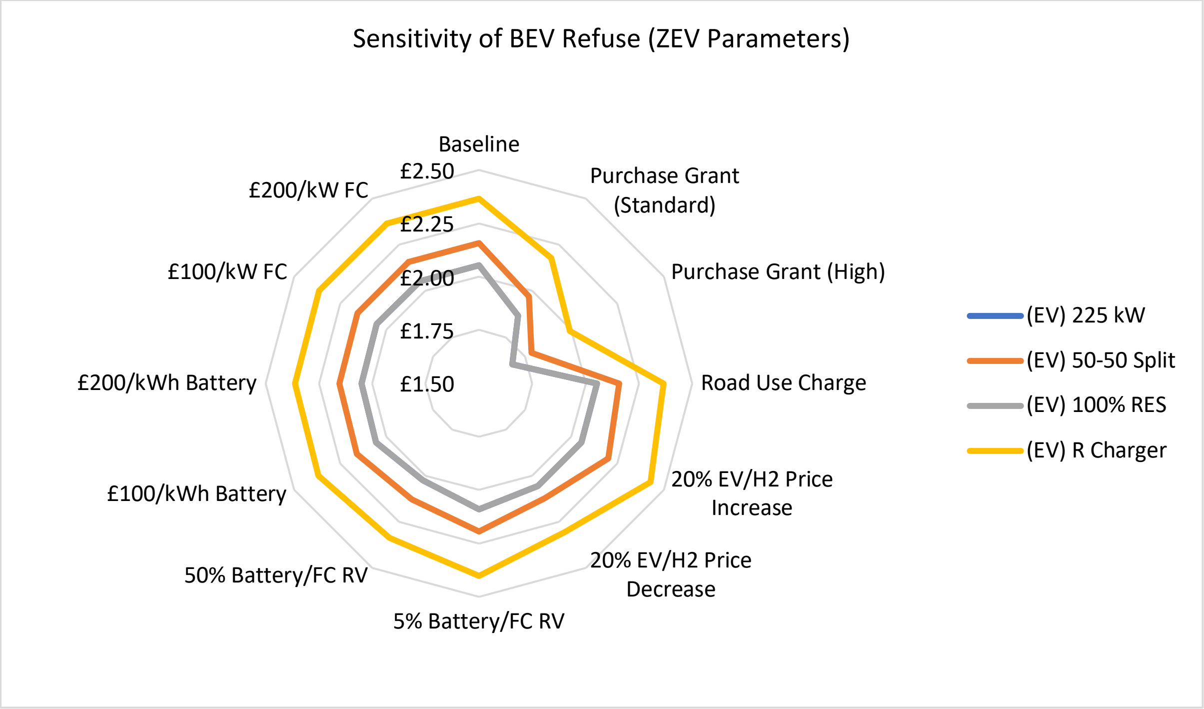


Figure 10-24 – Sensitivity of BEV refuse TCO to fuel-specific parameters.

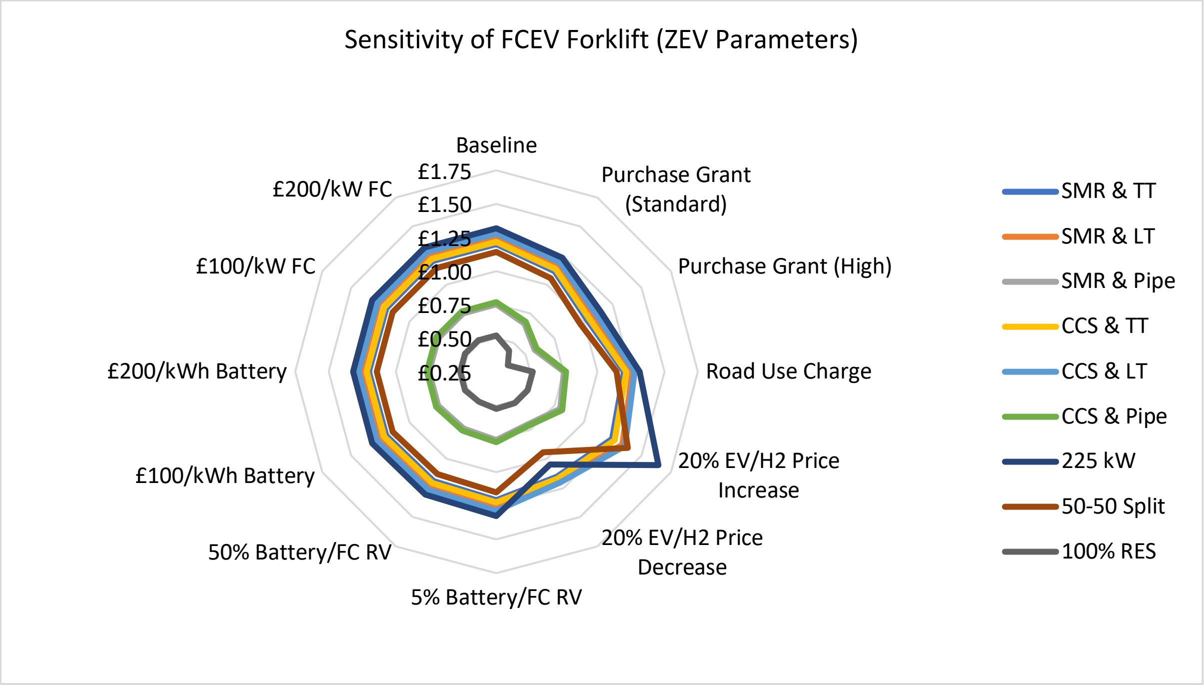


Figure 10-25 – Sensitivity of FCEV forklift TCO to fuel-specific parameters.

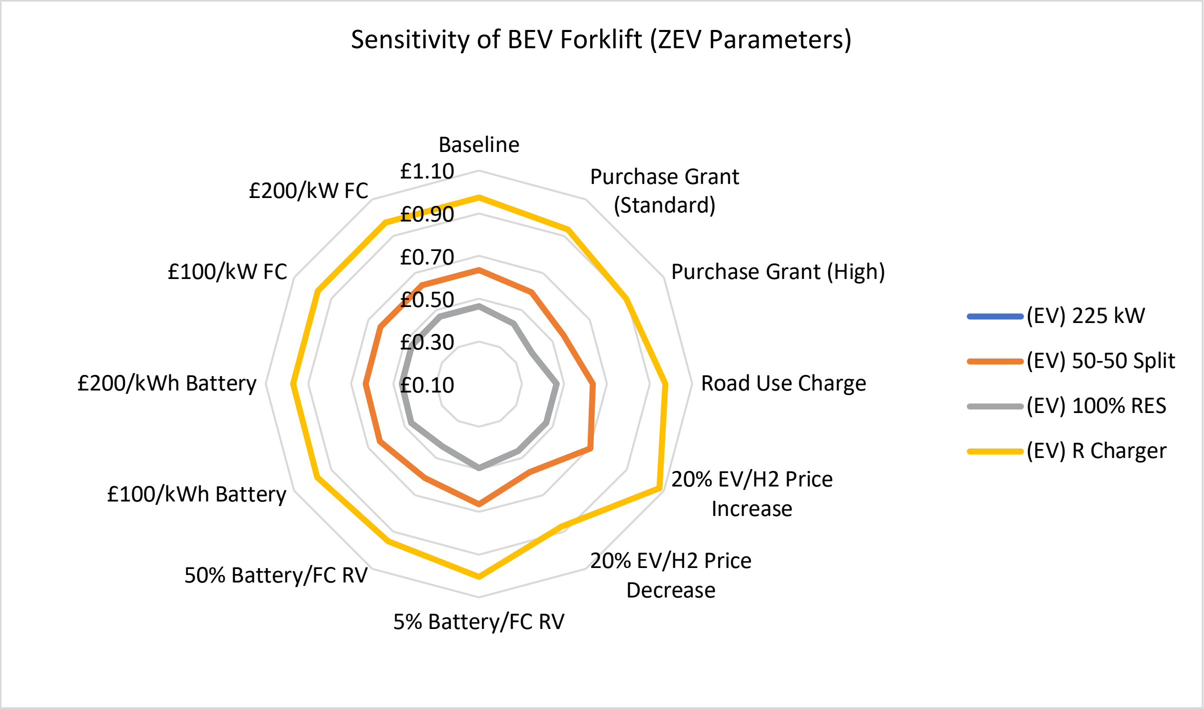


Figure 10-26 – Sensitivity of BEV forklift TCO to fuel-specific parameters.

10.4. Future Outlook – Base Case (£/km):

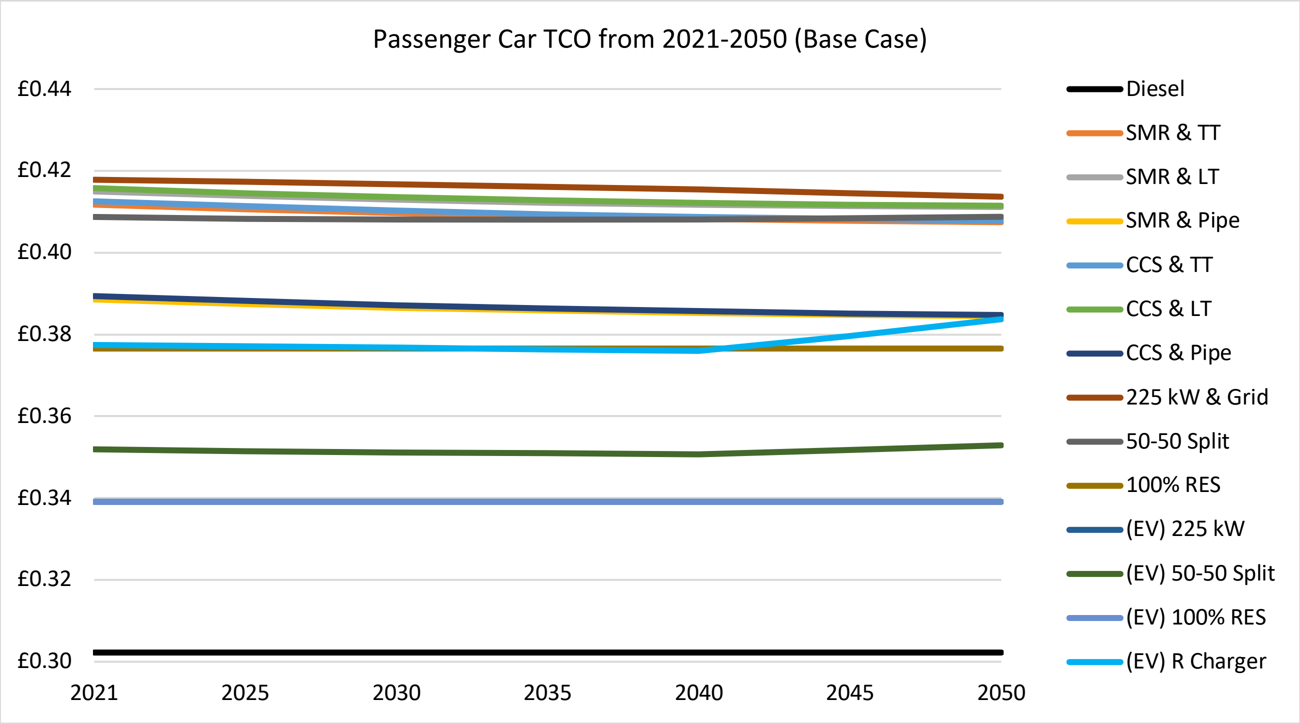


Figure 10-27 - Future TCO of a car from 2021-2050.

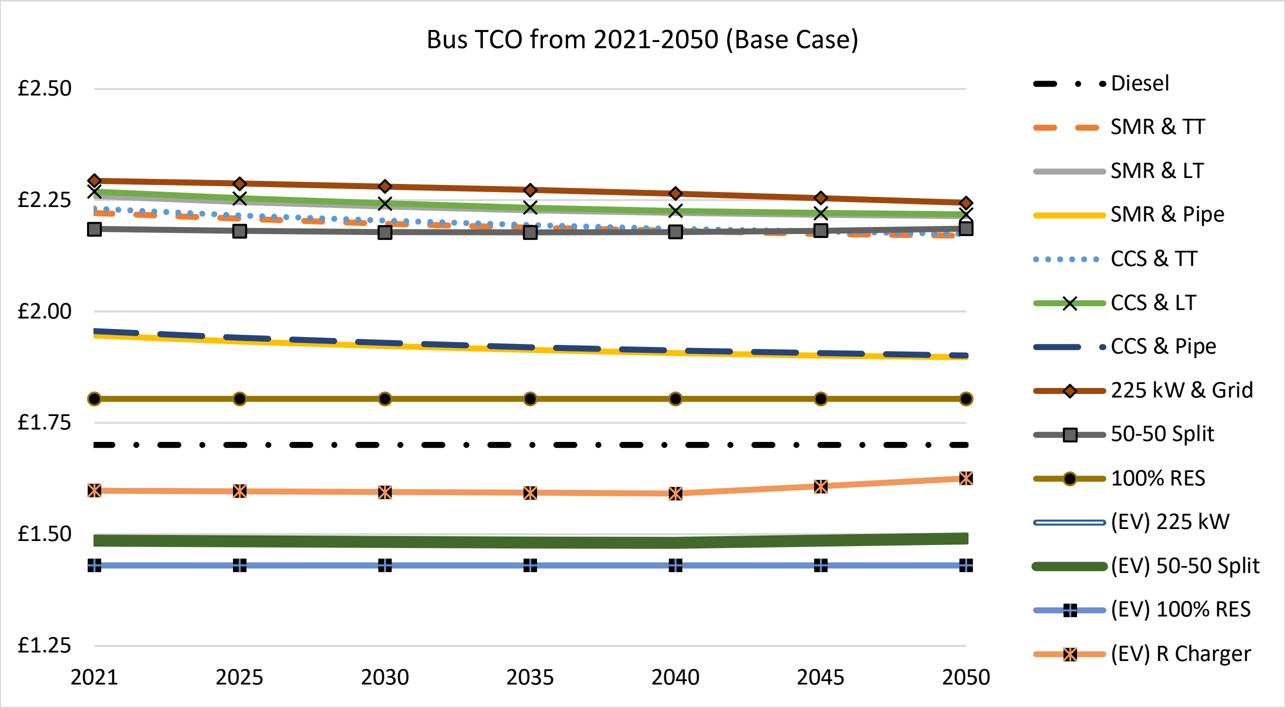


Figure 10-28 – Future TCO of a bus from 2021-2050.

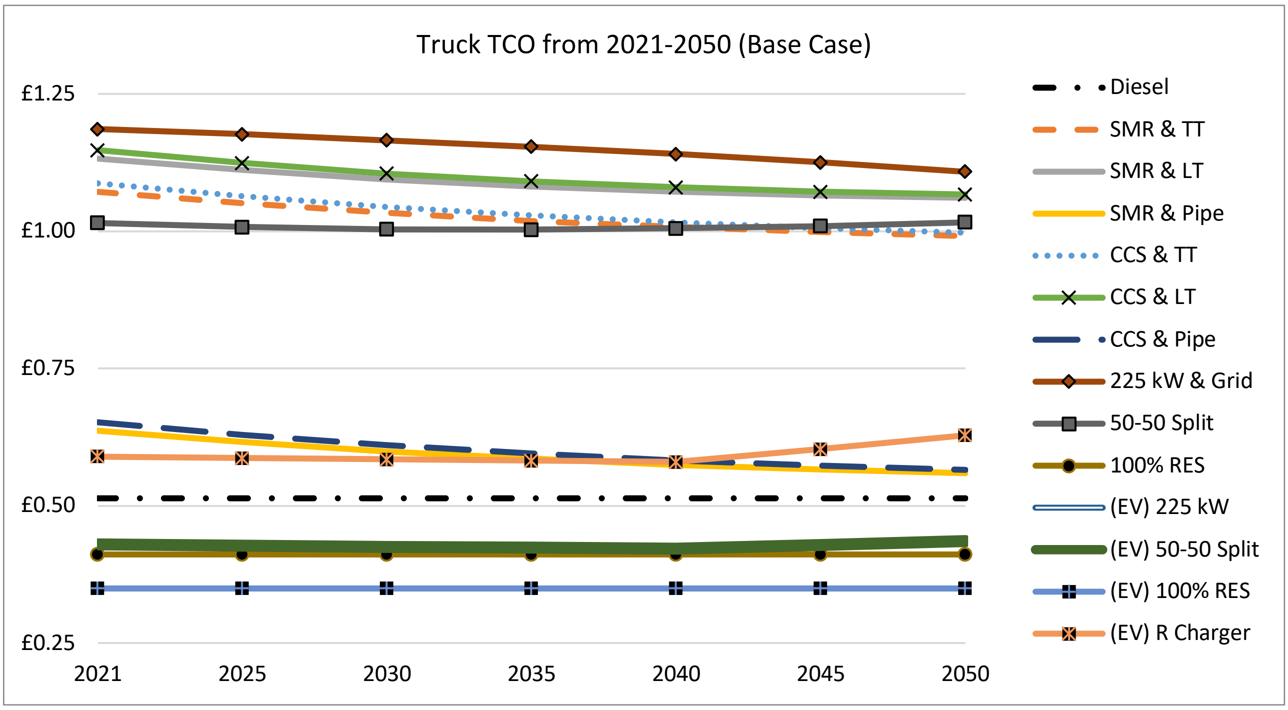


Figure 10-29 – Future TCO of a truck from 2021-2050.

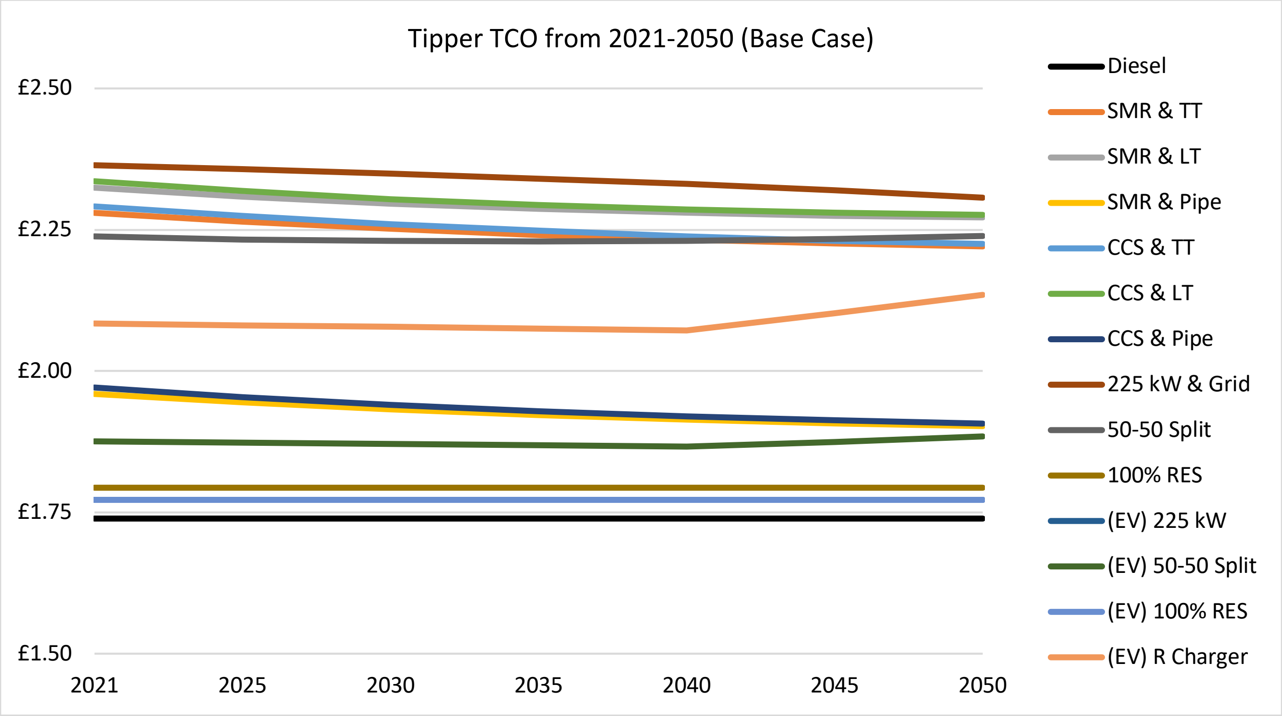


Figure 10-30 - Future TCO of a tipper from 2021-2050.

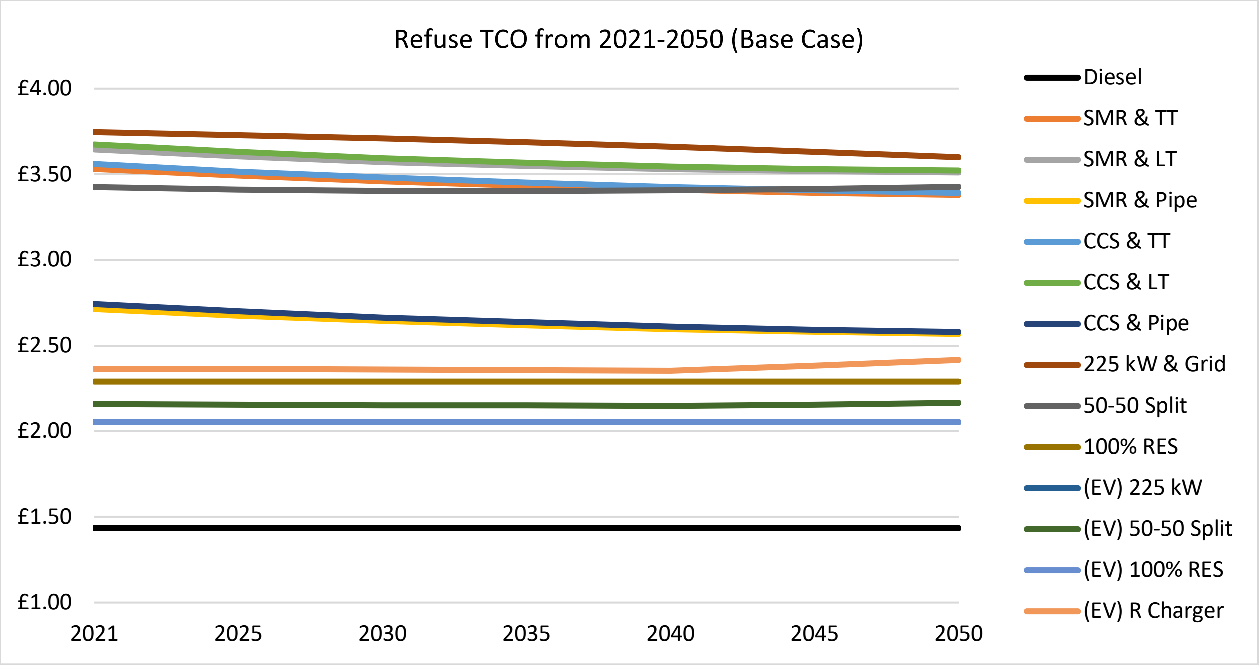


Figure 10-31 – Future TCO of a refuse from 2021-2050.

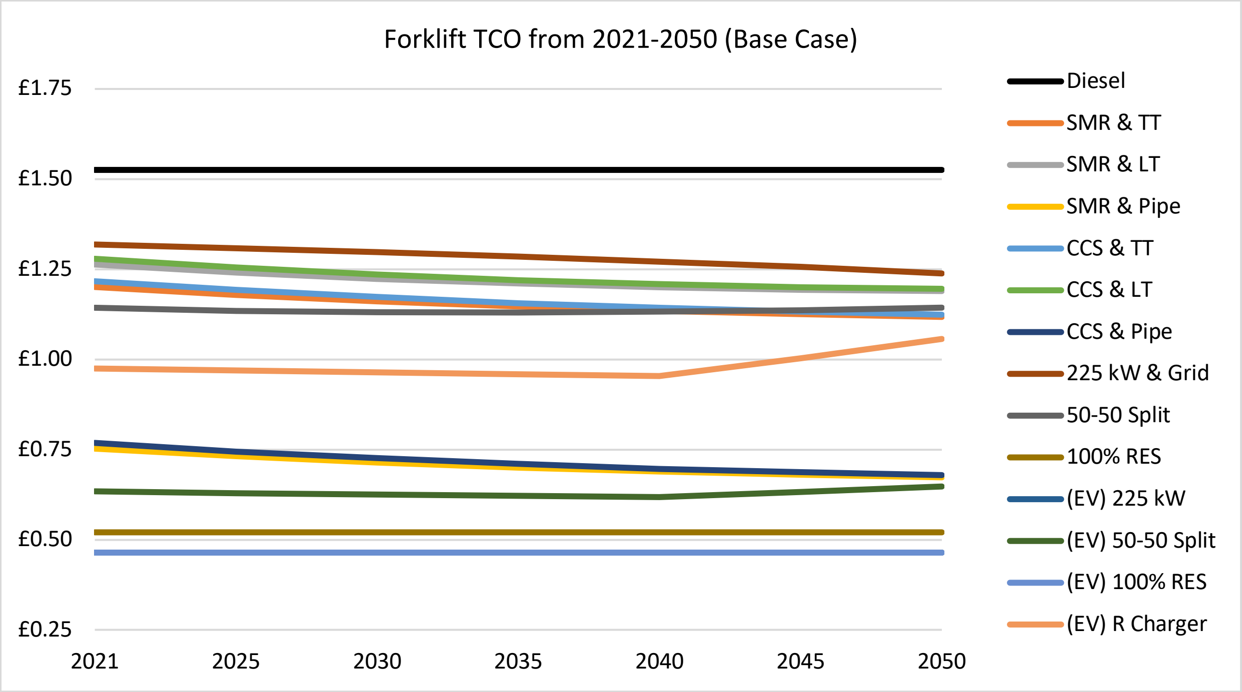


Figure 10-32 - Future TCO of a forklift from 2021-2050.

10.5. Future Outlook – Low Fossil Tax (£/km):

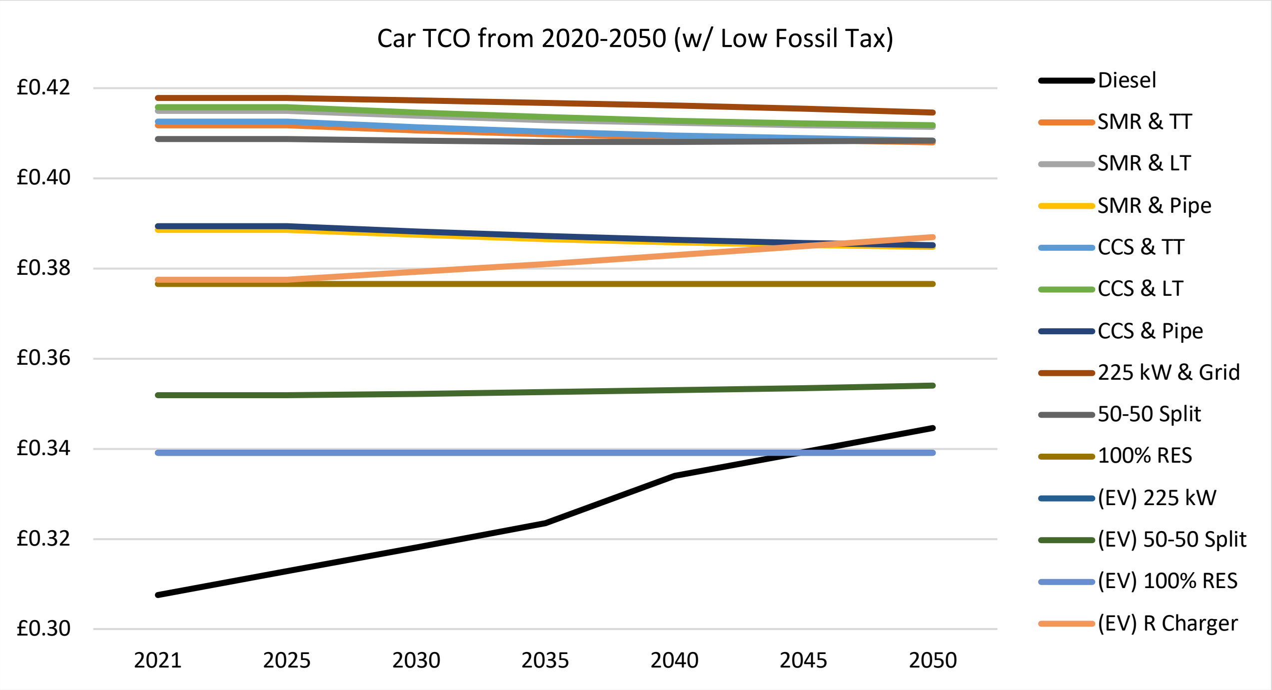


Figure 10-33 - Future TCO of a passenger car under a low fossil tax.

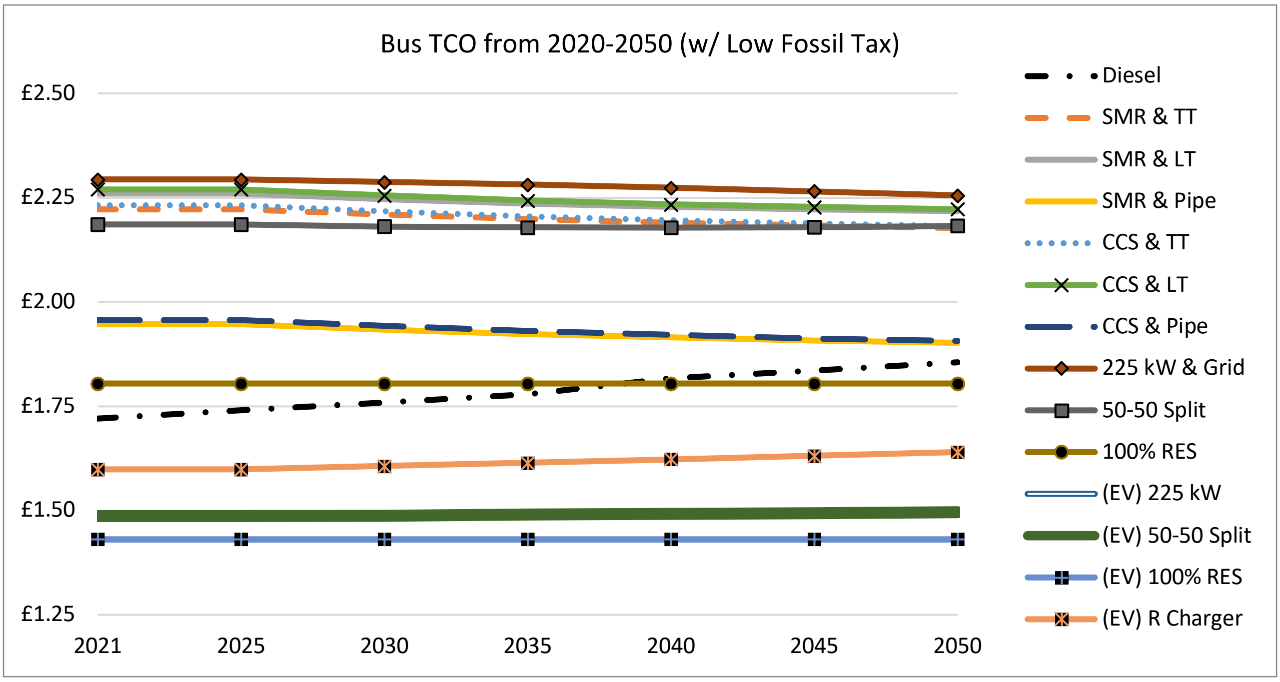


Figure 10-34 - Future TCO of a bus under a low fossil tax.

