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Life cycle assessment of construction and driving operation of a hydrogen-powered truck built from a used diesel truck

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ABSTRACT

One option to reduce greenhouse gas (GHG) emissions from heavy-duty vehicles is switching to hydrogen as a fuel, which is converted in drive trains powered by fuel cells. In addition to the production of new hydrogen trucks, it is also possible to convert used diesel-powered trucks to hydrogen-powered vehicles.

This paper aims to evaluate the environmental impact of a heavy-duty truck converted from diesel propulsion to a hydrogen fuel cell drive regarding life-cycle GHG emissions and mineral resource scarcity (MRS). This life cycle assessment focuses on the construction and end-of-life phases of the vehicle (first part) and on the entire life cycle, including the use phase (second part).

The largest share of GHG emissions for the hydrogen-powered truck (first part) originates from the tank system and the chassis, specifically due to the materials reinforced plastics, steel, and aluminum. The fuel cell system is responsible for half of the MRS, mainly due to the used platinum, which, as well as steel, accounts for about one-third of the MRS.

The hydrogen supply path is the most crucial factor determining the overall GHG emissions (second part). To reduce GHG emissions compared to a conventional diesel-driven truck, the share of renewable energy within the power mix has to be at least 61 %. The MRS increases with an increasing share of renewable energy within the power mix.

To reduce GHG emission of a converted hydrogen-powered truck, the use of reinforced plastics and platinum should be minimized, thus contributing to more efficient use of mineral resources.

1. Introduction

Road traffic, responsible for approximately 19 % of Germany's current greenhouse gas (GHG) emissions, stands as the third most significant contributor to pollution, following the energy sector and industrial activities. Commercial vehicles, on average, account for 39 % of the carbon dioxide (CO_2) emissions generated within the transportation sector of the European Union (EU) (DESTATIS, 2020; UBA, 2021). Although fleet limits for CO_2 are promoting the adoption of a growing proportion of electric and hydrogen-powered vehicles in individual transportation, over 90 % of vehicles in the heavy-duty transport sector continue to rely on diesel engines (BMU, 2020; KBA, 2021).

Hence, there is a need for alternatives, particularly in the heavy-duty transport sector. One potential solution is the utilization of trucks powered by hydrogen. In contrast to diesel-driven trucks, fuel cell propulsion technology can be operated without harmful local emissions; i.e. hydrogen-powered fuel cell trucks emit only water vapor during their operation. However, it is essential to consider emissions associated with the production of hydrogen used as fuel, as well as those linked to construction, conversion, and recycling when assessing the environmental impacts of various vehicle technologies. The life cycle assessment (LCA) method is an option of developing such a holistic view of the environmental impact from the truck production through the use phase till the recycling at the end-of-life.

One challenge in conducting such a LCA study for fuel cell driven trucks is the availability of reliable data. The current quantity of available vehicles in the market remains quite limited (Hyundai, 2020; KBA, 2021). Therefore, robust and up-to-date LCA data on fuel cell trucks are missing in literature. These trucks are only superficially examined without delving into specific details (e.g. (Hill et al., 2020; Lee et al., 2018)).

This paper aims to address this lack of component-specific LCA data through a detailed study of the construction and use of a heavy-duty fuel cell truck based on the conversion of a former diesel-powered truck.

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Original primary data are derived from a company pursuing a concept to convert used diesel trucks to new hydrogen-based fuel cell units operating as semi-trailer trucks with a total weight of 40 t (Clean Logistics, 2019). The concept involves utilizing the basic structures of a used / existing truck to build a "new" vehicle equipped with a fuel cell-powered drivetrain. One advantage of such a concept is the re-use of the used diesel truck chassis intended to save resources and to reduce the environmental impact compared to vehicles with a newly built chassis.

For this conversion concept the greenhouse gas emissions and mineral resource scarcity (MRS) are investigated for the construction phase, the use phase and the end-of-life phase. The respective results are compared to a conventional diesel-powered truck and a newly constructed hydrogen fuel cell truck.

