Article

Comparative Life Cycle Assessment of Propulsion Systems for Heavy-Duty Transport Applications

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Abstract: To meet climate change challenges, the UK government is aiming to reach zero emissions by 2050. The heavy-duty transportation sector contributes 17% to the UKs total emissions, so to combat this, alternative power units to traditional fossil fuel-reliant internal combustion engines (ICEs) are being utilized and investigated. Hydrogen fuel cells are a key area of interest to try and reduce these transportation emissions. To gain a true view of the impact that hydrogen fuel cells can have, this study looks at the impact the manufacturing of a fuel cell has upon the environment, from material extraction through to the usage phase. This was done through the use of a lifecycle assessment following ISO 14040 standards, with hydrogen systems being compared to alternative systems. This study has found that whilst fuel cells depend upon energy intensive materials for their construction, it is possible to reduce emissions by 34–87% compared to ICE systems, depending upon the source of hydrogen used. This study shows that hydrogen fuel cells are a viable option for heavy-duty transport that can be utilized to meet the target emissions reduction level by 2050.

Keywords: climate change; global warming potential; heavy-duty transport; hydrogen; fuel cell; life cycle analysis; greenhouse gas emissions

1. Introduction

Climate change is an issue that is prevalent worldwide, with an increase of 41% in the atmospheric concentrations of greenhouse gases from 1990 to 2020 [1], leading to global average temperatures increasing by 0.95 °C from the 20th century average [2]. This increase has accelerated dramatically over the past 20 years, with 2020 and 2016 tying for the hottest spring on record, meaning that the temperatures are exceedingly above average. Whilst there are many different aspects that contribute to this temperature increase, a strong association can be made to vehicle emissions, as in 2020 83% of homeowners own at least 2 cars compared to 15% owning any car in the 1980s [3]. Increases in temperature are linked to rising sea levels, increased frequency of weather extremes and altering rain patterns. [4] These issues have a large impact on a human level as they can lead to disruptions in food production from droughts and flooding, as well as damage to infrastructure from weather extremes. Without action the effects of climate change will cause irreversible damage globally.

This need for change has resulted in multiple countries signing treaties such as the Paris Agreement, which is a legally binding agreement for participating parties to reduce their emissions, to limit temperature rise to 2 °C above pre-industrial levels [5]. The United Kingdom is one of these countries and has subsequently passed the "net zero emissions law", setting the target for the UK to become carbon neutral before the year 2050 [6]. It is projected that without change, by 2070 the UK winter will be up to 4.5 °C warmer and 30% wetter, with summers potentially being 6 °C warmer and 60% drier [4].

With a global push to reduce emissions, one of the main aspects under consideration is how to reduce the dependency upon traditional fuel sources, with the UK using fossil fuel feedstocks for 78.3% of its energy needs in 2019 [7]. This has led to significant investment

and research into new technologies to try and utilize cleaner energy sources. One of the areas at the forefront of these technological advancements is the transport sector, as it is the largest contributor to the UK's emissions, at 28% [8]. This is due to the majority of modern vehicles relying on petrol or diesel internal combustion engines (ICEs) as their power units.

When looking at small/medium passenger vehicles, there has been a shift towards electrification, with battery electric vehicles (BEVs) accounting for 6.7% of new car registrations [9], although this trend has not currently translated across to heavy goods vehicles (HGVs) which account for over half of the transport emissions, at 17% of total emissions [10]. This has led to other technologies being investigated for use in HGVs. One such technology is proton-exchange membrane fuel cells (PEMFCs), which use hydrogen and oxygen to produce an electrical current. The only by-products in this reaction are water and heat. This then gives the advantage of, when a PEMFC system is used at a vehicle level, fuel cell electric vehicles (FCEVs) record zero tailpipe emissions. This has led to the creation of new companies focused solely on developing fuel cell electric trucks (FCETs) such as NIKOLA, Ballard and Plug Power Inc. Alongside this, collaboration agreements such as H2accelerate have been formed, where Daimler Truck AG, IVECO, OMV, Shell and the Volvo Group are working together to enable the mass-market roll-out of hydrogen trucks in Europe [11].

Whilst FCETs yield zero exhaust emissions, to obtain a true reflection of the emissions profile further investigation is required in order for PEMFCs emissions to be compared against competing technologies in HGVs. Whilst there has been a lot of research into the hydrogen production process itself and the emissions produced from this, there has been little investigation into the emissions produced during the construction of PEMFCs. For a true comparison, the systems cannot be compared solely at a vehicle level, and the manufacturing emissions must also be considered. This is due to the specialist materials required for the system and the quantity of these, as some materials could release a lot of emissions during their extraction and production processes.

The goal of this paper is to perform a lifecycle assessment (LCA) on the future application of hydrogen on UK's heavy-duty transport. Whilst that is a broad area to cover, this paper will focus upon the production of a PEMFC for the use in a FCET and comparison of CO_2 emissions against competing technologies, due to it being an area that has not thoroughly been investigated previously. Whilst studies such as K. S. Jeong's [12] and X. Liu's [13] have stated that a reduction in emissions can be obtained via a hydrogen system, these do not consider the power-unit manufacturing stages and solely focus upon the usage emissions. The best way in which this can be done is by performing a cradle-to-gate LCA on fuel cell, diesel, and battery electric systems. A cradle-to-gate analysis will yield a partial product lifecycle, detailing the steps taken from material extraction through to a completed final product, which in this case is the power unit. This method has been specifically chosen as it means that the manufacturing process can be analysed and broken down independently, to see the impact that this has on the system.

The efficiencies of the power units will also be analysed to gain an insight into the usage stage, considering the fuel production processes. Once these stages are completed, the results can be analysed and compared to see whether a PEMFC system is "cleaner" than the alternatives.

The secondary aim of this study is then to evaluate the efficiencies when the systems are in use, and the impact this has on the amount of CO_2-equivalent (CO_2e) produced by HGVs. These two aims combined will then give a full lifecycle overview and comparison of the systems.

This has become a recent area of interest, with L.Usai [14] producing a study in 2021 for light duty applications, modeling the production of an 80 kW fuel cell (FC) [14]. This is one of the most up to date pieces of research regarding FC production, in which they found that current production methods released $\approx$50 kg CO_2e/kW [14]. This gives conservative results compared to an older study performed in 2017 by S. Evangelisti et al. [15], which calculated the emissions at $\approx$110 kg CO_2e/kW. One of the reasons for the discrepancy between these results can be put down to the advancements of technology over the 4 years

between the two studies. In addition, the 2017 study was working from limited data sources due to the technology being at the beginning of its development.

2. Materials and Methods

The methodology for this investigation focuses around performing an LCA for the production methods for FC, ICE and full electric power units relating to heavy duty applications and is based upon the studies produced by A. Lotrič [16] and S. R Dhanushkodi [17] when looking at power unit production, utilising ISO 14040:2006 [18]. The LCA can then be combined with the usage phase to produce a full life-cycle overview. This mirrors the study by S. R Dhanushkodi [17], but for a HGV as opposed to a passenger vehicle.