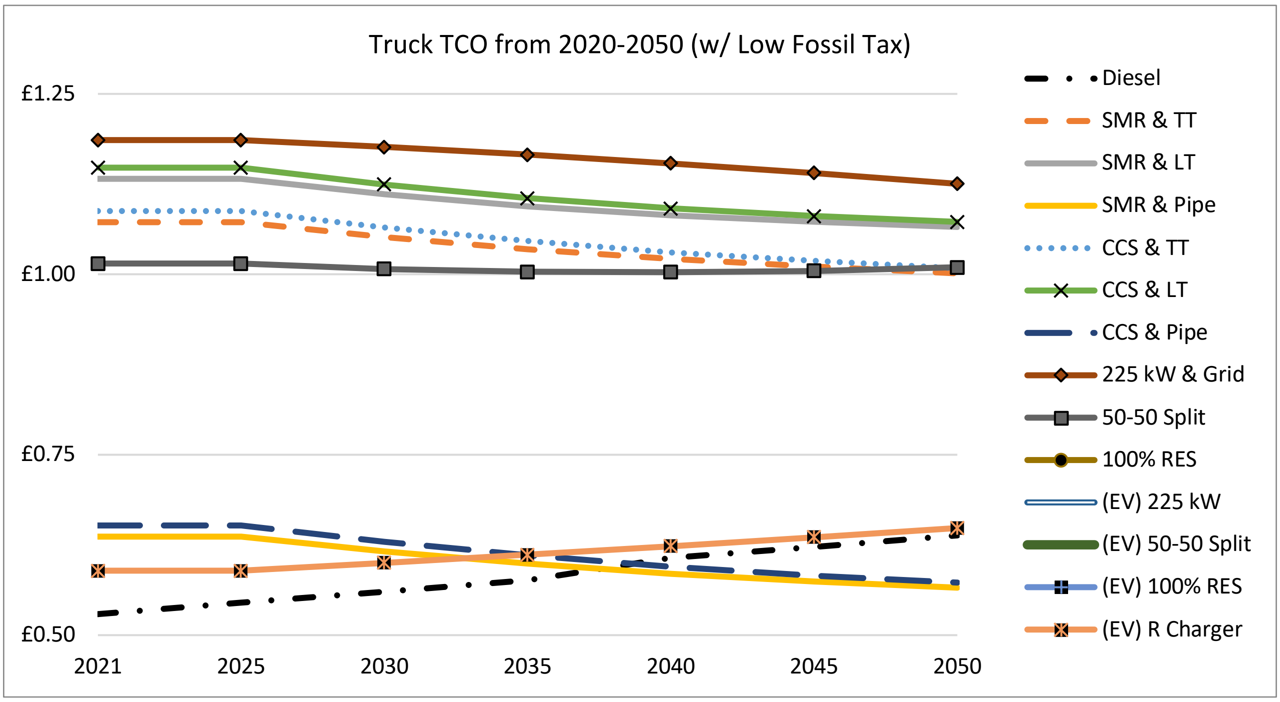


Figure 10-35 - Future TCO of a truck under a low fossil tax.

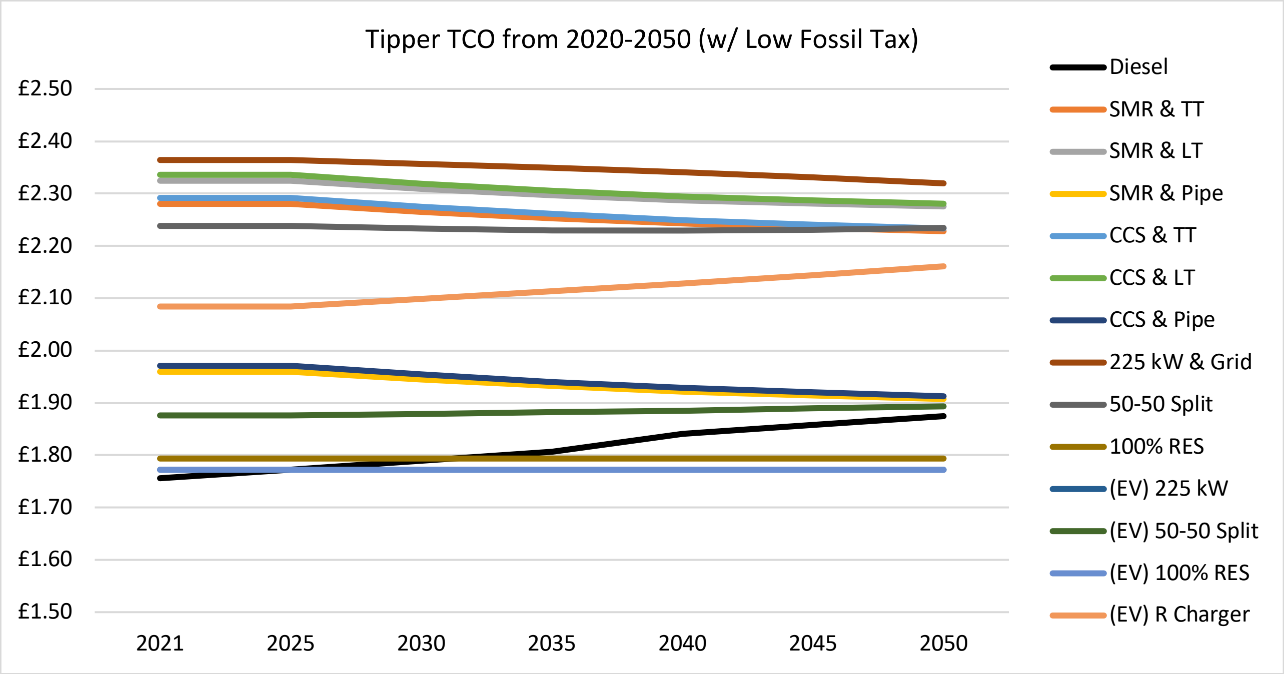


Figure 10-36 - Future TCO of a tipper under a low fossil tax.

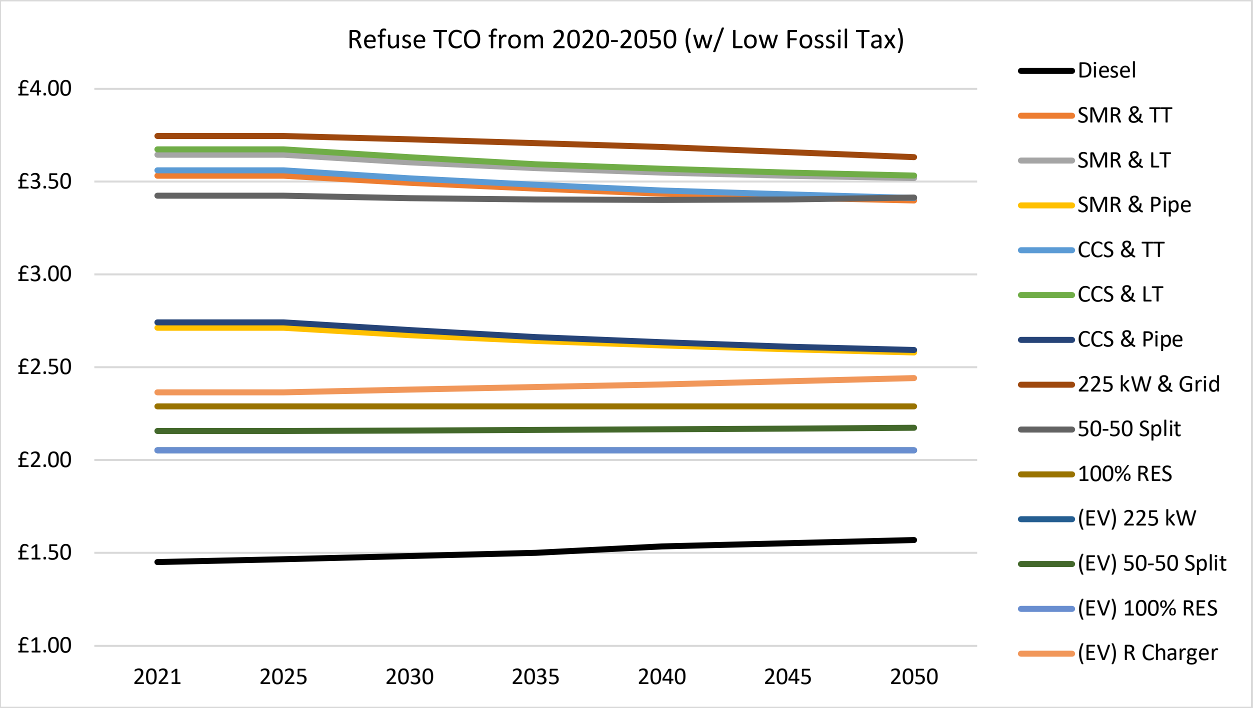


Figure 10-37 - Future TCO of a refuse under a low fossil tax.

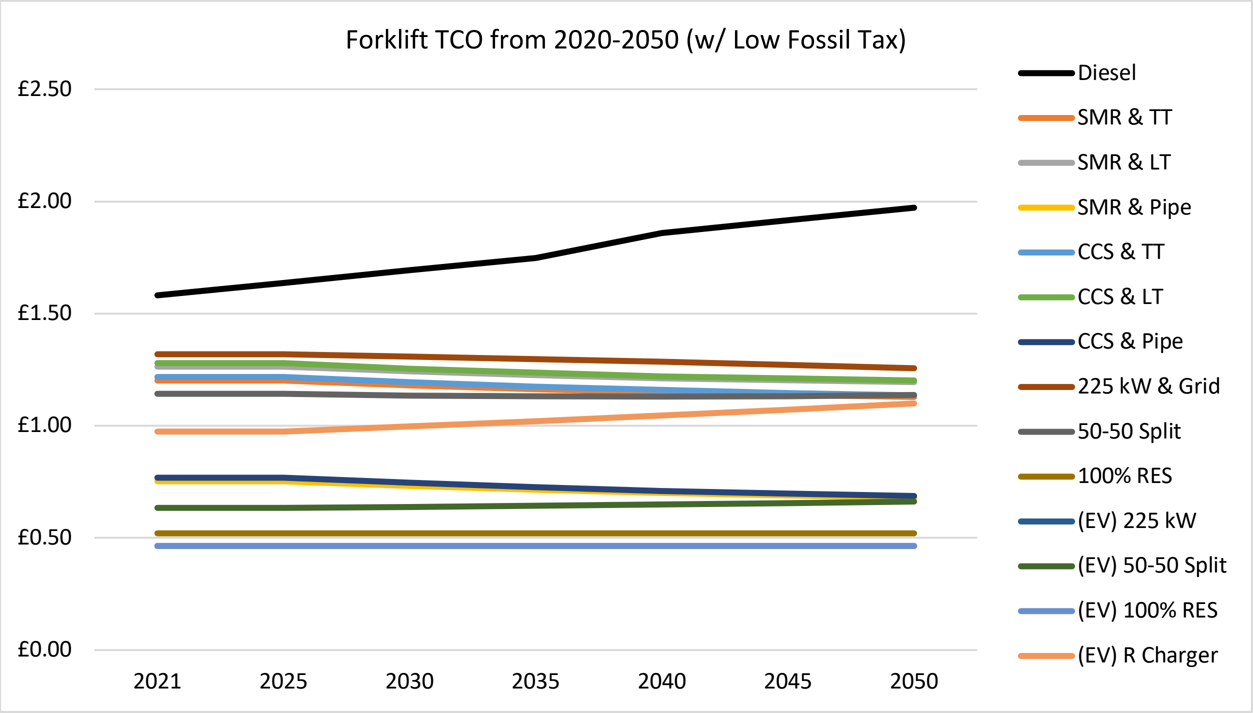


Figure 10-38 - Future TCO of a forklift under a low fossil tax.

10.6. Future Outlook – High Fossil Tax (£/km):

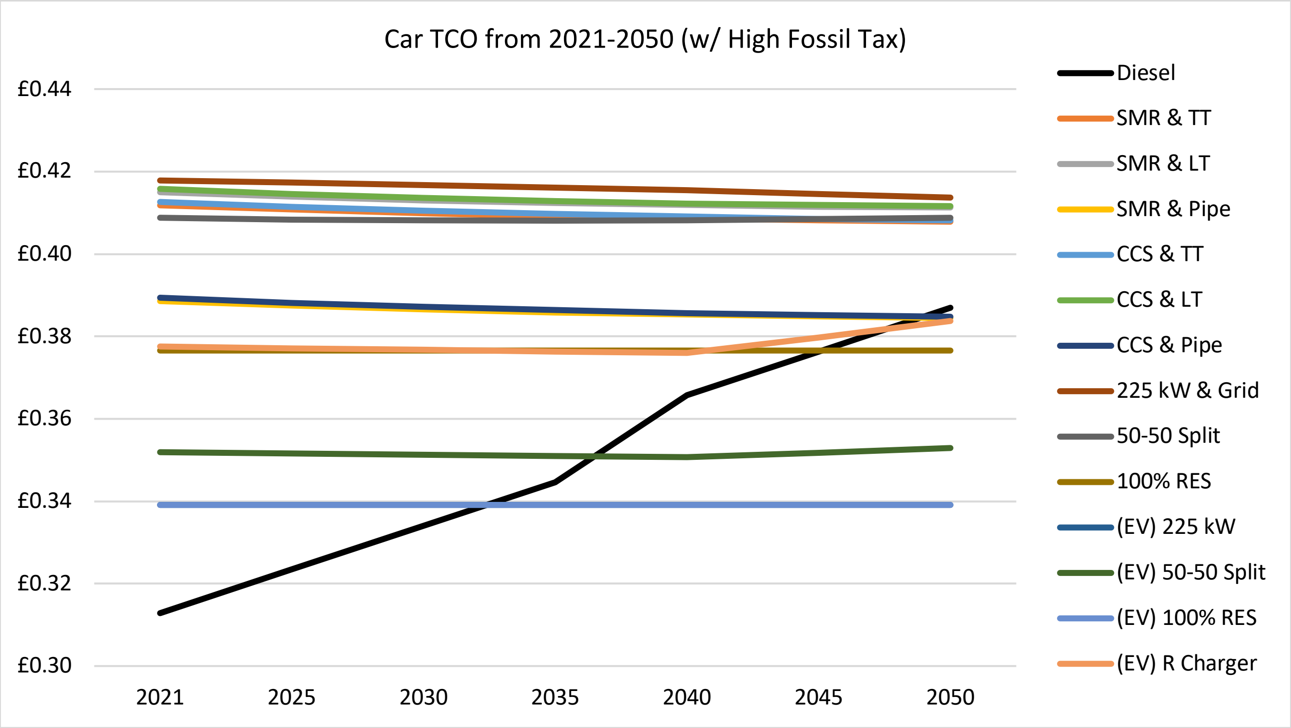


Figure 10-39 - Future TCO of a passenger car under a high fossil tax.

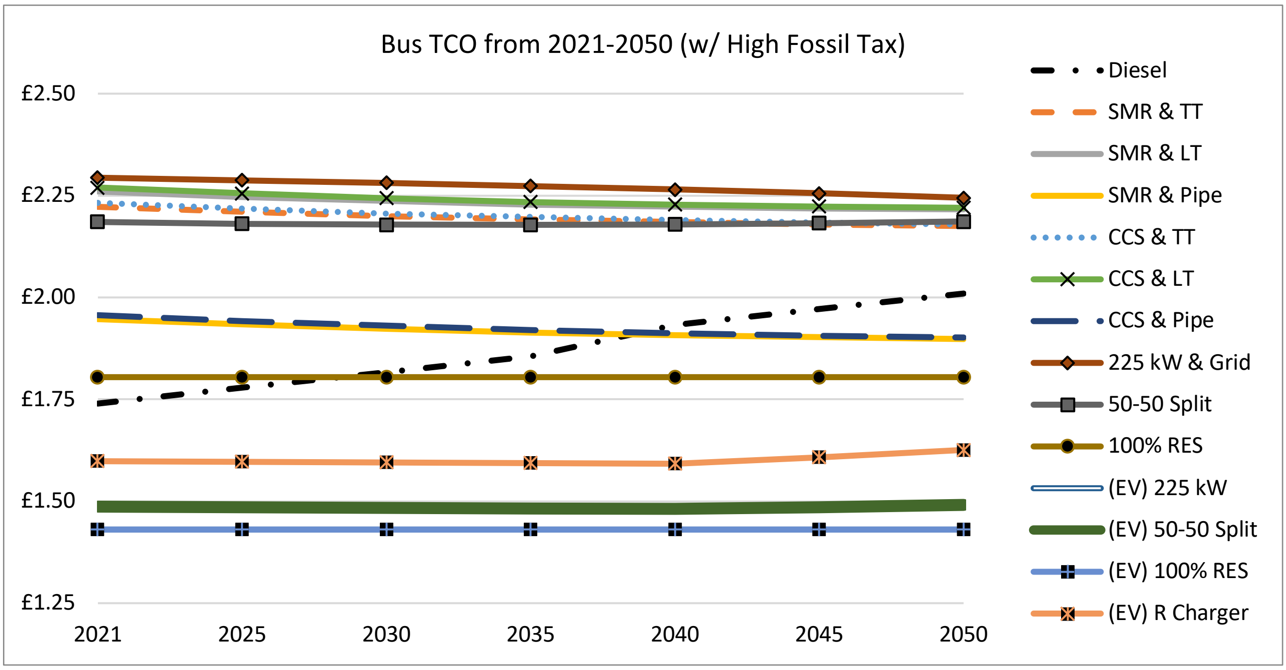


Figure 10-40 - Future TCO of a bus under a high fossil tax.

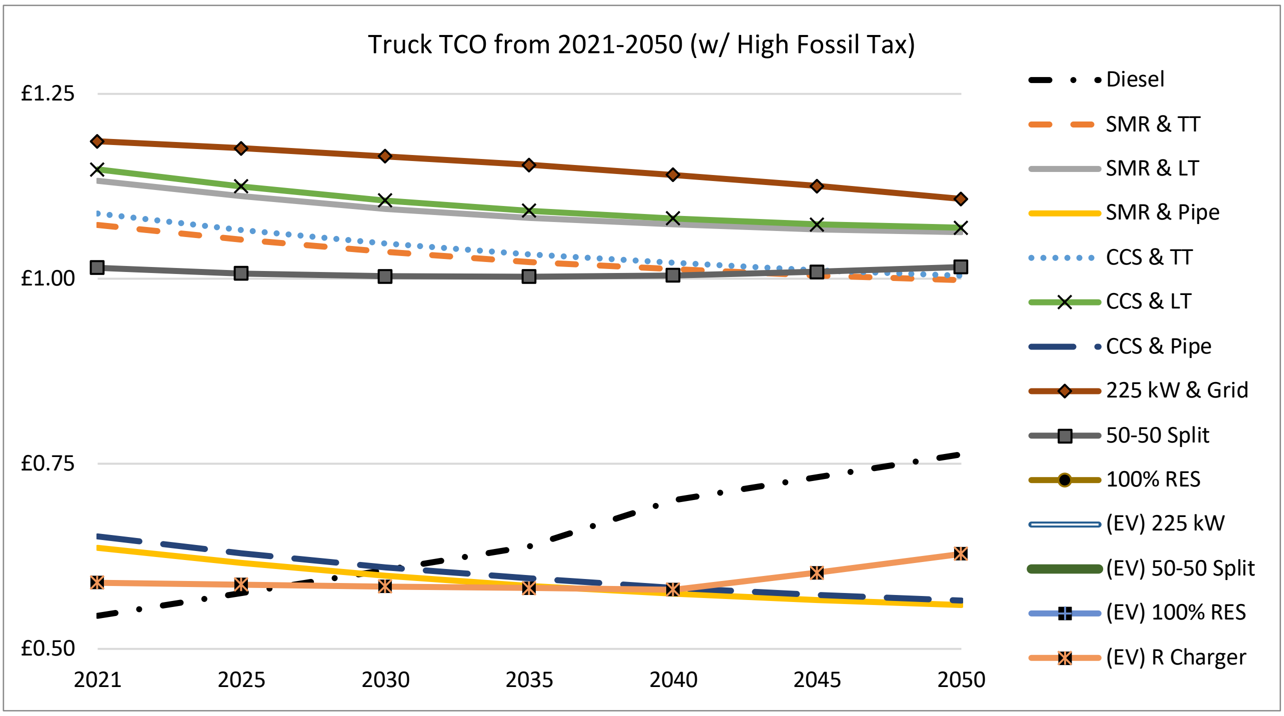


Figure 10-41 - Future TCO of a truck under a high fossil tax.

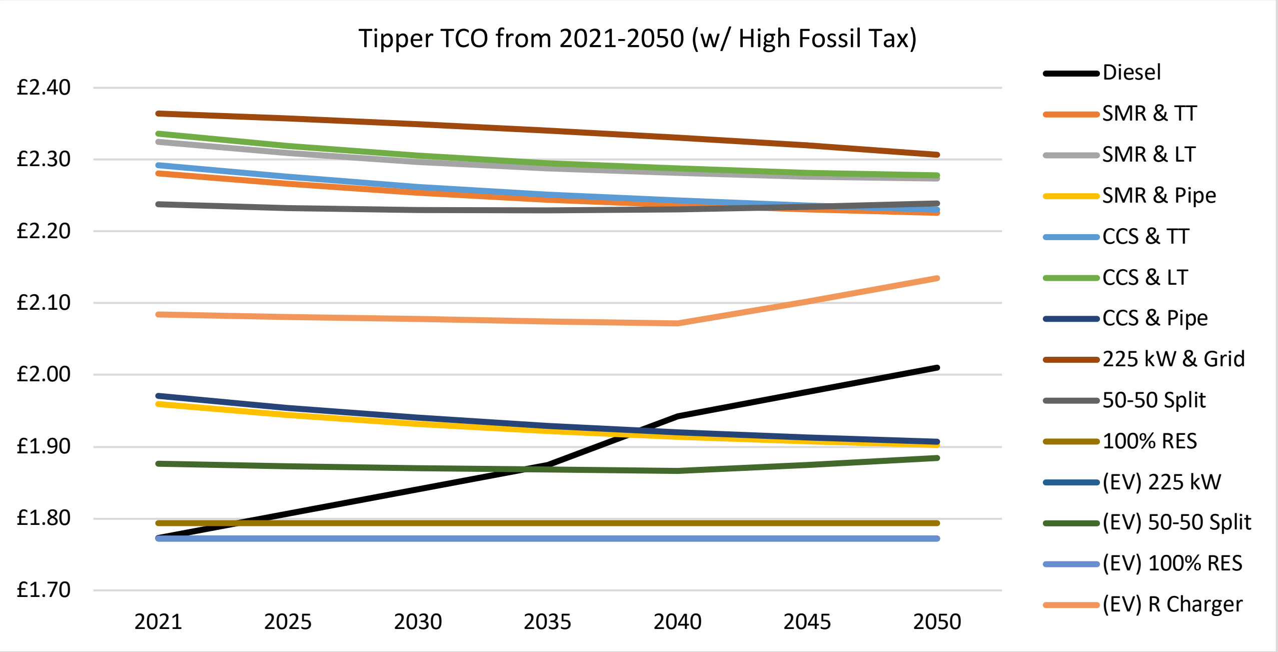


Figure 10-42 - Future TCO of a tipper under a high fossil tax.

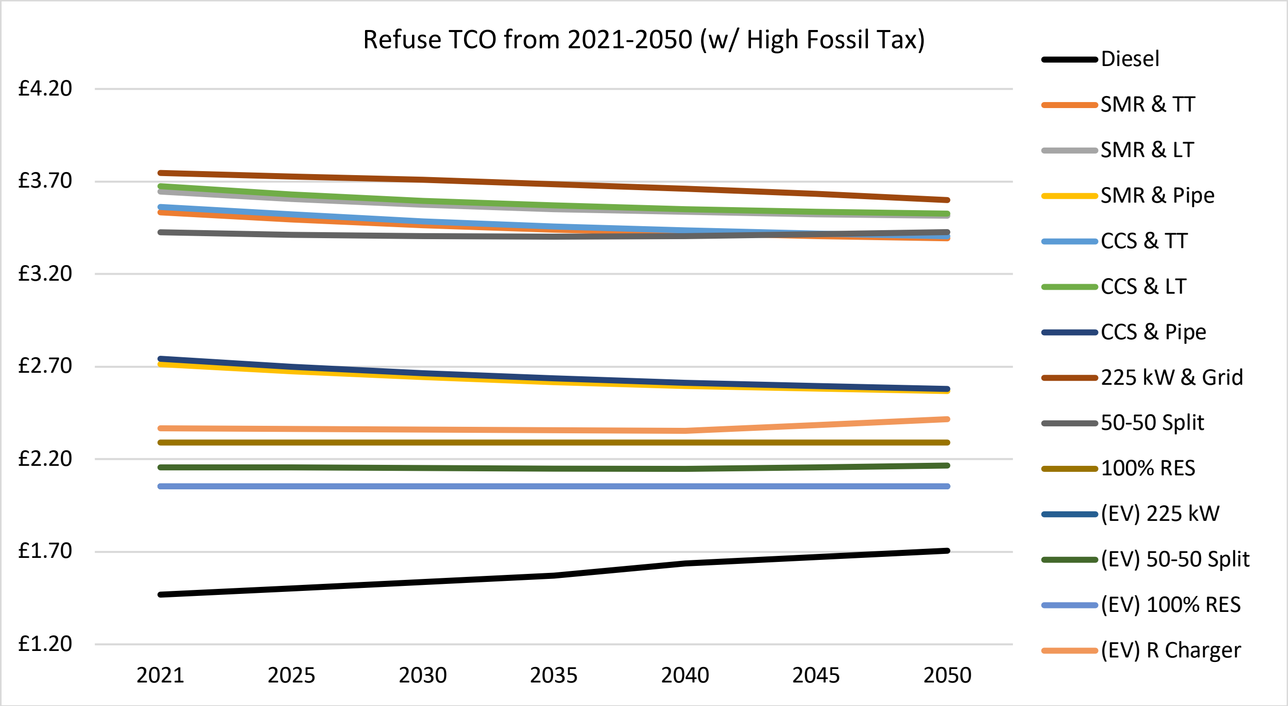


Figure 10-43 - Future TCO of a refuse under a high fossil tax.

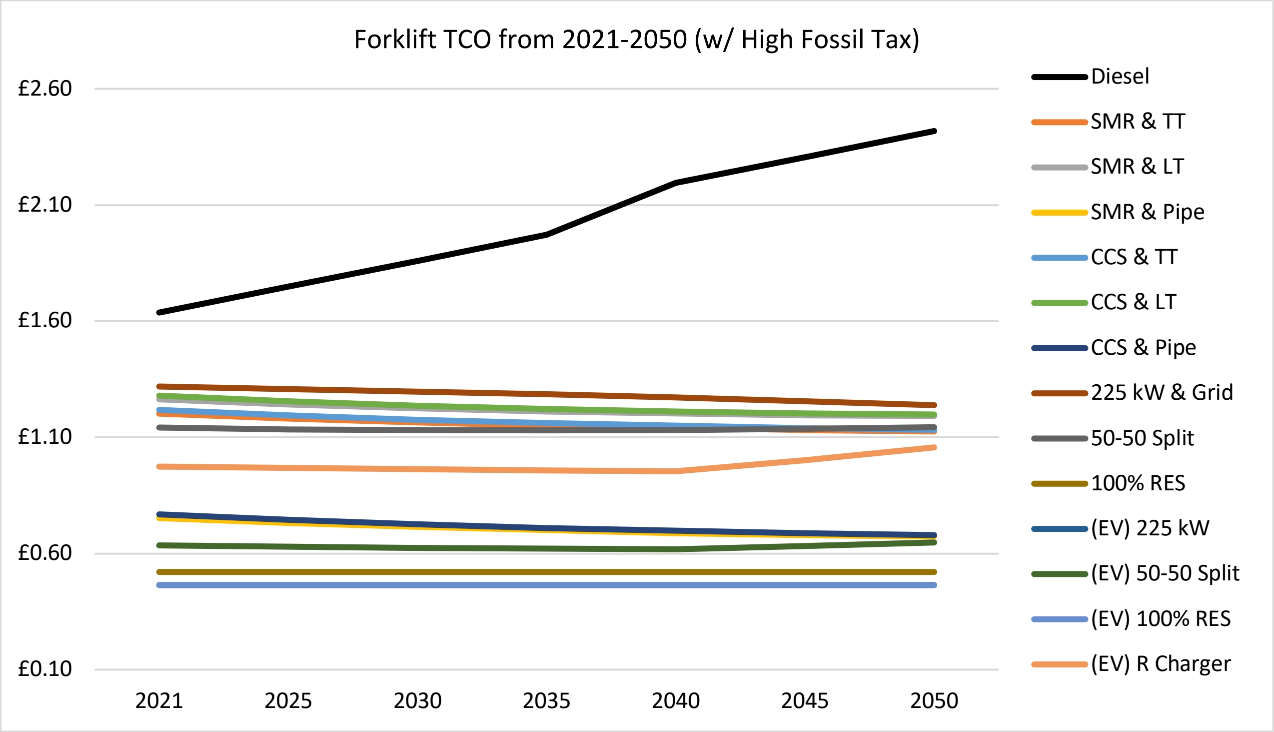


Figure 10-44 - Future TCO of a forklift under a high fossil tax.

