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Projektarbeit
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Life Cycle Assessment of Energy Storage and Supply of Electric Vehicles
Focus: Batteries and Fuel Cell Systems

vorgelegt durch
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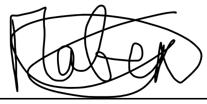

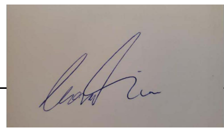

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Kurzfassung

Eine der größten Herausforderungen, vor denen die Gesellschaft derzeit steht, ist die Verringerung der Treibhausgasemissionen. Der Verkehrssektor trägt in erheblichem Maße zu den Treibhausgasemissionen bei. Zwei derzeit viel diskutierte Optionen für die Reduzierung sind batteriebetriebene Elektrofahrzeuge und Brennstoffzellen-Elektrofahrzeuge.

Die Auswirkungen auf den Lebenszyklus hängen von vielen Rahmenbedingungen ab, und ein praktischer und ganzheitlicher Ansatz zur Analyse beider Optionen für Busse, Pkw, Lkw und unter Einbeziehung variabler Randbedingungen ist bisher nicht verfügbar. Das Hauptziel dieser Studie ist es, die Auswirkungen von BEVs und FCEVs auf den Lebenszyklus von Bussen, LKWs und PKWs zu analysieren und dabei Protonenaustauschmembran-Brennstoffzellen mit Lithium-Ionen-Batterien wie Lithium-Eisenphosphat-Batterien, Lithium-Nickel-Mangan-Kobalt-Oxid und Lithium-Nickel-Kobalt-Aluminium-Oxid zu vergleichen. Bei den verglichenen Systemen wird von denselben Fahrgestellen, Motoren und Wechselrichtern ausgegangen. Daher werden nur die Batterie und die Brennstoffzelle sowie die für den Betrieb des Fahrzeugs benötigten Hilfsmittel in den Vergleich einbezogen. Die Ökobilanz wurde auf der Grundlage mehrerer Datenbanken durchgeführt, die durch Daten aus Forschung und Industrie ergänzt wurden. Insbesondere die Recycling-Phase war in den verwendeten Datenbanken begrenzt. Daher haben wir die vorhandenen Daten auf der Grundlage von Informationen von Industriepartnern und aus der Literatur ergänzt. Die Lebenszyklusphasen werden für einen Energiemix in einem Best-Case-Szenario, das auf 100% wiederverwendbaren Energiequellen basiert, mit dem aktuellen Energiemix in den Ländern verglichen, in denen die Produktion dieser Technologien derzeit stattfindet. Ein Python-Tool automatisiert die LCA und ermöglicht die effiziente Umsetzung verschiedener Szenarien und generiert die Ergebnisse für verschiedene Fahrzeugtypen.

Unsere Ergebnisse bestätigen, dass die Emissionsreduzierung durch Elektrofahrzeuge sowohl von der verwendeten Technologie als auch von den Betriebs- und Produktionsbedingungen abhängt. EVs und FCEVs können unter bestimmten Bedingungen besser abschneiden als die jeweils anderen. Unsere Forschung hat vor allem gezeigt, dass fahrzeugspezifische Ökobilanzen unter Berücksichtigung der individuellen Rahmenbedingungen notwendig sind. Daher ist das entwickelte Tool eine wichtige Lösung, um diese Ökobilanzen und damit ein umfassendes Verständnis der Umweltauswirkungen der verschiedenen Fahrzeuge zu ermöglichen und Entscheidungsprozesse für Politik, Unternehmen und Einzelpersonen zu unterstützen.

Abstract

One of the main challenges society currently faces is reducing greenhouse gas (GHGs) emissions in the transportation sector. For now, two highly discussed options for reducing greenhouse gas emissions are battery electric vehicles and fuel cell electric vehicles. This study analyses the life cycle impact of both technologies considering busses, trucks, and passenger vehicles, comparing proton-exchange membrane fuel cells with different cell chemistries of Li-ion batteries used in automotive applications. The LCA is performed based on several databases, which are complemented with research data. Notably, the recycling phase is limited in the used databases. Thus, we supplement the existing data based on information from the literature. The life cycle phases are compared for an energy mix in different regions, including electricity mixes from 2021 and forecasts for 2030 and 2050. Our results confirm that electric vehicle emission reductions depend on the technology used and the operating and production conditions. EVs and FCEVs can outperform each other under certain conditions. Above all, our research exhibits the need for vehicle-specific life cycle assessments, including their framework conditions.

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List of Abbreviations

Al ... Aluminium
BEB ... Battery Electric Bus
BET ... Battery Electric Truck
BEV ... Battery electric vehicle
BoP ... Balance of Plant
C ... Carbon
Co ... Cobalt
CO_2 ... Carbon dioxide
Cu ... Copper
DC ... Depot Charging
EoL ... End of life
EU ... European Union
FC ... Fuel cell
FCEB ... Fuel Cell Electric Bus
FCET ... Fuel cell electric truck, Fuel Cell Electric Truck
FCEV ... Fuel cell electric vehicles
Fe ... Iron
GHG ... Greenhouse gas
GVW ... Gross vehicle weight, Gross Vehicle Weight
GWP ... Global warming potential
ICE ... Internal combustion engine
kW ... kilowatt
LCA ... Life cycle assessment
LFP ... Lithium Iron Phosphate
Li ... Lithium
LPV ... Light passenger vehicles, Light Passenger Vehicle
Mn ... Manganese
NCA ... Lithium Nickel Cobalt Aluminium Oxide
Ni ... Nickel
NMC ... Lithium Nickel Manganese Cobalt Oxide
OC ... Opportunity Charging
SFC ... Specific Fuel Consumption
TCO ... Total cost of ownership
TEL ... Test Energy Low
tkm ... tonne-kilometre

1. Introduction

Due to its strong reliance on oil products, the transportation industry currently contributes to over 20% of global (GHG) emissions Feld (IEA 2021). However, the increasing popularity of alternative powertrain systems, such as electrification and hydrogen-based fuels, has been introduced to reduce emissions. To maximize the ecological benefits of the transition in transport towards electrification, minimizing GHG emissions with measures such as recycling of the used components or using renewable energy sources is essential. While internal combustion engines (ICEs) remain the most common form of powertrain, the number of battery electric vehicles (BEVs) has significantly increased, with a projected continued growth (Statista 2022). On the contrary, fuel cell electric vehicles (FCEVs) are relatively low in number and are expected to grow in popularity (Mathilde Carlier 2020). However, FCEVs have a well-to-wheel efficiency of only 30% in light passenger vehicles (LPV), which is significantly lower than the around 70% efficiency of BEVs (Gregor Fröhlich 2019; BMUV 2021). Additionally, BEVs often require larger battery packs, leading to higher weight and usage of metals, while FCEVs have smaller battery packs, leading to reduced vehicle weight and higher payload capacity. A comprehensive life cycle assessment (LCA) is necessary to determine which powertrain technology is more advantageous for different sorts of transportation vehicles.

The ecological aspects of BEVs and FCEVs are currently a topic of frequent discussions about the future of mobility. This raises high interest in this topic by both the scientific and engineering community. The topic of recycling and its ecological impacts is critical in these discussions. Hydrometallurgical and pyrometallurgical recycling of li-ion batteries are the two most frequently discussed options, which raised attention in recent years. Due to the Lithium Nickel Manganese Cobalt Oxide (NMC)-111 cell chemistry's commercial success, it became prevalent in research (Dai et al. 2019; Rajaeifar et al. 2021; Kallitsis et al. 2022; Sun et al. 2020). However, other cell chemistries, such as Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminium Oxide (NCA), and other proportions of NMC chemistries, are arousing interest in the industry and scientific community (Mohr et al. 2020; Tao et al. 2021; Ciez und Whitacre 2019).

Table 1 gives an overview of the global warming potentials of the production and recycling of li-ion batteries with different cell chemistries from different analysed studies. Dai et al. 2019 conducted an LCA for NMC111 batteries in automotive applications, which was used for further data analysis of EverBatt[1] and Ecoinvent[2] software. Rajaeifar et al. 2021 performed an LCA for different methods of pyrometallurgical recycling. The results varied between -0.77 and -1.22 kg carbon dioxide (CO_2) eq./kg

[1] Everbatt - https://www.anl.gov/amd/everbatt

[2] Ecoinvent - https://ecoinvent.org/the-ecoinvent-database/

NMC111 li-ion battery for the closed loop scenario. Kallitsis et al. 2022 evaluated the recycling of NMC111 batteries based on the recycling methods described by Mohr et al. 2020. They supplemented it with different pre-treatment steps, such as sorting, transporting, dismantling, etc. Also, state-of-the-art recycling processes for copper and aluminium were modelled. For the case of battery production and recycling in Europe, the results showed a decrease in global warming potential (GWP) by 27.4 % in the case of pyrometallurgical recycling and 29.9 % in the case of hydrometallurgical recycling. Sun et al. 2020 assessed the production and hydrometallurgical recycling of NMC622 batteries in China. They discovered that the production emits about 124.5 kg CO2 eq./kWh, while the total emissions could be reduced to 93.6 kg CO2 eq./kWh with hydrometallurgical recycling. Mohr et al. 2020 compared hydrometallurgical, pyrometallurgical, and advanced hydrometallurgical (Duesenfeld) recycling for LFP, NMC111, and NCA batteries based on information from the industry and GREET database. The results showed that the NCA cell chemistry has the highest benefit of recycling, while NMC111 has the lowest GWP from the production phase and, therefore, the lowest total GWP value among all cell chemistries. The results also showed that the LFP cell chemistry has the slightest decrease in GWP due to recycling, which can be explained by the lack of cobalt, nickel, or manganese in its cathode chemistry. Ciez und Whitacre 2019 also compared NMC, NCA, and LFP cell chemistries. However, in contrast to other research, the results showed significantly lesser benefits of recycling.