The methodology for performing an LCA is standardised process outlined by ISO 14040:2006 [18]. ISO14040:2006 provides a standard, encompassing the four main phases of an LCA which address the quantitative methods to assess the environmental impacts of a process for its life cycle. Within this, a framework is included to ensure the key stages of an LCA are met, as without these stages the investigation cannot be classed as an LCA; therefore, the ISO standard must be referenced and followed. The general schematics of an LCA as described by ISO 14040 are shown in Figure 1. The first stage is defining the goal and scope, which then enables the inventory analysis to be formed; this in turn allows the impact assessment stage to quantify the environmental impact. Each of these stages depends upon each other, with the goal and scope setting the boundaries for the inventory analysis and providing the data for the impact assessment. The final stage of the LCA is the interpretation, where the environmental issues are identified. This is linked to all the other stages as the conclusions are taken with regards to the goal and scope definition, the inventory analysis provides data that must be analysed, and the impact assessment gives the results to be assessed with regards to the previous stages. Once all these stages are fulfilled, this becomes the starting point for improving the environmental impacts of a product.
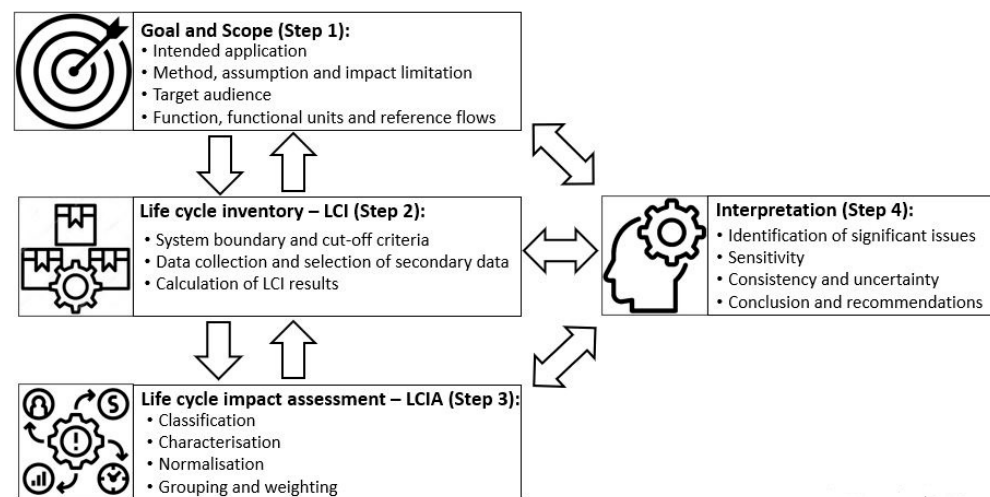

Figure 1. Life cycle assessment (LCA) framework (adapted from ISO 14040:2006 [18]).

By using an LCA, accurate quantitative data can be produced to identify environmental issues. In the case of this investigation, this is related to an area of high global warming potential (GWP) within the production process. It is widely accepted that an LCA is the best approach to quantify environmental impacts of a product throughout its entire lifecycle.

The first stage of the framework shown in Figure 1 that needs to be considered is the goal and scope of the project. The goals have previously been stated in Section 1. For the project scope, the system boundaries must first be defined. These boundaries are as follows: only technology that is currently available will be assessed, to gain an insight into

how these changes would affect the current greenhouse gas levels. Older technologies are excluded from this to ensure that only up to date technology is utilised to give a true representation of the current situation. It will be assumed that all materials used are from virgin sources, meaning material recycling is not considered; this enables a "worst-case" scenario to be investigated. As well as this, the calculations will be completed as though all components are produced within the UK, meaning material transportation emissions will not be included.

The next component of the scope is defining a functional unit, which states what is being studied. For this investigation, the functional unit is the power unit of an HGV. This investigation will produce data to enable the comparison of different power units, with regards to the emissions produced during their manufacturing process. Included within the scope is the lifecycle impact assessment method.

The next stage in the LCA framework from Figure 1 is to determine the life cycle impact assessment (LCIA). The LCIA classifies the results as specific indicators to give a clearer understanding of the environmental impact. For example, to measure climate change the global warming potential (GWP) is selected; this then reduces the results to the key areas of interest meaning that the highest contributors can easily be identified. Impact assessments can cover a wide range of themes, such as resource depletion, acidification, and eutrophication, not just climate change. The use of the impact assessment also means the results are represented in common units, enabling direct comparisons. GWP gives results in units of CO_2 equivalent (CO_2e), meaning that all the greenhouse gas emissions are relative to the GWP of CO_2, so CO_2 always has a GWP of 1 as it is the gas being used as a reference. There are 3 subcategories for GWP, GWP-20, GWP-100, and GWP-500. These categories represent the timespan over which the GWP is evaluated, as for emissions such as methane the GWP reduces over time due to it having a relatively short lifespan. For this investigation, GWP-100 will be used as it gives a good view of the future, whilst also being the most commonly available category for data collection. A breakdown of the GWP-100 values can be seen in Table 1 [19].

Table 1. Global Warming Potential for Major Greenhouse Gases [19].

Greenhouse Gas	Chemical Formula	Global Warming Potential (kgCO$_2$ e per kg of Gas)
Carbon Dioxide	CO_2	1
Methane	CH_4	25
Nitrous Oxide	N_2O	265
Chlorofluorocarbon-12 (CFC-12)	CCl_2F_2	10,200
Hydroflourocarbon-23 (HFC-23)	CHF_3	12,400
Sulfur Hexafluoride	SF_6	23,500
Nitrogen Trifluoride	NF_3	16,100

In addition, for this investigation, the life cycle inventory analysis (LCI) is required for each of the power units to supply the input data for the LCA, such as the raw materials, components and energy required; this is outlined in Figure 1 and provides the base data which the LCA is to be constructed from.

For the fuel cell (FC) system, a FC stack and battery are required, and the first step is to obtain a bill of material (BOM) for these systems as from this the raw materials required can be calculated. For this investigation, the material breakdowns are taken from the Argonne National Laboratory (ANL) for both the FC stack [20] and the battery [21]. This gives the system break down as a percentage of the total mass, meaning that it could be scaled to cover HGV applications when an initial mass is stated. The specifications for the systems have been taken from a Hyundai XCIENT fuel cell [22], which is one of the first mass produced FCETs.

The Hyundai XCIENT uses two 95 kW FC stacks to achieve a power output of 190 kW [22], although the FC stack mass is not stated as this is confidential information

and cannot be released to competitors. Due to this, for the FC stack, weight data has been taken by combing two Ballard FCveloCity-HD Heavy Duty FCs [23] which fit with the required power specifications, giving a total weight of 512 kg. For the battery, the manufacturer has been detailed by Hyundai as AKASOL. From this, it can be deduced that three OEM 37 PRC batteries [24] are utilised, giving a combined mass of 714 kg. Table 2 details the scaled BOM for a HGV FC stack based on the Ballard system, scaled using the ANL breakdown [20]. Table 3 details the BOM for the AKASOL Lithium-ion Battery, again scaled using the ANL breakdown [21]. Both BOMs include the balance of plant (BOP), meaning that ancillary components such as housings are covered.

Table 2. Scaled BOM for FC stack.