10.7. Future Outlook – Standard Grant (£/km):

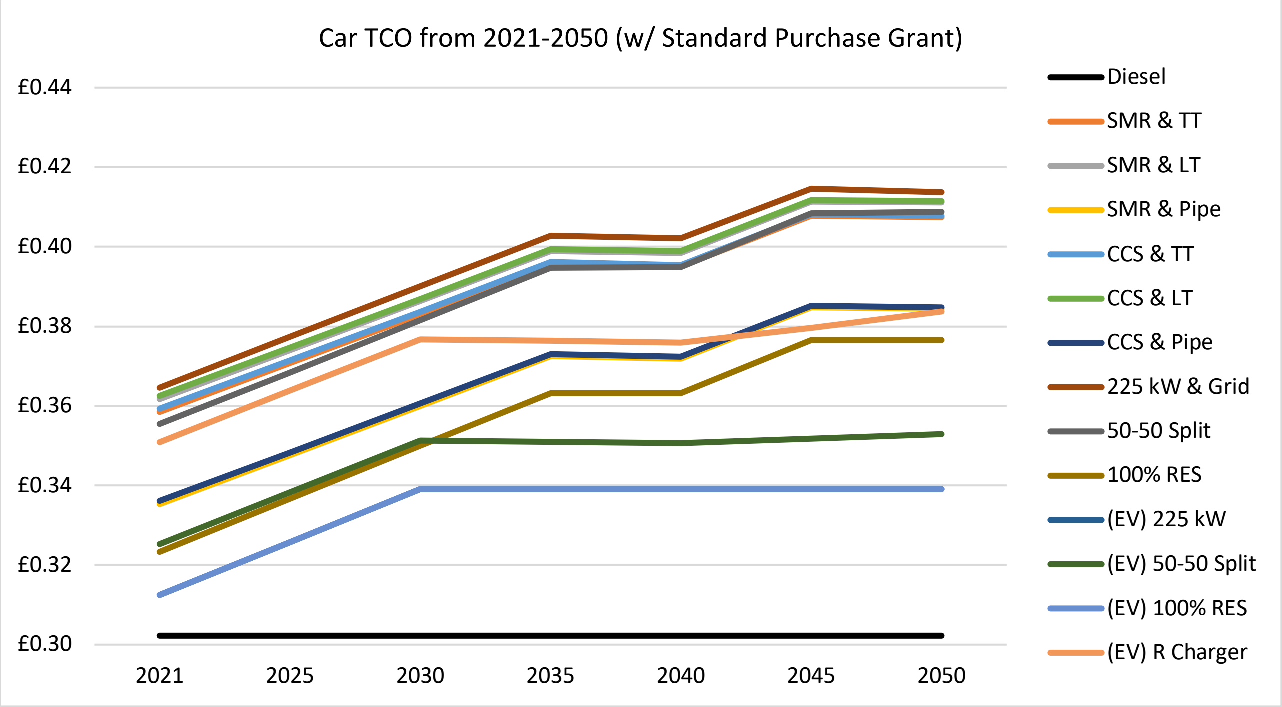


Figure 10-45 - Future TCO of a passenger car under a standard purchase grant.

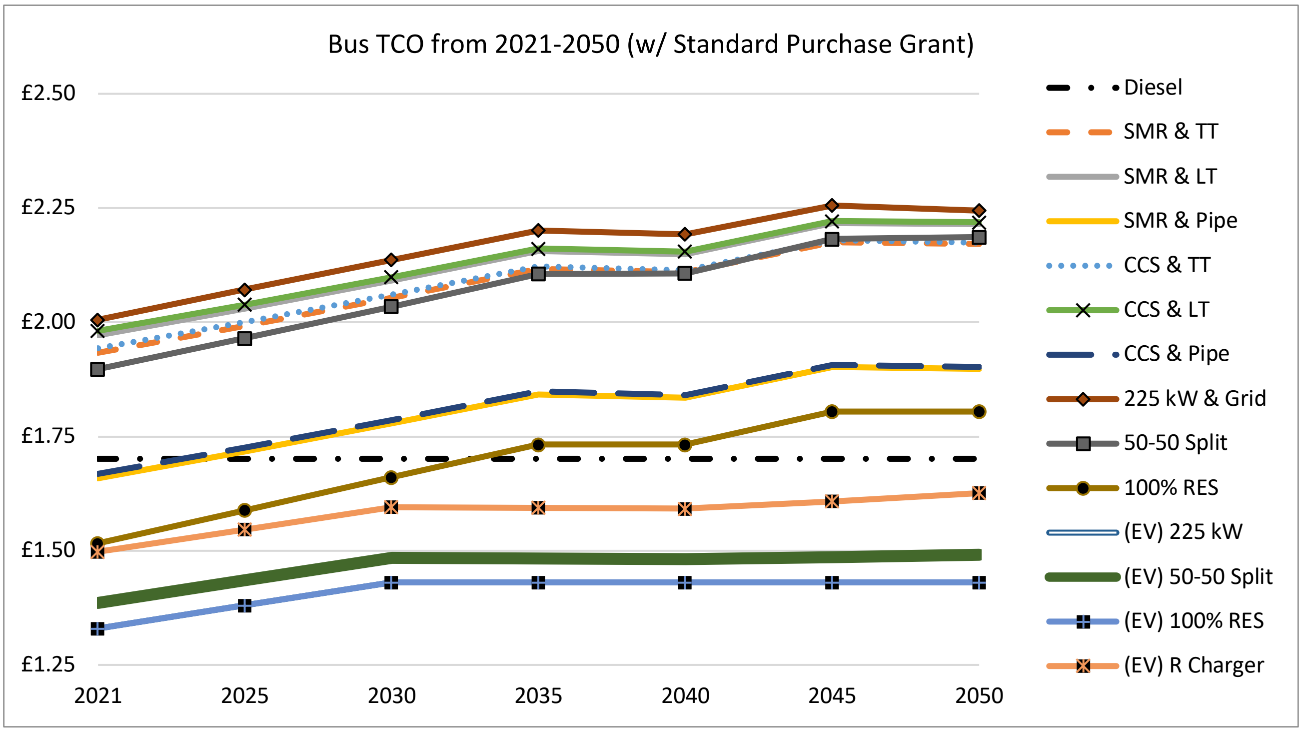


Figure 10-46 - Future TCO of a bus under a standard purchase grant.

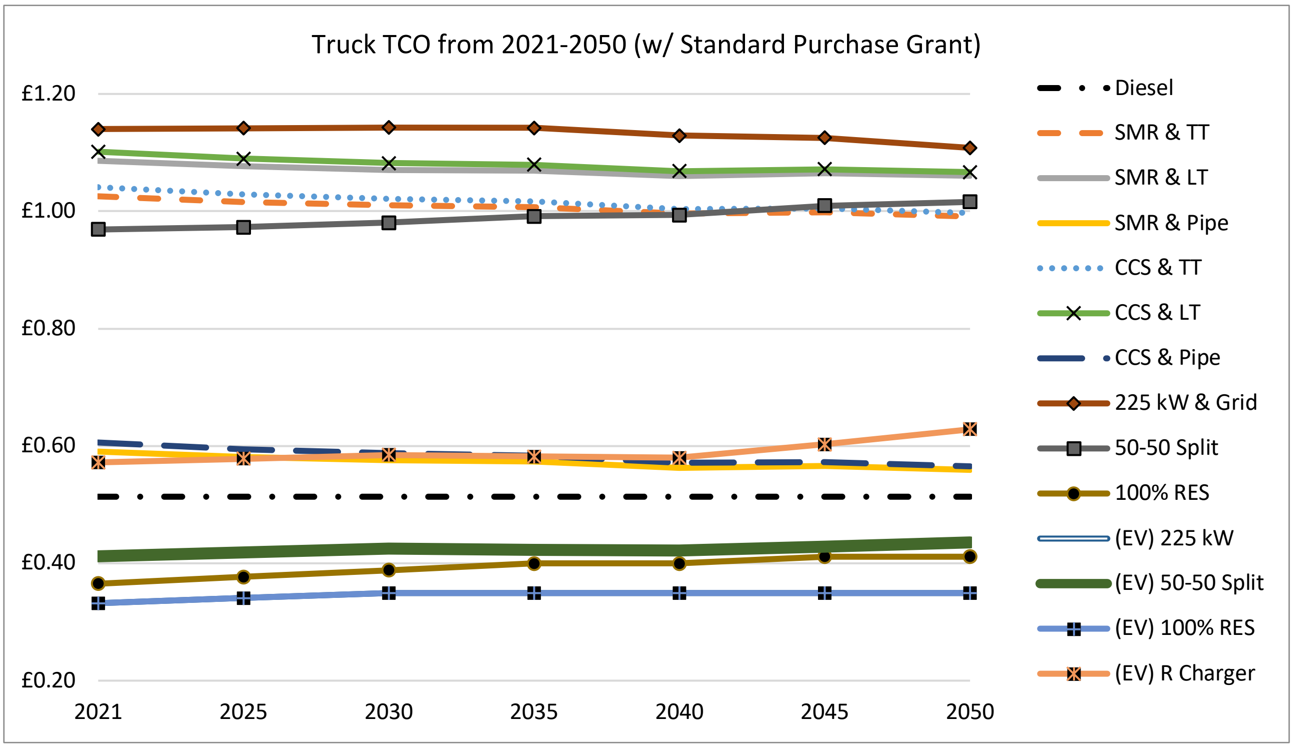


Figure 10-47 - Future TCO of a truck under a standard purchase grant.

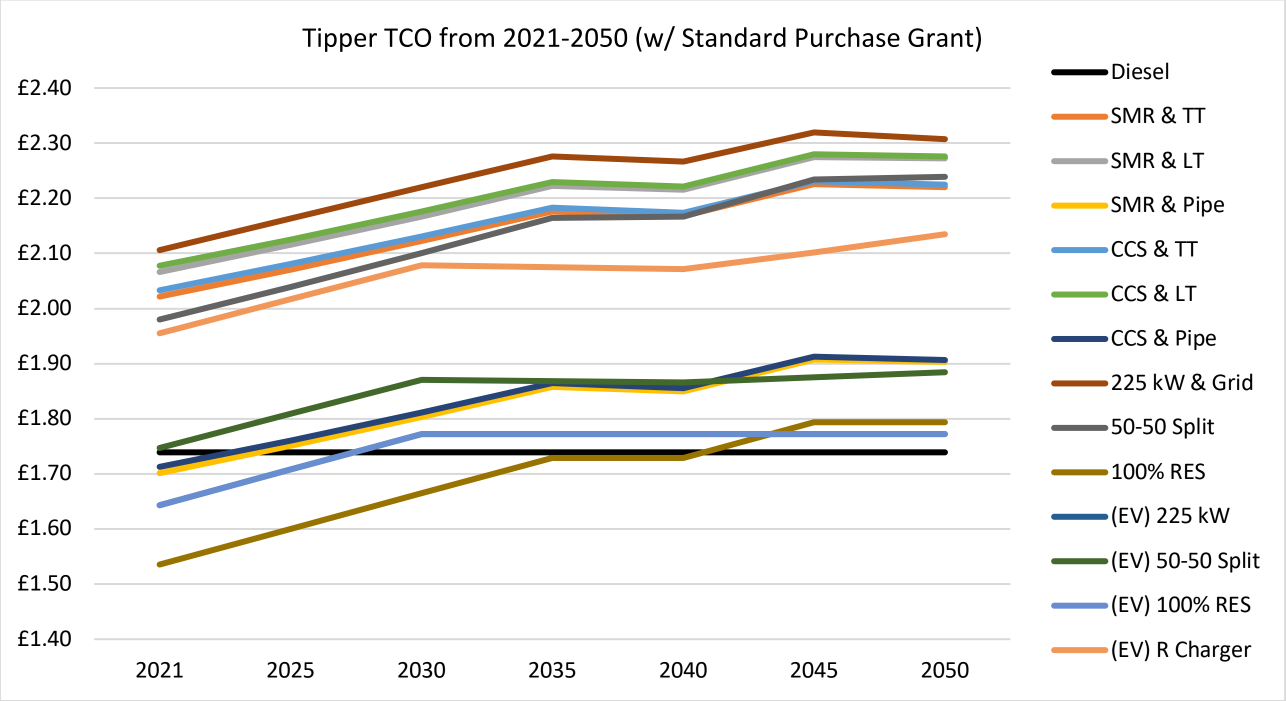


Figure 10-48 - Future TCO of a tipper under a standard purchase grant.

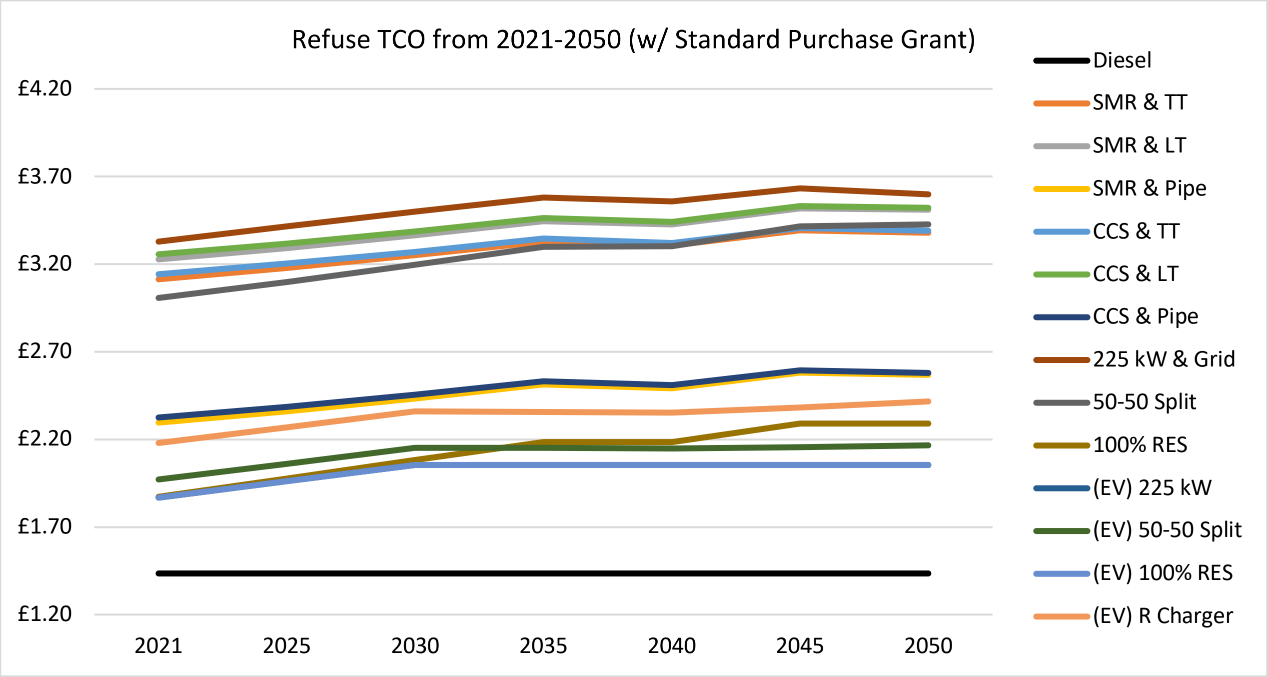


Figure 10-49 - Future TCO of a refuse under a standard purchase grant.

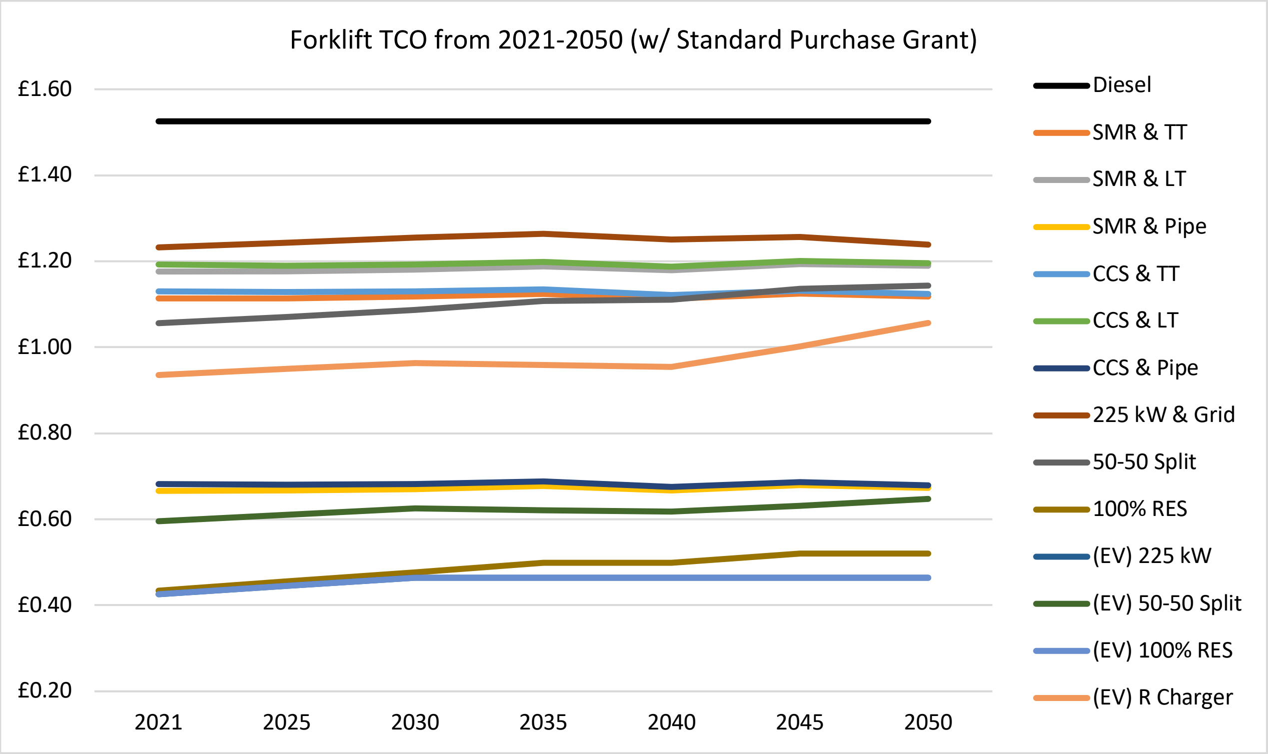


Figure 10-50 - Future TCO of a forklift under a standard purchase grant.

10.8. Future Outlook – High Grant (£/km):

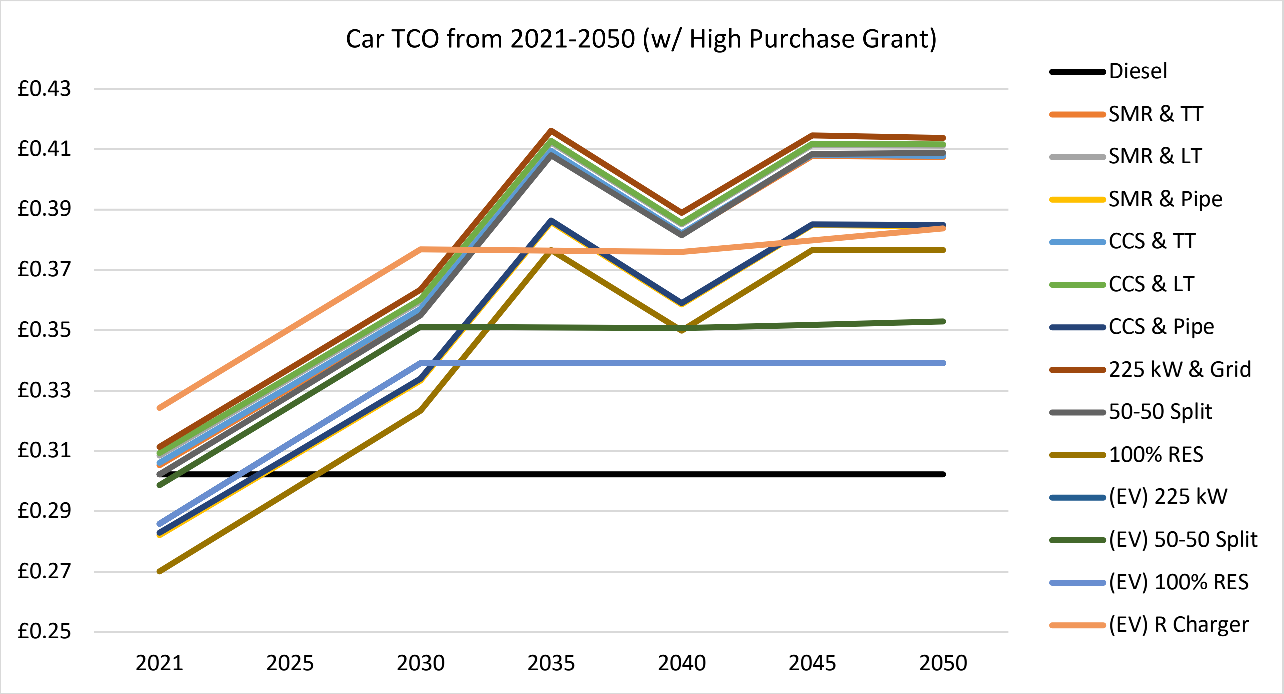


Figure 10-51 - Future TCO of a passenger car under a high purchase grant.

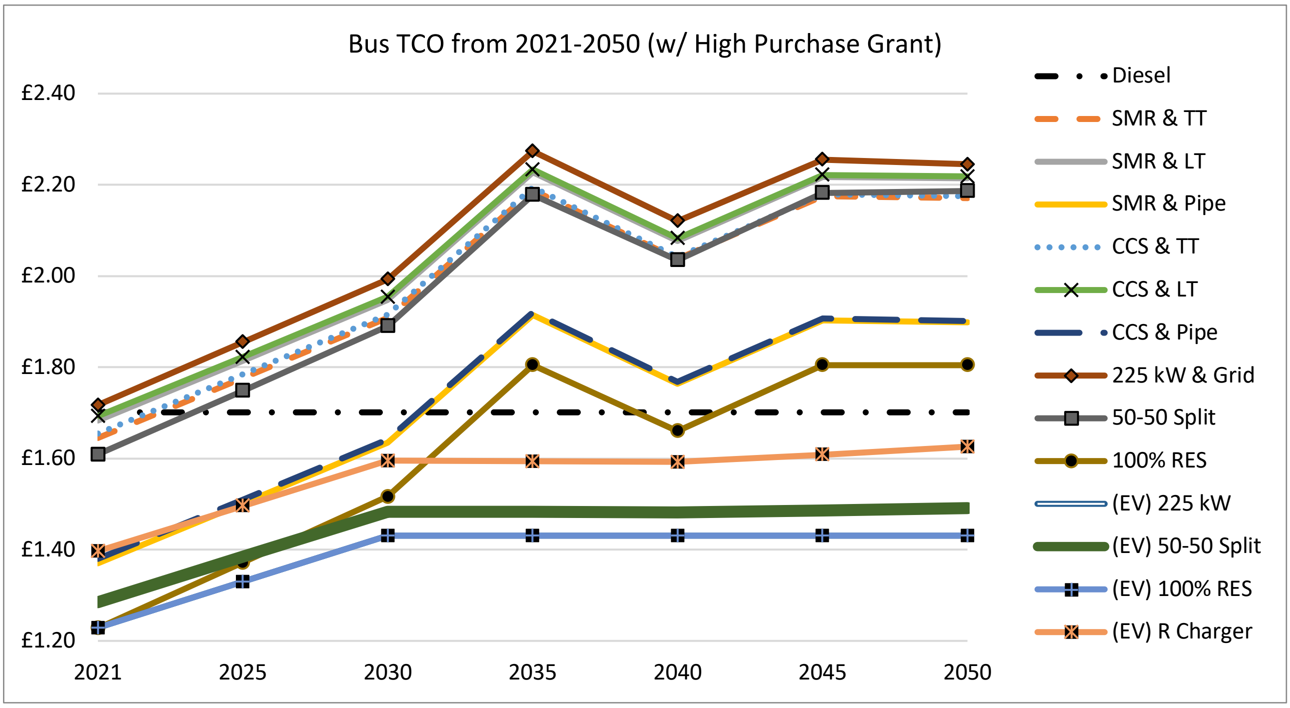


Figure 10-52 - Future TCO of a bus under a high purchase grant.

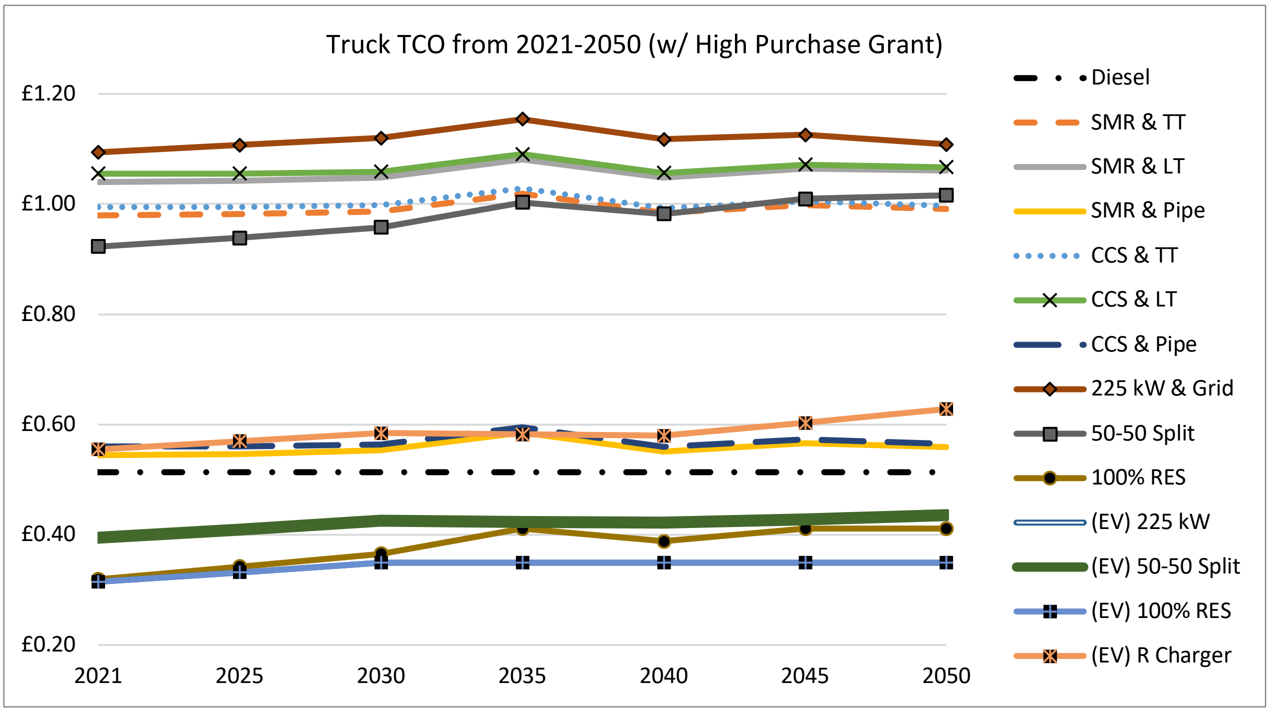


Figure 10-53 - Future TCO of a truck under a high purchase grant.

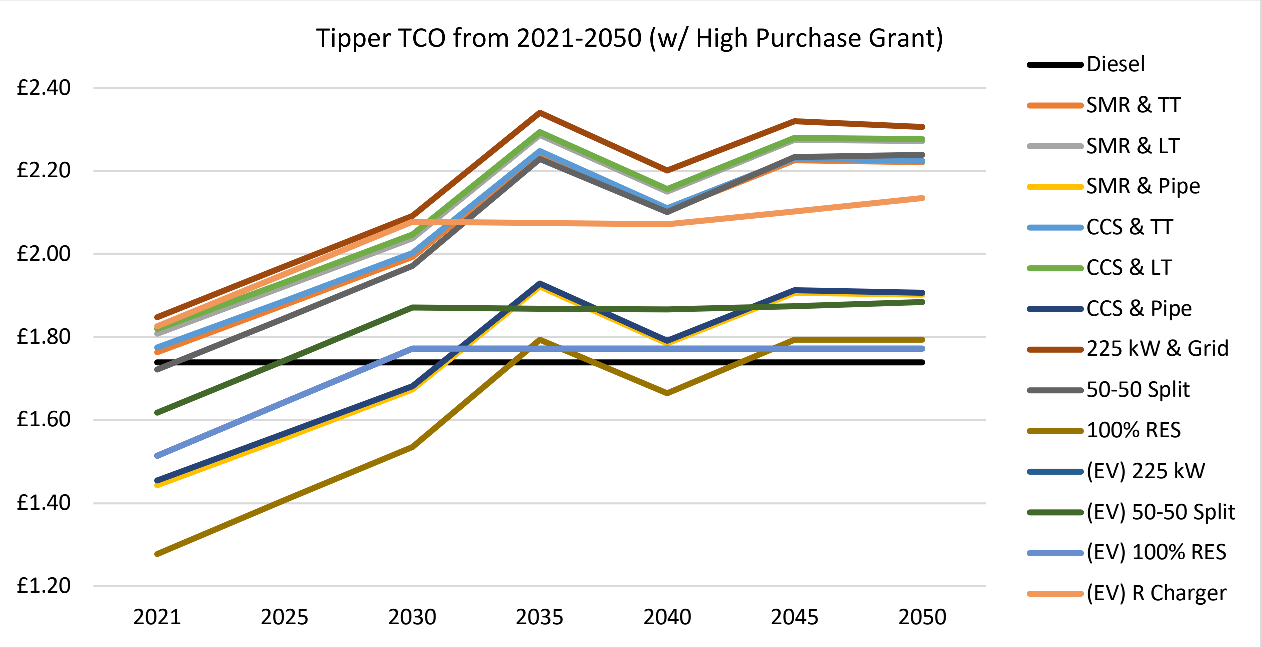


Figure 10-54 - Future TCO of a tipper under a high purchase grant.

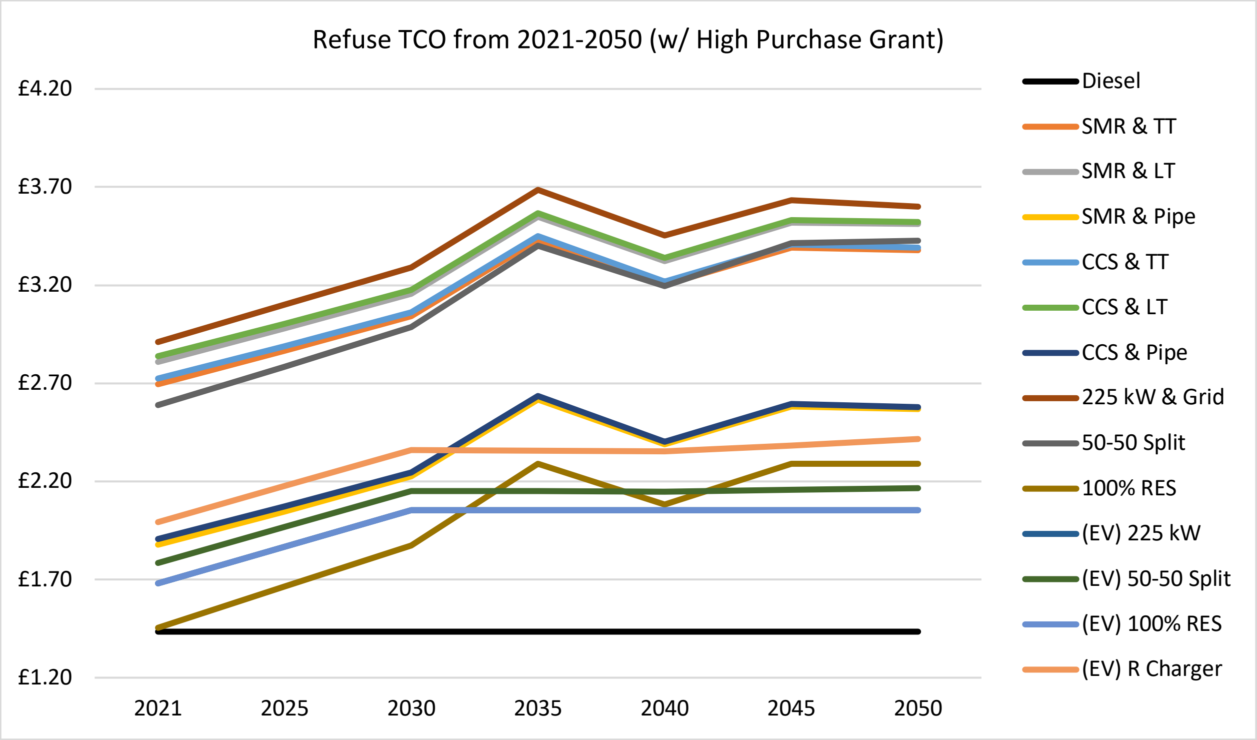


Figure 10-55 - Future TCO of a refuse under a high purchase grant.