Table 1: GWP of Li-Ion battery production and recycling in different studies

Reference	Cell/ Pack level	Region	Cathode chemistry	Energy density (kWh/kg)	GWP (kg CO_2 eq./kWh)		
					Production	Recycling	
						Hydro.	Pyro.
(Dai et al. 2019)	Pack	USA	NMC111	143	72.9	-	-
(Rajaeifar et al. 2021)	Pack	UK	NMC111	-	-	-	-0.77 (kg)
(Kallitsis et al. 2022)	Pack	China NA Europe	NMC111	105	168.8 133.8 124.1	-65.1 -45.1 -37.1	-59 -40.6 -34.1
(Sun et al. 2020)	Pack	China	NMC622	115	124.5	-30.9	-
(Mohr et al. 2020)	Cell	-	NMC111 NCA LFP	170 174 108	75.5 85.6 101	-16.4 -18.3 -3.52	-13.8 -15.9 0.45
(Ciez und Whitacre 2019)	Cell	USA	NMC622 NCA LFP	212 189 101	42 45 72	-5 -3.5 8	3 1.5 10

Despite the differences in evaluated cell chemistries, functional units, and system boundaries, all studies showed similarities, such as the higher efficiency of hydrometallurgical recycling over pyrometallurgical recycling in reducing the total GWP of the battery. That similarity explains the various materials that can be retrieved in both recycling types. Moreover, the studies that included the LFP battery also showed that recycling of this cell chemistry does not necessarily benefit total GWP.

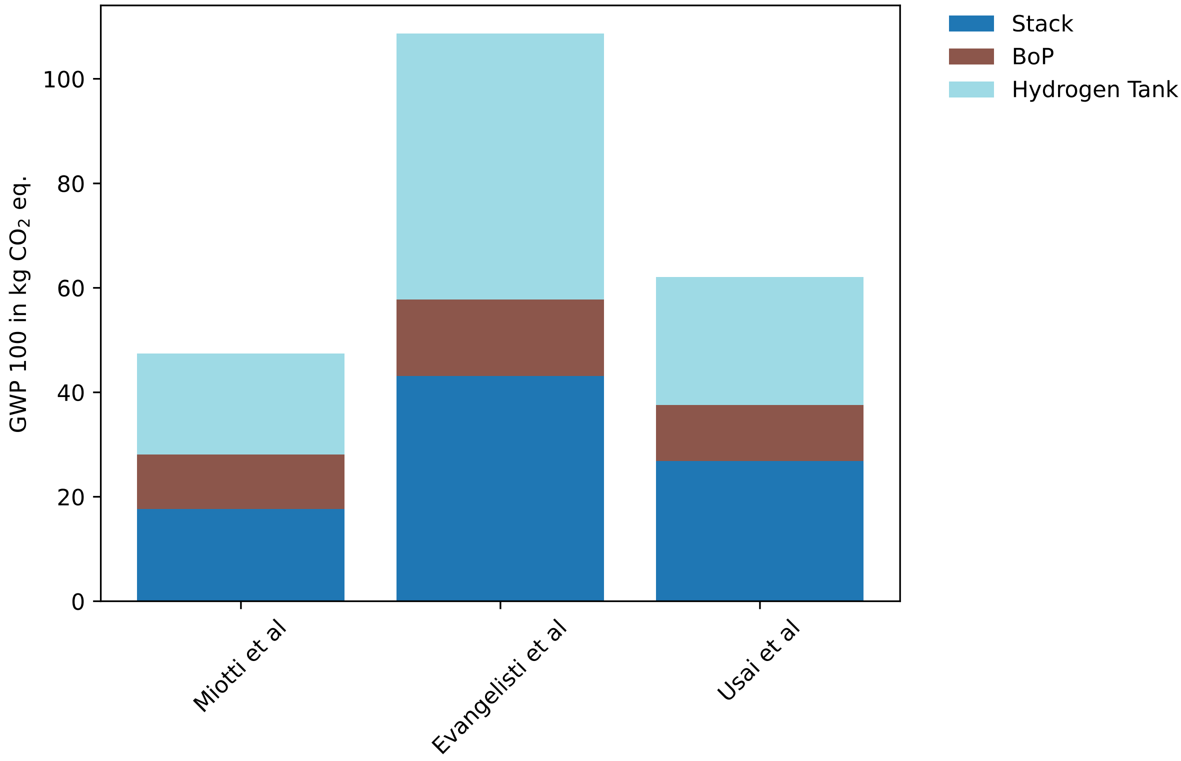

Figure 1: Comparison of the GWP impacts of a production phase for a fuel cell system, (kg CO_2-eq/kW)

The results of comparative studies for LCA of fuel cell (FC) systems are shown in Figure 1. All shown studies have performed an LCA for an 80 kW fuel cell system. Miotti et al. 2017 analysed a modern fuel cell technology with future scenarios using different materials. Usai et al. 2021 improved the data from the study of Miotti et al. 2017 with newer data about different fuel cell components. Evangelisti et al. 2017 assessed an equivalent system with different data for component production.

All analysed studies differ in the total GWP value per kW FC, primarily due to different platinum contents and different sizes of hydrogen tanks. However, all studies show a significant influence of hydrogen tank production and fuel cell stacks, which require platinum to produce the catalysator.

The analysed data shows the need for an LCA study that combines and compares all life phases of BEVs and FCEVs, using comparable vehicles as reference. This approach makes it necessary to analyse the pack level of the batteries with different battery chemistries in BEVs and includes the balance of plant (BoP) and hydrogen tank in FCEVs. Considering the electricity mixes in different regions and at different years can help to make predictions about the end of life (EoL) and use phase for the newly produced vehicles that will be used years later and will reach EoL in the future. Moreover, the recycling of fuel cells and the balance of plant are modelled despite the lack of comparable sources.

2. LCA Method

2.1 LCA Framework

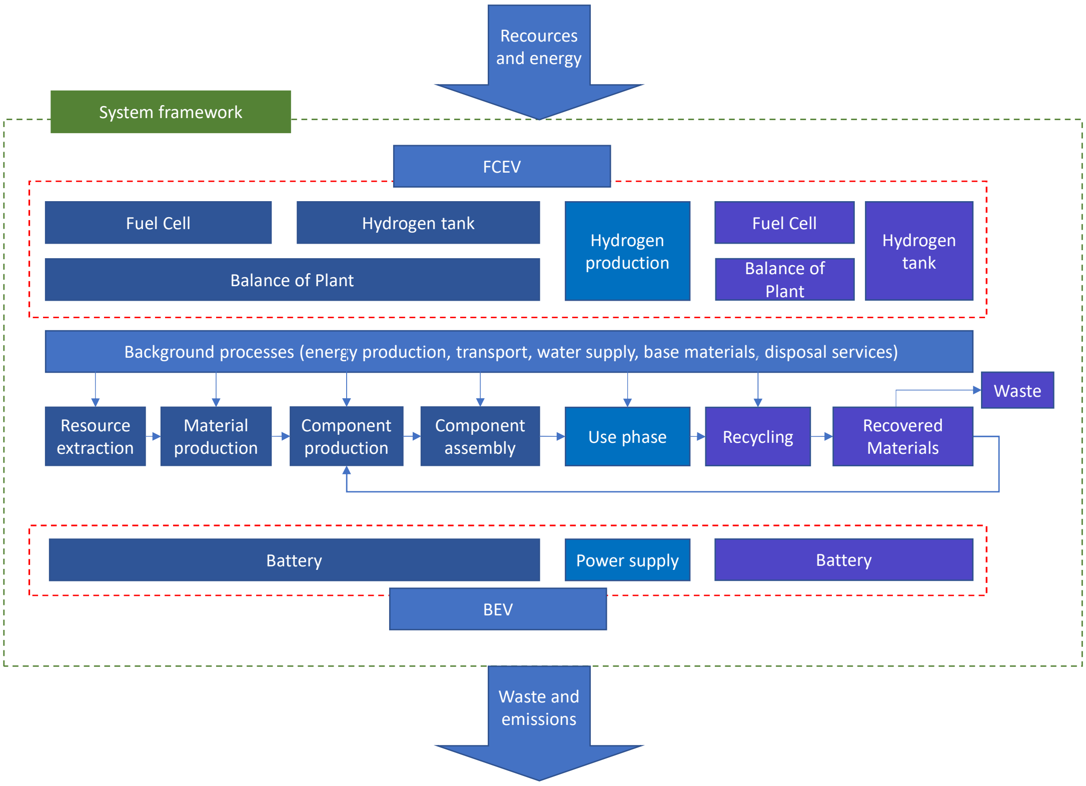

Figure 2: System framework

The LCA of battery and fuel cell electric powertrains is performed according to (DIN EN ISO 14044 - 2021). This analysis used the software OpenLCA in combination with the databank ecoinvent 3.9.1. External data sources were used if a component or a process was absent in the Ecoinvent databank. To ensure a complete comparison of both evaluated technologies, this study assessed the entire life cycle of the powertrains, including the production, use, and end-of-life phases. In both cases, recycling is assumed as an end-of-life process. The complete framework of the compared systems is depicted in Figure 2.