Material	Percentage (%)	Weight (kg)
Stainless Steel	31.3	160.256
Steel	18.7	95.744
Wrought Aluminum	16.8	86.016
Average plastic	16.6	84.992
Rubber	6.5	33.28
Glass Fibre Composite	2.6	13.312
PTFE	2.6	13.312
Carbon Paper	2.1	10.752
Copper	1.7	8.704
PFSA	0.6	3.072
Carbon	0.3	1.536
Cast Iron	0.08	0.4096
Silicon	0.05	0.256
Platinum	0.02	0.1024
Nickel	0.002	0.01024

Table 3. Scaled BOM for FC Battery.

Material	Percentage (%)	Weight (kg)
$LiMn_2O_4$	33	235.62
Graphite	15	107.1
Binder	2.5	17.85
Copper	11	78.54
Wrought Aluminium	19	135.66
$LiPF_6$	1.8	12.852
Ethylene carbonate	5.3	37.842
Dimethyl carbonate	5.3	37.842
Polypropylene	1.7	12.138
Polyethylene	0.29	2.0706
Polyethylene terephthalate	1.2	8.568
Steel	1.4	9.996
Thermal Insulation	0.34	2.4276
Glycol	1	7.14
Electronic Parts	1.1	7.854

The next LCI that needs compiling is for the ICE. The BOM for this was taken from S. Wolff's study [25]. As the ICE used in this study has similar power outputs to what would be expected from the Hyundai XCIENT, no scaling is required and the values in Table 4 can be used.

Table 4. BOM for ICE [25].

Material	Mass (kg)
Steel	342
Iron	513
Rubber	51.3
Wrought Aluminium	171
Plastic	51.3
Copper	11.4
Oil	36.02

S. Wolff's [25] study also states the mass of batteries required for a full electric HGV, and detailing that for a Li-ion battery system to produce the same power outputs as the ICE system a mass of 5265 kg is required. This can then be combined with the percentage breakdown produced by the ANL [21] to gain the scaled BOM in Table 5.

**Table 5.** Scaled BOM for Full Electric HGV Battery.

Material	Percentage (%)	Weight (kg)
$LiMn_2O_4$	33	1737.45
Graphite	15	789.75
Binder	2.5	131.625
Copper	11	579.15
Wrought Aluminium	19	1000.35
$LiPF_6$	1.8	94.77
Ethylene carbonate	5.3	279.045
Dimethyl carbonate	5.3	279.045
polypropylene	1.7	89.505
Polyethylene	0.29	15.2685
polyethylene terephthalate	1.2	63.18
Steel	1.4	73.71
Thermal Insulation	0.34	17.901
Glycol	1	52.65
Electronic Parts	1.1	57.915

When producing these LCI's, a range of data sources have been utilised to try and gain a true reflection of the impact and to model as though the components are produced within the UK. Where data was unavailable, values from the GREET database [26] were utilised. The other sources were verified against this database, to check their validity.

Once the LCI data has been compiled, the process of producing the LCA can be started. As this will cover the production of the power units, it will include the extraction of the required raw materials, production of these materials, and then the energy required to produce the power unit itself. This will be done for each of the power units, meaning that the Cradle-to-Gate section shown within Figure 2 will be satisfied. This is a similar approach to S. Wolff et al.'s [25] study, but with an emission focus, to ensure the main question of this study is answered.

The LCI input data was all scaled on a $kgCO_2e/kg$ basis, with the required masses of each component/materials being multiplied by this value to obtain the results. The material extraction stage covers the extraction of required raw materials, so for components such as stainless-steel, multiple elements are included within this. Where the material contribution was less than 0.1%, this has not been included, as it will have little effect on the results. The next stage of the LCA accounts for the material/component production, which covers the production of the separate components that contribute towards the power unit. For more technologically advanced components, such as carbon paper, there is limited information regarding contributing materials and extraction emissions. When this occurred, an overall $kgCO_2e/kg$ value was used and scaled to the required mass for the system. The final stage is the power unit production, which covers the energy required to assemble the

separate components into a functioning power unit. Within the results this is noted as the production electricity.
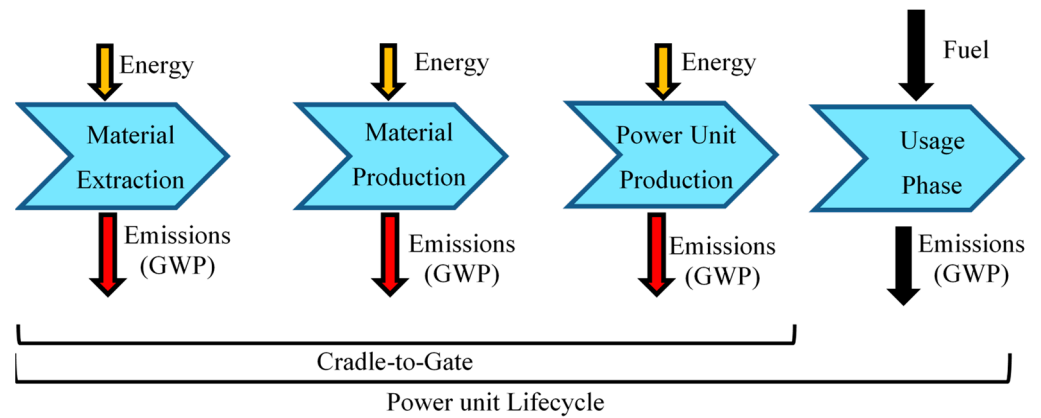
Figure 2. Simplified Overview of Methodology.

When looking at the BOM for the LCI, some assumptions must be made to ensure an accurate LCA. For each of the components listed, a specific material was defined so that accurate input data could be selected. The material assumptions made are shown in Table 6. The top 8 materials were selected due to them being the most regularly utilised variation in automotive applications. Alongside this criterion, specific material properties were also analysed to ensure that the material selected would be fit for purpose within the system it was required. For the bottom two components, these were modelled as in the report produced by the Argonne National Laboratory [21].

Table 6. Component Assumptions.

Component from BOM Breakdowns	Modelled As
Stainless Steel	Stainless Steel 304
Steel	Low Carbon Mild Steel
Average Plastic	Polypropylene
Glass Fibre Composite	Fibreglass Mat
Rubber	Synthetic EPDM Rubber
Carbon	Graphite
Binder	Polyvinylidene fluoride (PVDF)
Polyethylene	High Density Polyethylene
Thermal Insulation	Fiberglass
Electronic Parts	Battery Management System

The final assumption is that the electrical energy used throughout the power unit production has been calculated using the current UK electricity mix emissions (kgCO$_2$e/kWh) [27]. This then gives a representation of the emissions as though the power units have been manufactured within the UK. This is the final stage of the methodology, covering the usage of the power units. This is included to give an overview of how the driving emissions compare to the power unit production methods for HGVs, whilst also giving a future view as to which fuel, as well as source, yields the best reduction in emissions. This stage combines with the Cradle-to-Gate analysis to form the power unit's lifecycle. For this section, multiple methodologies are required. This is because for the ICE, exhaust gas emissions must be considered, with the other two systems having zero exhaust emissions; these can be seen below.