2. Methods

To study the environmental impacts of the mentioned fuel cell truck and to compare it to conventional trucks, the LCA method is used as defined by ISO 14040 and 14044. The quantification method is ReCiPe2016. In the first part, just the construction and end-of-life of the different trucks are investigated and in the second part also their use phase is taken into consideration. To facilitate the assessment, the software OpenLCA (GreenDelta, 2020) is used. Any data that could not be gathered from the manufacturer and its suppliers was taken from the databases Ecoinvent, using allocation at the point of substitution (APOS) (Wernet et al., 2016) and GREET2 (Argonne National Laboratory, 2020). Supplementary information to address the existing data gaps is obtained from literature sources.

2.1. Goal, scope and functional units

In the LCA, greenhouse gas emissions and mineral resource scarcity of differently operated trucks are determined. Therefore, two different propulsion technologies and manufacturing histories of the trucks investigated here are compared. The propulsion technologies under consideration include a diesel engine and a hydrogen-fueled fuel cell electric motor. The hydrogen-fueled truck is built based on a used / existing diesel truck. The diesel truck utilized for comparison is conventionally factory-built, reflecting the current state of technology. The two different levels of investigation are described below. Additionally, in the context of a sensitivity analysis, a variation of the share of renewable energies within the electricity mix are investigated to evaluate the influence on the assessed impact categories.

2.2. System boundaries

The system investigated here is described below in detail. It is divided into two different parts and therefore, two different functional units are defined.

2.2.1. Manufacture, construction and end-of-life

The LCA framework involves a cradle-to-grave perspective, encompassing the entire lifecycle from the extraction of raw materials, through the manufacturing of components, the assembly of the trucks, to the recycling and disposal of the vehicles at the conclusion of their technical lifespan. The use phase is not included in this part of the investigation. The functional unit is defined as an 18-ton tractor unit without the trailer. However, the term "truck" is still used to refer to the vehicle.

For the construction of the converted fuel cell truck, all parts belonging to the used diesel powertrain are removed and recycled, disposed or reused (i.e. second life). The remaining parts of the employed diesel tractor unit, primarily the foundational structure (to a large extend metal and glass) is used for building up the converted fuel cell truck. This part is called chassis. Important parts removed from the used diesel truck are the diesel tank, the combustion engine, the clutch, the gearbox, the tailpipe system, and the automotive battery.

The further use of these removed components is considered in the second part of the system; i.e. in the first part only the construction and end-of-life of the converted fuel cell truck is investigated. After removing the conventional parts, 15 new components are installed in addition to smaller parts being neglected here. All 15 components, besides the servo pump, are modeled in detail. For each of these components, the following points are included in the modeling to ensure a consistent assessment:

- Materials production
- Energy supply for assembly from the different materials
- Transport from final assembly to the construction site of the truck
- End-of-life modeling (recycling, disposal and reuse in secondary markets)

The technical lifetime of the converted fuel cell truck covers 10 years. Since the truck can be considered as a new vehicle after the conversion towards a fuel cell operated unit, the technical lifetime of the propulsion system is 20,000 h (Hilgers and Aschenbach, 2021). Upon reaching the end of this period, certain components remain operational and can be repurposed for a second life (i.e., through part recycling). Thus, allocations are made based on the total lifetime of the components in relation to the lifetime of the converted fuel cell truck.

As the chassis is employed in both the used and the new vehicle, an allocation must also be conducted in this regard. The chassis is assumed to be a co-product (European Commission, 2011), with the diesel truck life cycle considered as the primary and the converted fuel cell truck life cycle as the secondary system. Since the chassis has already a positive market value at the end of the primary life cycle without further pretreatment, an allocation via market value is not possible (European Commission, 2011). Hence, an allocation is determined based on the overall mileage of the chassis (i.e., the converted fuel cell truck is assigned two-thirds of the environmental impact, encompassing raw material extraction to chassis disposal, due to the chassis being driven 500,000 km with the diesel truck and 1,000,000 km with the converted fuel cell truck). All environmental impacts are considered until the chassis reaches a state where it can be utilized equivalently for both product systems (European Commission, 2011). The corresponding flow diagram of the converted fuel cell truck system is shown in Fig. 1.

A newly constructed fuel cell tractor unit is also assumed to analyze the influence of a newly built chassis within an excursus. The framework of this fuel cell truck is identical to the system presented in Fig. 1, except of the chassis being completely within the system borders of the fuel cell tractor unit.