For the BEVs, four different cell chemistries were compared. Such cell chemistries as NCA, LFP, and NMC with different proportions of nickel, cobalt, and manganese

(NMC111 and NMC 811) were considered. Ecoinvent 3.9 database includes the production processes of all four cell chemistries. These cell chemistries have a relatively high energy density, which makes them well-suitable for automotive applications. Table 2 gives an overview of energy densities of compared battery cells and packs. However, Ecoinvent 3.9 does not include the recycling processes for these batteries. Therefore, it was taken from the EverBatt software, which considers hydrometallurgical, pyrometallurgical, and direct cathode recycling and transportation and dismantling of battery packs. The choice of this software is dedicated to the fact that it uses the same data source for battery production and recycling as Ecoinvent 3.9. Electric mixes from Germany, China, and European Union (EU) from different years were compared for the use phase. Although Ecoinvent 3.9 includes multiple electricity mixes that could potentially be used for the LCA of the use phase, these electricity mixes do not correspond with the newest data from the government authorities and are replaced with the new data (German Federal Government), (Strom-Report), (Fraunhofer ISE - Energy-Charts), (Energie.de), (Feldhaus et al.), (Burstedde und Nicolosi), (Feldhaus et al.).

Table 2: Energy densities of battery cells and packs, (Wh/kg)

	Energy density, cell	Energy density, pack
NMC111	197	143
NMC811	209	149
NCA	224	158
LFP	159	116

As for the FCEV, the production process was modelled in Ecoinvent 3.9 based on the data from the article about the current state-of-the-art of fuel cell technologies by Usai et al. 2021. This data set includes the production of the fuel cell stack, auxiliary systems, and hydrogen tank. The use phase of the FCEV was also modelled in Ecoinvent with the help of data from ((Burchart et al. 2022), (IEA 2021)). Finally, the recycling process of the FCEV powertrain was modelled using catalysator recycling data from Duclos et al. 2017. Combined with our assumptions on recycling of other stack components and the hydrogen tank and BoP.

The considered fuel cell is a low-temperature proton exchange membrane fuel cell. For a comparison of the vehicles, the key facts from the most recent on the market available FC system were considered, which is available in four power categories (detailed data in supplementary materials). In addition, the powertrain contains hydrogen tanks and the BoP. The weight of one tank and the BoP for the FCEV is based on Usai et al. 2021. Each tank is considered a 5 kg hydrogen tank with a weight of 101.2 kg per tank, adding the 5 kg hydrogen. For the BoP, a weight of 85.3 kg for an 80-kW fuel cell stack is given. That value is scaled for each stack (Table 3). The energy consumption is based on kWh, so the energy density of hydrogen will be calculated with 33,3 kWh/kg.

Table 3: Symbio Fuel Cell StackPack overview

	StackPack 40	StackPack 75	StackPack 150	StackPack 300
Power (kW)	40	75	150	300
Weight (kg)	72	80	140	280
Durability (h)	7.000	20.000 / 7.000 (HD/LD)	20.000	20.000
Coolant outlet temperature (°C)	80	85	85	85
Weight BoP (kg)	42.65	79.96	159.94	319.88

The impact assessment of this LCA is based on the ReCiPe 2016 (Huijbregts et al. 2017), which is the state-of-the-art impact assessment method, that is widely used in other studies about battery and fuel cell production and recycling. This study is mainly focused on the environmental scores of GWP, although other scores (Terrestrial Acidification Potential (TAP), Freshwater Eutrophication Potential (FEP), Freshwater Ecotoxicity Potential (FETP), Terrestrial Ecotoxicity Potential (TETP), Human Toxicity Potential, cancer (HTP), Metal Depletion Potential (MDP) and Cumulative Energy Demand (CED)) are also included in supplementary materials. This study uses a consequential modelling approach, as it is more suitable for the modelled recycling processes.

2.2 Inventory

This study combined inventories for several processes, such as fuel cell recycling, Li-ion battery recycling, hydrogen production, and electricity generation in Germany, China, and the EU. The fuel cell recycling inventory was developed based on the fuel cell production process (Usai et al. 2021). According to the used production data, the fuel cell powertrain is split into different components, which can be found in the supplementary materials (S1). The recycling process suggested by Duclos et al. 2017 is assumed to recycle the fuel cell catalysator. For other components of the fuel cell stack and the BoP, it was assumed that plastic and electronic components are treated as waste materials. At the same time, metals such as copper, steel, and aluminium are modeled as materials for recycling. Second life was considered as fate of the hydrogen tank after the use phase. The air management system's production is modelled using permanent magnets, so a suitable recycling process for these magnets was added based on data from Jin et al. 2018.

As for hydrogen production, the mix of hydrogen produced by different sources was modelled (IEA 2021), which states that in 2020, 59 % of hydrogen was produced by steam methane reforming, followed by hydrogen production as a by-product of other processes (21 %) and coal gasification (19 %). Hydrogen production with oil and fossil fuels, with carbon capture being the least popular sources of hydrogen production, accounting for 0.6 % and 0.7 % of the total hydrogen production. Processes for methane steam reforming and petroleum refinery operations are present in Ecoinvent and therefore were directly taken from the database. However, the processes for hydrogen production with coal gasification, fossil fuels with carbon capture, and by-product production were not present in Ecoinvent. Therefore, the coal gasification process data was taken from Burchart et al. 2022. Hydrogen production with carbon capture was assumed as a part of the steam reforming process. It is assumed that hydrogen as a by-product of other processes does not impact the GWP of hydrogen, as its emissions are included in the processes of the main product.

The data for the recycling process of the li-ion battery was taken from the EverBatt software by Argonne National Laboratory, which used different sources for different recycling steps. The whole recycling process is divided into three steps. The first step is transporting the battery pack to the recycling facility. The second step is disassembling the battery pack, which helps separate the battery modules from each other and the battery pack and gives access to the first recyclable components. Further, there are two possible recycling processes for the batteries. The first is hydrometallurgical recycling. For hydrometallurgical recycling, the batteries need to undergo a mechanical recycling process, which separates the cathode from the rest of the battery. In this step, the disassembled battery modules are shredded into smaller pieces. After that, the binder and electrolyte are burnt in a calcination process. The shredded pieces of batteries are then sorted to obtain such materials as aluminium, steel, copper, graphite, and plastics. Eventually, the sorted rests undergo a leaching process and solvent extraction to gain cobalt, nickel, manganese, and lithium compounds.

In the case of pyrometallurgical recycling, batteries are fed into the smelter, where the electrolyte and plastics are burnt to produce heat for the thermic reaction. Some materials (Al, Li, C) are oxidized during smelting and end up in the slag. Other materials (Fe, Cu, Ni, Co, Mn) end up in matte, which can be recycled to separate the materials. Both slag and matte can further be treated to gain materials, but only the matte treatment is analysed in EverBatt. Further recycling steps for the matte are analogue to the final steps of hydrometallurgical recycling: the matte undergoes the processes of acid leaching, precipitation, and solvent extraction. The EverBatt data for hydrometallurgical and pyrometallurgical recycling processes are divided into three categories – transportation, dismantling, and pyrometallurgical/hydrometallurgical recycling. All steps after dismantling are summarised in EverBatt and therefore modelled in the same way in Ecoinvent. The detailed inputs and outputs of the recycling processes can be found in supplementary materials (S1).

The electricity mix was also obtained from external data sources. Electricity mixes from Germany, China, and the EU were compared in this study. Cases for three years –

2021, 2030, and 2050 were modelled for Germany and the EU, while only 2021 was modelled for China due to insufficient data for the future energy mix. 2021 was chosen as the last representative year instead of 2022, which included significant changes in the European energy market that led to increased consumption of fossil energy sources and is treated as an outlier. It should also be noted that many prognoses for the German energy mix are slightly outdated and do not consider the recently approved coal phase-out act, which intends to decommission all German coal power plants by 2038 (German Federal Government). The German electricity mix for 2021 is modelled according to (Strom-Report), the EU 2021 mix is modelled according to the data from (Fraunhofer ISE - Energy-Charts), and the data for the Chinese 2021 mix is obtained from (IEA 2023). The prognoses for future electricity mixes are obtained from the following sources: Germany 2030 – (Energie.de), EU 2030 – (Feldhaus et al.), Germany 2050 – (Burstedde und Nicolosi), EU 2050 – (Feldhaus et al.). The background of analysing future electricity mixes is connected to the fact that the vehicles produced now will be used and used in the future. Moreover, future electricity mixes help to show the dynamics of the changes in ecological aspects of both compared powertrains.

3. Case Study

3.1 Vehicles

Both powertrain types consider for busses and trucks, a battery change after six years ((Kim et al. 2021b), (Göhlich et al. 2018)) and a lifetime of 12 years for the investigated vehicle types ((Göhlich et al. 2018), (Ferrara et al. 2023)). Every vehicle consists of a battery with a battery capacity. An FCEV contains, in addition, a fuel cell with a specific power plus its BoP and a hydrogen tank weighing 101.2 kg (Miotti et al. 2017). For calculating the BEV consumption, a state of charge of 80% will be used (Wolff et al. 2021). The considered yearly mileage can be found in the appropriate vehicle section. The data in the following tables are marked in bold if values had to be calculated. Furthermore, the supplemental material provides more information about vehicles available on the market, including values that were calculated or estimated (marked in bold). The following three parts define the details of modelled trucks, busses and LPVs used for the case studies.

Trucks

The Trucks are split into the gross vehicle weight (GVW) categories of 18 t, 25 t, and 40 t. In Ferrara et al. 2023 an overall total cost of ownership (TCO) for fuel cell electric trucks (FCET) has been determined (Ferrara et al. 2023). For the FCET, the recommended combination of 300 kW fuel cell stack power with a 100 kWh battery will be considered (Further referred to as FC 300 kW B 100 kWh). In addition, a truck similar to the Hyundai XCIENT (Further referred to as FC 150 kW B 72 kWh) will be modelled, representing a realistic combination of fuel cell and Battery. The number of tanks is calculated by the simulated specific fuel consumption (SFC) and with the range of the compared battery electric trucks (BETs). The following BETs are comparable models to the Daimler Truck eActros (Further referred to as Daimler) and the eForce one EF18 (Further referred to as EFORCE). In addition, to show the influence of a higher range for BET, an extended range version of the Daimler eActros is added in the 25 t GVW category (Further referred to as Daimler ER). Likewise, the corresponding payload for the Daimler and Daimler ER is halved due to the energy consumption data based on 50 % payload (Mercedes Benz Trucks 2023). The following Table 4, Table 5, and Table 6 show the parameters used for our calculations.