Diesel ICE methodology:

1. $\frac{Annual\ Distance}{Efficiency} = Annual\ Usage$

2. *Production emissions per MJ * Energy Density = Production emissions per L*

3. *Annual Usage ∗ Production emissions per L = Annual Production Emissions* (kg CO$_2$e)
4. *Exhaust emissions per Km ∗ Annual Distance = Annual exhaust emissions* (kg CO$_2$e)
5. *Annual exhaust emissions + Annual Production emissions = Annual total emissions* (kg CO$_2$e)

FC methodology:

1. $\frac{Annual\ Distance}{Efficiency}$ *= Annual Usage*
2. *Annual Usage ∗ Production emissions per kg = Annual Production Emissions* (kg CO$_2$e)

Full electric methodology:

1. $\frac{Annual\ Distance}{Efficiency}$ *= Annual Usage*
2. *Annual Usage ∗ Production emissions per kWh = Annual Production Emissions* (kg CO$_2$e)

when looking at the hydrogen production the following methods have been analysed: Steam Methane Reforming (SMR), SMR with Carbon Capture Storage (CCS), Proton-exchange Membrane (PEM) Electrolysis, and PEM Electrolysis with renewable energy sources (PEM-R). This is so that the full picture for hydrogen can be obtained. For the full electric system, the UK electricity mix [27] has been used to give the kgCO$_2$e/kWh input value.

3. Results

This section displays the results obtained for both the Cradle-to-Gate and lifecycle methodologies, accompanied by analysis.

3.1. LCA Results

The first set of results shown in Figure 3 give a comparison for the emissions produced by the different power units' manufacturing. It is clear from this figure that the battery electric truck's (BET) power unit of a Li-ion battery has the highest GWP, producing 7.8-times the emissions of the ICE, and 3.7-times the FC system. This can be compared to S. Wolff's study [25] which yields a range of 52,834.44 kgCO$_2$e up to 121,925.63 kgCO$_2$e for BET battery production, as they state that battery production can account for between 13 to 30% of total manufacturing GWP [25]. This investigation is on the conservative side of this range with a value of 62,757.37 kgCO$_2$e. A key factor in the large GWP is the substantial mass of the battery that is needed to meet the power requirements for a HGV. Interestingly, when looking at the breakdown for the FC system there is a near 50:50 split of emissions between the FC stack and the battery, totaling 16,966.61 kgCO$_2$e. When compared to the reports produced by L. Usai [14] and S. Evangelisti [15], which state a value of 50 kgCO$_2$e/kW$_{net}$ and 100 kgCO$_2$e/kW$_{net}$ respectively, this investigation yields a value of 89.30 kgCO$_2$e/kW$_{net}$. From Figure 3 it can be summarised that the ICE yields the lowest GWP, then the FC system, and the battery system has the highest. These results are within the expected ranges and are supported by previous literature.

To gain further insight, the power units can be broken down to a component level to see individual GWP contributions. Figure 4 details this for the FC stack, showing that the highest contribution comes from platinum, accounting for 3379.20 kgCO$_2$e. Whilst there is a relatively small mass required at 0.1024 kg, the extraction and processing methods are very energy intensive, which results in an emissions value of 33,000 kgCO$_2$e/kg.

Platinum on its own contributes 40% of the total kgCO$_2$e for the entire FC stack. This is one of the major influencing factors for the increased GWP compared to L. Usai's study as recycled Platinum accounted for 30% of their total [14]. The reduced value is due to L. Usai accounting for secondary material sources, whereas this investigation does not utilise any recycled materials and will therefore yield a higher GWP and percentage contribution. The two next largest contributors are wrought aluminium at 1400.67 kgCO$_2$e and carbon paper with 1339.81 kgCO$_2$e, which can be seen to contribute 16.5% and 15.8% respectively. So, whilst these components are still relatively energy intensive, they still contribute less combined than platinum. From this, it can be deduced that to reduce the stack production

emissions, platinum sources must be considered. When analysing certain components, they have a high kgCO$_2$e/kg value, but due to the low mass required within the system, they make a small impact on the total emissions. An example of this is nickel which produces 7.64 kgCO$_2$e/kg, but only a small mass of 0.01024 kg is required. This then results in it only contributing 0.08 kgCO$_2$e, or 0.000946 % of the system's GWP. The production electricity scaled from A. Lotrič's study [16] yields a significant GWP of 887.76 kgCO$_2$e, at 16.9 kWh/kW of FC power. This value can alter depending upon the electricity mix being used, giving the potential for a further reduction as the UK transitions to renewable sources.
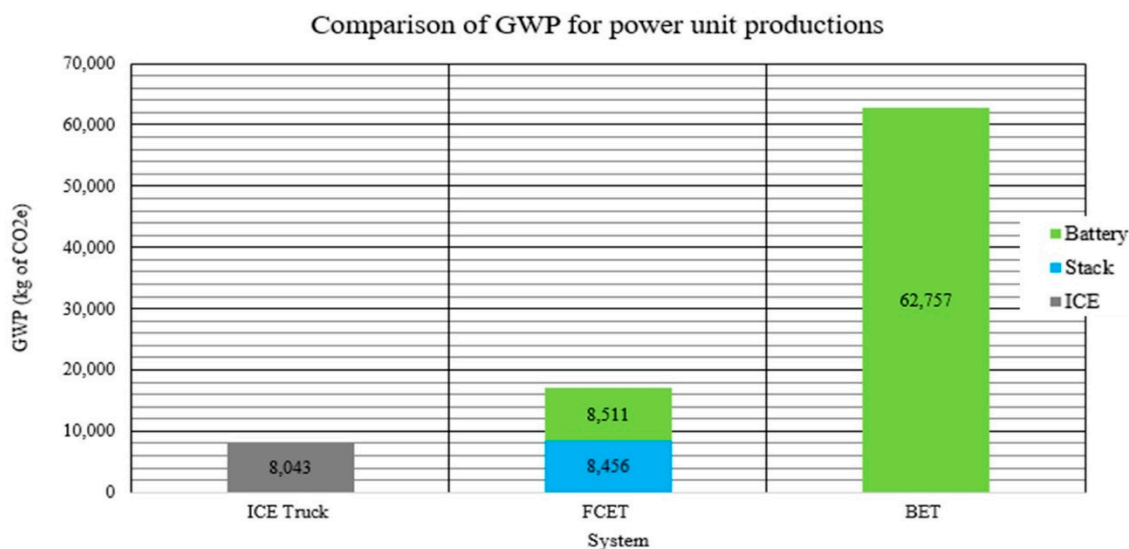

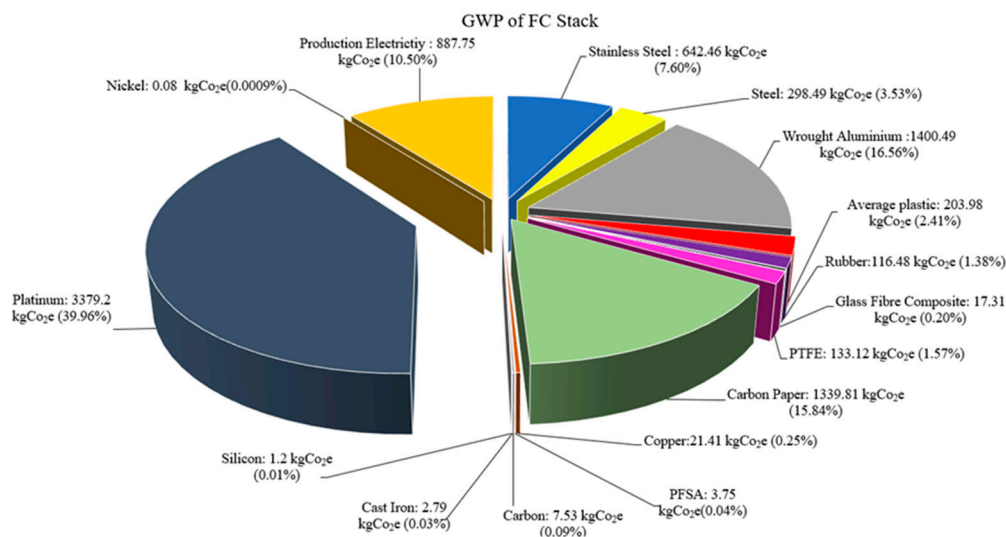**Figure 3.** Comparison of GWP per System.