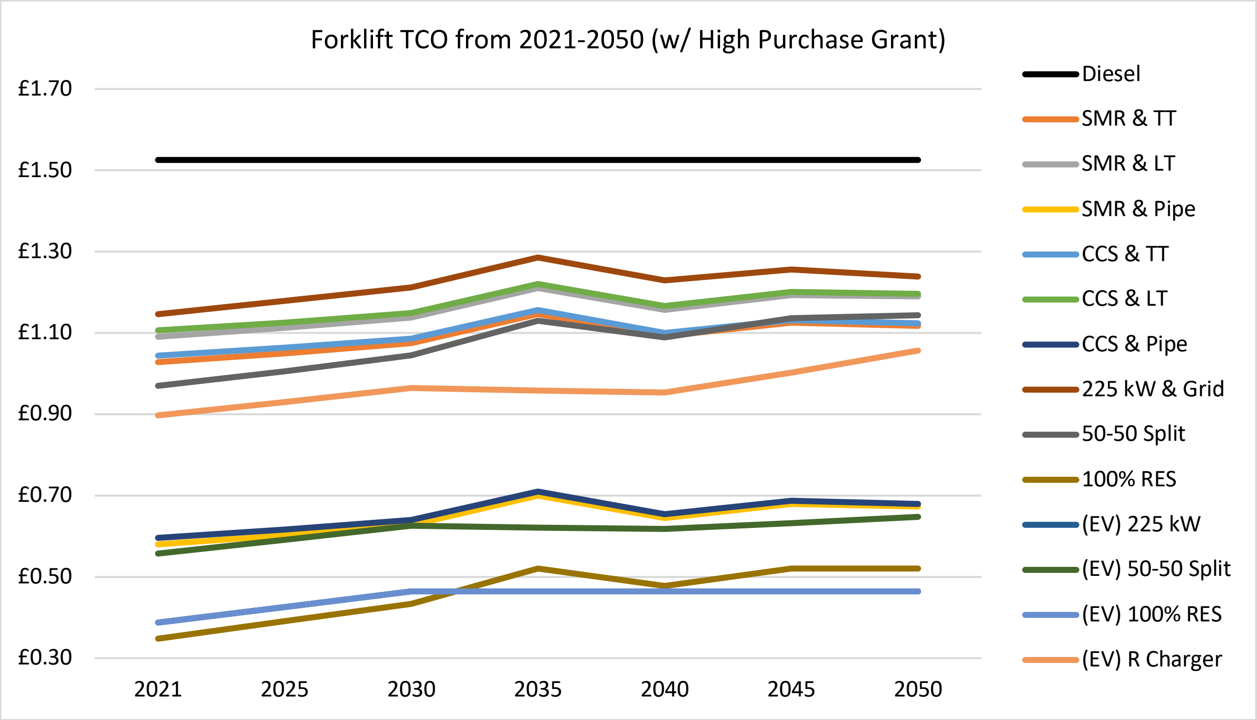


Figure 10-56 - Future TCO of a forklift under a high purchase grant.

11. Appendix 2 – Life Cycle Assessment

11.1. Vehicle Weight Breakdown:

11.1.1. Passenger Cars:

Table 11-1 - Weight composition breakdown for passenger cars.

Powertrain:	Component:	Weight (kg):	Weight Composition (%):	References/Comments:
ICEV	Combustion Engine	432	22.7	Weight est. using [122].
	Diesel Tank	15.1	0.8	Weight estimated using [122].
	Gearbox	94.8	5	9-G Tronic automatic transmission (from Mercedes email). [198]
	Glider (& Remaining Items)	1358	71.5	Kerb - Engine – Tank – Gearbox = Glider (1900-432-15-95 = 1358 kg)
	Total Weight	1900	100	1900 kg kerb weight reported for Mercedes E400d
				Mercedes E400d
FCEV	Hydrogen Tank	93	5.3	Taken from [85] and [70].
	Electric Motor	71	4.1	Scaled from Ecoinvent (53 kg for a 100 kW motor). Toyota Mirai has a ~134 kW motor, so 134/100 = 1.34 x 53 kg = 71 kg.
	Fuel Cell	178	10.2	115 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 115 x 1.55 = ~178 kg
	Battery	44.6	2.6	Mirai has a 1.24 kWh battery and its weight is reported at 44.6 kg.
	Glider (& Remaining Items)	1358	77.8	Same glider for all powertrain types.
	Total Weight	1745	100	Weight of glider and PT components.
				Toyota Mirai
BEV	Battery	478	23.7	Based on Tesla Model 3 with 80 kWh battery. Weight reported at 478 kg. [56]
	Electric Motor	178	8.8	Scaled from Ecoinvent (53 kg for a 100 kW motor). Tesla Model 3 has a 335 kW motor. 335/100 = 3.35 x 53 kg =178 kg.
	Glider (& Remaining Items)	1358	67.4	Same glider for all powertrain types.
	Total Weight	2014	100	Weight of glider and major PT components.
				Tesla Model 3

11.1.2. 12m Buses:

Table 11-2 - Weight composition breakdown for buses.

Powertrain:	**Component:**	**Weight (kg):**	**Weight Composition (%):**	**References/Comments:**
ICEV	Combustion Engine	767	6.4	Weight est. using torque (1500 Nm) in Fries 2017 paper [122]
	Diesel Tank	37.6	0.31	Weight estimated using [122].
	Gearbox	340	2.8	Estimated from spec sheets (ZF 6S 1600 model). [199]
	Glider (& Other Items)	13,026	90.5	(12000-767-38-340 = 10855). 20% extra for repairs.
	Total Weight	12,000	100	Glider + PT components.
				IVECO Crossway Intercity
FCEV	Hydrogen Tank	558	4.8	Taken from [85] and [70]. One tank weighs 93 kg and bus uses 6 tanks so (6 x 93 kg) = 558 kg.
	Electric Motor	71	0.6	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). FCEV bus has a ~134 kW motor. 134/100 = 1.34 x 53 kg = 71 kg.
	Fuel Cell	116	1	75 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 75 x 1.55 = ~116 kg
	Battery	80	0.7	Li-ion batteries have a density of 250 Wh/kg. FCEV bus has a 20 kWh battery. Estimated weight is 20/0.25 = 80 kg.
	Glider (& Other Items)	13,026	92.9	Same glider for all powertrain types.
	Total Weight	11,680	100	Weight of glider and PT components.
				Wrightbus Hydroliner
BEV	Battery	1400	11.3	Li-ion batteries have a density of 250 Wh/kg. BEV bus has a 350 kWh battery. 350/0.25 = 1400 kg.
	Electric Motor	143.1	1.1	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). BEV bus has a ~270 kW motor. 270/100 = 2.7 x 53 kg = 143.1 kg.
	Glider (& Other Items)	13,026	87.6	Same glider for all powertrain types.
	Total Weight	12,398	100	Weight of glider and PT components.
				Ebusco Electric Bus

11.1.3. Heavy Duty Trucks:

Table 11-3 - Weight composition breakdown for trucks.

Powertrain:	**Component:**	**Weight (kg):**	**Weight Composition (%):**	**References/Comments:**
ICEV	Combustion Engine	1365.7	7.6	Weight estimated using torque (3000 Nm) in Fries 2017 paper. [122]
	Diesel Tank	47.9	0.3	Weight estimated using [122].
	Gearbox	270	1.5	Has a 12-speed Powershift 3 transmission. Weight is estimated using the average weight of all specs in Mercedes data sheet. [200]
	Glider (& Other Items)	19,580	90.6	(18,000-1365-48-270 = 16,316). 20% extra for repairs. Same glider for all powertrain types.
	Total Weight	18,000	100	Use kerb weight of ICEV to calculate glider weight.
				Mercedes Actros 1863
FCEV	Hydrogen Tank	1302	6.9	Taken from [85] and [70]. One tank weighs 93 kg and truck uses 14 tanks so (14 x 93 kg) = 1302 kg.
	Electric Motor	238.5	1.3	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). FCEV truck has a 450 kW motor. 450/100 = 4.5 x 53 kg = 238.5 kg.
	Fuel Cell	372	2.0	Excel model assumes 240 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 240 x 1.55 = 372 kg
	Battery	560	3.0	Li-ion batteries have a density of 250 Wh/kg. FCEV truck has a 140 kWh battery. 140/0.25 = 560 kg.
	Glider (& Other Items)	19,580	86.8	Same glider (platform and trailer) for all powertrain types.
	Total Weight	18,789	100	Weight of glider and PT components.
				Nikola Truck (FCEV Version of Tre)
BEV	Battery	1260	7.1	Li-ion batteries have a density of 250 Wh/kg. BEV truck has a 315 kWh battery. 315/0.25 = 1260 kg.
	Electric Motor	212	1.1	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). BEV truck has a 400 kW motor. 400/100 = 4 x 53 kg = 212 kg.
	Glider (& Other Items)	19,580	91.7	Same glider (platform and trailer) for all powertrain types.
	Total Weight	17,788	100	Weight of glider and PT components.
				Mercedes eActros 300 (6x2)

11.1.4. Tipper Trucks:

Table 11-4 - Weight composition breakdown for tipper trucks.

Powertrain:	**Component:**	**Weight (kg):**	**Weight Composition (%):**	**References/Comments:**
ICEV	Combustion Engine	614.6	4.4	Weight estimated using torque (1150 Nm) in Fries 2017 paper. [122]
	Diesel Tank	43	0.3	Weight estimated using [122].
	Gearbox	180	1.3	9-speed manual synchromesh gearbox. Weight estimated using same gearbox from Volvo data sheets, since MAN don't specify. [201] [202]
	Glider (& Other Items)	15,794	94.0	(14,000-614.6-43-180 = 13,162). 20% extra for repairs. Same glider for all powertrain types.
	Total Weight	14,000	100	26t GVW – 12t payload weight = 14t kerb weight.
				MAN TGM 6x4
FCEV	Hydrogen Tank	558	3.9	Taken from [85] and [70]. One tank weighs 93 kg and tipper truck uses 6 tanks so (6 x 93 kg) = 558 kg.
	Electric Motor	132.5	0.93	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). FCEV tipper truck has a 250 kW motor. 250/100 = 2.5 x 53 kg = 132.5 kg.
	Fuel Cell	124	0.87	Excel model assumes 80 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 80 x 1.55 = 124 kg
	Battery	280	2.0	Li-ion batteries have a density of 250 Wh/kg. FCEV tipper has a 70 kWh battery. 70/0.25 = 280 kg.
	Glider (& Other Items)	15,794	92.3	Same glider for all powertrain types.
	Total Weight	14,257	100	Weight of glider and PT components.
				HYZON HYMAX FCEV
BEV	Battery	1060	7.4	Li-ion batteries have a density of 250 Wh/kg. BEV tipper has a 265 kWh battery. 265/0.25 = 1060 kg.
	Electric Motor	196.1	1.4	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). BEV tipper has a 370 kW motor. 370/100 = 3.7 x 53 kg = 196.1 kg.
	Glider (& Other Items)	15,794	91.3	Same glider for all powertrain types.
	Total Weight	14,418	100	Weight of glider and PT components.
				Renault Truck D Wide ZE

11.1.5. Refuse Collection Vehicles:

Table 11-5 - Weight composition breakdown for refuse vehicles.

Powertrain:	**Component:**	**Weight (kg):**	**Weight Composition (%):**	**References/Comments:**
ICEV	Combustion Engine	635	4.0	Weight estimated using torque (1200 Nm) in Fries 2017 paper. [122]
	Diesel Tank	43	0.3	Weight estimated using [122].
	Gearbox	191.5	1.2	6-speed automatic transmission. Weight estimated from Mercedes data sheet for 6-speed synchronised transmission. [203]
	Glider (& Other Items)	18,157	94.6	16,000 – 635 – 43-191.5 = 15,131 kg. 20% extra for repairs. Same glider for all powertrain types.
	Total Weight	16,000	100	Weight of glider and PT components.
				Daimler Econic Mercedes NGE-L62N
FCEV	Hydrogen Tank	558	3.5	Taken from [85] and [70]. One tank weighs 93 kg and RCV uses 6 tanks so (6 x 93 kg) = 558 kg.
	Electric Motor	132.5	0.83	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). FCEV RCV has a 250 kW motor. 250/100 = 2.5 x 53 kg = 132.5 kg.
	Fuel Cell	108.5	0.68	Excel model assumes 70 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 70 x 1.55 = 108.5 kg
	Battery	120	0.75	Li-ion batteries have a density of 250 Wh/kg. FCEV RCV has a 30 kWh battery. 30/0.25 = 120 kg.
	Glider (& Other Items)	18,157	94.3	Same glider for all powertrain types.
	Total Weight	16,051	100	Weight of glider and PT components.
				Arcola/Ballard FCEV RCV
BEV	Battery	800	5.0	Li-ion batteries have a density of 250 Wh/kg. BEV RCV has a 200 kWh battery. 200/0.25 = 800 kg.
	Electric Motor	196.1	1.2	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). BEV RCV has a 370 kW motor. 370/100 = 3.7 x 53 kg = 196.1 kg.
	Glider (& Other Items)	18,157	93.8	Same glider for all powertrain types.
	Total Weight	16,127	100	Weight of glider and PT components.
				Renault Truck D Wide ZE

11.1.6. Forklifts:

Table 11-6 - Weight composition breakdown for forklifts.

Powertrain:	**Component:**	**Weight (kg):**	**Weight Composition (%):**	**References/Comments:**
ICEV	Combustion Engine	340.5	1.9	Weight estimated using torque (475 Nm) in Fries 2017 paper. [122]
	Diesel Tank	34.2	0.2	Weight estimated using [122].
	Gearbox	250	1.4	AVTEC/TRT2221-3 hydraulic model (taken from Kalmar specs). [204]
	Glider (& Other Items)	21,109	96.6	(18,215-340.5-34-250 = 17,591). 20% extra for repairs. Same glider for all powertrain types.
	Total Weight	18,215	100	Unladen weight of 18,215 kg. (Reference vehicles section).
				Kalmar FLT12
FCEV	Hydrogen Tank	279	1.5	Taken from [85] and [70]. One tank weighs 93 kg and forklift uses 3 tanks so (3 x 93 kg) = 279 kg.
	Electric Motor	11.1	0.1	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). FCEV forklift has a 21kW motor. 21/100 = 0.21 x 53 kg = 11.13 kg.
	Fuel Cell	38.8	0.2	Excel model assumes 25 kW power and 1.55 kg/kW for FC system specific mass, taken from [119]. 25 x 1.55 = 38.8 kg
	Battery	941	0.7	Assuming the battery size is 1/3 of the BEV forklift battery. This equates to (0.33 x 2824) = 941 kg
	Glider (& Other Items)	21,109	97.5	Same glider for as ICEV forklifts.
	Total Weight	18,861	100	Weight of glider and PT components.
				FCEV Forklift
BEV	Battery	2824	13.8	BEV forklift has a 90 kWh battery. 2824 kg battery weight provided in vehicle specs sheets.
	Electric Motor	11.1	0.05	Taken from Ecoinvent (53 kg for a motor with a max output of 100 kW). BEV forklift has a 21 kW motor. 21/100 = 0.21 x 53 kg = 11.13 kg.
	Glider (& Other Items)	21,109	86.1	Same glider for as ICEV forklifts.
	Total Weight	20,426	100	Weight of glider and PT components.
				STILL RX 60-80/900

11.2. Life Cycle Emissions Breakdown:

11.2.1. GWP Impact Category:

Table 11-7 - Breakdown of life cycle emissions for passenger cars under base case conditions (GWP).

	Passenger Cars - GWP							
	Vehicle Production:	Fuel Production:	Fuel Distribution:	Fuel Conditioning:	Vehicle Use:	EOL:	Component Replacement:	Total:
Diesel	18.5%	10.8%	1.3%	0.0%	67.5%	1.9%	0.0%	100%
SMR (Pipeline)	58.7%	37.6%	0.0%	4.2%	0.0%	-14.6%	14.0%	100%
SMR (Tube Trailer)	58.5%	37.5%	0.3%	4.2%	0.0%	-14.5%	13.9%	100%
SMR (Liquid Tanker)	51.3%	32.9%	0.3%	16.0%	0.0%	-12.7%	12.2%	100%
SMR w/ CCS (Pipeline)	77.6%	17.6%	0.0%	5.6%	0.0%	-19.3%	18.4%	100%
SMR w/ CCS (Tube Trailer)	77.2%	17.6%	0.5%	5.6%	0.0%	-19.2%	18.4%	100%
SMR w/ CCS (Liquid Tanker)	65.2%	14.8%	0.4%	20.3%	0.0%	-16.2%	15.5%	100%
(FCEV) 225 kW WT (+ Grid)	48.2%	48.8%	0.0%	3.5%	0.0%	-12.0%	11.5%	100%
(FCEV) 100% RES	94.9%	6.1%	0.0%	0.0%	0.0%	-23.6%	22.6%	100%
(FCEV) 100% Grid	42.3%	55.1%	0.0%	3.1%	0.0%	-10.5%	10.1%	100%
(FCEV) 50/50 Split	58.5%	40.0%	0.0%	2.1%	0.0%	-14.5%	13.9%	100%
(BEV) 225 kW	58.4%	2.2%	0.0%	0.0%	0.0%	5.5%	33.9%	100%
(BEV) 100% RES	58.4%	2.2%	0.0%	0.0%	0.0%	5.5%	33.9%	100%
(BEV) Rapid Charger	41.2%	31.0%	0.0%	0.0%	0.0%	3.9%	23.9%	100%
(BEV) 50-50 Split	48.3%	19.1%	0.0%	0.0%	0.0%	4.6%	28.0%	100%

Table 11-8 - Breakdown of life cycle emissions for buses under generic mileage conditions (GWP).

	City Buses - GWP							
	Vehicle Production:	Fuel Production:	Fuel Distribution:	Fuel Conditioning:	Vehicle Use:	EOL:	Component Replacement:	Total:
Diesel	9.8%	12.8%	1.5%	0.0%	75.8%	0.1%	0.0%	100%
SMR (Pipeline)	14.2%	76.6%	0.0%	8.6%	0.0%	-1.2%	1.7%	100%
SMR (Tube Trailer)	14.1%	76.1%	0.7%	8.6%	0.0%	-1.2%	1.7%	100%
SMR (Liquid Tanker)	11.0%	59.2%	0.5%	28.8%	0.0%	-0.9%	1.3%	100%
SMR w/ CCS (Pipeline)	28.2%	53.7%	0.0%	17.1%	0.0%	-2.4%	3.4%	100%
SMR w/ CCS (Tube Trailer)	27.8%	53.0%	1.4%	16.8%	0.0%	-2.3%	3.4%	100%
SMR w/ CCS (Liquid Tanker)	17.8%	34.0%	0.9%	46.6%	0.0%	-1.5%	2.2%	100%
(FCEV) 225 kW WT (+ Grid)	9.9%	83.8%	0.0%	6.0%	0.0%	-0.8%	1.2%	100%
(FCEV) 100% RES	63.5%	34.1%	0.0%	0.0%	0.0%	-5.4%	7.7%	100%
(FCEV) 100% Grid	8.0%	86.9%	0.0%	4.8%	0.0%	-0.7%	1.0%	100%
(FCEV) 50/50 Split	14.1%	81.0%	0.0%	4.3%	0.0%	-1.2%	1.7%	100%
(BEV) 225 kW	51.4%	4.3%	0.0%	0.0%	0.0%	0.7%	43.7%	100%

(BEV) 100% RES	51.4%	4.3%	0.0%	0.0%	0.0%	0.7%	43.7%	100%
(BEV) Rapid Charger	28.2%	47.4%	0.0%	0.0%	0.0%	0.4%	24.0%	100%
(BEV) 50-50 Split	36.4%	32.1%	0.0%	0.0%	0.0%	0.5%	30.9%	100%

Table 11-9 - Breakdown of life cycle emissions for trucks under generic mileage conditions (GWP).

	Trucks - GWP							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement:	Total:
Diesel	3.1%	7.0%	0.8%	0.0%	89.0%	0.0%	0.0%	100%
SMR (Pipeline)	5.0%	82.5%	0.0%	9.3%	0.0%	-0.6%	3.7%	100%
SMR (Tube Trailer)	5.0%	81.9%	0.7%	9.2%	0.0%	-0.6%	3.7%	100%
SMR (Liquid Tanker)	3.8%	62.7%	0.6%	30.5%	0.0%	-0.4%	2.8%	100%
SMR w/ CCS (Pipeline)	10.7%	62.6%	0.0%	19.9%	0.0%	-1.2%	8.0%	100%
SMR w/ CCS (Tube Trailer)	10.6%	61.6%	1.6%	19.6%	0.0%	-1.2%	7.9%	100%
SMR w/ CCS (Liquid Tanker)	6.4%	37.3%	1.0%	51.2%	0.0%	-0.7%	4.8%	100%
(FCEV) 225 kW WT (+ Grid)	3.4%	88.2%	0.0%	6.3%	0.0%	-0.4%	2.5%	100%
(FCEV) 100% RES	30.5%	50.2%	0.0%	0.0%	0.0%	-3.5%	22.7%	100%
(FCEV) 100% Grid	2.7%	90.6%	0.0%	5.0%	0.0%	-0.3%	2.0%	100%
(FCEV) 50/50 Split	5.0%	87.3%	0.0%	4.6%	0.0%	-0.6%	3.7%	100%
(BEV) 225 kW	33.1%	10.1%	0.0%	0.0%	0.0%	0.3%	56.5%	100%
(BEV) 100% RES	33.1%	10.1%	0.0%	0.0%	0.0%	0.3%	56.5%	100%
(BEV) Rapid Charger	11.2%	69.6%	0.0%	0.0%	0.0%	0.1%	19.1%	100%
(BEV) 50-50 Split	16.7%	54.5%	0.0%	0.0%	0.0%	0.2%	28.6%	100%

Table 11-10 - Breakdown of life cycle emissions for tippers under generic mileage conditions (GWP).

	Tippers - GWP							
	Vehicle Production:	Fuel Production:	Fuel Distribution:	Fuel Conditioning:	Vehicle Use:	EOL:	Component Replacement:	Total:
Diesel	27.2%	6.7%	0.8%	0.0%	65.0%	0.2%	0.0%	100%
SMR (Pipeline)	40.1%	54.6%	0.0%	6.2%	0.0%	-2.3%	1.4%	100%
SMR (Tube Trailer)	39.9%	54.3%	0.5%	6.1%	0.0%	-2.3%	1.4%	100%
SMR (Liquid Tanker)	33.2%	45.2%	0.4%	22.0%	0.0%	-1.9%	1.2%	100%
SMR w/ CCS (Pipeline)	61.9%	29.9%	0.0%	9.5%	0.0%	-3.5%	2.2%	100%
SMR w/ CCS (Tube Trailer)	61.5%	29.7%	0.8%	9.4%	0.0%	-3.5%	2.2%	100%
SMR w/ CCS (Liquid Tanker)	46.8%	22.6%	0.6%	31.0%	0.0%	-2.7%	1.7%	100%
(FCEV) 225 kW WT (+ Grid)	30.4%	65.5%	0.0%	4.7%	0.0%	-1.7%	1.1%	100%
(FCEV) 100% RES	89.7%	12.2%	0.0%	0.0%	0.0%	-5.1%	3.2%	100%
(FCEV) 100% Grid	25.7%	70.9%	0.0%	3.9%	0.0%	-1.5%	0.9%	100%

(FCEV) 50/50 Split	39.9%	57.9%	0.0%	3.1%	0.0%	-2.3%	1.4%	100%
(BEV) 225 kW	83.0%	3.1%	0.0%	0.0%	0.0%	0.9%	13.0%	100%
(BEV) 100% RES	83.0%	3.1%	0.0%	0.0%	0.0%	0.9%	13.0%	100%
(BEV) Rapid Charger	51.9%	39.4%	0.0%	0.0%	0.0%	0.6%	8.1%	100%
(BEV) 50-50 Split	63.8%	25.5%	0.0%	0.0%	0.0%	0.7%	10.0%	100%

Table 11-11 - Breakdown of life cycle emissions for refuse vehicles under generic mileage conditions (GWP).

	Refuse - GWP							
	Vehicle Production:	Fuel Production:	Fuel Distribution:	Fuel Conditioning:	Vehicle Use:	EOL:	Component Replacement:	Total:
Diesel	18.5%	7.1%	0.9%	0.0%	73.3%	0.2%	0.0%	100%
SMR (Pipeline)	14.5%	77.1%	0.0%	8.7%	0.0%	-0.6%	0.4%	100%
SMR (Tube Trailer)	14.4%	76.5%	0.7%	8.6%	0.0%	-0.6%	0.4%	100%
SMR (Liquid Tanker)	11.2%	59.5%	0.5%	29.0%	0.0%	-0.5%	0.3%	100%
SMR w/ CCS (Pipeline)	28.9%	54.4%	0.0%	17.3%	0.0%	-1.3%	0.7%	100%
SMR w/ CCS (Tube Trailer)	28.5%	53.6%	1.4%	17.1%	0.0%	-1.2%	0.7%	100%
SMR w/ CCS (Liquid Tanker)	18.2%	34.3%	0.9%	47.0%	0.0%	-0.8%	0.4%	100%
(FCEV) 225 kW WT (+ Grid)	10.0%	84.2%	0.0%	6.0%	0.0%	-0.4%	0.2%	100%
(FCEV) 100% RES	66.1%	35.1%	0.0%	0.0%	0.0%	-2.9%	1.6%	100%
(FCEV) 100% Grid	8.1%	87.2%	0.0%	4.8%	0.0%	-0.4%	0.2%	100%
(FCEV) 50/50 Split	14.4%	81.6%	0.0%	4.3%	0.0%	-0.6%	0.4%	100%
(BEV) 225 kW	84.6%	5.0%	0.0%	0.0%	0.0%	1.0%	9.4%	100%
(BEV) 100% RES	84.6%	5.0%	0.0%	0.0%	0.0%	1.0%	9.4%	100%
(BEV) Rapid Charger	43.3%	51.4%	0.0%	0.0%	0.0%	0.5%	4.8%	100%
(BEV) 50-50 Split	57.3%	35.7%	0.0%	0.0%	0.0%	0.7%	6.4%	100%

Table 11-12 - Breakdown of life cycle emissions for forklifts under generic mileage conditions (GWP).

	Forklifts - GWP							
	Vehicle Production:	Fuel Production:	Fuel Distribution:	Fuel Conditioning:	Vehicle Use:	EOL:	Component Replacement:	Total:
Diesel	18.3%	11.7%	1.4%	0.0%	68.5%	0.2%	0.0%	100%
SMR (Pipeline)	37.3%	56.8%	0.0%	6.4%	0.0%	-0.9%	0.4%	100%
SMR (Tube Trailer)	37.1%	56.5%	0.5%	6.4%	0.0%	-0.9%	0.4%	100%
SMR (Liquid Tanker)	30.7%	46.7%	0.4%	22.7%	0.0%	-0.8%	0.3%	100%
SMR w/ CCS (Pipeline)	58.9%	31.8%	0.0%	10.1%	0.0%	-1.5%	0.7%	100%
SMR w/ CCS (Tube Trailer)	58.5%	31.5%	0.8%	10.0%	0.0%	-1.5%	0.7%	100%
SMR w/ CCS (Liquid Tanker)	43.9%	23.7%	0.6%	32.5%	0.0%	-1.1%	0.5%	100%
(FCEV) 225 kW WT (+ Grid)	28.1%	67.5%	0.0%	4.8%	0.0%	-0.7%	0.3%	100%

(FCEV) 100% RES	87.9%	13.4%	0.0%	0.0%	0.0%	-2.2%	1.0%	100%
(FCEV) 100% Grid	23.5%	72.8%	0.0%	4.0%	0.0%	-0.6%	0.3%	100%
(FCEV) 50/50 Split	37.1%	60.2%	0.0%	3.2%	0.0%	-0.9%	0.4%	100%
(BEV) 225 kW	90.1%	4.5%	0.0%	0.0%	0.0%	1.1%	4.3%	100%
(BEV) 100% RES	90.1%	4.5%	0.0%	0.0%	0.0%	1.1%	4.3%	100%
(BEV) Rapid Charger	48.3%	48.8%	0.0%	0.0%	0.0%	0.6%	2.3%	100%
(BEV) 50-50 Split	62.8%	33.4%	0.0%	0.0%	0.0%	0.8%	3.0%	100%

11.2.2. PM Impact Category:

Table 11-13 - Breakdown of life cycle emissions for cars under generic mileage conditions (PM).

	Passenger Cars - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	56.9%	34.1%	0.5%	0.0%	6.5%	2.0%	0.0%	100.0%
SMR (Pipeline)	126.9%	-3.3%	0.0%	0.7%	3.7%	-73.7%	45.6%	100.0%
SMR (Tube Trailer)	126.7%	-3.3%	0.1%	0.7%	3.7%	-73.6%	45.6%	100.0%
SMR (Liquid Tanker)	123.7%	-3.2%	0.1%	3.1%	3.7%	-71.8%	44.5%	100.0%
SMR w/ CCS (Pipeline)	122.8%	0.1%	0.0%	0.7%	3.6%	-71.3%	44.1%	100.0%
SMR w/ CCS (Tube Trailer)	122.6%	0.1%	0.1%	0.7%	3.6%	-71.2%	44.1%	100.0%
SMR w/ CCS (Liquid Tanker)	119.8%	0.1%	0.1%	3.0%	3.5%	-69.6%	43.1%	100.0%
(FCEV) 225 kW WT (+ Grid)	110.8%	9.8%	0.0%	0.6%	3.3%	-64.3%	39.8%	100.0%
(FCEV) 100% RES	119.2%	3.6%	0.0%	0.0%	3.5%	-69.2%	42.9%	100.0%
(FCEV) 100% Grid	108.9%	11.3%	0.0%	0.6%	3.2%	-63.3%	39.2%	100.0%
(FCEV) 50/50 Split	113.8%	7.7%	0.0%	0.3%	3.4%	-66.1%	40.9%	100.0%
(BEV) 225 kW	46.1%	1.2%	0.0%	0.0%	2.5%	1.1%	49.0%	100.0%
(BEV) 100% RES	46.1%	1.2%	0.0%	0.0%	2.5%	1.1%	49.0%	100.0%
(BEV) Rapid Charger	44.8%	4.1%	0.0%	0.0%	2.5%	1.1%	47.6%	100.0%
(BEV) 50-50 Split	45.4%	2.7%	0.0%	0.0%	2.5%	1.1%	48.3%	100.0%

Table 11-14 - Breakdown of life cycle emissions for buses under generic mileage conditions (PM).