Table 4: Parameters for Trucks with GVW 18, 25, 40 t

		Range (km)			SFC (kg / kWh)/100 **km**			Battery Size (kWh)/ Fuel Cell Size (kW)
	GVW	18 t	25 t	40 t	18 t	25 t	40 t	18 t / 25 t / 40 t
Fuel Cell	FC 300 kW **B 100 kWh**	**346**	**346**	**257**	6.81	7.21	9.7	100/300
	FC 150 kW **B 72 kWh**	**381**	**367**	**270**	**6.56**	**6.81**	**9.25**	72/**150**
Battery	B **450 kWh**	350	300	260	**102.9**	**120**	**138.5**	450
	B 448 **kWh**		400			**89.6**		448
	B **336 kWh**	330	300	220	**76.8**	**89.6**	**122.2**	336

Every truck consists of a homologated chassis, given in Table 5 according to Gray et al. 2022. The payload results from our Python tool calculating the powertrain masses based on the energy densities of the battery packs and fuel cell packs, same as their auxiliaries. Finally, the GVW subtracted by the vehicle weight multiplied by the payload factor results the payload.

Table 5: Truck weight composition

Unit	Weight per unit (kg)
Electric Machine	308
Electric System	265
Chassis and Frame	3439
Suspension	2329
Brake System	784
Cabin	1153
Body	2100
Wheels	1352
Other	1158

The considered kilometres per year are based on Ferrara et al. 2023 over a period of 12 years and are given in Table 6:

Table 6: Trucks, yearly Mileage

	GVW 18 t	GVW 25 t	GVW 40 t
Mileage per year (km)	115000	95000	67415

Buses

Busses are classified in different lengths and single deck or double deck busses. The 12 m fuel cell electric bus (FCEB) and the battery electric bus (BEB) will be compared. A detailed list of available hydrogen projects for city buses can be found in (Elise Ravoire 2019). Ravoire (2019) analysed different hydrogen city buses and provided critical facts for this work. Regarding BEB Göhlich et al. 2018 procured comprehensive data for TCO-optimized BEBs, which will be considered here. The article considers a bus for opportunity charging (OC) with 90 kWh and a bus for depot charging (DC) with a battery capacity of 300 kWh. As FCEB, a configuration similar to the "Solaris Urbino 12 Hydrogen" with a consumption of 8 - 9 kg/100 km is used (Table 7)((Kim et al. 2021b), (Elise Ravoire 2019), (WSW 2021)).

Table 7: Data for FCEB and BEB

	Fuel Cell Bus	Battery Electric Bus	
	FC 70 kW B 31 kWh	B 300 kWh	B 90 kWh
Range per day (km)	350	350	330
SFC (kg / kWh)/100 km	**8.5**	333	325
Battery size (kWh)	31	300	90
Fuel Cell size (kW)	70	-	-
Passenger Capacity	75	85	100

Finally, the CO_2 emissions per person km are calculated. Previous studies used or calculated values for an average yearly millage between 45.000 km and even 256.500 km per year (Sayer et al. 2022; Kim et al. 2021a) The considered yearly range is 60.000 km with an average passenger occupancy of 65% which assumes 3.8 driving days per week to compensate for maintenance days and holidays with less occupancy of the bus fleet.

Passenger Vehicles

The following analyses in Table 8 show the LCA results for different on-the-market available vehicles and demonstrate possible use cases for these light passenger vehicles (LPV). Moreover, the vehicles are chosen to be comparable regarding their weight and vehicle class (coupé and SUV). Since an advantage of the FCEV is its range, we added the Mercedes EQS 580 4Matic to represent long, and medium vehicle ranges.

Table 8: Data for FCEV and BEV

	FCEV		BEV		
	Toyota Mirai 2[3]	Hyundai Nexo[4]	VW ID.3[5]	VW ID.4[6]	Mercedes Benz EQS 580 4Matic[7]
Range (km)	650	666	426	346	672
SFC (kg/kWh)/100 km	0.84	0.95	15.5	16.7	17.7
Battery size (kWh)	0.95	1.56	62	55	120
Fuel Cell size (kW)	128	95	0	0	0
H2 Tank size (kg)	6.2	6.33	0	0	0
Passenger Capacity	4.5	4.5	4.5	4.5	4.5
Empty weight (kg)	1950	1948	1805	1966	2585
Vehicle Class	Coupé	SUV	Coupé	SUV	Coupé

The data considers the actual battery capacity to calculate proper values regarding production and recycling. Moreover, the consumption data is based on the WLTP cycle with low test energy (TEL) to use standardized BEV values. The table shows that the SUVs consume more energy independent of the weight than a coupé, which usually comes from a bigger surface, causing a higher wind resistance. The considered lifetime km is 180,000 km over 12 years (Koroma et al. 2022), which takes an average yearly mileage of 15,000 km per year into account.

3.2 Energy mix

Considering a realistic energy mix is exceptionally important for the use phase. Seven different energy mixes were used to assess the emissions of the considered vehicles for the use phase. Electricity mixes for Germany, China, and the EU in 2021 were compared with the future forecast for the German and European electricity mixes in 2030 and 2050 to show how the impact of the use phase changes with time Table 9.

As for the production phase, it is considered that battery production takes place in China, so the Chinese electricity mix from 2021 is used. For the end-of-life phase, possibilities of recycling in Germany and the EU are considered. To simulate the recycling of batteries for vehicles that are produced now, electricity mixes for 2030 are applied.

[3] (GreenGear.de 2021)
[4] (GreenGear.de 2018)
[5] (EV Database 2023a)
[6] (EV Database 2023b)
[7] (EV Database 2023c)

Table 9: Energy sources for different energy mixes in different regions, (%)

Energy source,	2021 China[8]	2021 EU[9]	2021 Germany[10]	2030 EU[11]	2030 Germany[12]	2050 EU[11]	2050 Germany[13]
Hydropower	15.28	12.82	3.98	12.89	15.25	12.96	5.58
Solar power	3.84	5.31	9.98	12.32	35.25	18.02	42.45
Wind power	7.7	14.55	23.23	8.31	23.77	14.02	33.02
Biomass	2.31	3.3	8.88	0	0	0	1.24
NPP	4.79	27.59	13.46	38.31	0	46.53	0
Gas power	3.2	17.09	10.53	3.37	11.48	0.51	17.71
Lignite	0	8.33	20.38	6.63	2.79	3.37	0
Hard coal	62.74	7.45	9.56	17.59	9.84	4.59	0
Other	0	3.57	0	0.57	1.64	0	0

4. Results

4.1 Production Phase

Battery

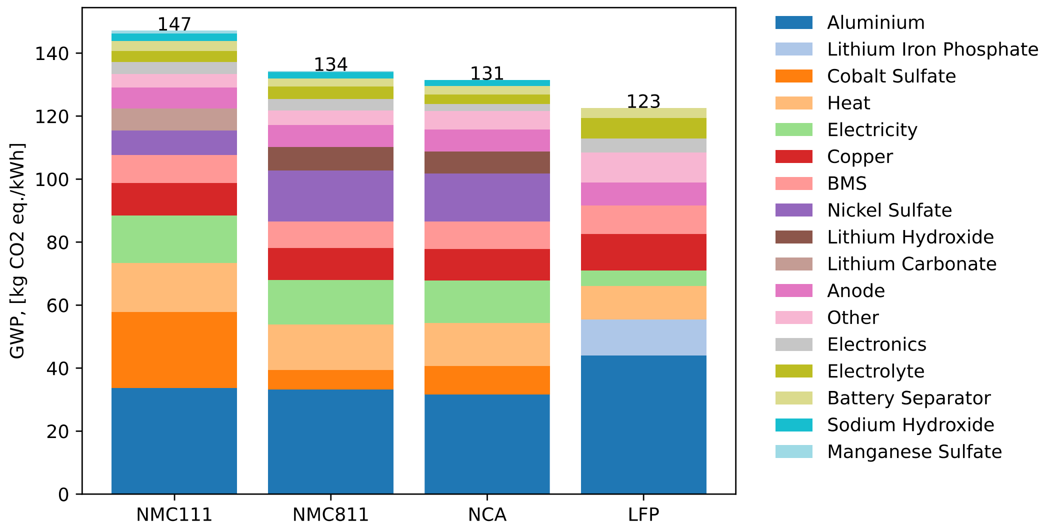

Figure 3: Influence of different battery pack materials and processes in different cell chemistries, (kg CO_2 eq./ kWh)

[8] (IEA 2023)
[9] (Fraunhofer ISE - Energy-Charts)
[10] (Strom-Report)
[11] (Feldhaus et al.)
[12] (Energie.de)
[13] (Burstedde und Nicolosi)

The results of the LCA for the production phase are shown in Figure 3. Despite the relatively high energy density of NMC111, this cell chemistry has the highest GWP of all, which can be conducted with high cobalt content, significantly influencing the battery's GWP. NMC811 and NCA have lower GWPs due to reduced cobalt content in these cell chemistries. The cobalt content in these batteries is compensated by a higher concentration of nickel, which shows a significantly more considerable influence on the GWP of the two cell chemistries. Although the cobalt content of the NCA is higher than that of the NMC811, it still has a lower GWP due to its highest energy density among all examined cell chemistries. The LFP cell chemistry shows the lowest GWP of all cell chemistries due to different kinds of cathode chemistry that do not include cobalt or nickel. Lithium iron phosphate has the smallest GWP compared to other cathodes. However, due to its low energy density, the overall GWP of the LFP battery is still close to other chemistries. Another attribute of the low energy density of the LFP chemistry is the exceptionally high impact of aluminium in its GWP. Aluminium has a significant role in the GWP of all cell chemistries, as it is used as a casing material for prismatic cells in Ecoinvent. Nevertheless, LFP has the least GWP of all cells on the pack level.