Figure 4. GWP contributions for FC stack. Abbreviations: Polytetrafluoroethylene (PTFE).

The next system that can be analysed is the battery required in the FC system, with the GWP breakdown shown in Figure 5. Similarly to the FC stack, wrought aluminium is one of the largest contributors to the GWP, producing 2208.99 kgCO$_2$e and 26% of the total GWP, although the largest contributor is the active cathode material of lithium manganese oxide (LiMn$_2$O$_4$), which produces 4882.86 kgCO$_2$e accounting for 57% of the total GWP. Whist this is a high value, LiMn$_2$O$_4$ accounts for 33% of the total mass at 235.62 kg, so it is expected that it will have a large contribution, although it still has a relatively high emissions intensity at 12.78 kgCO$_2$e/kg. In comparison, the major electrolyte materials of

ethylene carbonate (EC) and dimethyl carbonate (DMC) have very low kgCO$_2$e/kg values. This means that whilst they have large masses, both 37.842 kg, they account for a combined amount of 60.17 kgCO$_2$e. This is only 0.00707% of the total GWP, yet they account for 10.6% of the mass. The final material for the electrolyte, lithium hexafluorophosphate (LiPF$_6$), offsets this; however, it has a smaller mass at 12.852 kg, yet accounts for 0.015% of the total GWP with 131.86 kgCO$_2$e. This is a 119.15% increase, despite the other electrolyte materials accounting for nearly six-times more of the total battery mass.
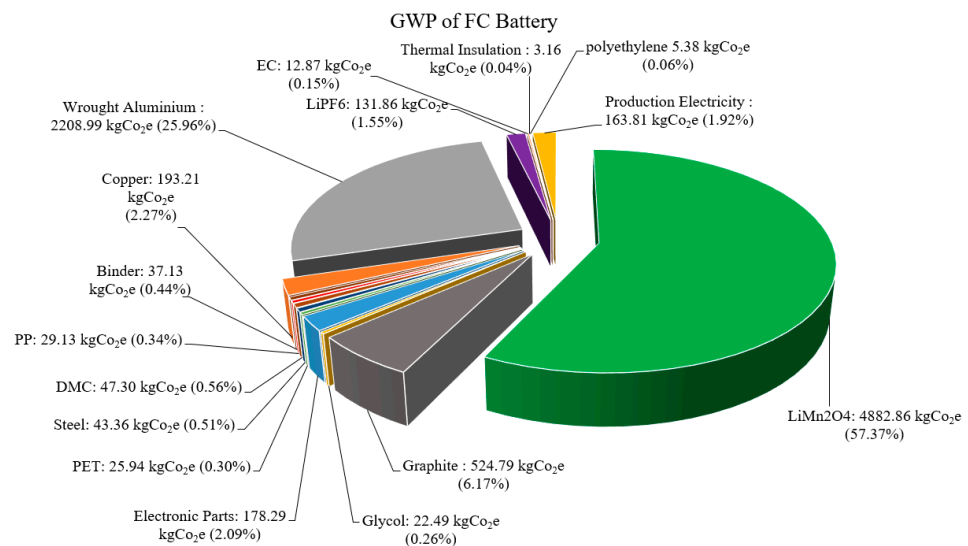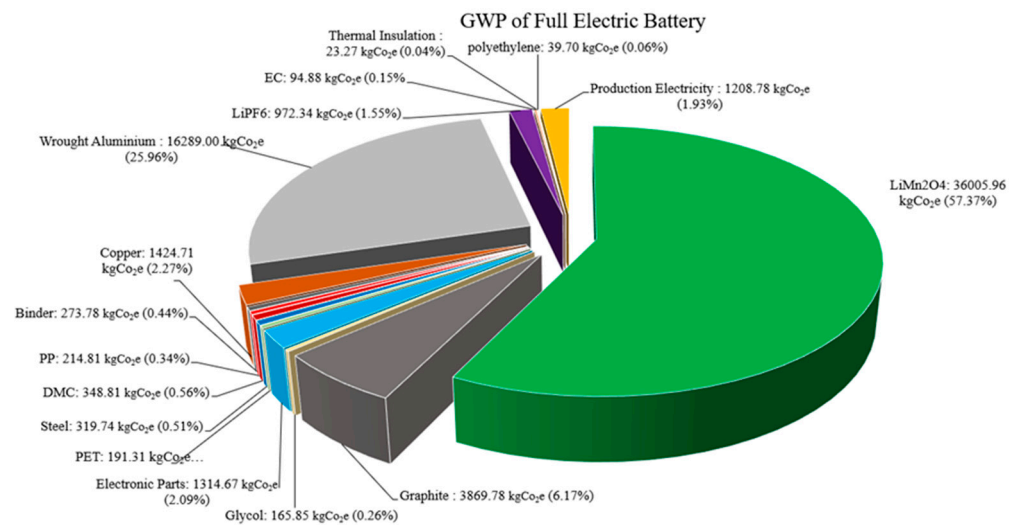

Figure 5. GWP contributions for FC battery. Abbreviations: Ethylene carbonate (EC), Dimethyl Carbonate (DMC), polypropylene (PP), polyethylene terephthalate (PET).

When Figures 4 and 5 are combined, the largest contributors to the FC system are the platinum for the catalyst on the electrodes and the LiMn$_2$O$_4$ for the active cathode material. These two materials are vital for the system to function, whilst alternative materials are being investigated. It is yet to be seen as to whether those alternatives will lead to a GWP reduction.

Due to the same percentage breakdown being used for the full electric and FC batteries, the GWP percentage contributions are the same, but there is a large variation in the masses. This yields the GWP alterations shown in Figure 6. Due to the large mass increase, LiMn$_2$O$_4$ contributes 36,005.96 kgCO$_2$e, which is more than the total GWP for the ICE and FC power units combined. Again, due to the large mass needed for the required power outputs, this means that even components that have low emission intensity end up with a large GWP. This can be seen with EC which still contributes 94.88 kgCO$_2$e, despite having a very low value of 0.34 kgCO$_2$e/kg. This is a key weakness of using a full electric power unit for a HGV, as for the power requirements to be met the mass of the batteries becomes very high. This then has knock on effects in the utilisation phase, which will be explored within the discussion section.