	Buses - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	22.3%	34.1%	0.5%	0.0%	43.1%	0.0%	0.0%	100.0%
SMR (Pipeline)	65.9%	-24.2%	0.0%	5.4%	53.2%	-20.0%	19.7%	100.0%
SMR (Tube Trailer)	65.4%	-24.0%	0.8%	5.3%	52.7%	-19.8%	19.5%	100.0%
SMR (Liquid Tanker)	55.5%	-20.4%	0.7%	19.5%	44.8%	-16.8%	16.6%	100.0%
SMR w/ CCS (Pipeline)	52.9%	0.4%	0.0%	4.3%	42.7%	-16.0%	15.8%	100.0%

SMR w/ CCS (Tube Trailer)	52.5%	0.4%	0.7%	4.3%	42.4%	-15.9%	15.7%	100.0%
SMR w/ CCS (Liquid Tanker)	46.0%	0.3%	0.6%	16.2%	37.1%	-13.9%	13.7%	100.0%
(FCEV) 225 kW WT (+ Grid)	31.9%	40.0%	0.0%	2.6%	25.7%	-9.6%	9.5%	100.0%
(FCEV) 100% RES	44.7%	19.4%	0.0%	0.0%	36.1%	-13.5%	13.3%	100.0%
(FCEV) 100% Grid	29.8%	43.9%	0.0%	2.4%	24.0%	-9.0%	8.9%	100.0%
(FCEV) 50/50 Split	35.8%	34.1%	0.0%	1.5%	28.9%	-10.8%	10.7%	100.0%
(BEV) 225 kW	30.2%	1.9%	0.0%	0.0%	20.1%	0.1%	47.8%	100.0%
(BEV) 100% RES	30.2%	1.9%	0.0%	0.0%	20.1%	0.1%	47.8%	100.0%
(BEV) Rapid Charger	28.9%	6.1%	0.0%	0.0%	19.2%	0.1%	45.8%	100.0%
(BEV) 50-50 Split	29.5%	4.0%	0.0%	0.0%	19.7%	0.1%	46.7%	100.0%

Table 11-15 - Breakdown of life cycle emissions for trucks under generic mileage conditions (PM).

	Trucks - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	1.7%	5.3%	0.1%	0.0%	92.9%	0.0%	0.0%	100.0%
SMR (Pipeline)	3.7%	-4.0%	0.0%	0.9%	94.5%	-1.3%	6.2%	100.0%
SMR (Tube Trailer)	3.7%	-4.0%	0.1%	0.9%	94.4%	-1.3%	6.2%	100.0%
SMR (Liquid Tanker)	3.6%	-3.9%	0.1%	3.7%	91.7%	-1.3%	6.0%	100.0%
SMR w/ CCS (Pipeline)	3.5%	0.1%	0.0%	0.8%	90.9%	-1.3%	6.0%	100.0%
SMR w/ CCS (Tube Trailer)	3.5%	0.1%	0.1%	0.8%	90.7%	-1.3%	6.0%	100.0%
SMR w/ CCS (Liquid Tanker)	3.4%	0.1%	0.1%	3.6%	88.2%	-1.2%	5.8%	100.0%
(FCEV) 225 kW WT (+ Grid)	3.1%	11.5%	0.0%	0.7%	80.4%	-1.1%	5.3%	100.0%
(FCEV) 100% RES	3.4%	4.4%	0.0%	0.0%	87.7%	-1.2%	5.8%	100.0%
(FCEV) 100% Grid	3.1%	13.3%	0.0%	0.7%	78.8%	-1.1%	5.2%	100.0%
(FCEV) 50/50 Split	3.2%	9.1%	0.0%	0.4%	83.0%	-1.2%	5.5%	100.0%
(BEV) 225 kW	2.1%	0.7%	0.0%	0.0%	87.6%	0.0%	9.6%	100.0%
(BEV) 100% RES	2.1%	0.7%	0.0%	0.0%	87.6%	0.0%	9.6%	100.0%
(BEV) Rapid Charger	2.1%	2.3%	0.0%	0.0%	86.2%	0.0%	9.4%	100.0%
(BEV) 50-50 Split	2.1%	1.5%	0.0%	0.0%	86.9%	0.0%	9.5%	100.0%

Table 11-16 - Breakdown of life cycle emissions for tippers under generic mileage conditions (PM).

	Tipper - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	29.6%	10.0%	0.1%	0.0%	60.2%	0.1%	0.0%	100.0%
SMR (Pipeline)	49.4%	-5.2%	0.0%	1.2%	61.8%	-11.8%	4.6%	100.0%
SMR (Tube Trailer)	49.3%	-5.2%	0.2%	1.2%	61.7%	-11.8%	4.6%	100.0%
SMR (Liquid Tanker)	47.5%	-5.0%	0.2%	4.8%	59.4%	-11.3%	4.5%	100.0%

SMR w/ CCS (Pipeline)	46.9%	0.1%	0.0%	1.1%	58.7%	-11.2%	4.4%	100.0%
SMR w/ CCS (Tube Trailer)	46.8%	0.1%	0.2%	1.1%	58.6%	-11.2%	4.4%	100.0%
SMR w/ CCS (Liquid Tanker)	45.1%	0.1%	0.2%	4.6%	56.5%	-10.8%	4.2%	100.0%
(FCEV) 225 kW WT (+ Grid)	40.1%	14.5%	0.0%	0.9%	50.2%	-9.6%	3.8%	100.0%
(FCEV) 100% RES	44.8%	5.6%	0.0%	0.0%	56.1%	-10.7%	4.2%	100.0%
(FCEV) 100% Grid	39.1%	16.6%	0.0%	0.9%	49.0%	-9.3%	3.7%	100.0%
(FCEV) 50/50 Split	41.8%	11.5%	0.0%	0.5%	52.3%	-10.0%	3.9%	100.0%
(BEV) 225 kW	37.5%	1.3%	0.0%	0.0%	47.4%	0.1%	13.8%	100.0%
(BEV) 100% RES	37.5%	1.3%	0.0%	0.0%	47.4%	0.1%	13.8%	100.0%
(BEV) Rapid Charger	36.3%	4.4%	0.0%	0.0%	45.9%	0.1%	13.3%	100.0%
(BEV) 50-50 Split	36.9%	2.9%	0.0%	0.0%	46.6%	0.1%	13.5%	100.0%

Table 11-17 - Breakdown of life cycle emissions for refuse vehicles under generic mileage conditions (PM).

	Refuse - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	21.0%	11.2%	0.2%	0.0%	67.6%	0.0%	0.0%	100.0%
SMR (Pipeline)	38.2%	-17.4%	0.0%	3.9%	80.7%	-8.2%	2.8%	100.0%
SMR (Tube Trailer)	37.9%	-17.3%	0.6%	3.8%	80.2%	-8.1%	2.8%	100.0%
SMR (Liquid Tanker)	33.6%	-15.4%	0.5%	14.8%	71.1%	-7.2%	2.5%	100.0%
SMR w/ CCS (Pipeline)	32.4%	0.3%	0.0%	3.3%	68.5%	-6.9%	2.4%	100.0%
SMR w/ CCS (Tube Trailer)	32.2%	0.3%	0.5%	3.3%	68.2%	-6.9%	2.4%	100.0%
SMR w/ CCS (Liquid Tanker)	29.1%	0.3%	0.5%	12.8%	61.5%	-6.2%	2.2%	100.0%
(FCEV) 225 kW WT (+ Grid)	21.6%	33.7%	0.0%	2.2%	45.6%	-4.6%	1.6%	100.0%
(FCEV) 100% RES	28.5%	15.4%	0.0%	0.0%	60.2%	-6.1%	2.1%	100.0%
(FCEV) 100% Grid	20.4%	37.4%	0.0%	2.1%	43.1%	-4.4%	1.5%	100.0%
(FCEV) 50/50 Split	23.7%	28.2%	0.0%	1.2%	50.2%	-5.1%	1.8%	100.0%
(BEV) 225 kW	28.2%	1.7%	0.0%	0.0%	61.8%	0.1%	8.2%	100.0%
(BEV) 100% RES	28.2%	1.7%	0.0%	0.0%	61.8%	0.1%	8.2%	100.0%
(BEV) Rapid Charger	27.1%	5.6%	0.0%	0.0%	59.3%	0.1%	7.9%	100.0%
(BEV) 50-50 Split	27.6%	3.7%	0.0%	0.0%	60.5%	0.1%	8.0%	100.0%

Table 11-18 - Breakdown of life cycle emissions for forklifts under generic mileage conditions (PM).

	Forklift - PM							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	11.7%	11.1%	0.2%	0.0%	77.0%	0.0%	0.0%	100.0%
SMR (Pipeline)	55.8%	-8.8%	0.0%	2.0%	58.8%	-9.8%	2.1%	100.0%
SMR (Tube Trailer)	55.6%	-8.8%	0.3%	1.9%	58.6%	-9.8%	2.1%	100.0%

SMR (Liquid Tanker)	52.2%	-8.3%	0.3%	7.9%	55.0%	-9.2%	2.0%	100.0%
SMR w/ CCS (Pipeline)	51.2%	0.2%	0.0%	1.8%	53.9%	-9.0%	1.9%	100.0%
SMR w/ CCS (Tube Trailer)	51.0%	0.2%	0.3%	1.8%	53.8%	-9.0%	1.9%	100.0%
SMR w/ CCS (Liquid Tanker)	48.1%	0.2%	0.3%	7.3%	50.8%	-8.5%	1.8%	100.0%
(FCEV) 225 kW WT (+ Grid)	40.1%	21.7%	0.0%	1.4%	42.3%	-7.1%	1.5%	100.0%
(FCEV) 100% RES	40.7%	22.0%	0.0%	0.0%	42.9%	-7.2%	1.5%	100.0%
(FCEV) 100% Grid	38.7%	24.6%	0.0%	1.4%	40.8%	-6.8%	1.5%	100.0%
(FCEV) 50/50 Split	42.6%	17.5%	0.0%	0.7%	45.0%	-7.5%	1.6%	100.0%
(BEV) 225 kW	43.6%	2.7%	0.0%	0.0%	47.0%	0.1%	6.6%	100.0%
(BEV) 100% RES	43.6%	2.7%	0.0%	0.0%	47.0%	0.1%	6.6%	100.0%
(BEV) Rapid Charger	40.9%	8.7%	0.0%	0.0%	44.2%	0.1%	6.1%	100.0%
(BEV) 50-50 Split	42.2%	5.8%	0.0%	0.0%	45.5%	0.1%	6.3%	100.0%

11.2.3. FS Impact Category:

Table 11-19 - Breakdown of life cycle emissions for cars under generic mileage conditions (FS).

	Cars - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	18%	81%	1%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	58%	41%	0%	5%	0%	-19%	15%	100.0%
SMR (Tube Trailer)	58%	41%	0%	5%	0%	-19%	15%	100.0%
SMR (Liquid Tanker)	50%	35%	0%	19%	0%	-17%	13%	100.0%
SMR w/ CCS (Pipeline)	54%	45%	0%	5%	0%	-18%	14%	100.0%
SMR w/ CCS (Tube Trailer)	54%	45%	0%	5%	0%	-18%	14%	100.0%
SMR w/ CCS (Liquid Tanker)	47%	39%	0%	18%	0%	-16%	12%	100.0%
(FCEV) 225 kW WT (+ Grid)	45%	55%	0%	4%	0%	-15%	11%	100.0%
(FCEV) 100% RES	102%	5%	0%	0%	0%	-34%	26%	100.0%
(FCEV) 100% Grid	39%	61%	0%	3%	0%	-13%	10%	100.0%
(FCEV) 50/50 Split	56%	46%	0%	2%	0%	-19%	14%	100.0%
(BEV) 225 kW	60%	2%	0%	0%	0%	1%	37%	100.0%
(BEV) 100% RES	60%	2%	0%	0%	0%	1%	37%	100.0%
(BEV) Rapid Charger	38%	37%	0%	0%	0%	0%	24%	100.0%
(BEV) 50-50 Split	47%	23%	0%	0%	0%	1%	29%	100.0%

Table 11-20 - Breakdown of life cycle emissions for buses under generic mileage conditions (FS).

	Buses - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total

Diesel	9%	90%	1%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	13%	77%	0%	9%	0%	-1%	2%	100.0%
SMR (Tube Trailer)	13%	76%	1%	9%	0%	-1%	2%	100.0%
SMR (Liquid Tanker)	10%	58%	1%	31%	0%	-1%	1%	100.0%
SMR w/ CCS (Pipeline)	12%	79%	0%	8%	0%	-1%	1%	100.0%
SMR w/ CCS (Tube Trailer)	12%	79%	1%	8%	0%	-1%	1%	100.0%
SMR w/ CCS (Liquid Tanker)	9%	62%	0%	28%	0%	-1%	1%	100.0%
(FCEV) 225 kW WT (+ Grid)	9%	85%	0%	6%	0%	-1%	1%	100.0%
(FCEV) 100% RES	68%	29%	0%	0%	0%	-6%	8%	100.0%
(FCEV) 100% Grid	7%	88%	0%	5%	0%	-1%	1%	100.0%
(FCEV) 50/50 Split	13%	82%	0%	4%	0%	-1%	2%	100.0%
(BEV) 225 kW	52%	4%	0%	0%	0%	1%	44%	100.0%
(BEV) 100% RES	52%	4%	0%	0%	0%	1%	44%	100.0%
(BEV) Rapid Charger	26%	52%	0%	0%	0%	0%	22%	100.0%
(BEV) 50-50 Split	35%	36%	0%	0%	0%	1%	29%	100.0%

Table 11-21 - Breakdown of life cycle emissions for trucks under generic mileage conditions (FS).

	Trucks - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	6%	94%	1%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	5%	82%	0%	10%	0%	-1%	4%	100.0%
SMR (Tube Trailer)	5%	82%	1%	10%	0%	-1%	4%	100.0%
SMR (Liquid Tanker)	4%	61%	1%	32%	0%	0%	3%	100.0%
SMR w/ CCS (Pipeline)	4%	84%	0%	9%	0%	0%	3%	100.0%
SMR w/ CCS (Tube Trailer)	4%	84%	1%	9%	0%	0%	3%	100.0%
SMR w/ CCS (Liquid Tanker)	3%	65%	0%	29%	0%	0%	2%	100.0%
(FCEV) 225 kW WT (+ Grid)	3%	89%	0%	6%	0%	0%	2%	100.0%
(FCEV) 100% RES	34%	44%	0%	0%	0%	-4%	25%	100.0%
(FCEV) 100% Grid	2%	91%	0%	5%	0%	0%	2%	100.0%
(FCEV) 50/50 Split	4%	88%	0%	5%	0%	0%	3%	100.0%
(BEV) 225 kW	34%	8%	0%	0%	0%	0%	57%	100.0%
(BEV) 100% RES	34%	8%	0%	0%	0%	0%	57%	100.0%
(BEV) Rapid Charger	10%	73%	0%	0%	0%	0%	17%	100.0%
(BEV) 50-50 Split	16%	58%	0%	0%	0%	0%	26%	100.0%

Table 11-22 - Breakdown of life cycle emissions for tippers under generic mileage conditions (FS).

	Tippers - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	33%	66%	0%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	36%	58%	0%	7%	0%	-2%	1%	100.0%
SMR (Tube Trailer)	36%	57%	1%	7%	0%	-2%	1%	100.0%
SMR (Liquid Tanker)	29%	47%	0%	25%	0%	-2%	1%	100.0%
SMR w/ CCS (Pipeline)	33%	61%	0%	6%	0%	-2%	1%	100.0%
SMR w/ CCS (Tube Trailer)	33%	61%	0%	6%	0%	-2%	1%	100.0%
SMR w/ CCS (Liquid Tanker)	27%	50%	0%	23%	0%	-2%	1%	100.0%
(FCEV) 225 kW WT (+ Grid)	25%	70%	0%	5%	0%	-2%	1%	100.0%
(FCEV) 100% RES	91%	11%	0%	0%	0%	-6%	4%	100.0%
(FCEV) 100% Grid	21%	75%	0%	4%	0%	-1%	1%	100.0%
(FCEV) 50/50 Split	34%	63%	0%	3%	0%	-2%	1%	100.0%
(BEV) 225 kW	82%	3%	0%	0%	0%	1%	14%	100.0%
(BEV) 100% RES	82%	3%	0%	0%	0%	1%	14%	100.0%
(BEV) Rapid Charger	46%	46%	0%	0%	0%	1%	8%	100.0%
(BEV) 50-50 Split	59%	30%	0%	0%	0%	1%	10%	100.0%

Table 11-23 - Breakdown of life cycle emissions for refuse vehicles under generic mileage conditions (FS).

	Refuse - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	24%	75%	0%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	12%	78%	0%	10%	0%	-1%	0%	100.0%
SMR (Tube Trailer)	12%	78%	1%	10%	0%	-1%	0%	100.0%
SMR (Liquid Tanker)	9%	59%	1%	31%	0%	0%	0%	100.0%
SMR w/ CCS (Pipeline)	11%	81%	0%	8%	0%	-1%	0%	100.0%
SMR w/ CCS (Tube Trailer)	11%	80%	1%	8%	0%	-1%	0%	100.0%
SMR w/ CCS (Liquid Tanker)	8%	63%	0%	28%	0%	0%	0%	100.0%
(FCEV) 225 kW WT (+ Grid)	8%	86%	0%	6%	0%	0%	0%	100.0%
(FCEV) 100% RES	69%	33%	0%	0%	0%	-3%	2%	100.0%
(FCEV) 100% Grid	6%	89%	0%	5%	0%	0%	0%	100.0%
(FCEV) 50/50 Split	12%	84%	0%	4%	0%	-1%	0%	100.0%
(BEV) 225 kW	84%	4%	0%	0%	0%	1%	10%	100.0%
(BEV) 100% RES	84%	4%	0%	0%	0%	1%	10%	100.0%
(BEV) Rapid Charger	37%	58%	0%	0%	0%	1%	5%	100.0%
(BEV) 50-50 Split	51%	42%	0%	0%	0%	1%	6%	100.0%

Table 11-24 - Breakdown of life cycle emissions for forklifts under generic mileage conditions (FS).

	Forklift - FS							
	Vehicle Production	Fuel Production	Fuel Distribution	Fuel Conditioning	Vehicle Use	EOL	Component Replacement	Total
Diesel	16%	83%	1%	0%	0%	0%	0%	100.0%
SMR (Pipeline)	32%	61%	0%	7%	0%	-1%	0%	100.0%
SMR (Tube Trailer)	32%	60%	1%	7%	0%	-1%	0%	100.0%
SMR (Liquid Tanker)	26%	48%	0%	26%	0%	-1%	0%	100.0%
SMR w/ CCS (Pipeline)	29%	64%	0%	7%	0%	-1%	0%	100.0%
SMR w/ CCS (Tube Trailer)	29%	64%	0%	7%	0%	-1%	0%	100.0%
SMR w/ CCS (Liquid Tanker)	24%	52%	0%	24%	0%	-1%	0%	100.0%
(FCEV) 225 kW WT (+ Grid)	23%	73%	0%	5%	0%	-1%	0%	100.0%
(FCEV) 100% RES	89%	13%	0%	0%	0%	-2%	1%	100.0%
(FCEV) 100% Grid	19%	77%	0%	4%	0%	-1%	0%	100.0%
(FCEV) 50/50 Split	31%	66%	0%	4%	0%	-1%	0%	100.0%
(BEV) 225 kW	90%	4%	0%	0%	0%	2%	5%	100.0%
(BEV) 100% RES	90%	4%	0%	0%	0%	2%	5%	100.0%
(BEV) Rapid Charger	41%	56%	0%	0%	0%	1%	2%	100.0%
(BEV) 50-50 Split	56%	40%	0%	0%	0%	1%	3%	100.0%

11.3. Truck Production Emissions Network:

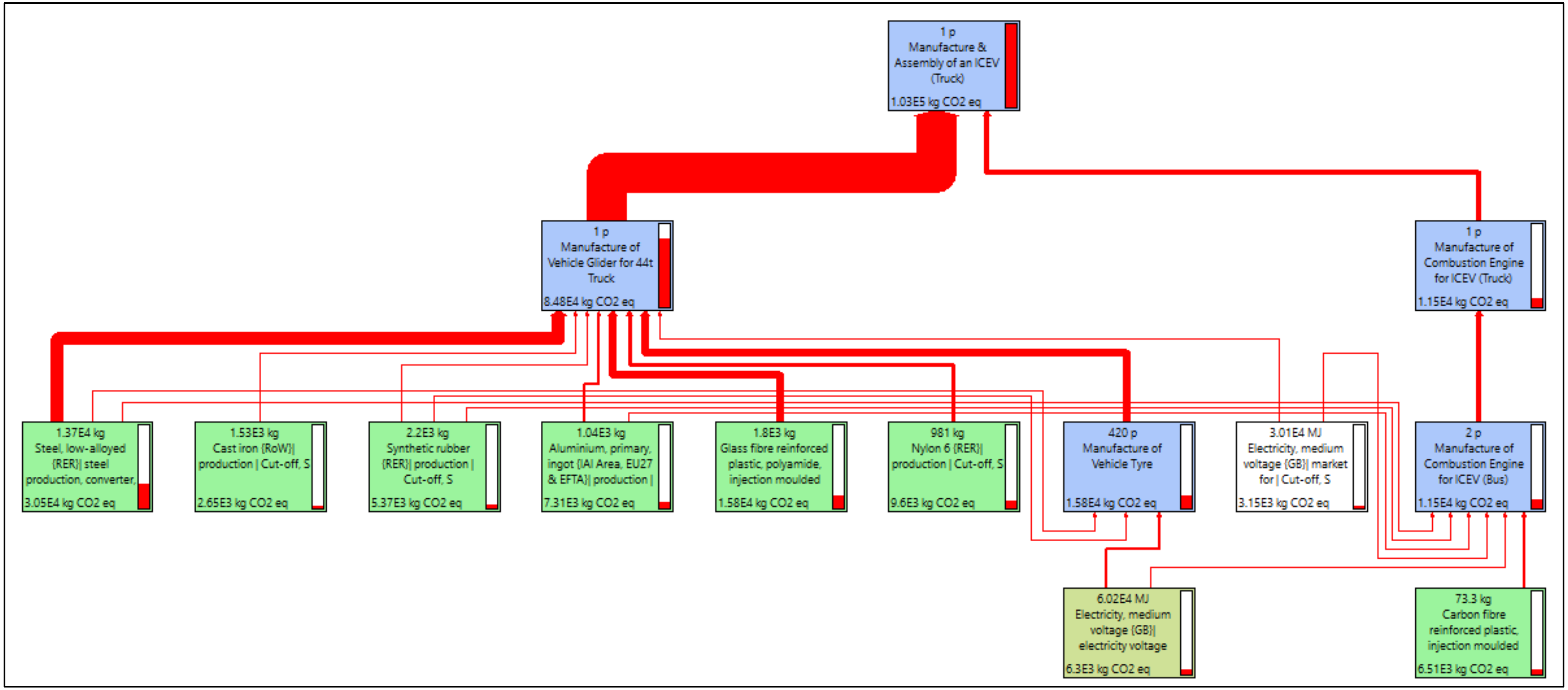


Figure 11-1 – GWP network for a ICEV truck with a 2.5% contribution cut-off.

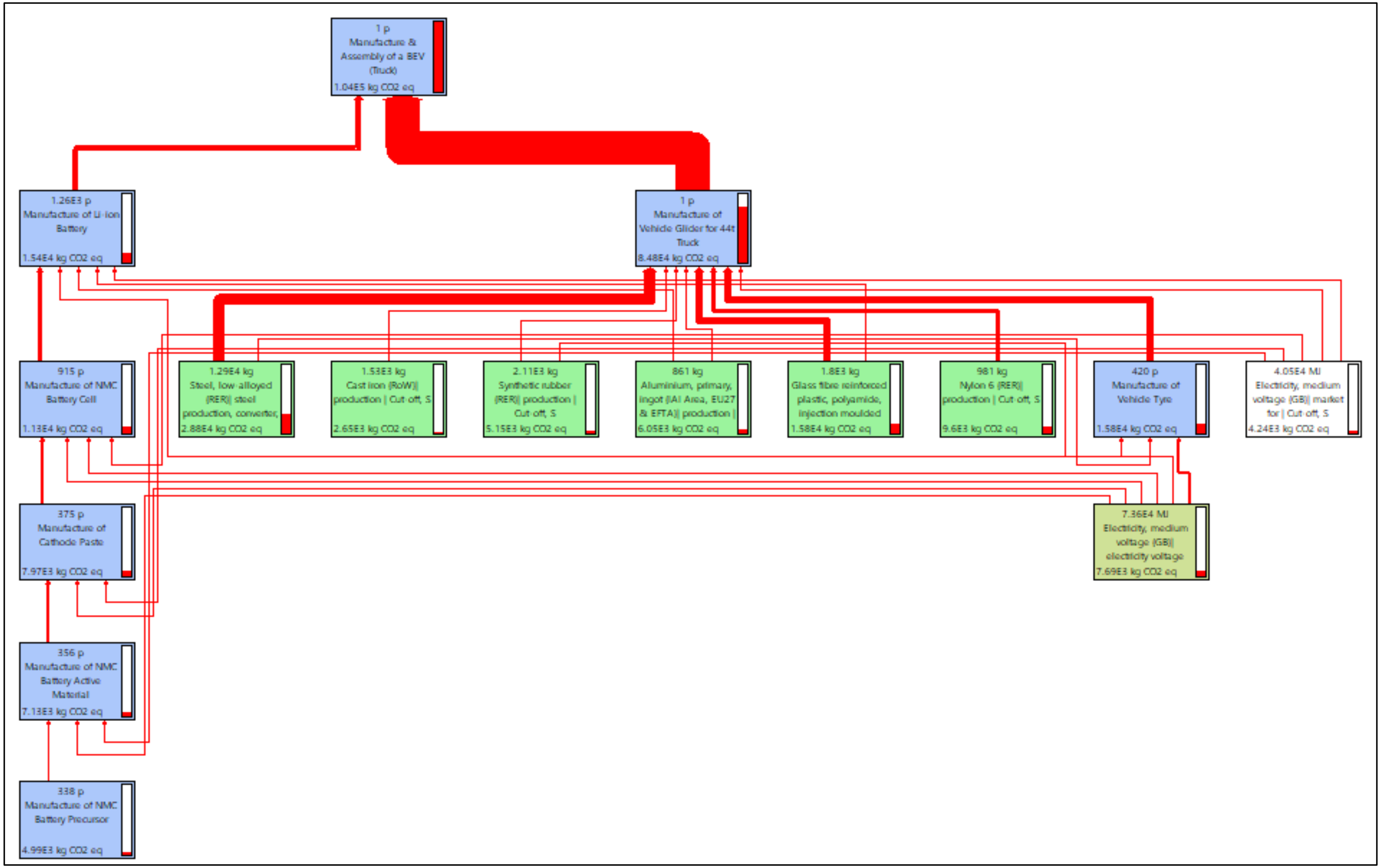


Figure 11-2 – GWP network for a BEV truck with 2.5% contribution cut-off.

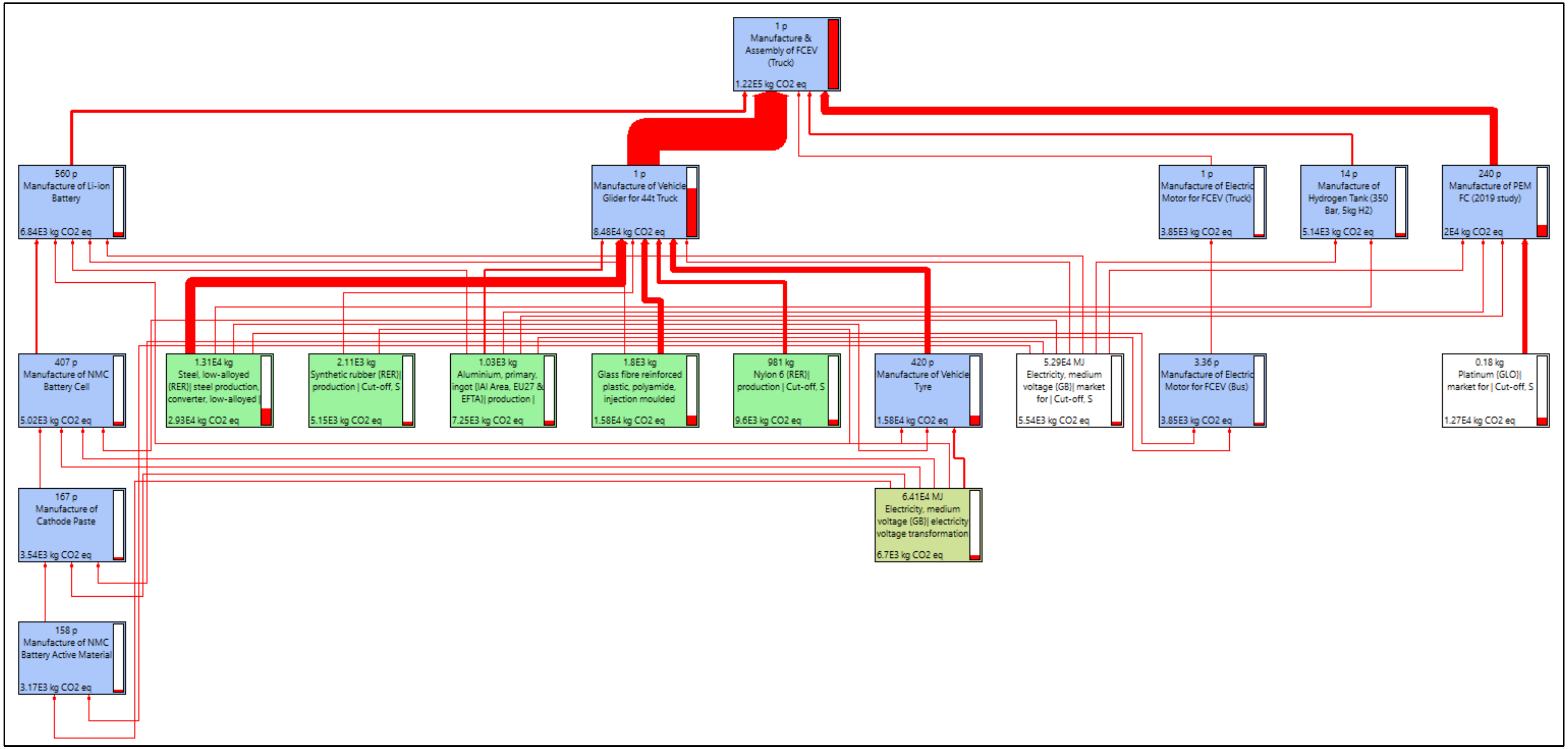


Figure 11-3 – GWP network of a FCEV truck with 2.5% contribution cut-off.