4.2 End-of-Life

Batteries

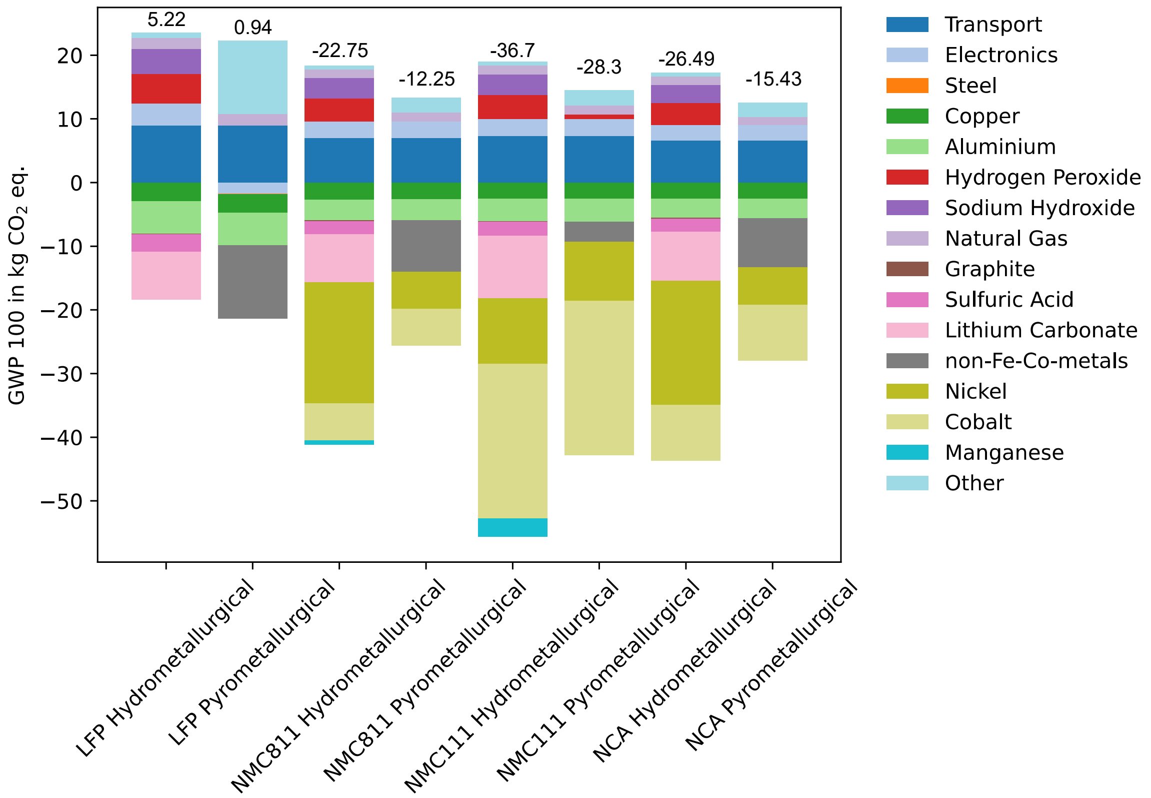

Figure 4: GWP of hydrometallurgical and pyrometallurgical battery recycling for different cell chemistries, (kg CO2 eq./kWh)

Figure 4 depicts the results of LCA for different kinds of battery recycling applied to batteries with varying cell chemistries. The positive values show the processes marked as the effort of the recycling, and the negative processes depict the benefit. All three recycling stages are considered: transportation, disassembly, and hydrometallurgical/pyrometallurgical recycling. This figure shows the significant advantages of hydrometallurgical recycling over pyrometallurgical in all cases, varying between 23% for NMC111 to 47% for NMC811. Nickel and cobalt are the materials with the most substantial influence on the overall decrease in GWP, followed by lithium carbonate. It is also noticeable that the recycling of the LFP batteries does not reduce its overall GWP since this cathode chemistry lacks nickel or cobalt, which reduces the GWP more than other battery materials.

Compared to the production phase (Figure 5), hydrometallurgical recycling of NMC111 batteries shows 25% of, the highest reduction of GWP among all cell chemistries and recycling methods. However, the NCA battery shows the lowest GWP after the recycling phase – 107 kg CO_2 eq/ kWh. The LFP shows the highest GWP after the recycling phase – 128 kg CO_2 eq/ kWh.

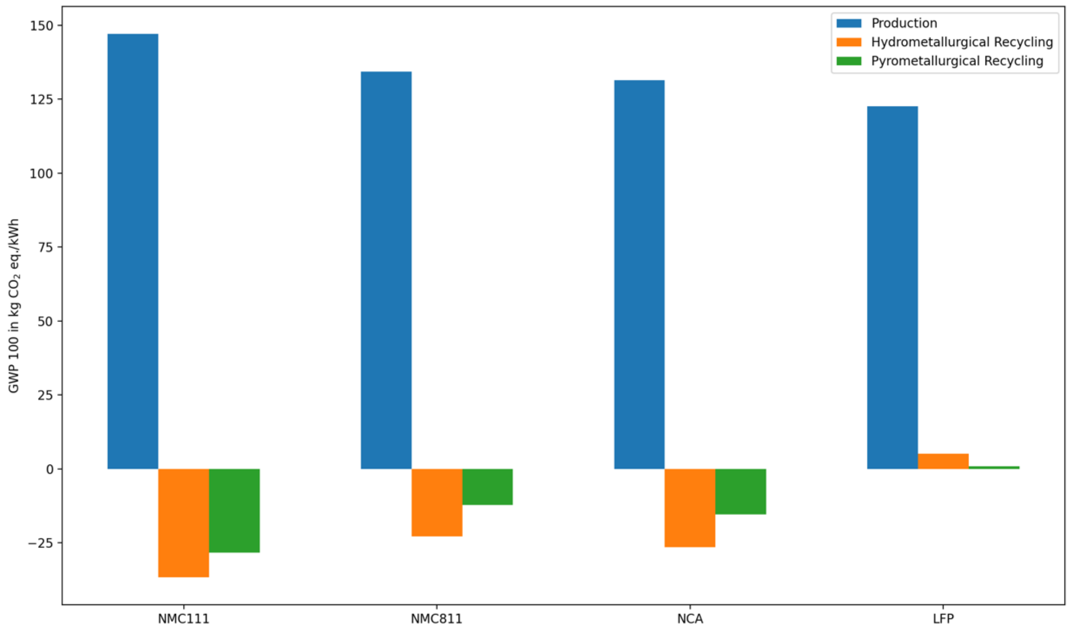

Figure 5: GWP of battery recycling, compared with production, (kg CO_2 eq./kWh)

Fuel Cells

The production phase of the fuel cells shows almost identical results with the source (Usai et al. 2021), having only a slight deviation in the production of the fuel cell stack and hydrogen fuel tank. This study uses a newer version of the Ecoinvent database, which is combined with newer electricity mixes than the data from (Usai et al. 2021). Figure 6 depicts the GWP for recycling and producing a 1 kW fuel cell. All components of the fuel cell are included in the recycling process. Since the hydrogen tank contributes most to the production emissions, it also significantly decreases its GWP when granted a second life. Recycling the proton exchange membrane with the catalyst also shows a significant reduction in GWP, reducing the GWP to 25 % of the production result. As a rare metal, platinum has an exceptionally high GWP in the production phase, which can be reduced with less effort during recycling. The recycling of the balance of plant and stack components reduces about 20% of the GWP emissions from the production phase, which is the most negligible substantial impact in the recycling phase. However, recyclable parts of the BoP are copper, steel, aluminium, and electronic components, which do not reduce the GWP significantly in the recycling process.

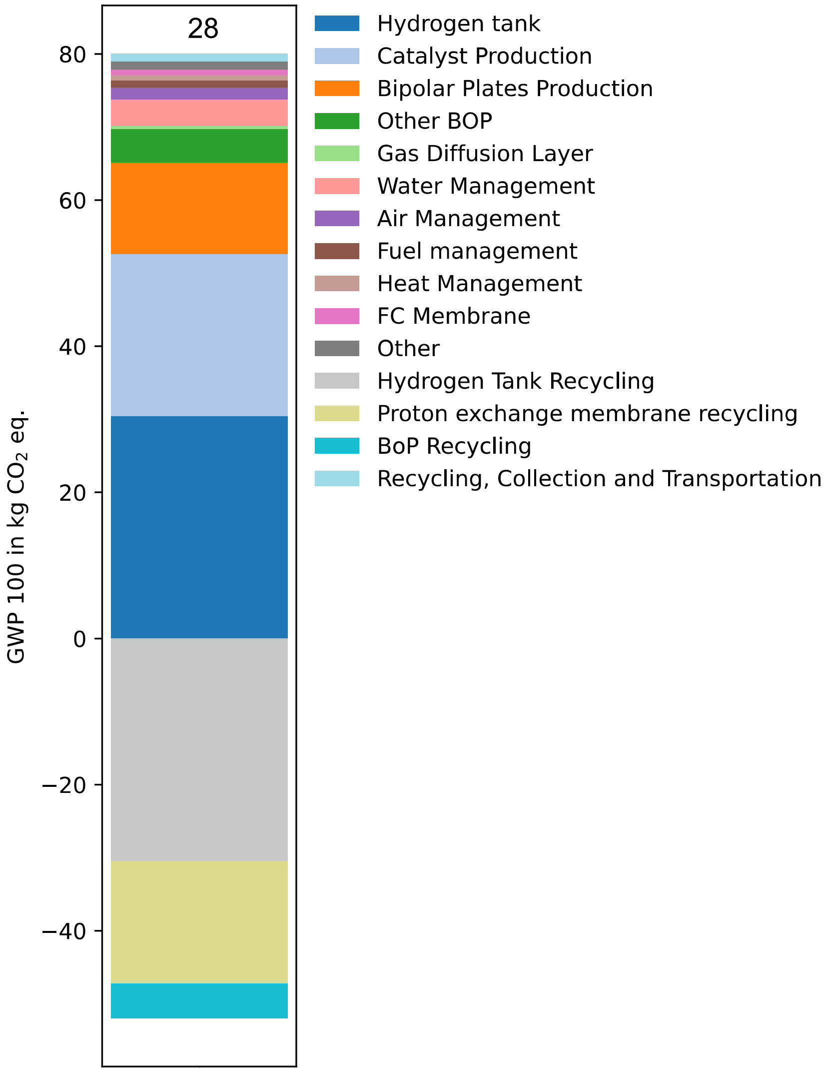

Figure 6: GWP of fuel cell component recycling (kg CO_2 eq./kW)