The final set LCA results relate to the production of the ICE power unit, which as shown in Figure 3 has the lowest GWP. The GWP breakdown for the ICE is shown in Figure 7. For this power unit, the largest contributor is iron, producing 3498.66 kgCO$_2$e, 43% of the total, although a high percentage would be expected as it accounts for 43% of the total mass. As in previous systems, wrought aluminium is a large contributor, producing 2784.44 kgCO$_2$e, 35% of the system's emissions. For each of the systems this can be attributed to the energy intensive extraction and production process, although the mass required for an ICE is considerably less than what is required for both the FC and battery systems. This is a factor in why the ICE has the lowest overall GWP, alongside the simplistic design and lack of specialist materials such as platinum, carbon paper and LiMn$_2$O$_4$.

Figure 6. GWP contributions for a full electric battery. Abbreviations: ethylene carbonate (EC), dimethyl carbonate (DMC), polypropylene (PP), polyethylene terephthalate (PET).
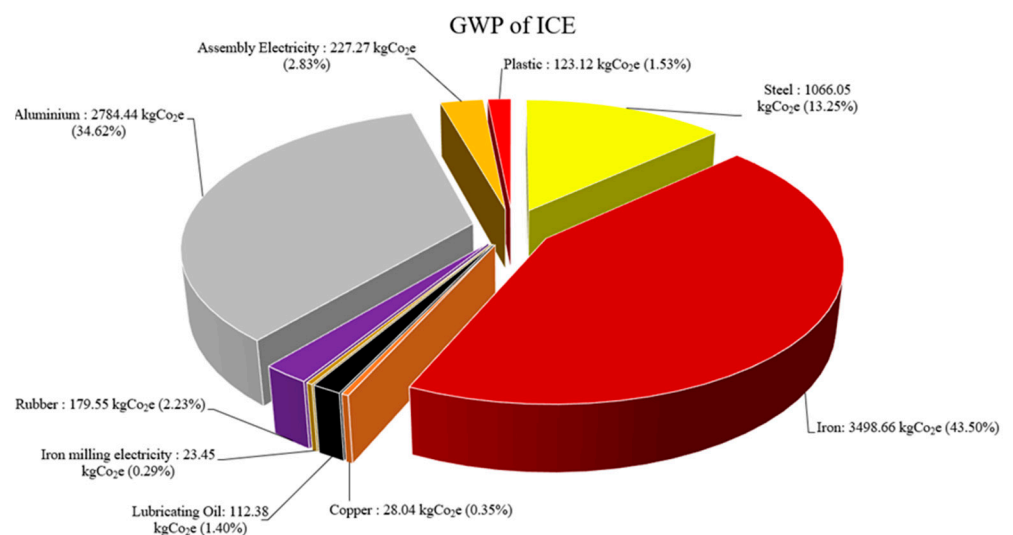
Figure 7. GWP contributions for ICE.

From the power unit breakdowns, it can be summarised that for both the FC and battery power units the majority of their GWP stems from one or more specialist materials that are crucial for them to function, whereas the simplistic design and use of more "traditional" materials in the ICE results in a lower GWP.

3.2. Usage Phase Results

For the Usage Phase results, the calculations and results are detailed in Tables 7–9. For these calculations the annual distance travelled by a HGV is assumed to be 125,000 miles [28]. The results for the annual usage emissions can be seen in Figure 8. Interestingly, from these results it is shown that hydrogen produced via electrolysis using a PEM produces the highest GWP at 4.77×10^5 kgCO$_2$e. For this process, the high levels of electricity required is the main reasoning behind the GWP value, with A. Mehmeti [29] stating that regardless of electrolyser technology, electrolysis is an energy-intensive method of hydrogen production. When renewable sources are used to produce electrical energy (PEM-R), in this case wind, there is a large reduction in the GWP, with PEM-R producing 3.57×10^4 kgCO$_2$e. The switch to a renewable electricity source reduces the GWP by 92.5%

annually, although it is not an emissions-free system due to the energy required for the construction of the PEM electrolyser and water treatment.

**Table 7.** Diesel ICE Powertrain Usage Calculations.

km/L	Annual Usage (L)	Production Emissions (kgCO$_2$e/L)	Annual Production Emissions (kgCO$_2$e)	Exhaust Emissions (kgCO$_2$e/km)	Annual Exhaust Emissions (kgCO$_2$e)	Annual Total Emissions (kgCO$_2$e)
4.301	46,772.38	3202.25	149,777.04	0.738	148,461.98	298,239.02

Table 8. Full Electric Powertrain Usage Calculations.

kWh/km	Annual Usage (kWh)	Production Emissions (kgCO$_2$e/kWh)	Annual Production Emissions (kgCO$_2$e)
1.5	301,752	0.309	93,241.368

Table 9. Hydrogen Fuel Cell Powertrain Usage Calculations (Acronyms—SMR: Steam Methane Reforming, SMR+CCS: Steam Methane Reforming with Carbon Capture Storage, PEM: Proton-exchange Membrane Electrolysis, PEM-R: Proton-exchange Membrane Electrolysis with Renewable Sources.

Production Method	km/kg	Annual Usage (kg)	Production Emissions (kgCO$_2$e/kg of H$_2$)	Annual production Emissions (kgCO$_2$e)
SMR	12.465	16,138.69	12.13	195,761.56
SMR+CCS	12.465	16,138.69	3.4	54,871.36
PEM	12.465	16,138.69	29.54	476,735.08
PEM-R	12.465	16,138.69	2.21	35,666.37
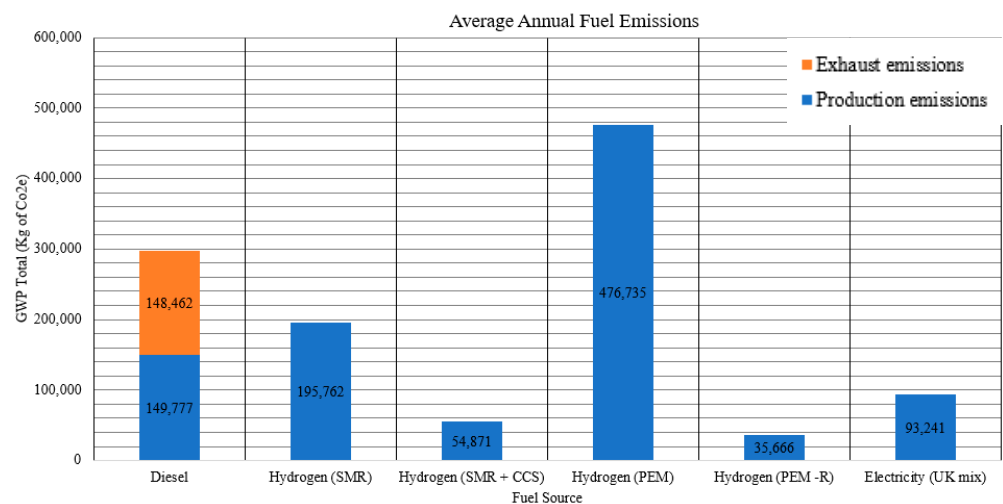
Figure 8. GWP of Different Fuel Production Methods.