11.4. Breakdown of Vehicle Production Emissions:

11.4.1. ICEVs:

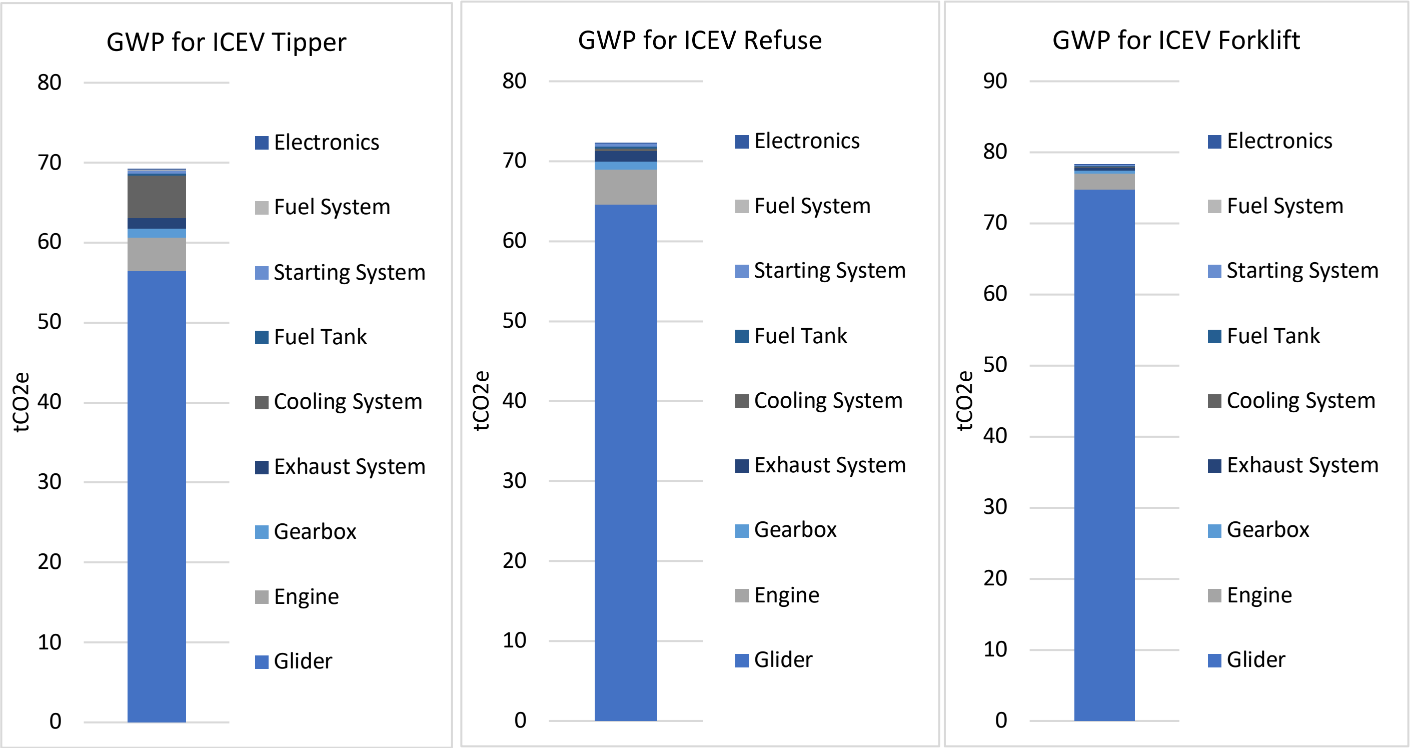


Figure 11-4 - GWP from ICEV tippers, RCVs, and forklifts.

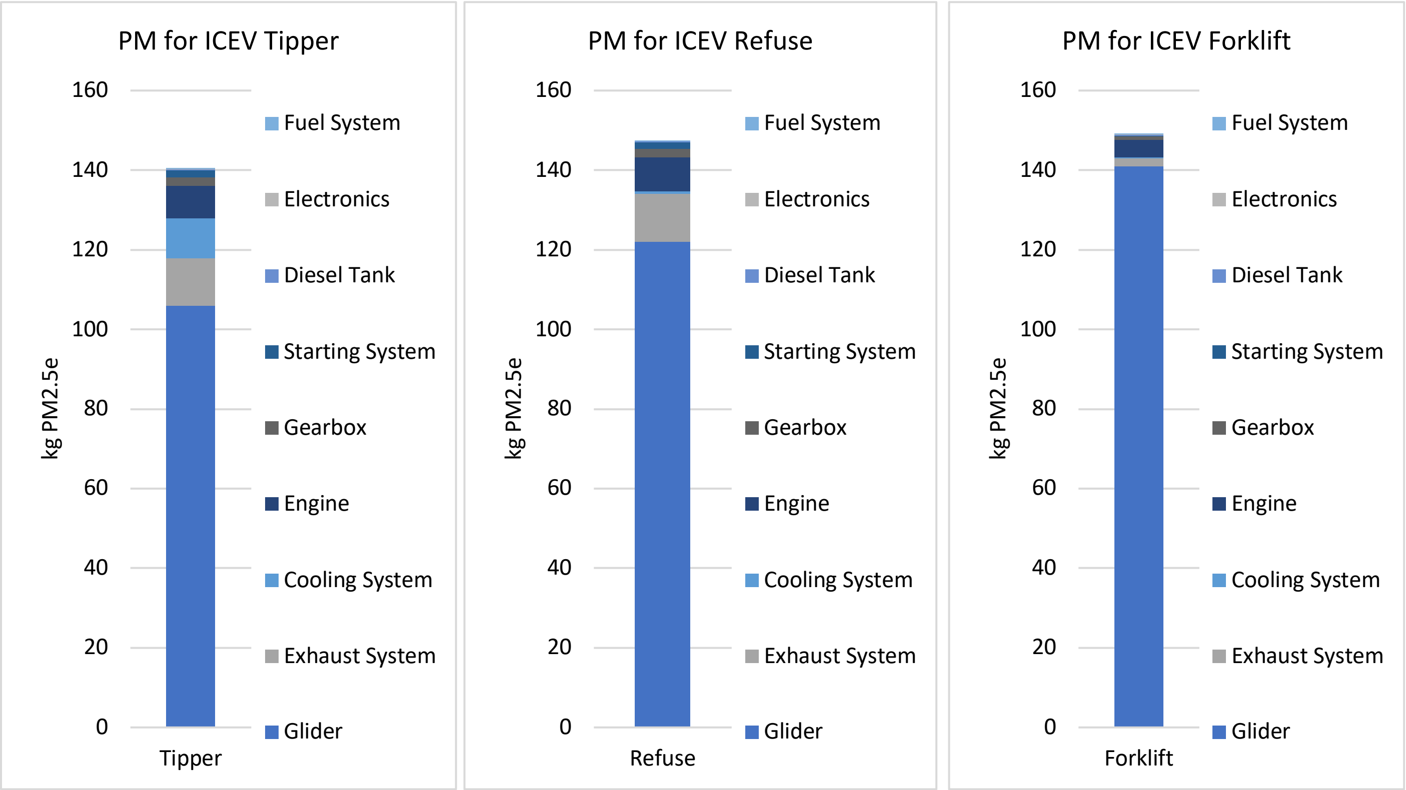


Figure 11-5 – PM from ICEV tippers, RCVs, and forklifts.

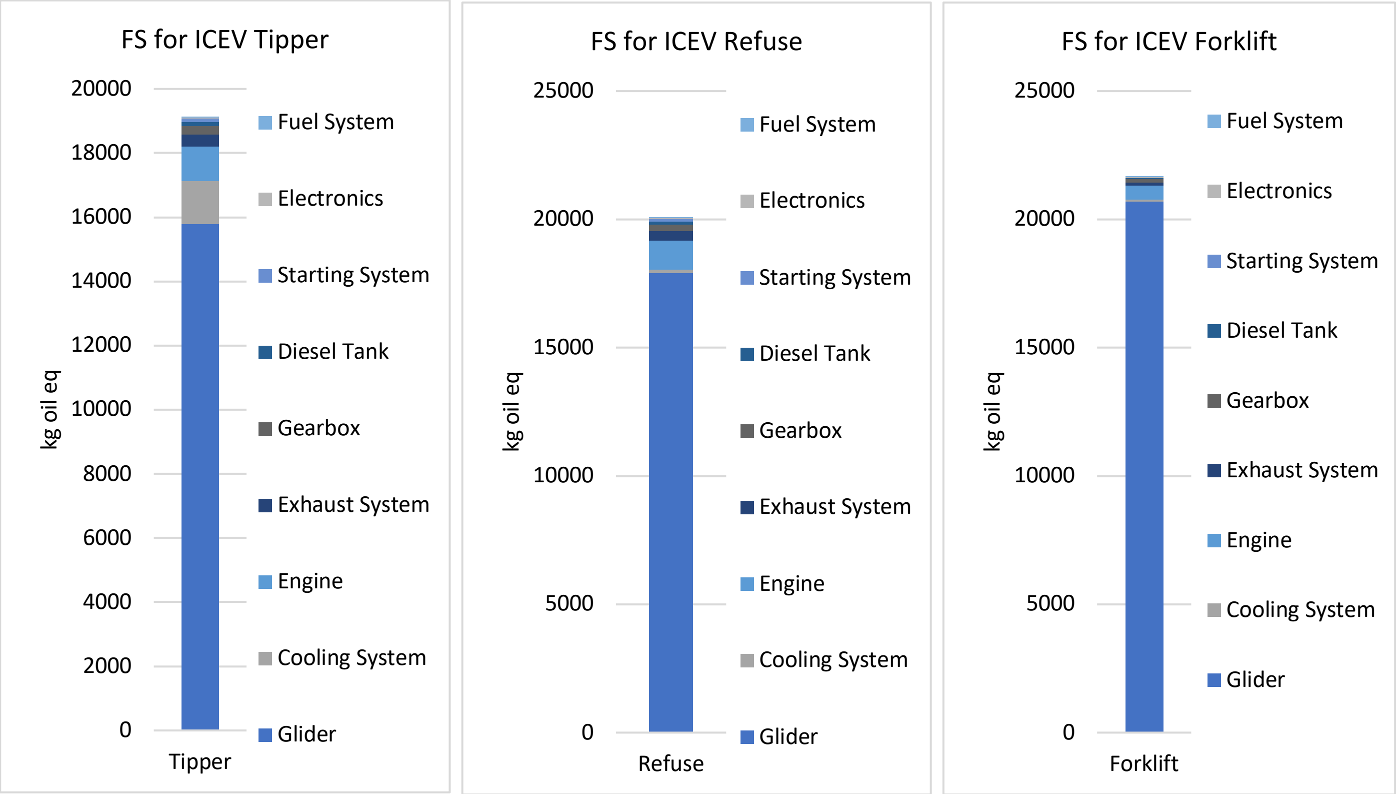


Figure 11-6 - FS from ICEV tippers, RCVs, and forklifts.

11.4.2. BEVs:

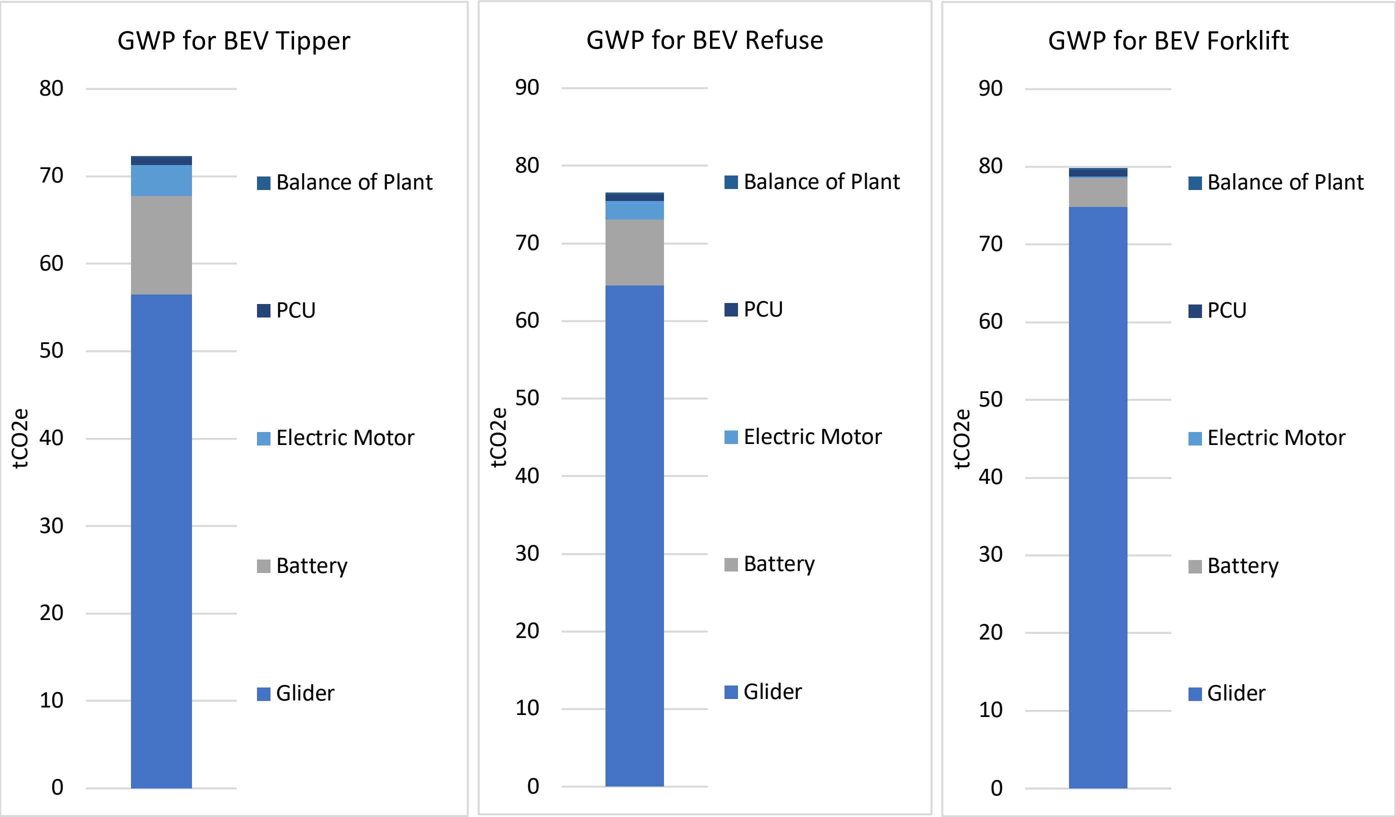


Figure 11-7 - GWP from BEV tippers, RCVs, and forklifts.

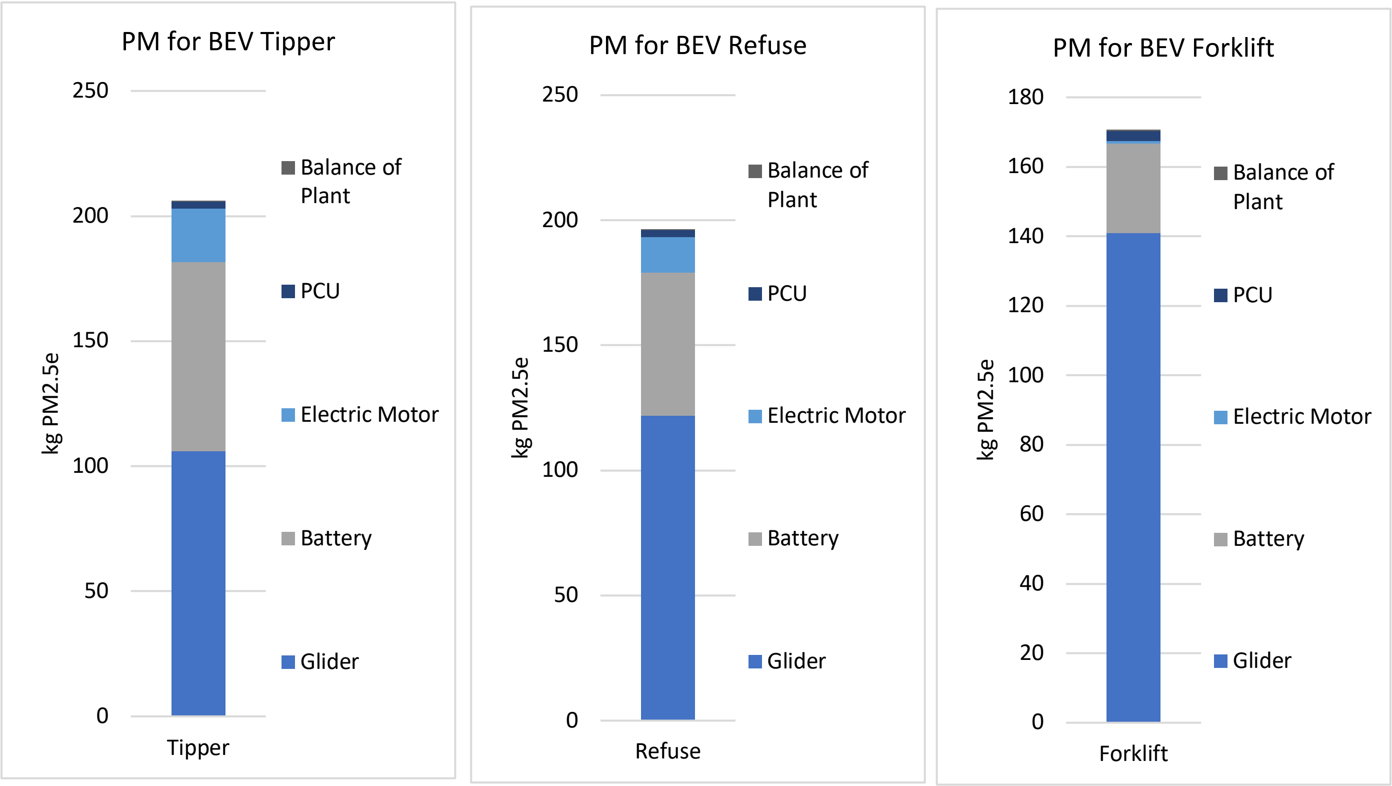


Figure 11-8 – PM from BEV tippers, RCVs, and forklifts.

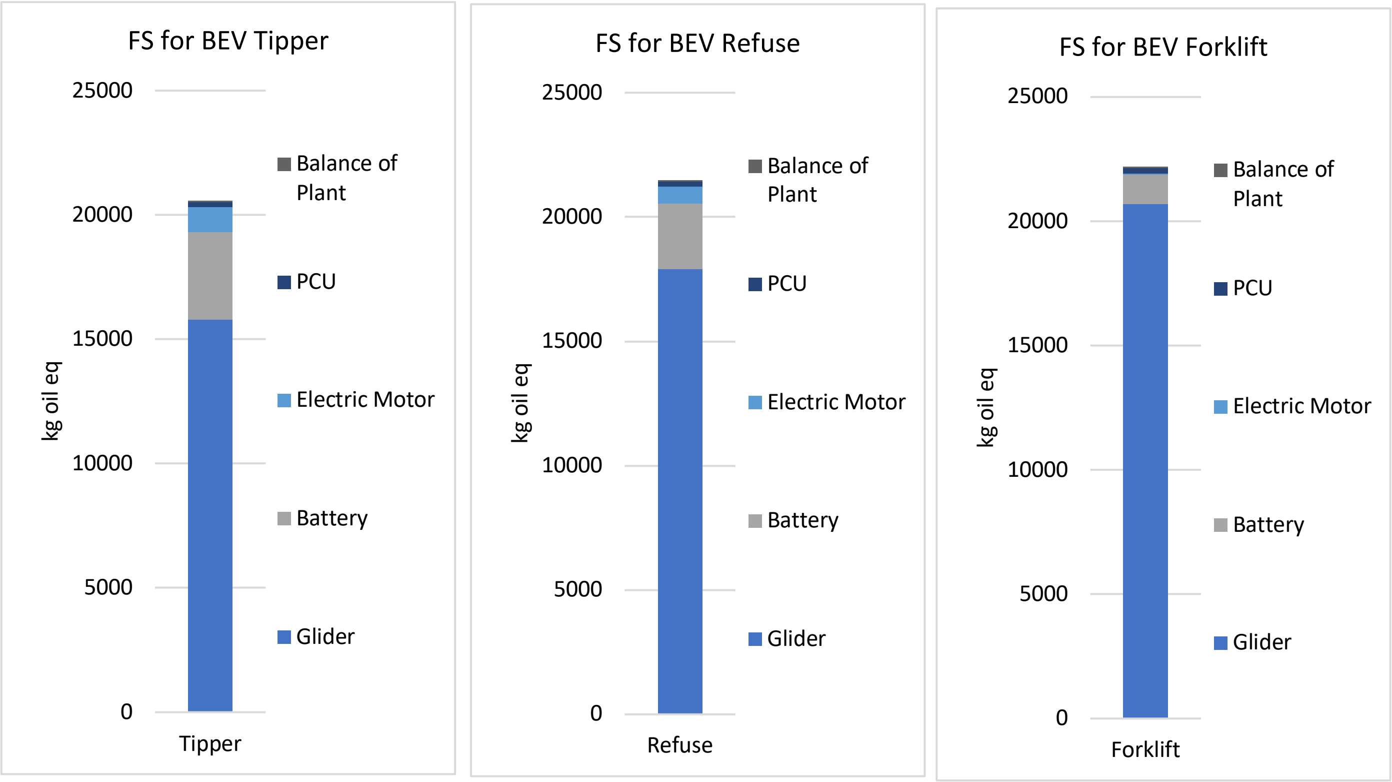


Figure 11-9 - FS from BEV tippers, RCVs, and forklifts.

11.4.3. FCEVs:

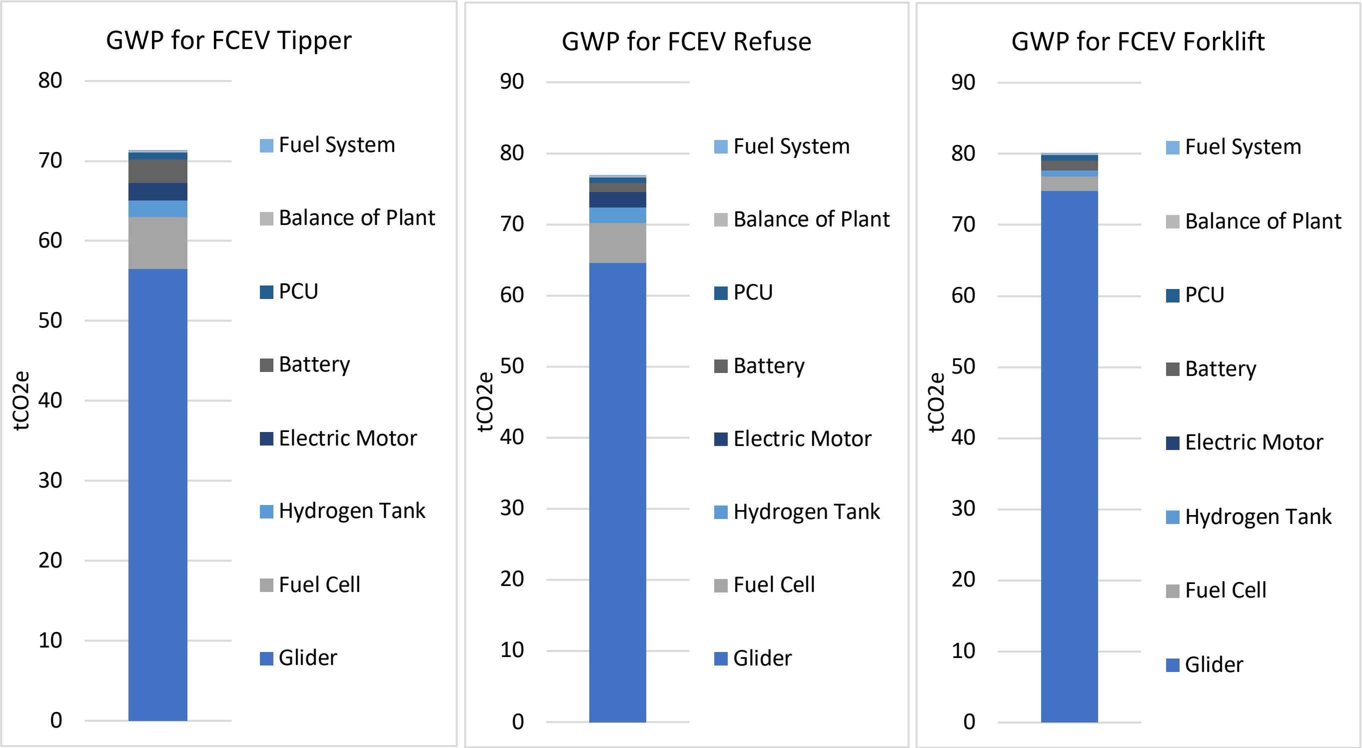


Figure 11-10 - GWP from FCEV tippers, RCVs, and forklifts.

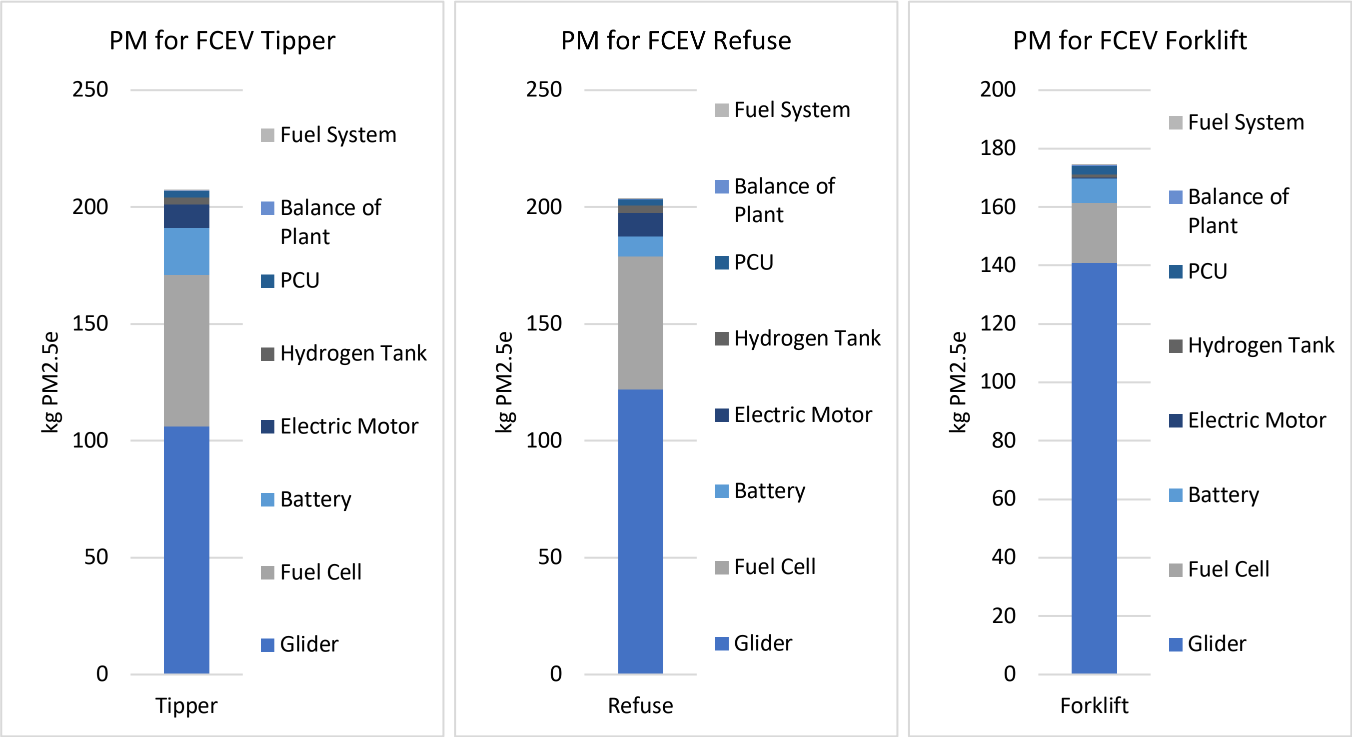


Figure 11-11 - PM from FCEV tippers, RCVs, and forklifts.

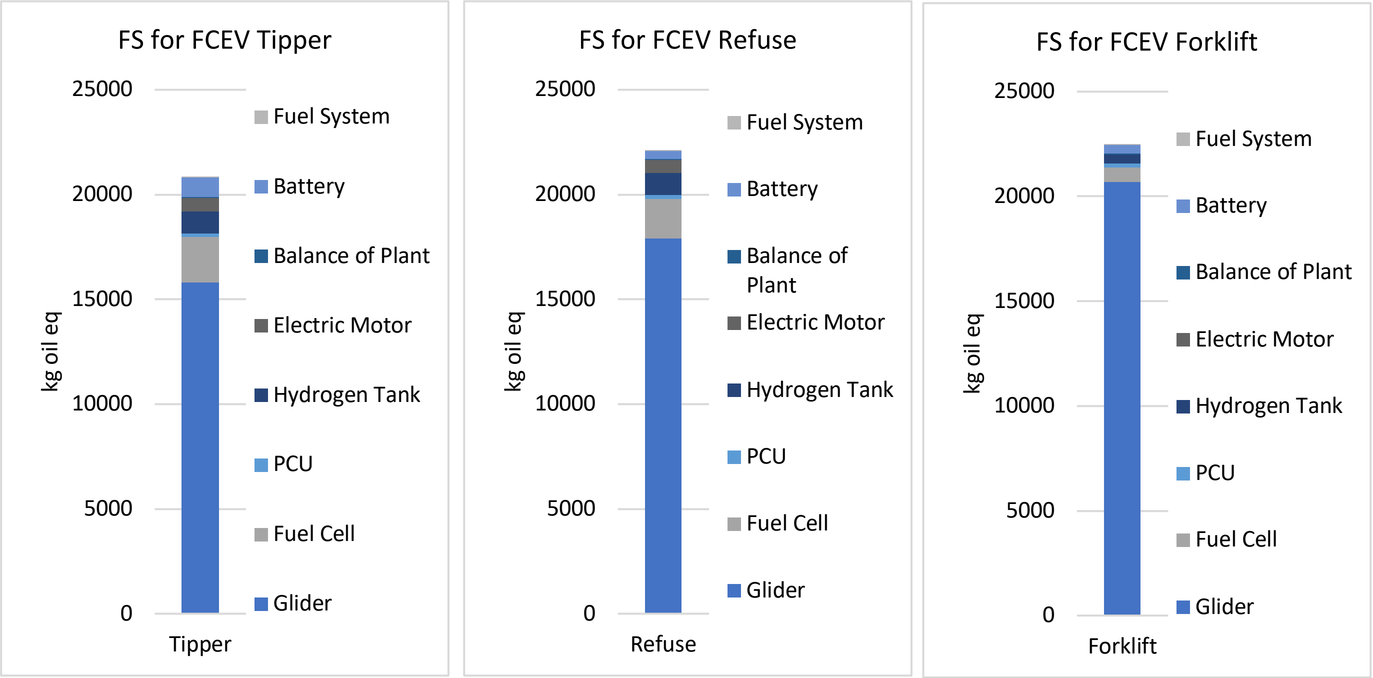


Figure 11-12 - FS from FCEV tippers, RCVs, and forklifts.