4.3 Applications

Trucks

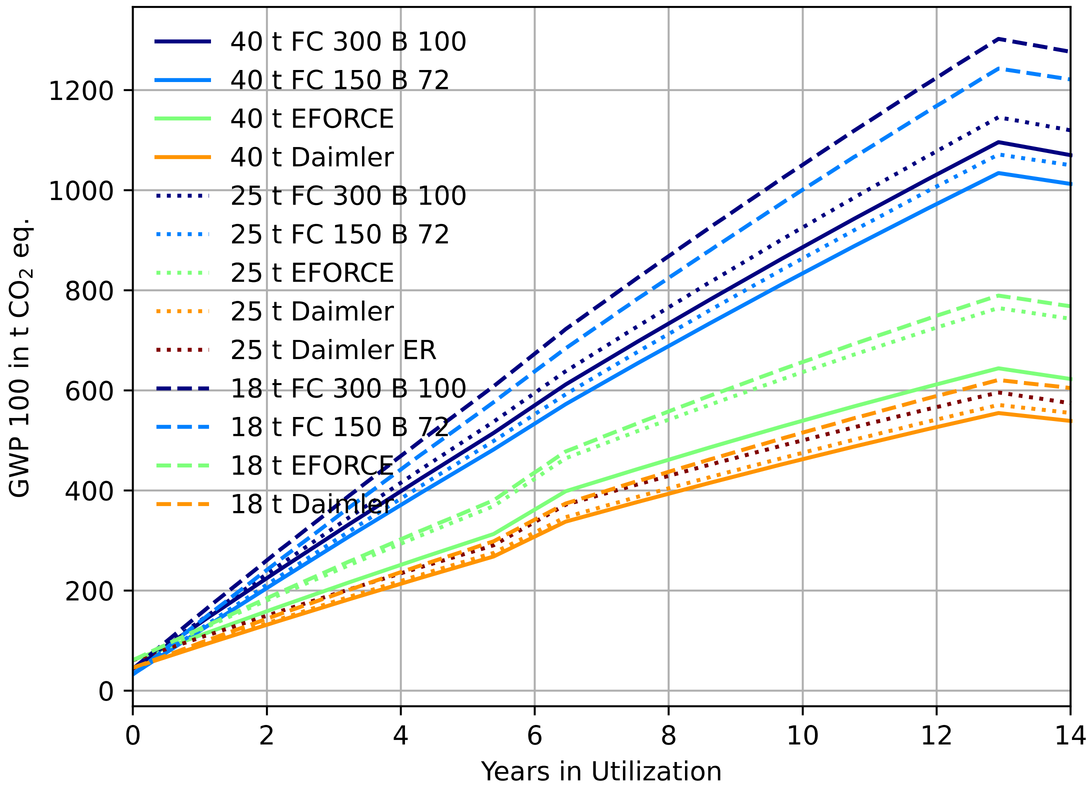

Figure 7: Overall GWP of all compared trucks, by years in utilization, (kg CO_2 eq.)

The GWP of different trucks is depicted in Figure 7. The overall pattern here is the significantly lower GWP of the battery-powered trucks over the fuel-cell trucks. In contrast to buses, where the mass of the powertrain system dominates the energy consumption, the energy consumption of the trucks is dominated by the mass of the freight, making the discrepancies in the powertrain masses insignificant compared to the mass of a truck with freight. However, when not the whole GWP is considered, but the impact per (tonne-kilometre) tkm, the impact of the fuel cell trucks is smaller compared to the battery-powered trucks (see **Fehler! Verweisquelle konnte nicht gefunden werden.**).

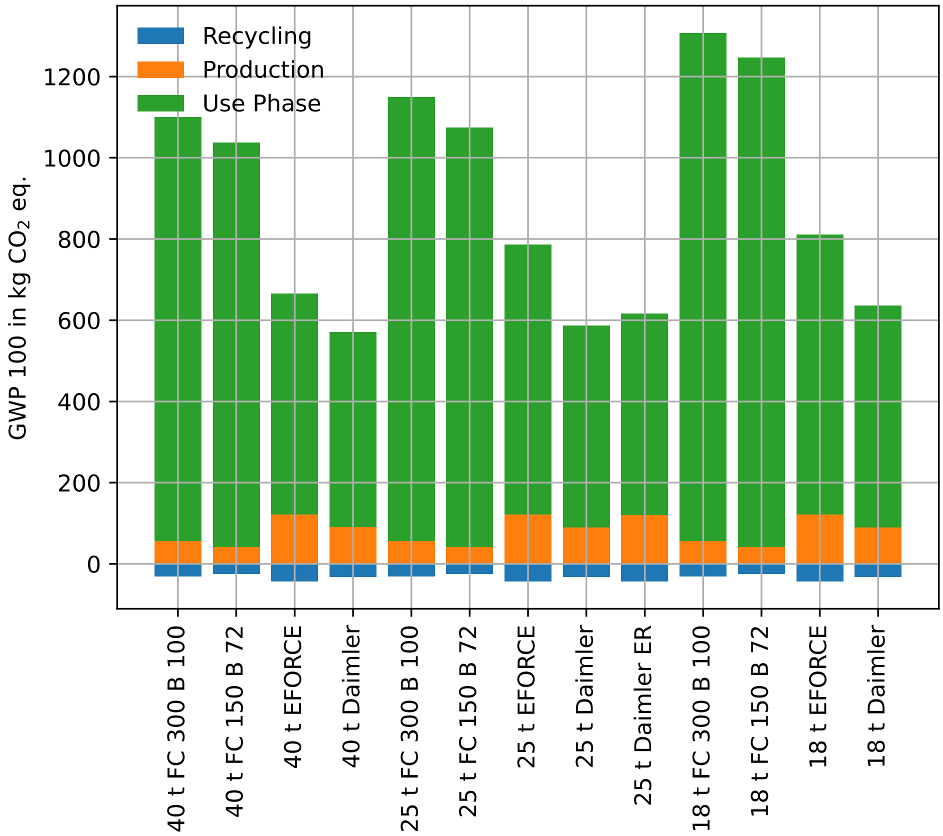

Figure 8: Overall GWP of the different life phases of analysed trucks (kg CO_2 eq.)

		Production	Recycling	Use	t km
40t	FC 300 B 100	56934.08	-30754.41	1043825.18	0.0482
	FC 150 B 72	42089.23	-25149.45	995400.3	0.0448
	EFORCE	121538.4	-42789.64	543873	0.0590
	Daimler	90748.67	-31949.6	479926.72	0.0495
25t	FC 300 B 100	56934.08	-30754.41	1093347.88	0.0879
	FC 150 B 72	42089.23	-25149.45	1032690.57	0.0787
	EFORCE	121538.4	-42789.64	664227.21	0.1323
	Daimler	90748.67	-31949.6	495956.32	0.0911
	Daimler ER	120998.23	-42599.47	495956.32	0.1021
18t	FC 300 B 100	56934.08	-30754.41	1250099.12	0.2578
	FC 150 B 72	42089.23	-25149.45	1204207.08	0.2150
	EFORCE	121538.4	-42789.64	689198.16	0.4909
	Daimler	90748.67	-31949.6	545789.25	0.2830