For a diesel ICE's usage, the production process accounts for approximately 50% of the emissions, which would put it as the 3rd highest GWP. Therefore, the exhaust emissions must be considered, as with these included has the second highest GWP, producing 2.98×10^5 kgCO$_2$e annually. Hydrogen production via SMR still relies upon fossil fuel feedstocks, in this case natural gas. This means that it has a relatively large GWP of 4.77×10^5 kgCO$_2$e, which is higher than the production emissions for the ICE. This can be combatted by combing SMR with CCS, which reduces the emissions by 88.49% to 5.49×10^4 kgCO$_2$e. The electricity production emits a relatively low GWP of 9.32×10^5 kgCO$_2$e, although this is still a 69.76% and 161.06% increase over SMR+CCS

and PEM-R respectively. Additionally, when considering the efficiency of the full electric system, it must be noted that it cannot be ran until the stage of charge is 0%, as this damages the battery. For this study, a battery utilisation rate of 90% was assumed. These results are heavily dependent on the annual mileage of the HGVs, but enable a direct comparison between the different production methods for trends to be analysed.

3.3. Vehicle Life Cycle Results

The final set of results are shown in Figure 9, which combines the LCA results with the usage phase results, giving a vehicle lifecycle overview for a 10-year period. This assumes that the power units have a lifespan of 10+ years, with the same annual distance travelled each year. From these results a hydrogen system using PEM produces the highest annual GWP, with 4.94×10^5 kgCO$_2$e in the first year, going up to 4.78×10^6 kgCO$_2$e by year 10. This yields an annual increase of 96.36%, meaning that as the years progress the GWP gap between this and the other methods only increases. Due to the large power unit manufacturing emissions coupled with the high kgCO$_2$e/kg for hydrogen produced using a PEM, this option currently has a higher GWP than using an ICE system. The ICE system emits 62% of the emissions of that produced by the hydrogen PEM system, producing 2.99×10^6 kgCO$_2$e over 10 years. In comparison, a hydrogen using PEM produces this amount in a 6-year period. Of the technologies analysed, the hydrogen system using a PEM with renewable energy (PEM-R) sources yields the lowest GWP over the 10 years with a total of 3.74×10^5 kgCO$_2$e, which is less emissions than are produced by running an ICE system over the first 2 years. Whilst this system yields the lowest GWP, there are external factors that need to be considered before it can be implemented, which will be covered further in the discussion section.
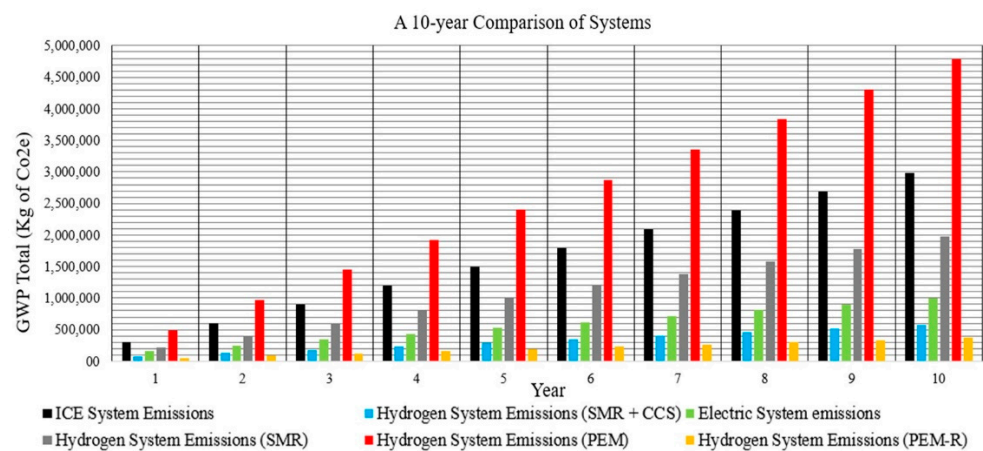

Figure 9. Power Unit Life Cycle GWPs over 10 years.

Of the hydrogen systems that utilise SMR, both offer a reduction in GWP over 10 years compared to an ICE system. The hydrogen system using solely SMR produces 1.97×10^6 kgCO$_2$e and the hydrogen system using SMR+CCS produces 5.66×10^5 kgCO$_2$e, resulting in a decrease of 34.11% and 81.07%, respectively, when compared to an ICE system. The full electric system yields the third-lowest GWP value over the 10 years at 9.95×10^5 kgCO$_2$e, despite the manufacturing emissions being much larger than those for the other systems. Over the 10-year period, the full electric system produces fewer emissions than ICE system does in 4 years, whilst the hydrogen system using SMR+CCS produces fewer emissions than the ICE system does in 2 years.

The GWP of the full electric system has the potential to be reduced as the UK transitions to a use of higher percentage of renewable sources for its electricity mix, in the same way as the PEM-R system. It should be noted that these comparisons are heavily dependent upon the annual distance travelled, meaning that these results are specific to this study.

4. Discussion

When analysing the full life cycle analysis produced in Figure 9, the main finding is that hydrogen can reduce emissions in HGVs compared to ICE systems. Although this is heavily dependent upon the hydrogen production methods utilised, as if electrolysis using non-renewable sources is utilised, this will lead to an increase in emissions. As the UK currently relies upon SMR for most of its hydrogen production, it would be unrealistic to assume that an instantaneous switch could be made to another system in order to reduce the emissions by 2050. This is due to the amount of infrastructure alterations that would be required and the cost of these changes. However, this investigation shows that if a hydrogen SMR system was to be adopted for HGVs it could lead to an instant reduction in emissions. As compared to the ICE system, the GWP is reduced by 30% in the first year alone, rising to 34% after 10 years. This first phase of emission reduction would involve using and expanding on the infrastructure that is already in place. After this, the second stage can begin which would be the incorporation of SMR+CCS systems, which offer a further reduction of 66–71% and 76–81% compared to the hydrogen SMR and ICE systems, respectively. This 2-phase transition could also be applied to the hydrogen systems using electrolysis for production. For this to happen, however, it would require the emissions to be first increased by 61–60% using a PEM system. After this increase, a PEM-R system could then be utilised to reduce the emissions by 83–87% compared to the ICE system. The issue with this approach is that there would have to first be an increase in the emissions before the large reduction can be obtained.

The results obtained for a full electric system offer a reduction compared to the ICE system and the PEM and SMR hydrogen systems. Due to this being calculated at the current electricity mix, the investigation does not consider future developments. This is a limitation in the scope of this report, especially as the UK government have announced they will aim to have 87% of electricity coming from nuclear or renewable sources by 2030 [30]. This gives the potential for a reduction in GWP for the full electric system, as well as the hydrogen PEM system, although due to its already-high GWP, it may still struggle to achieve a lower GWP than an ICE system. Based on the results of this study it can be stated that using a hydrogen SMR system and then transitioning to a hydrogen SMR+CCS system gives the best opportunity for the UK 2050 emissions targets to be met. This process will offer a significant reduction in GWP compared to current fossil fuel-based ICE systems, although it is not possible to achieve zero emissions from the system alone so some carbon offsetting would be required to achieve this.