11.5. Fuel Cycle Emissions (PM & FS):

11.5.1. Hydrogen Distribution and Delivery Emissions:

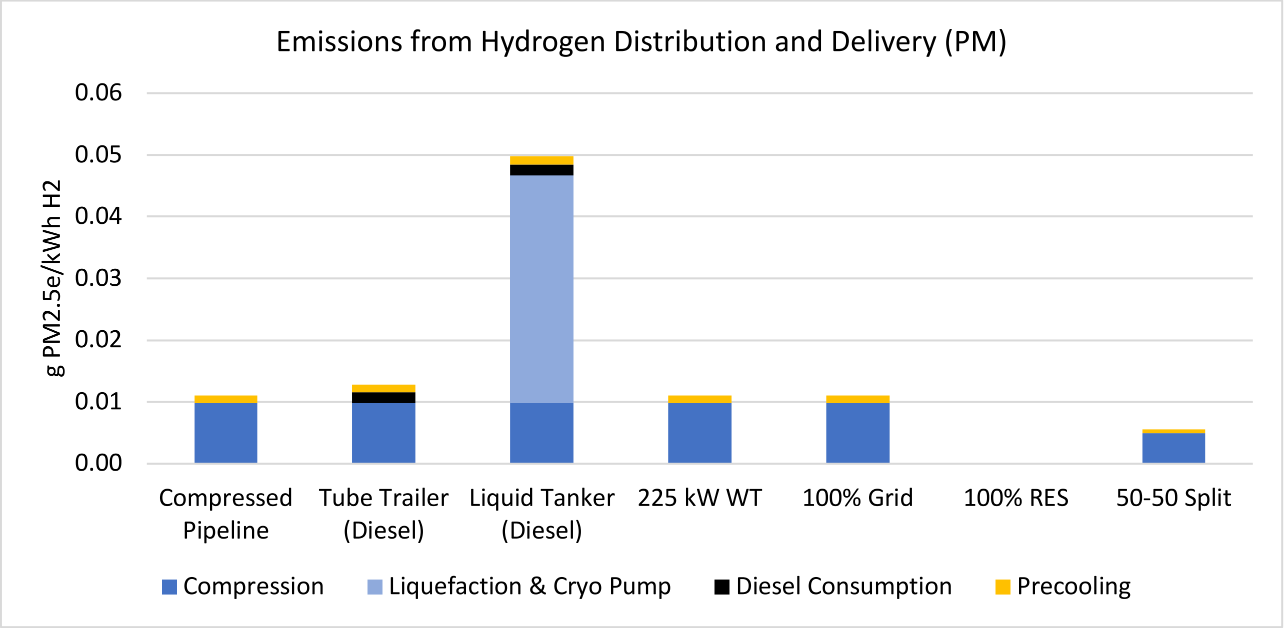


Figure 11-13 - Distribution and delivery emissions for hydrogen fuel in terms of PM.

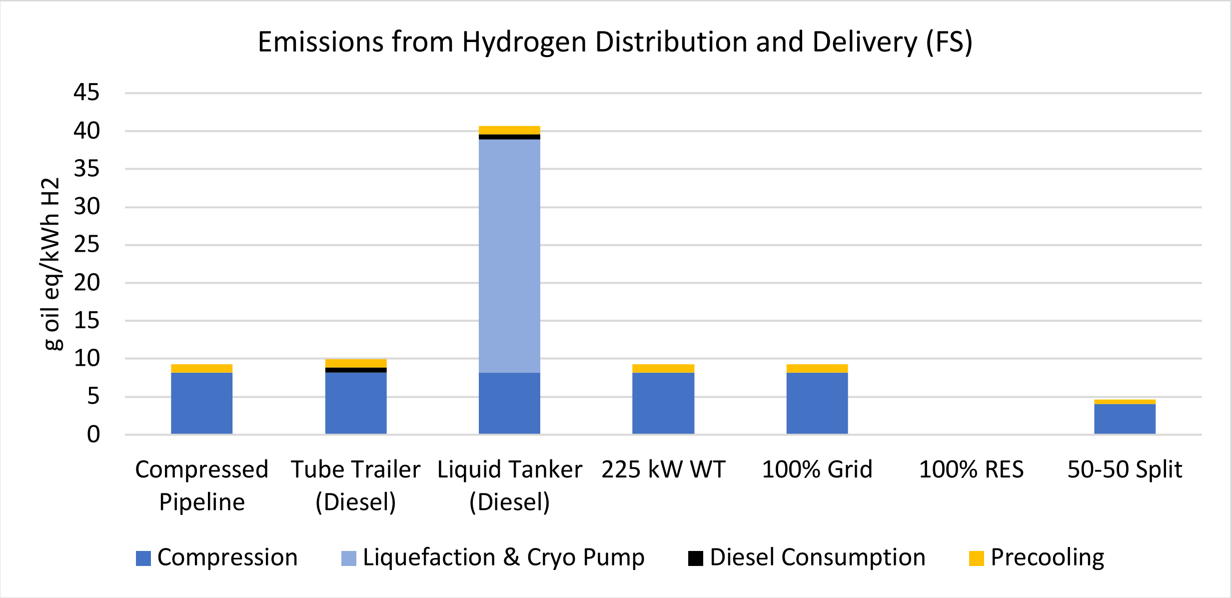


Figure 11-14 - Distribution and delivery emissions for hydrogen fuel in terms of FS.

11.5.2. Contributions to Total Transport Fuel Emissions:

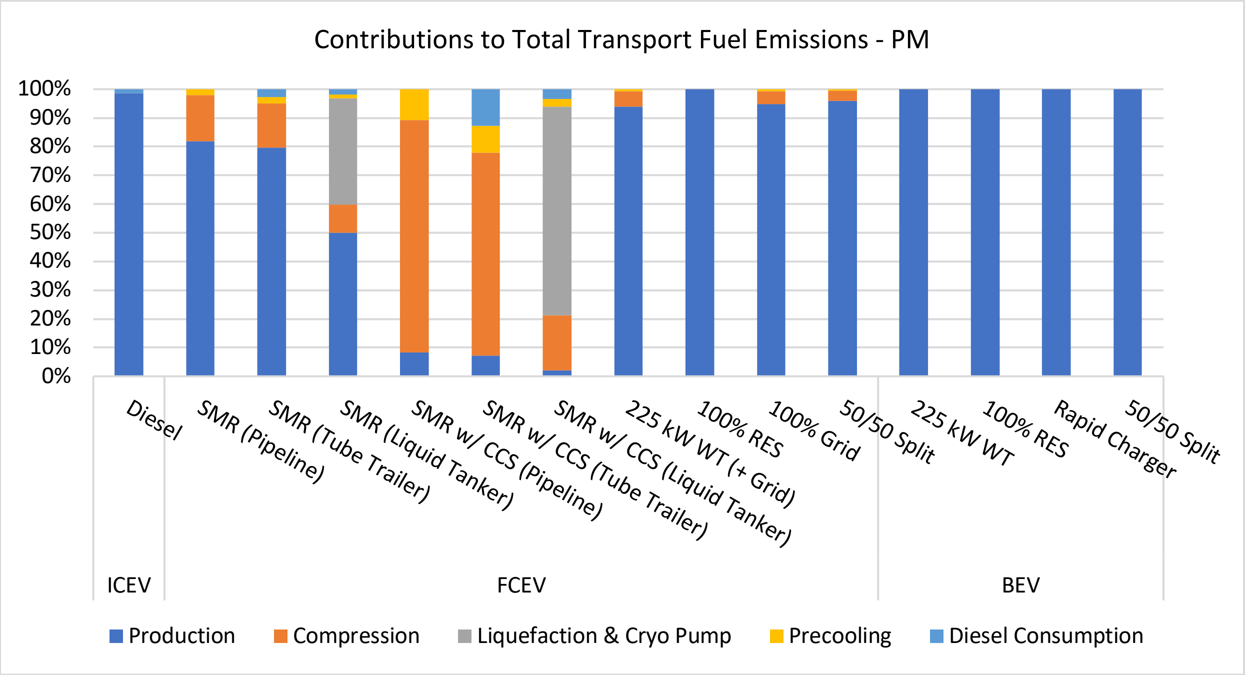


Figure 11-15 – Contribution to total fuel emissions (in terms of PM).

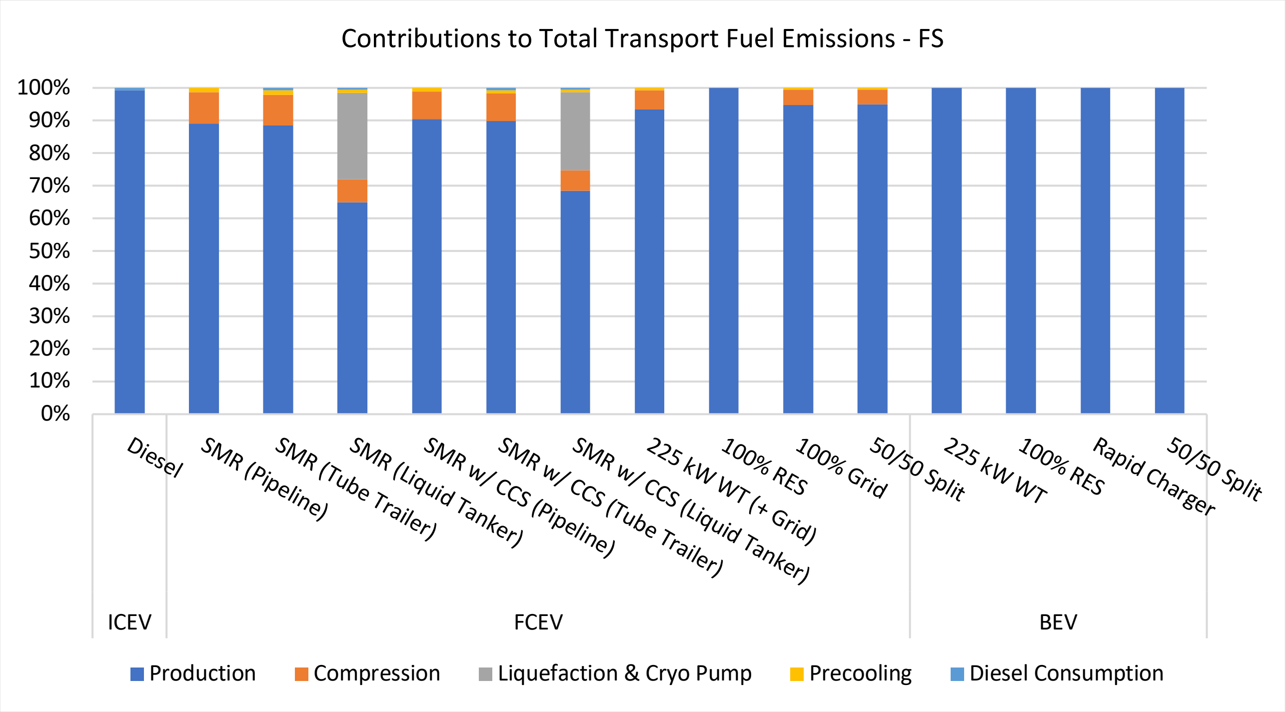


Figure 11-16 - Contribution to total fuel emissions (in terms of FS).

11.6. Vehicle End of Life Emissions:

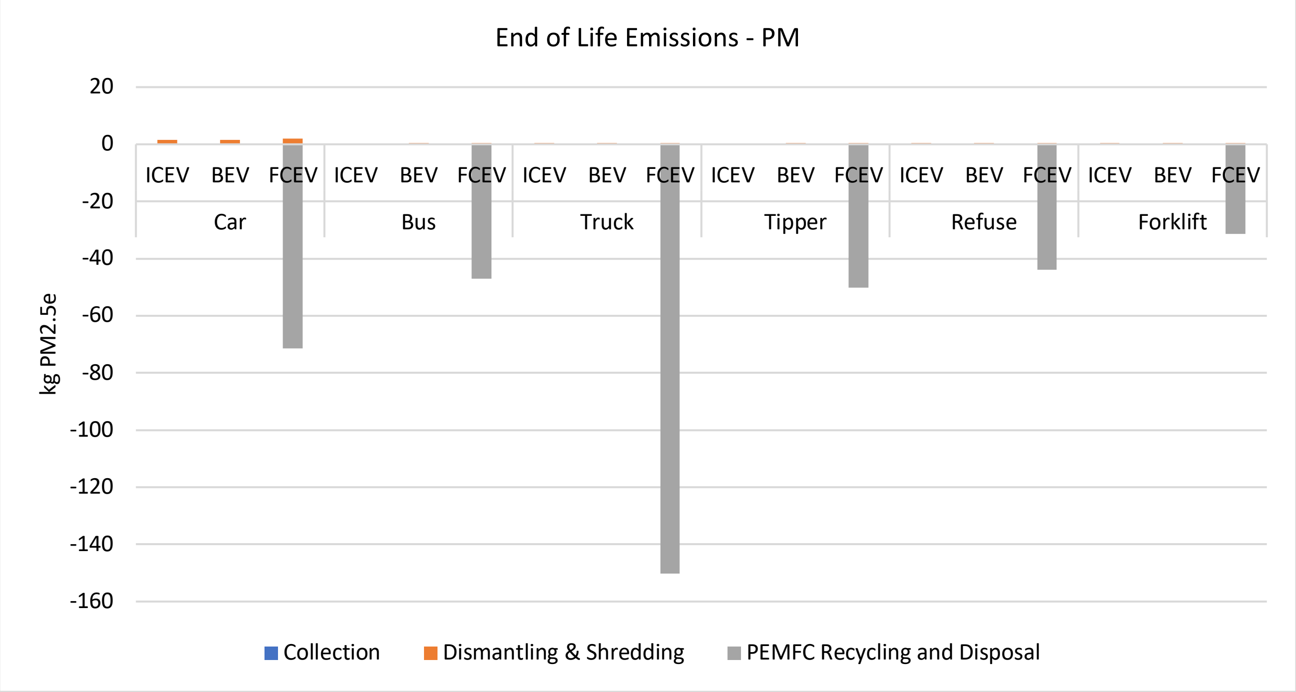


Figure 11-17 - Vehicle EOL emissions in terms of PM.

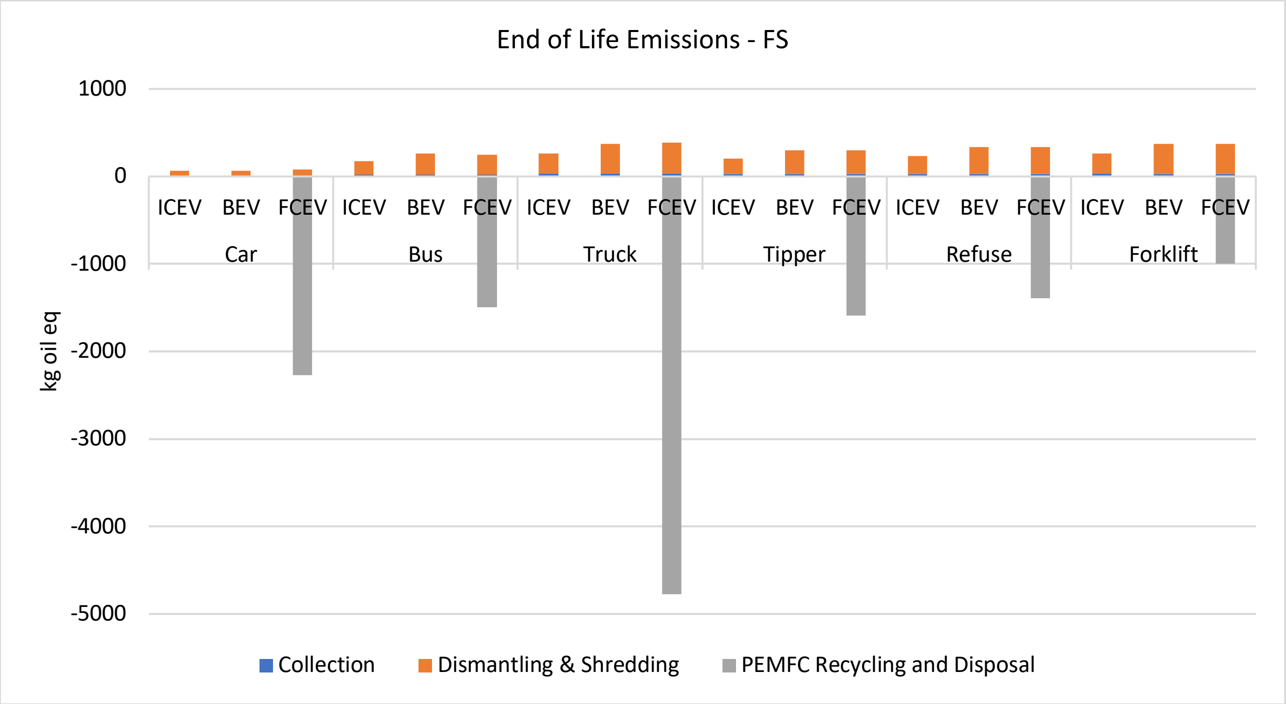


Figure 11-18 - Vehicle EOL emissions in terms of FS.

11.7. Future Outlook:

11.7.1. 2050 Grid Mix:

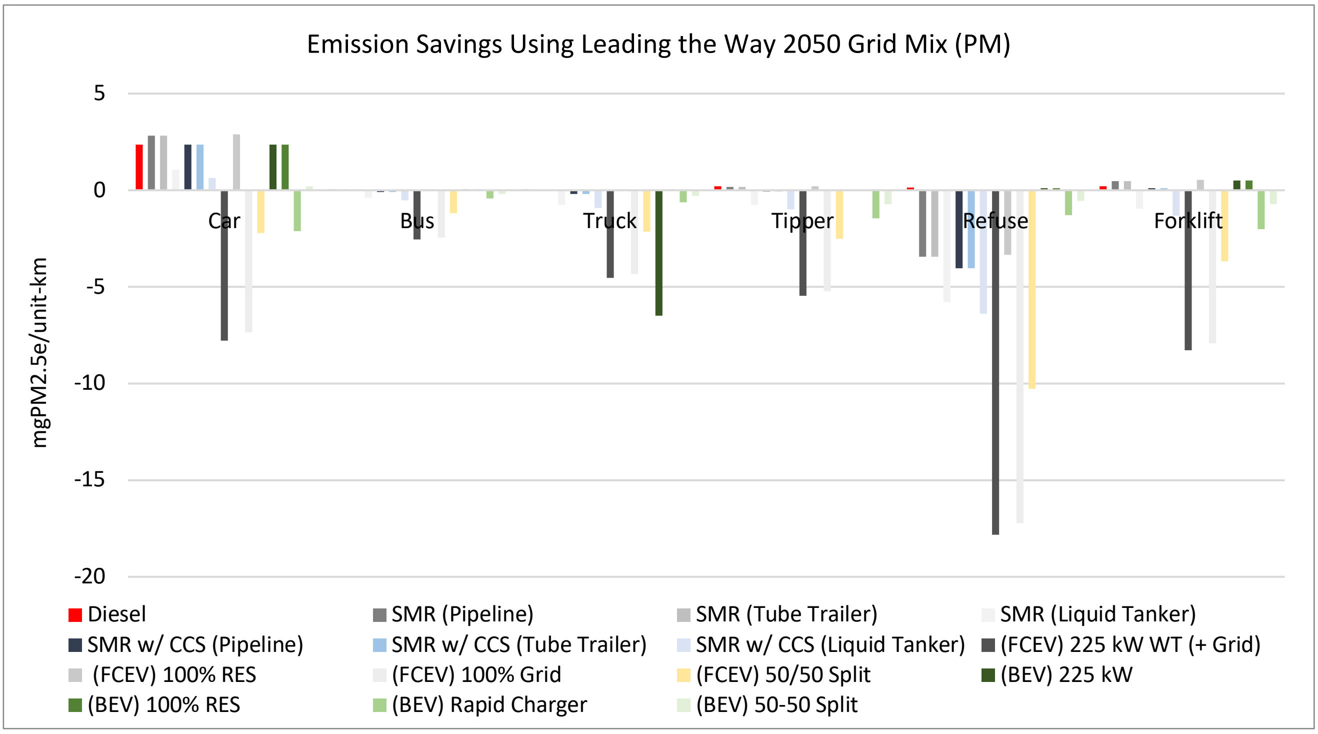


Figure 11-19 - CTG emission savings under 2050 grid mix (PM).

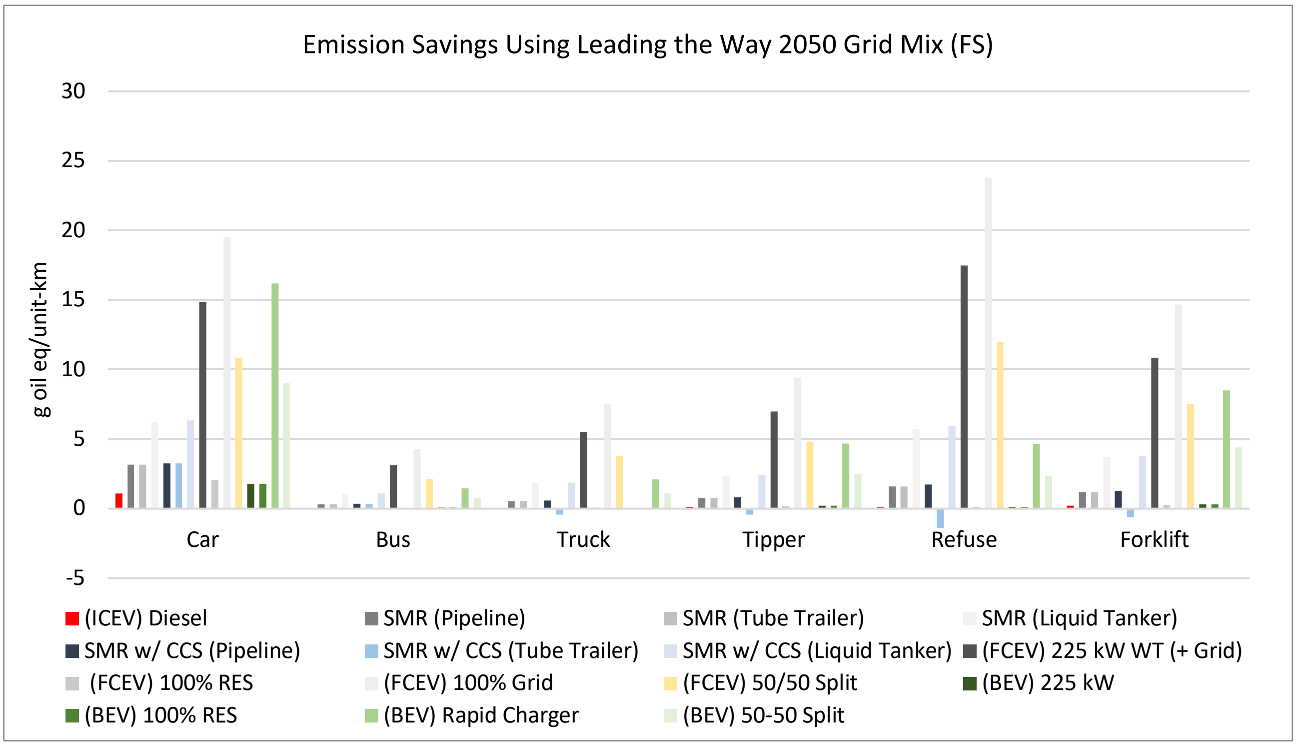


Figure 11-20 - CTG emission savings under LtW 2050 grid mix (in terms of FS).

11.7.2. Electrolyser Efficiency:

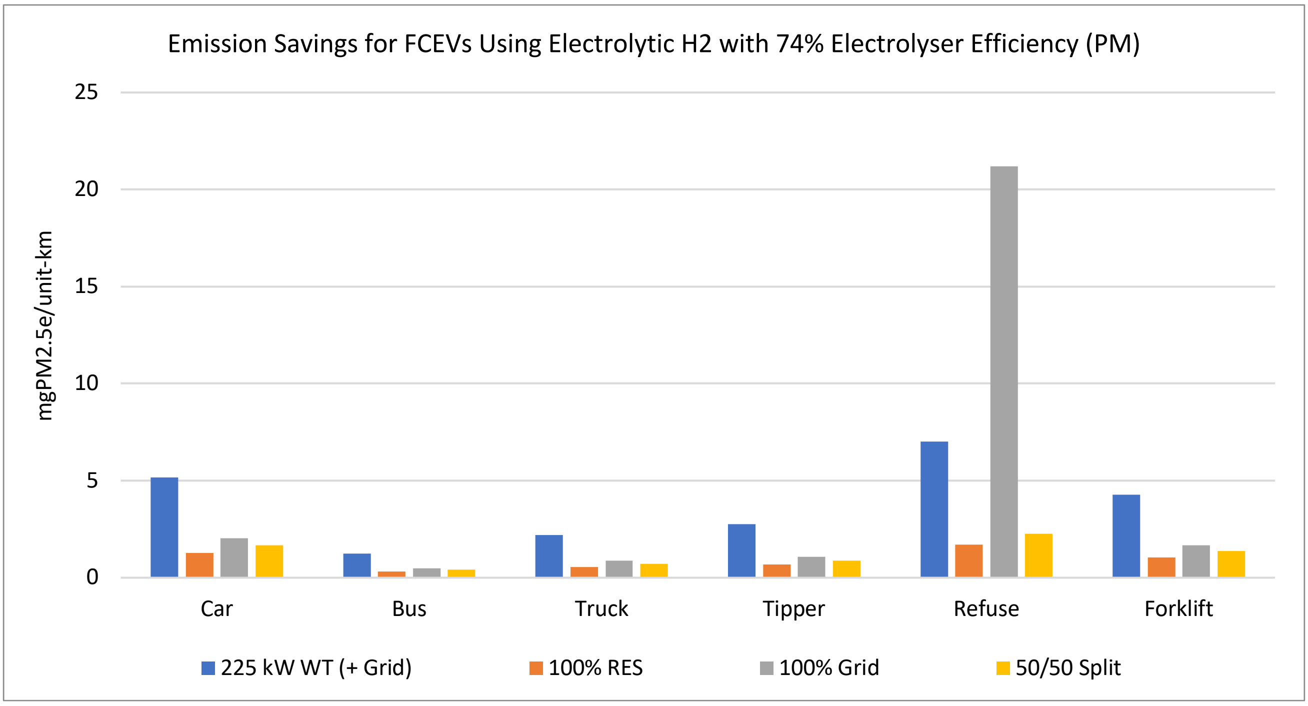


Figure 11-21 – Life cycle emissions of FCEVs under an increased electrolyser efficiency of 74% (PM).

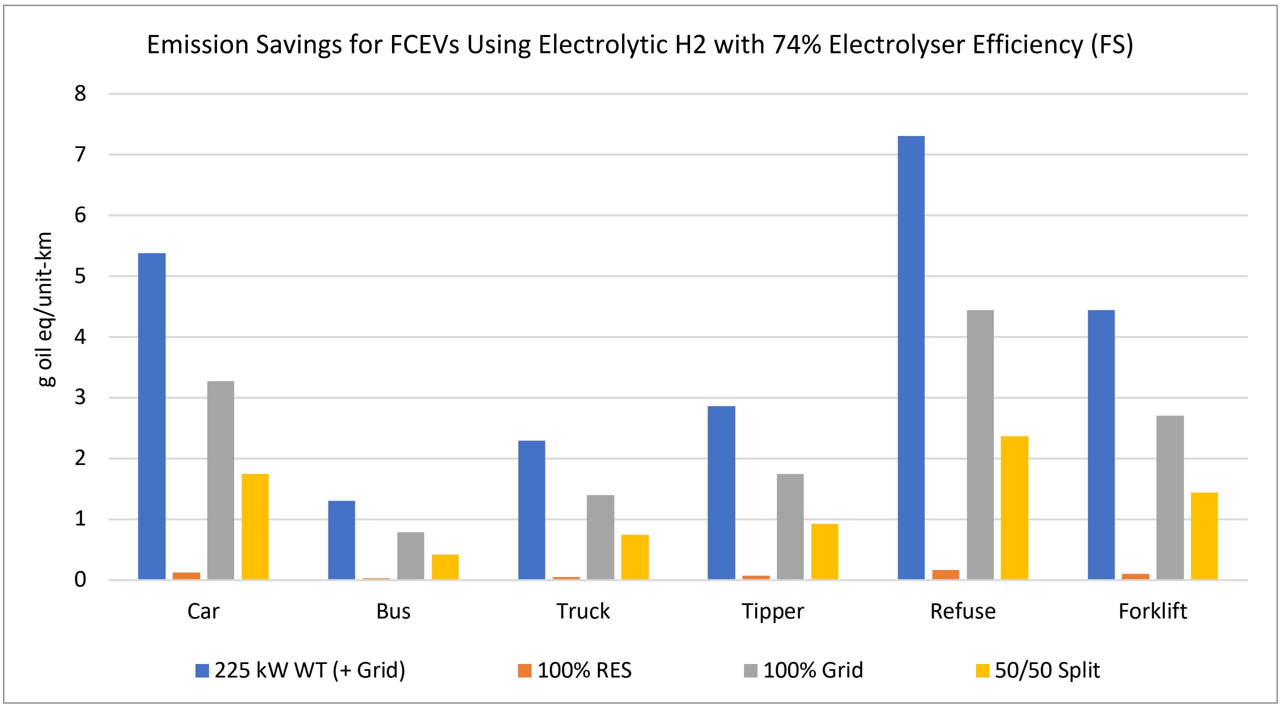


Figure 11-22 – Life cycle emissions of FCEVs under an increased electrolyser efficiency of 74% (FS).