Busses

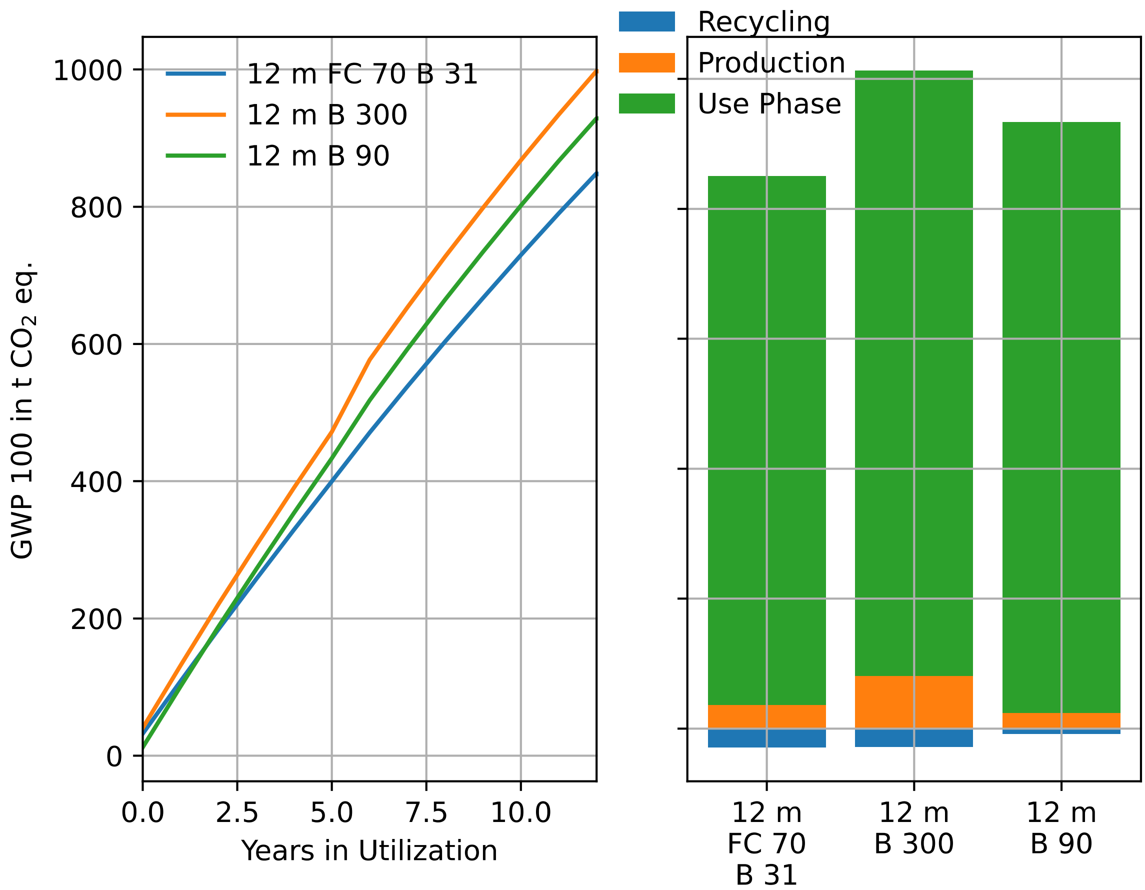

Figure 9: GWP comparison of buses over 12 years with 60.000 km/year, (kg CO_2 eq.)

Figure 9 depicts the total GWP for the investigated 12 m busses. The battery buses show slightly higher values of GWP than the fuel cell bus. This result is mainly associated with the high energy consumption of battery electric buses, which results from the high weight of the batteries. The 300-kWh bus with the biggest battery shows the highest GWP, followed by the 90-kWh and fuel cell buses. However, the production and EoL phase of the fuel cell bus contributes to the overall lifetime emissions less than the other two busses due to the relatively small battery.

Table 10: GWP of buses, Emissions per phase, (kg CO_2 eq.)

Model	Production Phase	Recycling Phase	Use Phase	Passenger Emissions
FC 70 B 31	36,348.1	-28,897.9	814,084.8	0.021
B 300	81,025.6	-28,526.4	931,316.5	0.023
B 90	24,307.6	-8,558.0	908,942.4	0.018

Moreover, the results in Table 10 show that for mid-distance ranges, the B 90 bus causes the lowest CO_2 eq emissions per passenger after 12 years of usage and an annual mileage of 60,000 km per year. Nonetheless, the 90-kWh bus has a lower range than the other two busses. It therefore requires additional charging infrastructure or more charging management, to profit from OC.

Passenger vehicles

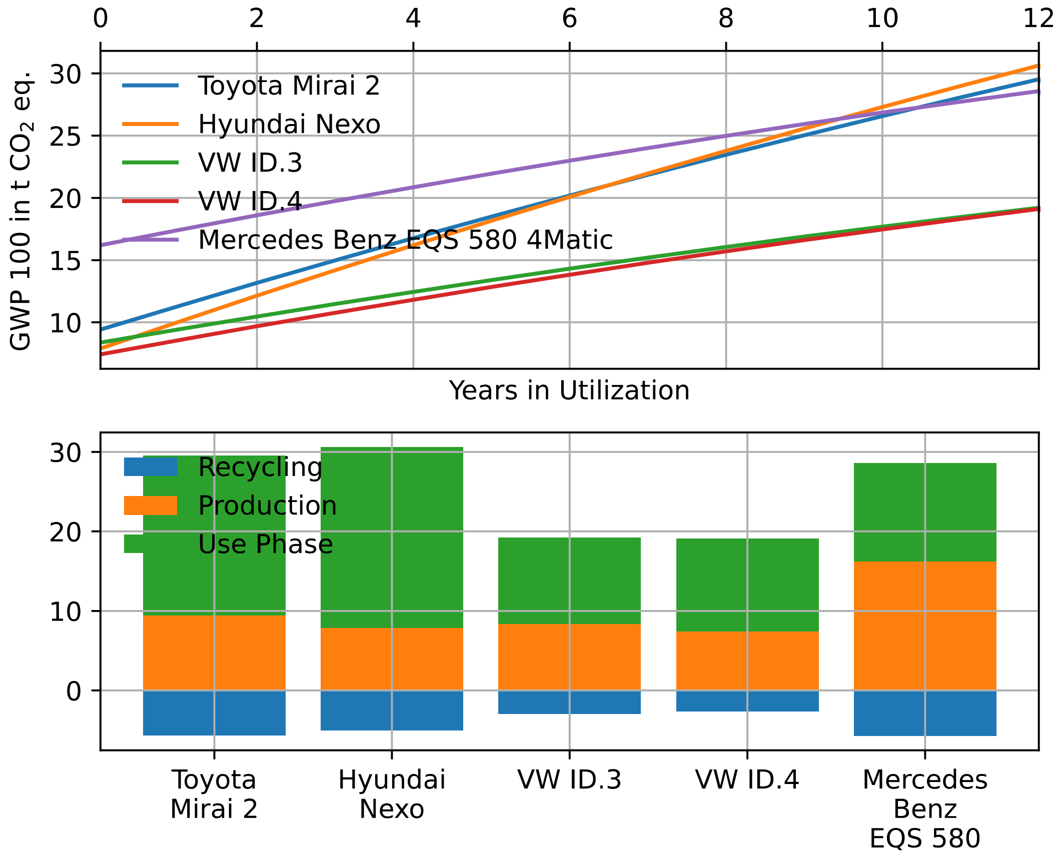

Figure 10: GWP comparison of LPVs over 15 years with 15,000 km/year (kg CO_2. eq.)

The results for LPVs are visualized in Figure 10 and show the benefits of BEV cars in the private-use sector. The VW ID.3 has the lowest overall GWP impact, which is slightly higher than that of the VW ID.4. VW ID.3 has a bigger battery than VW ID.4. However, its overall vehicle mass is lower compared to the ID.4, which reduces the energy consumption in the use phase. The FCEVs have a higher GWP impact overall due to higher use phase emissions. However, the production emissions are comparable with VW ID.3 and VW ID.4, which can be further reduced with recycling to a greater extent than recycling Li-ion batteries.

Table 11: GWP for the life cycle of light passenger vehicles, (kg CO2 eq.)

Model	Production Phase	Recycling Phase	Use Phase	Total emissions
Mirai 2	9414.78	-5628.22	20112.68	23,899.24
Nexo	7895.02	-5009.87	22746.49	25631.64
ID.3	8372.65	-2947.73	10837.39	16262.31
ID.4	7427.35	-2614.92	11676.42	16488.85
EQS 580	16205.12	-5705.29	12375.60	22875.43

5. Discussion

The results of this study show high benefits of recycling in all cases except for the LFP batteries, where the decrease in GWP cannot be reached with either hydrometallurgical or pyrometallurgical recycling. Also, the fuel cell recycling results showed a significant benefit, which increases even further if the hydrogen tanks are used for a second life. However, the analysed method of fuel cell recycling is absent on the industrial scale, making the same recycling benefit on the industrial scale questionable.

The results of the production phase show slightly higher GWP for nickel-cobalt-based cathode chemistries than for the LFP batteries. Compared to other studies (pack and cell level displayed for better comparability), our results show a relatively low overall discrepancy, except for the LFP batteries, where it reaches max. ca 50% of the compared value of (Mohr et al. 2020) The overall discrepancies are attributed to different data sets used as data sources and different energy densities of analysed batteries. In the case of the LFP batteries, the difference is mainly the result of the different energy densities of the analysed cells. While this study considers 159 Wh/kg, Mohr et al. consider 108 Wh/kg.

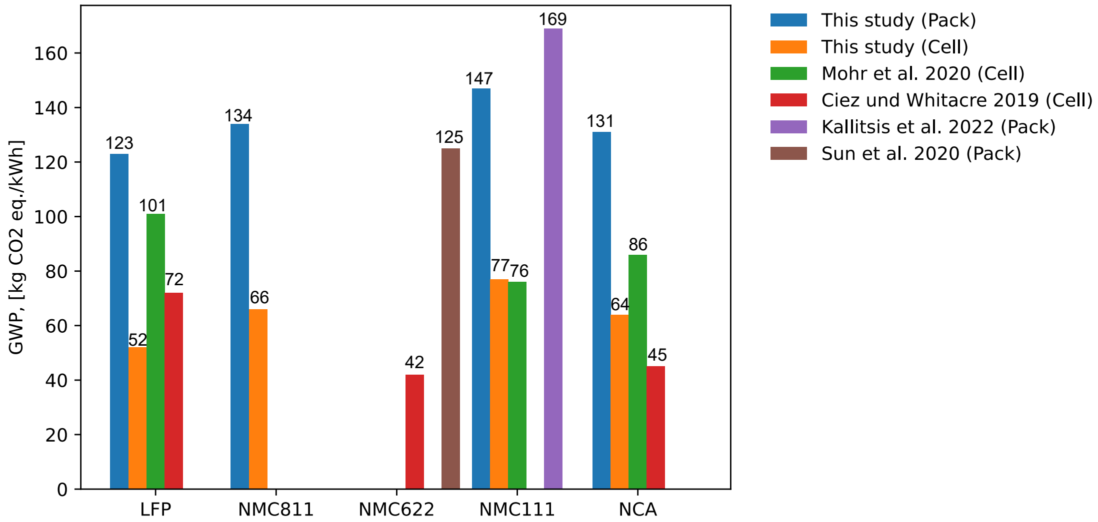

Figure 11: GWP of different cell chemistries, compared to other studies, cell and pack level, (kg CO_2 eq./kWh)