Another key finding from this study is that whilst the power unit production must be considered, when looking at future technologies, the usage phase will always contribute to most of the emissions. This has been shown in previous studies on passenger vehicles [12,13], but when considering a HGV, the high annual mileage exacerbates this, meaning that a small decrease in $kgCO_2e$/mile can drastically alter the annual GWP. This provides a large advantage to the full electric and hydrogen systems (excluding PEM). Despite their power unit production processes yielding much larger GWPs than the ICE, their reduction in usage emissions coupled with the large distances travelled offsets the increased manufacturing emissions. It can be stated that, theoretically, if the hydrogen process and full electric systems could produce zero net emissions during their usage, whether utilising high levels of CCS or renewable energy sources for the fuel production, this would mean that only a direct comparison of the power unit production would be required. In this case, the FC system is the better option, as the full electric battery system produces close to 4 times the GWP. This can be attributed to the large mass of battery that is required to achieve the desired power outputs for a HGV, with S. Wolff [25] stating the battery can account for 46–56% of the tractor weight. This then has a knock-on effect with the efficiency as when the battery charge reduces the mass does not, unlike the FC and ICE systems where the fuel loads reduce. As a side effect of this, haulage companies are less likely to adopt full electric systems, as the weight of the batteries reduces the payload

that can be transported by the vehicles, meaning that companies will make less money compared to ICE or FC systems, which have smaller masses.

The final finding from this study can be taken from Figure 8, in relation to the exhaust emissions. One of the key advantages of the hydrogen systems is the lack of exhaust emissions at a vehicle level. As the production process for ICE system has a lower GWP than that of hydrogen system using SMR, the exhaust emissions close to double the total GWP, making it more polluting than the hydrogen system. This can be noted for all the other technologies, except for a hydrogen system using PEM, as this yields a higher GWP than the ICE system, even with the exhaust emissions included.

When looking at the future of hydrogen systems within the UK, it should be noted that this change cannot instantly be made. This study shows the possibilities of the technology but does not account for external factors, such as refueling infrastructure, liquid or gaseous hydrogen transportation, capability to meet hydrogen production demands and the high cost associated with these. This will influence how quickly the systems can be implemented to reduce the emissions. One key obstacle is whether the production capability can meet the demand; this is especially true for a PEM-R system. Despite this yielding the lowest GWP, it is not possible to transition all HGVs across to this, as currently within the UK there is no capability to supply solely renewable electricity on this scale.

As part of this discussion the results of this study can be compared to those of previous literature to check their validity. As mentioned within Section 3.1, there is variation for the production processes. This is shown in Table 10.

Table 10. Production Emissions Validity.

	System Production (kgCO$_2$e/kg)		
	Diesel ICE	**FC System (Stack and Battery)**	**Full Electric System**
This Study	6.84	13.84	11.93
L. Usai [14]	-	21.807	-
Z. Liu [31]	10.58	-	-
Q. Dai [32]	-	-	10.39

This study yields a lower kgCO$_2$e/kg value compared to L. Usai's [14] study, but this can partly be attributed to the different scopes of the studies, as they have included the hydrogen storage tank production within their study, accounting for 40% of the GWP. Taking this into account, similar results are obtained and L. Usai's [14] study supports this investigation. The next area of interest is the variation between the ICE results. Again, for this there is a difference in scope as Z. Liu's [31] study looks at production processes in China, whereas this study focuses upon UK production. This leads to differences as there will be variation in energy mixes used and material extraction GWPs can vary. Another influencing factor is that the database used by Z. Liu [31] was produced in 2010, so this will not account for changes in material extraction methods or the transition to renewable energy sources that have occurred since then. For the full electric system, the study produced by Q. Dai [32] yields only a small decrease, which can be attributed to slight differences in design, as they state that the battery design and configuration can affect the BOM and supply chain [32], which then in turn affects the GWP. They also utilised secondary material sources, which were not included in the scope of this study as the results are aimed to reflect the worst-case scenario for each of the systems.

The results from Figure 9 can also partially be validated against previous studies by scaling them to a kgCO$_2$e/mile basis. This is shown in Table 11, although not all the methods can be compared to previous studies due to limited research conducted on full system lifecycles for FC HGVs. From this, the results obtained in this study correlate with the previous literature that has been produced. The study produced by D.Y Lee [33] yields a more accurate representation, as for the usage phase they have utilised drive cycles to obtain the emissions, as opposed to this study which utilised an average mileage value. The full electric system yields the largest range between this study and B. Sen's [34],

but one of their main assumptions is that the battery will need replacing every 3 years. This will lead to an increase in the total emissions, as every 3 years there will be an added set of manufacturing emission, as opposed to this study that only accounts for the manufacturing process once. This means that over a 10-year period, rather than one set of manufacturing emissions, as in this study, B. Sen's [34] study includes four sets of manufacturing emissions. As with other studies performed [35–37], the location also has an effect, as different countries use varying electricity mixes which then have a knock-on effect on the GWP.

Table 11. System Life Cycle Validity.

	System (kgCO$_2$e/mile)					
	Diesel	**Hydrogen (SMR)**	**Hydrogen (SMR+CCS)**	**Full Electric**	**Hydrogen (PEM)**	**Hydrogen (PEM-R)**
This Study	2.448	1.696	0.5744	1.248	3.952	0.4208
D. Y Lee [33]	2.25	1.5	-	-	-	0.3
B. Sen [34]	-	-	-	2.08	-	-

When comparing this investigation to previous literature, it can be summarised that when all variations in scope and data sources are considered, the results follow the same trends and yield similar values. This provides validation for the results of this study.

5. Conclusions

From the results and discussion produced in this study, it can be concluded that whilst a hydrogen FC system has a higher GWP than a diesel ICE system at the power unit manufacturing stage, for the full lifecycle a reduction can be obtained. This is due to the manufacturing emissions playing a small role in the total GWP compared to the usage phase. FC systems have the potential to reduce HGV lifecycle emissions by 34–87 % compared to those of ICE systems, depending on the hydrogen fuel production process utilised. This is despite the manufacturing of a FC power unit producing more than double the emissions of an ICE unit, due to the required materials having energy-intensive extraction processes. Whilst FC systems do not offer a zero-emission solution, they can yield a major reduction in GHG emissions to try and reach the UK government's 2050 goals. Within the first year alone a GWP reduction of 30% can be achieved by replacing a diesel ICE with a hydrogen system using SMR, aiming to a further reduction of 76% if SMR+CCS is utilised. The opportunities that are presented by FC systems offer a realistic path to reduce vehicle emissions and this will only change positively as the technology improves.

When looking solely at the manufacturing process, the full electric and FC systems both have an increased GWP compared to an ICE system. This can largely be attributed to their dependency upon specialist materials, such as platinum and LiMn$_2$O$_4$, which combined account for 48% of the FC system's GWP, whereas the simplistic design and use of "traditional" materials in the ICE system yields the lowest GWP, as the FC and full electric systems produce 2.1-times and 7.8-times more CO$_2$e, respectively. However, due to the high annual mileage of HGVs, the power unit manufacturing only has a small impact upon the annual emissions, and the main contribution is from the fuel production process, meaning that manufacturing GWP can largely be offset by the usage phase.

Therefore, from the outcome of this work it can be concluded that whilst hydrogen systems can reduce GWP, not all production pathways do so and if these are utilised, they can lead to an increase in CO$_2$e, compared to the ICE. This is demonstrated with the PEM system as over a 10-year period it produces 46% more CO$_2$e, due to the high energy demands of hydrogen production via electrolysis, meaning this system would not be a viable option to reduce the UK's emissions by 2050. The results of this study allow the key trends and variations to be analysed, to obtain an overall view of the future HGV powertrain technologies and how they are compared. From these trends it can be

summarised that, for HGVs, FC systems can offer a large reduction in GWP compared to the current ICE systems if the correct hydrogen production method is utilised.

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