11.7.3. Fuel/Energy Consumption:

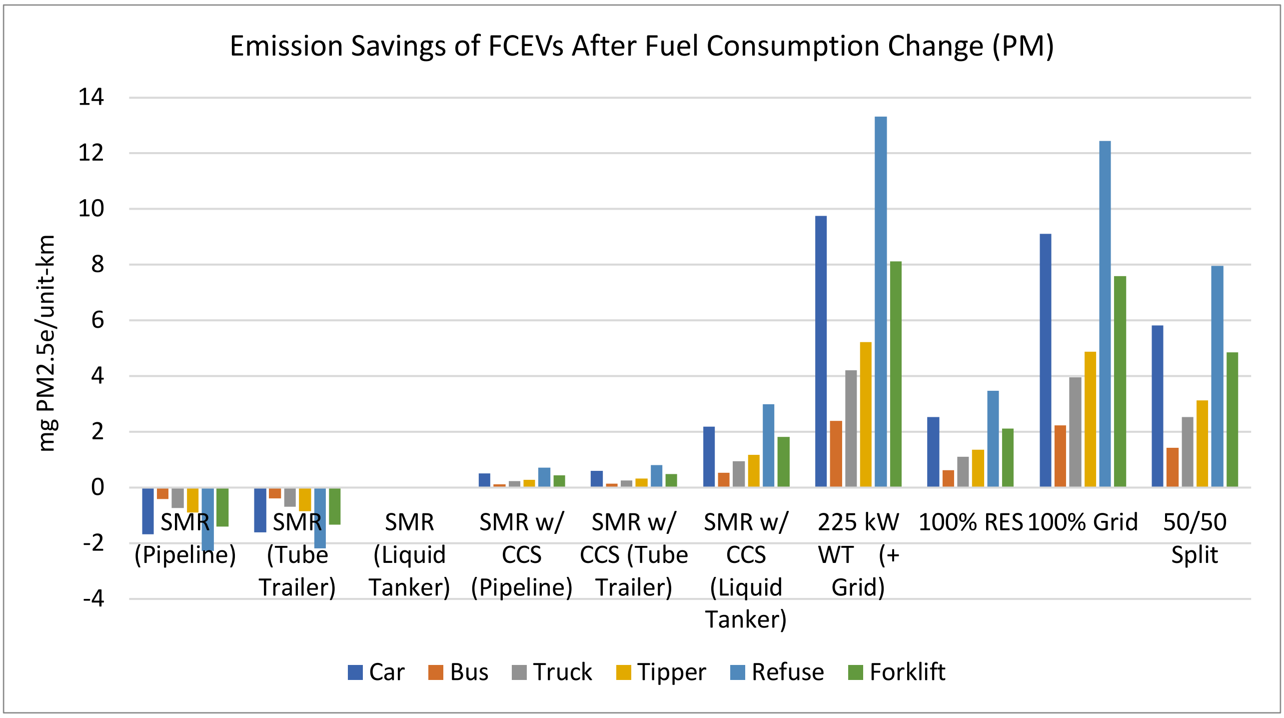


Figure 11-23 - CTG emissions of FCEVs under current and future fuel/energy consumption (in terms of PM).

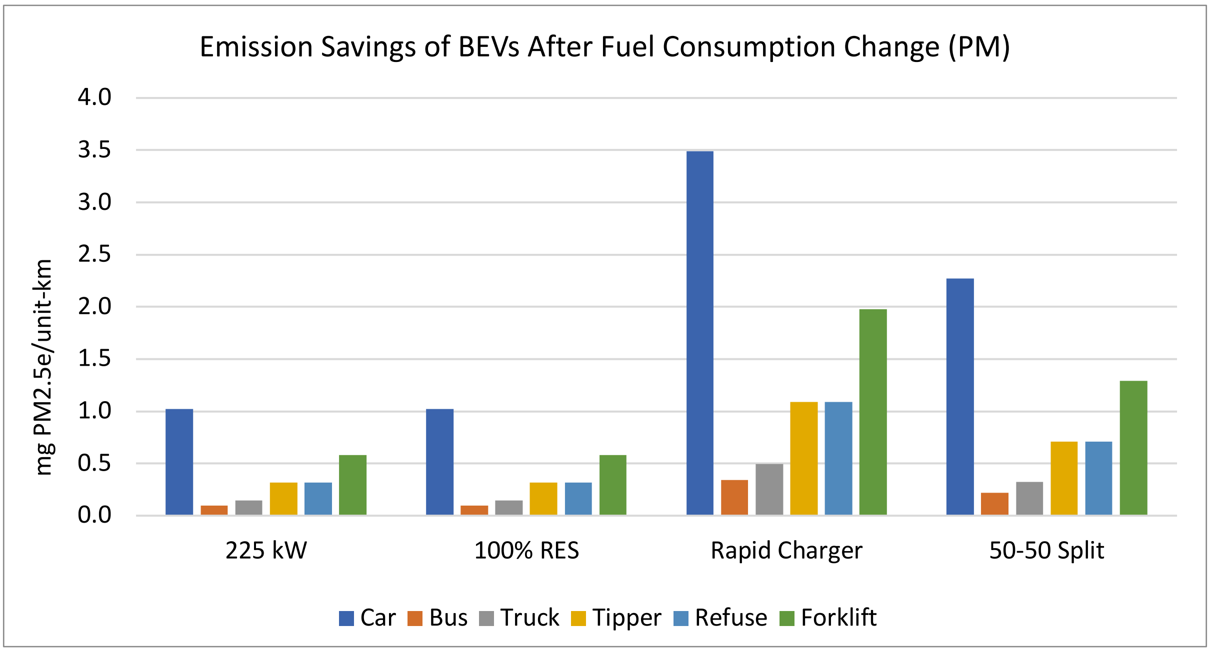


Figure 11-24 - CTG emissions of BEVs under current and future fuel/energy consumption (in terms of PM).

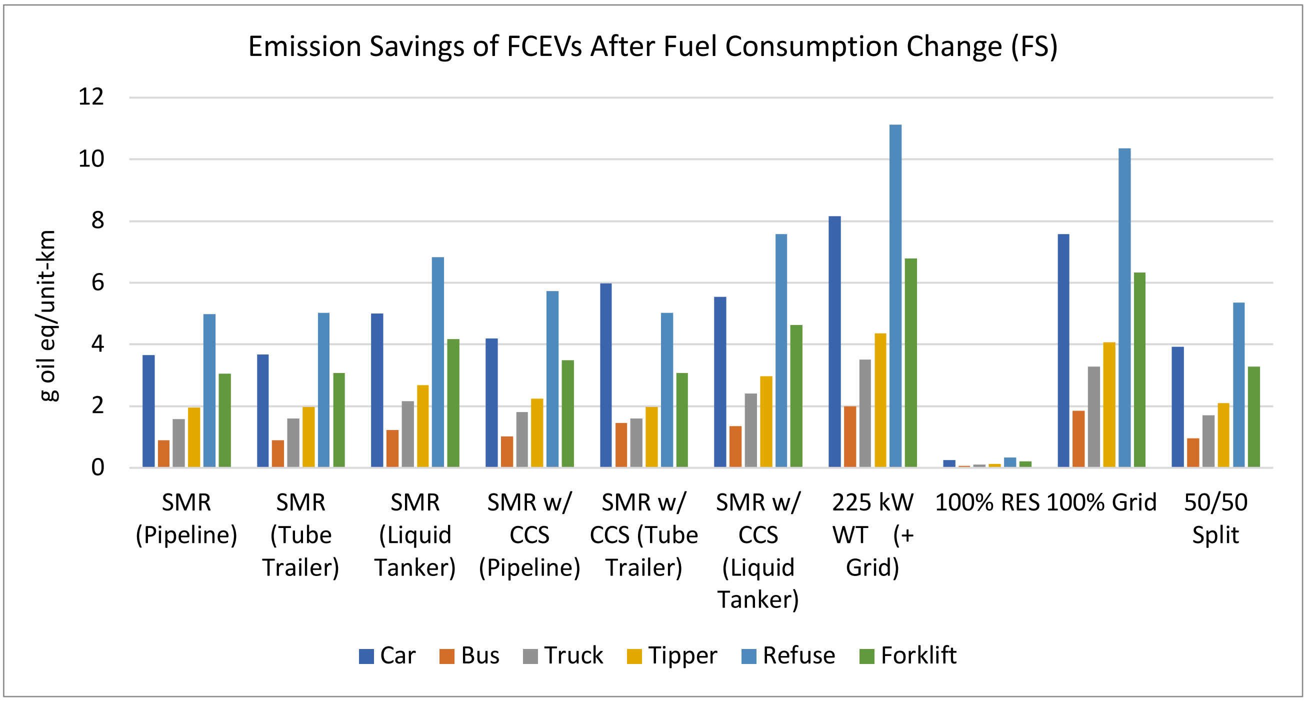


Figure 11-25 - CTG emissions of FCEVs under current and future fuel/energy consumption (in terms of FS).

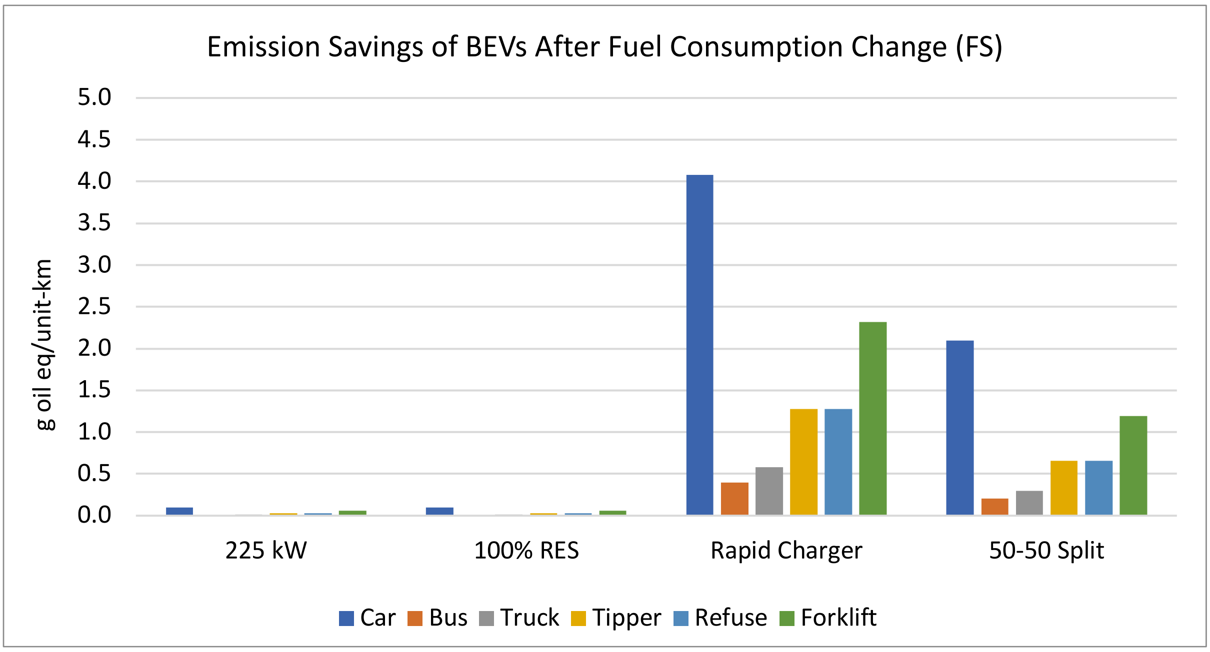


Figure 11-26 - CTG emissions of BEVs under current and future fuel/energy consumption (in terms of FS).

12. Appendix 3 – Total Emissions of Ownership

12.1. Total Emissions of Ownership:

12.1.1. Global Warming Potential:

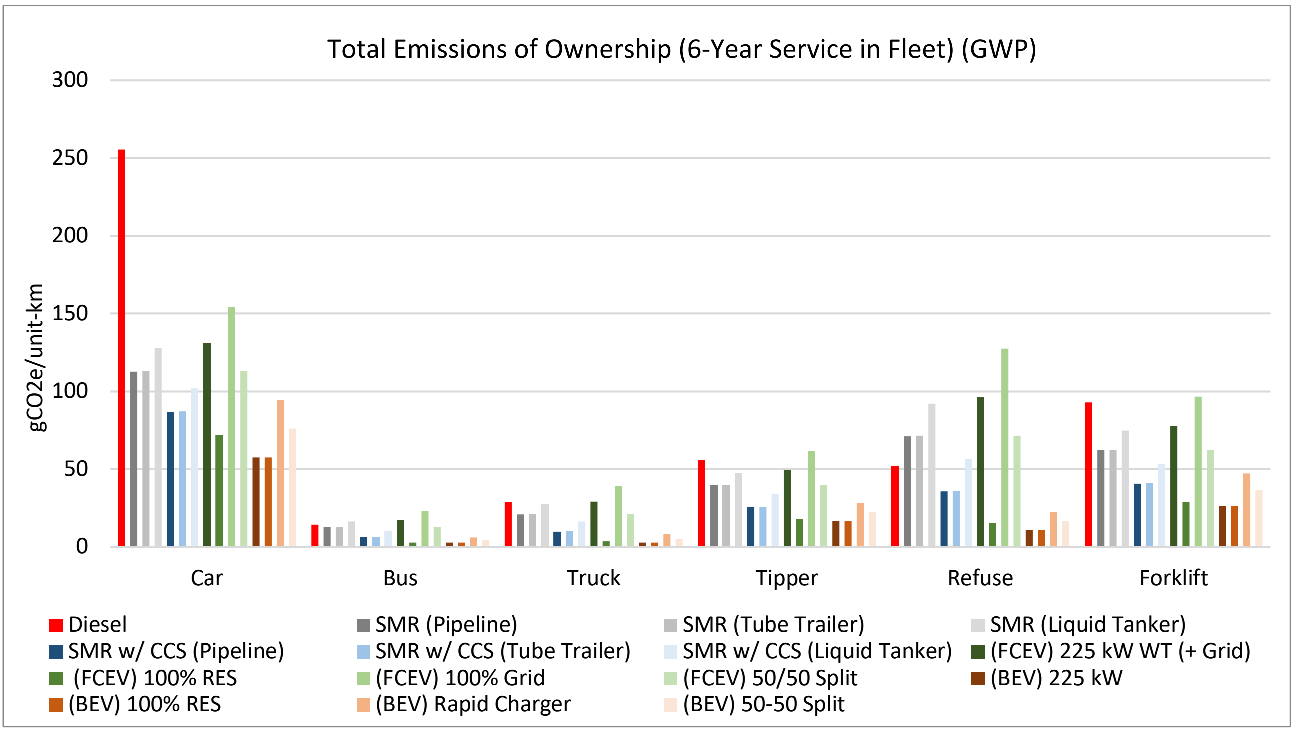


Figure 12-1 - TEO under a 6 year service period (GWP).

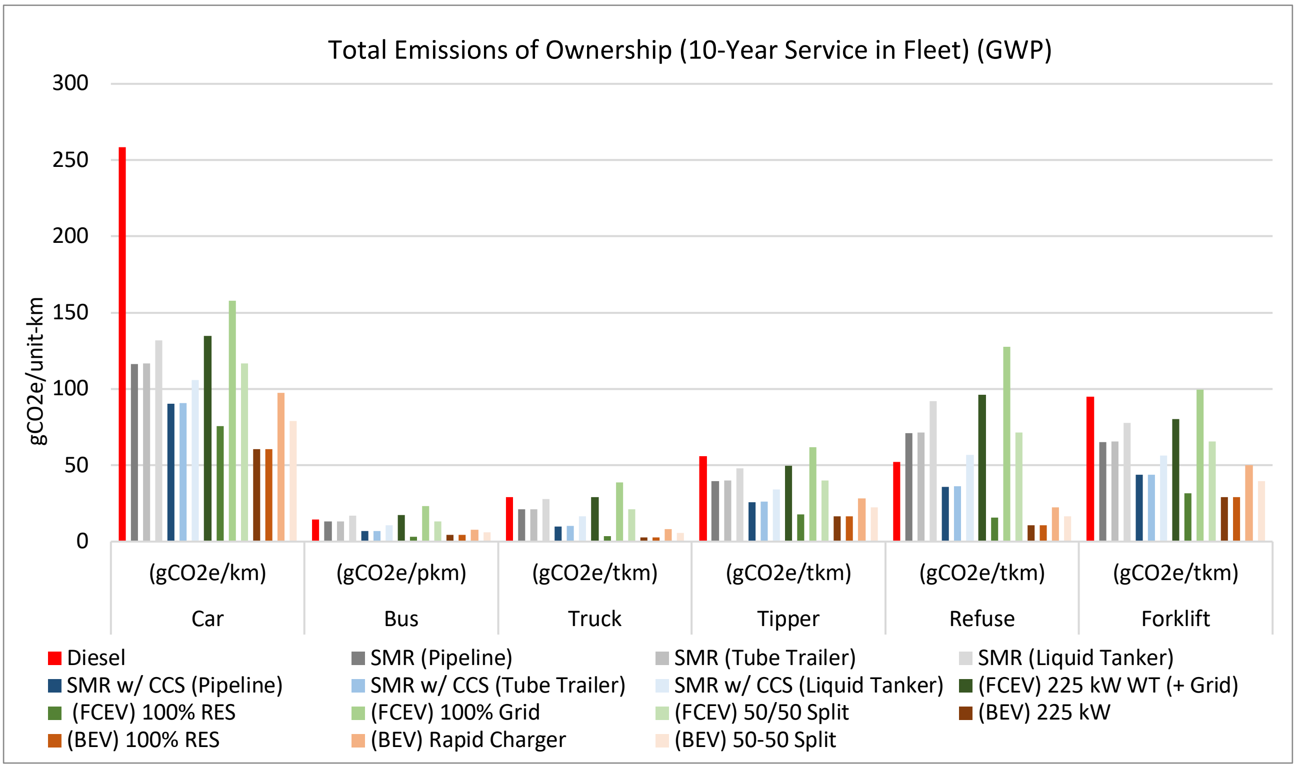


Figure 12-2 - TEO under a 10 year service period (GWP).

12.1.2. Fossil Scarcity:

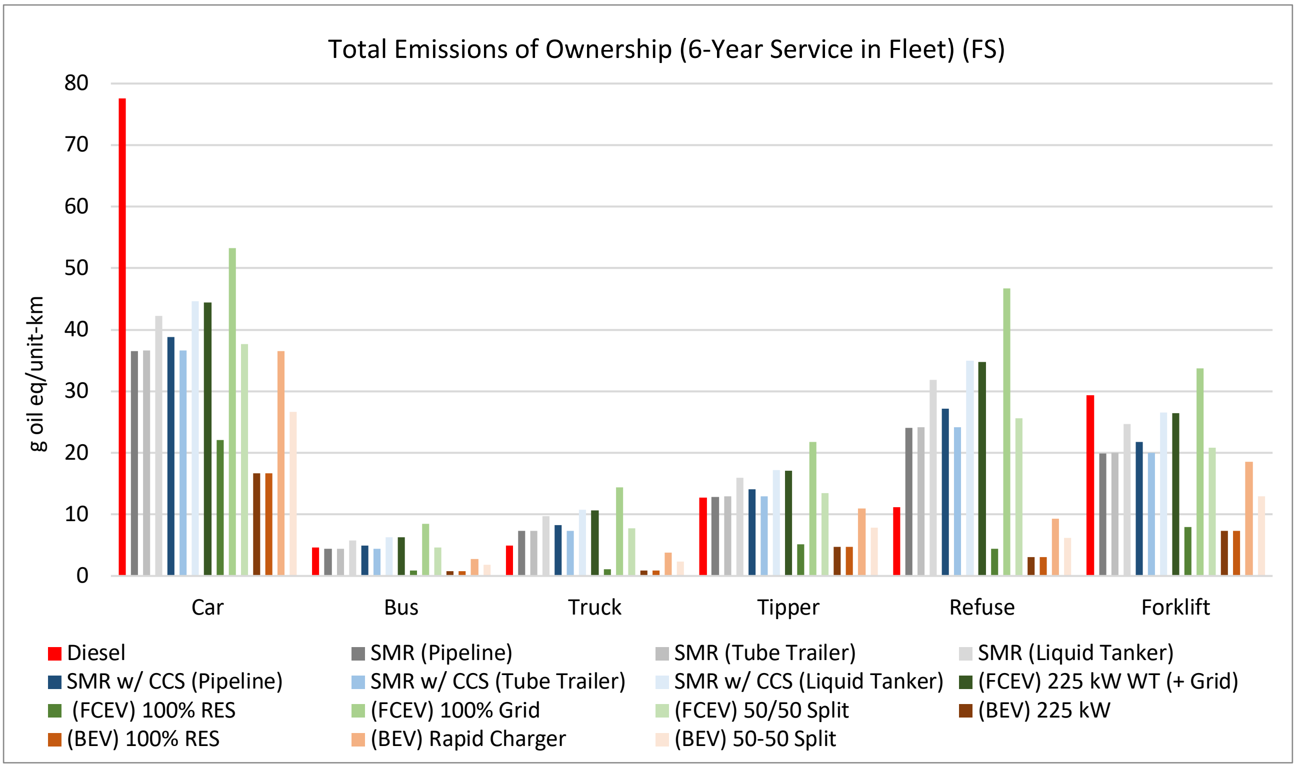


Figure 12-3 - TEO under a 6 year service period (FS).

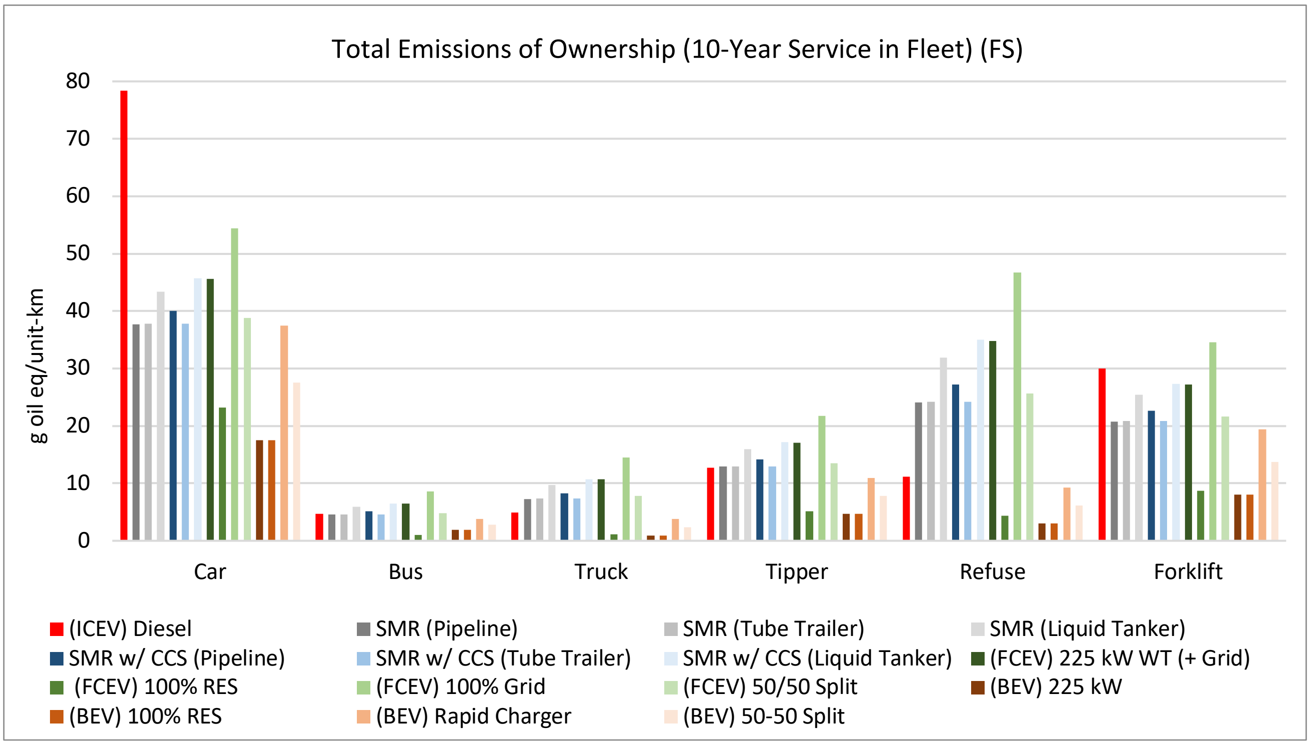


Figure 12-4 - TEO under a 10 year service period (FS).

12.1.3. Particulate Matter:

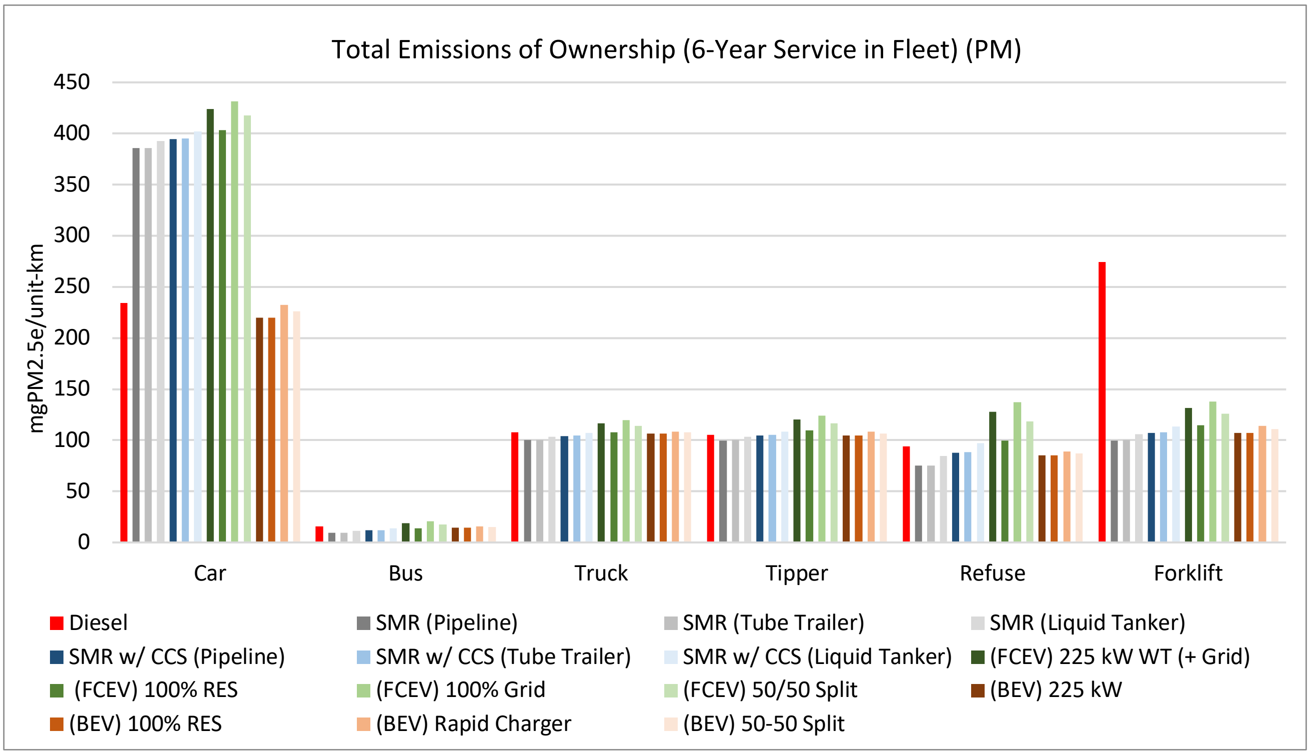


Figure 12-5 - TEO under a 6 year service period (PM).

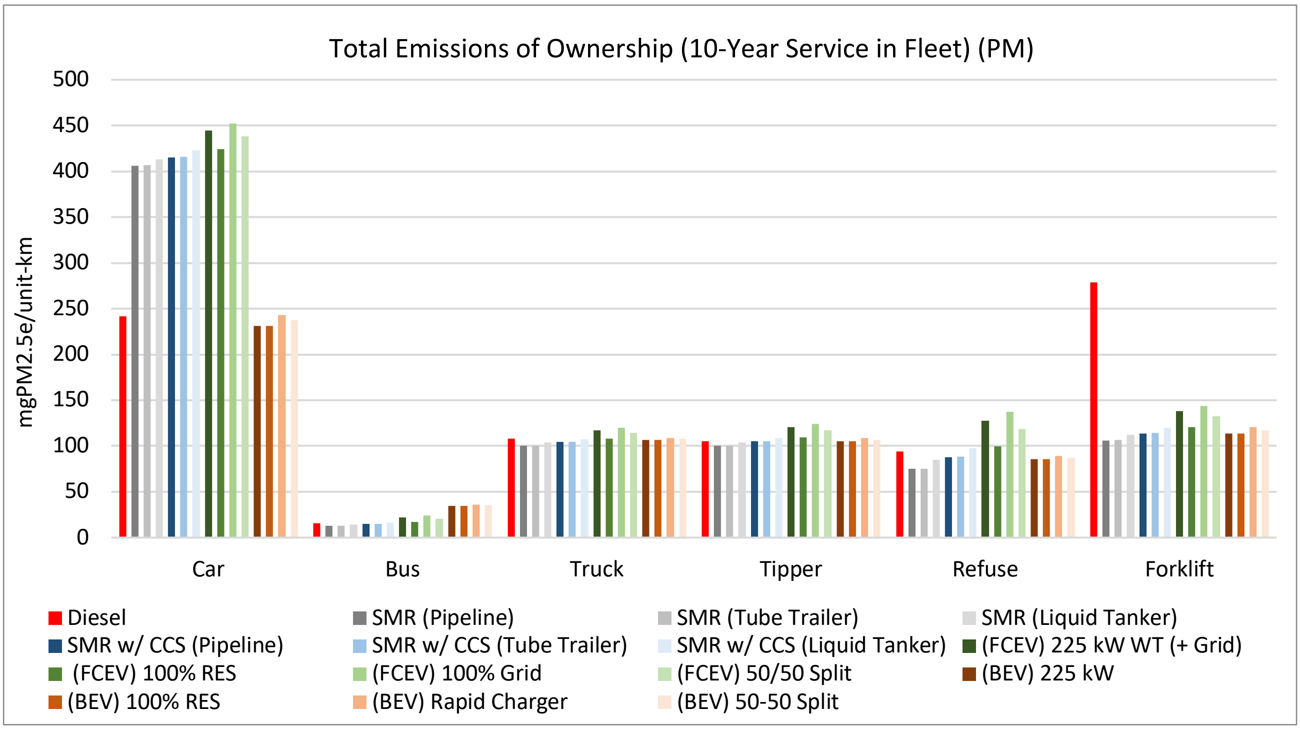


Figure 12-6 - TEO under a 10 year service period (PM).

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