Recycling in the EoL phase shows high benefits from hydrometallurgical recycling of nickel-cobalt-based batteries and intermediate results in the case of pyrometallurgical recycling, while the results for the LFP batteries show that none of the analysed recycling methods recycling brings any benefits to its GWP. Compared to the other studies, our results for hydrometallurgical recycling are slightly higher, while the results for pyrometallurgical recycling are relatively low. Out of all studies listed in Table 12, only (Kallitsis et al. 2022). analysed the pack level of the batteries, making the results of other studies primarily relevant to compare the ratios of hydrometallurgical and pyrometallurgical recycling. The result of hydrometallurgical recycling for the NMC111 batteries is almost identical to (Kallitsis et al. 2022), although the calculated impact of the pyrometallurgical recycling is not that significant in this study. While this study only splits recycling into collecting and transportation, disassembly, and hydrometallurgical/pyrometallurgical processing, (Kallitsis et al. 2022) consider shredding and sorting and use new processes for Cu, Al, and steel treatment, which is one source for the discrepancy. Another source is the same recovery rate for both hydrometallurgical and pyrometallurgical recycling, used by (Kallitsis et al. 2022). As for the EoL of the fuel cell powertrain, the results show a significant potential of the recycling technology for the catalysator, especially if it is supplemented by using the hydrogen tank for the second life. However, the analysed recycling approach does not depict the recycling on an industrial scale, which can impact the results in different ways.

Table 12: GWP of recycling of different cell chemistries compared to other studies, (kg CO_2 eq.)

Cell chemistry	NMC111		NMC811		NCA		LFP	
Recycling method	Hydro	Pyro	Hydro	Pyro	Hydro	Pyro	Hydro	Pyro
This study	-37	-22	-21	-12	-25	-9	7	11
Mohr et al	-16.4	-13.8	-	-	-18.3	-15.9	-3.52	0.45
Kallitsis et al	-37.1	-34.1	-	-	-	-	-	-
Ciez and Whitecare	-	-	-	-	-3.5	1.5	8	10

The application of LCA on various types of vehicles has produced different outcomes. The findings for passenger vehicles indicate that FCEVs have a higher overall GWP than BEVs, primarily due to the elevated energy demand during the use phase. Since identical vehicles with battery or fuel cell powertrains are unavailable, vehicles with comparable ranges, weight and vehicle class are compared. The compared vehicles cannot be treated as equal ones. Therefore, the results show minor deviations due to different gliders, system efficiencies, and vehicle masses. The outcomes for trucks reveal a similar pattern to passenger vehicles, with fuel cell trucks exhibiting a higher GWP than BEVs.

Nevertheless, if the outcomes are normalized to tkm, the pattern changes, and the GWP of fuel cell trucks reduces per tkm compared to BEVs. Due to the higher weight of the battery electric trucks, the mean GWP related to the total vehicle mass is greater than that of the lighter fuel cell trucks. The findings for buses also emphasize the significance of powertrain mass on energy consumption and emissions. Differing from other vehicles compared, battery electrical buses exhibit a higher GWP than fuel cell buses. However, the buses with a smaller 90 kWh battery show the lowest GWP normalized to passenger emissions, followed by the fuel cell bus. In this case, the outcomes are also strongly influenced by the vehicle mass.

Overall, the results prove that fuel cell vehicles have higher GWP in most cases if the battery electric vehicles are powered by the German electricity mix of between 2021 and 2050. However, the results for other regions in the supplementary materials show a slightly different picture. Furthermore, the losses of electricity and hydrogen transportation and compression of hydrogen, are not included in our calculations, which makes the results further deviate from reality.

Due to the wide range of data considered and compared in this study, it is crucial to maintain a high degree of informativity without oversimplifying or delving too deeply into every discussed topic. Increasing the level of detail in this study would also increase the amount of data required for the sensitivity analysis, which would sophisticate this study to a further extent. The FCEVs show advantages regarding kilogram CO_2 eq. in all the GVW classes per ton kilometre results. Since information regarding consumption and payload were missing and are based on our assumptions, we propose to investigate our results or provide us more data for better results.

6. Conclusion

This study's objective was to comprehensively compare the complete life cycle of battery electric and fuel cell electric powertrains. The study modelled and compared all life phases, and the results were generally plausible and comparable to moderate discrepancies with other studies. The primary challenge in modelling this life cycle assessment was the correct application of data on the system. For instance, the battery recycling in Everbatt did not account for the prismatic casing modelled in Ecoinvent. Another challenge was finding comparable vehicles, as there are presently no vehicles on the market that can be sold in both BEV and FCEV versions. Comparing vehicles with similar parameters is an appropriate approximation, although it introduces a noticeable uncertainty. Recycling of fuel cell powertrain components and hydrogen tanks provides data that can be easily compared to the recycling of Li-ion batteries. However, the described recycling processes have yet to achieve an industrial scale and, therefore, cannot provide data of the same quality as battery recycling.

The primary outcome of this study is the provision of a cradle-to-grave life cycle analysis that is comparable between BEVs and FCEVs. Comparing both technologies demonstrated that fuel cell electric vehicles have slightly lower emissions during the production phase, which could be further reduced in the case of recycling in the end-of-life phase. The recycling of FCEVs offers a substantial potential for reducing their carbon footprint. Nonetheless, this research also illustrated the advantages of recycling for Li-ion batteries for four different cathode chemistries on the pack level, closing a gap in the research. Battery recycling presents significant potential and has space for improvement, with the highest outcome being a 25% decrease in GWP for an NMC111 battery. The assessed recycling processes primarily focus on nickel and cobalt, as the recovery of these materials is possible with high recovery rates and offers more financial potential, leaving considerably less potential for the LFP cell chemistry, which does not include these metals.

The comparison of the two powertrain technologies, considering the entire life cycle, revealed a distinct scenario. Due to the higher global warming potential of hydrogen per kilometre than that of electricity, the BEVs have an advantage during the use phase. Consequently, when considering the entire life cycle, the GWP level of FCEV trucks reaches the level of BEVs after 4-6 years of operation and continues to increase thereafter. At the predicted end-of-life after 12 years, the GWP of FCEVs is almost double that of BEVs. Busses and passenger vehicles showed an analog pattern, with FCEVs reaching the GWP level of the BEVs after 3-5 years of operation and showing almost double GWP at the end-of-life phase.

The decision-making on one of both assessed technologies in specific applications primarily depends on the economic potential of both technologies. Nonetheless, the ecological potential of Li-ion batteries and fuel cells in mobility applications is an essential decisive factor in decision-making. The results of this study can be used to seek potential in the recycling of Li-ion batteries, for example, developing recycling plants with a higher focus on lithium for LFP batteries or to decide on choosing the powertrain for a vehicle in a particular application. This study addressed such problems as recycling the battery pack instead of concentrating on the cell level, the potential for recycling the fuel cell powertrain, and comparing different vehicle types with battery electric and fuel cell electric powertrains in different conditions. All the addressed topics can be used to reduce the carbon footprint of mobility applications in the near future.

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8. Appendix

Trucks detailed results:

GVW 40 t

GVW 40 t	Fuel Cell Trucks		Battery Electric Trucks
	FC 300 E 100 kWh	E 450 kWh	eActros 300 4x2 tractor
Range (km)	257	260	220
SFC (kg / kWh)/100 km	9,7		
Battery size (kWh)	100	450	336
Battery weight (t) (NMC111/ NMC811/ LFP/ NCA)	1,11 / 1,09 / 2,4 / 1,09	1,66 / 1,36 / 3,6 / 1,36	1,24 / 1,22 / 2,69 / 1,22
Fuel Cell size (kW)	300	0	0
Fuel Cell weight (kg)	280	0	0
Fuel Cell BoP weight (kg)	319,88	0	0
Tank weight (kg)	5 x 101,2	0	0
Powertrain weight (t)	2,22 – 3,5	1,36 – 3,6	1,22 – 2,69

GVW 25 t	FC 300/100	E-Force one AG EF18	eActros 300 6x2	eActros 300 6x2 extended range
Range (km)	346	300	300	400
SFC (kg / kWh)/100 km	7,21			
Battery size (kWh)	100	450	336	448
Battery weight (kg) (NMC111/ NMC811/ LFP/ NCA)	1,11 / 1,09 / 2,4 1,09	1,66 / 1,36 / 3,6/1,36	1,24 / 1,22 / 2,69 / 1,22	1,66 / 1,63 / 3,58 / 1,63
Fuel Cell size (kW)	300	0	0	0
Fuel Cell weight (kg)	280	0	0	0

Fuel Cell BoP weight (kg)	319,88	0	0	0
Tank weight (kg)	5 x 101,2			
Powertrain weight (t)	2,22 – 3,5	1,36 – 3,6	1,22 – 2,69	1,63 – 3,58

GVW 18t	FC 300/100	E-Force one AG EF18	eActros 300 4x2
Range (km)	346	350	330
SFC (kg / kWh)/100 km	6,81		
Battery size (kWh)	100	450	336
Battery weight (kg) (NMC111/ NMC811/ LFP/ NCA)	1,11 / 1,09 / 2,4 / 1,09	1,66 / 1,36 / 3,6/1,36	1,24 / 1,22 / 2,69 / 1,22
Fuel Cell size (kW)	300	0	0
Fuel Cell weight (kg)	280	0	0
Fuel Cell BoP weight (kg)	319,88	0	0
Tank weight (kg)	5 x 101,2	0	0
Powertrain weight (t)	2,22 – 3,5	1,36 – 3,6	1,22 – 2,69