The second considered truck is a conventional diesel-fueled truck. The respective data are taken from the Ecoinvent database and modified to a similar size (Wernet et al., 2016). The disposal part of the dataset was removed and replaced by own calculations in form of end-of-life modeling. The diesel-fueled truck is modeled from cradle-to-grave, without including driving operations. The system flow chart of this truck corresponds to that of the converted fuel cell truck in Fig. 1 without utilizing a used diesel-fueled truck chassis.

2.2.2. Credits for end-of-life treatment

Potential savings of resources, energy and emissions resulting from the re-use of the used diesel-fueled truck chassis are taken into account by giving credits to the investigated systems while ensuring that no double crediting of savings occurs. To conduct a proper accounting of credits, the The Circular Footprint Formula (CFF), 2020 is applied (European Commission, 2017) in a modular way. Thus, here only the material component of the formula is used.

Within the material category, the credits and debits of the secondary material input are calculated, as shown in Eq. (1), as well as burdens and credits of the secondary material output, as shown in Eq. (2).

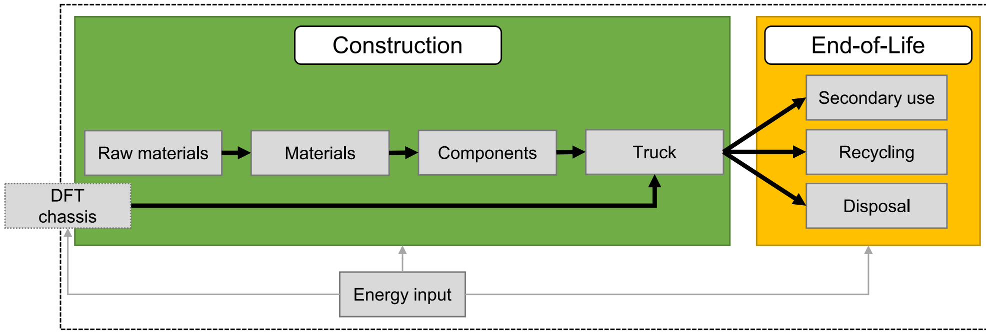

Fig. 1. Flow diagram of construction and disposal of the converted fuel cell truck (DFT diesel-fueled truck).

$$-(1-A)R_1\left(E_{Recycled}-E_V\frac{Q_{Sin}}{Q_P}\right) \quad (1)$$

$$-(1-A)R_2\left(E_{RecycledEoL}-E_V^*\frac{Q_{Sout}}{Q_P}\right) \quad (2)$$

A describes the allocation factor (between 0.2 und 0.8) and R_1 and R_2 the recycling share at the material input and at the material output, respectively. Q_{Sin} and Q_{Sout} is the material quality of the secondary material input and the secondary material output, respectively, and Q_P is the quality of the primary material. $E_{RecycledEoL}$ are the emissions from recycling material at the end of the product's life and $E_{Recycled}$ are the emissions from recycling secondary material in the material input. E_V describes the emissions released by the production of a primary material and E^*_V are the emissions to be avoided in the production of a primary material.

The emissions from material recycling at the end of the truck's life are equivalent to the emissions from recycling secondary material in the material input (European Commission, DG, ENV, 2020). Equations (1) and (2) are applied for metals, glass and plastics. Parameter values provided by European Commission (2017) were implemented and details regarding the precise values employed are provided in the supplementary material (S6, Table 26). Metals were categorized into aluminum, stainless steel, iron and steel, copper, and other metals.

2.2.3. Use phase

Besides the truck construction, the use phase is included in the assessment in the second part. This requires the incorporation of the chassis from the used diesel truck into the system (Klöpffer and Grahl, 2014). As the chassis is used for two vehicles (i.e., the used diesel truck and the converted fuel cell truck), a clear separation into two independent systems is not possible. Therefore, the system is expanded by including a diesel-fueled truck (DFT) in the first life and the converted fuel cell truck (CFCT) in the second life. For comparison, two life cycles of a diesel-fueled truck are assessed including all life phases (Chapter 2.2.1). The two trucks are assumed to be maintenance-free within their overall life cycles (it is assumed that the maintenance efforts are comparable between all systems / configurations analyzed here; based on this assumption maintenance can be neglected because it does not change the relation between the various systems). The system flow diagram for the expanded system, including the use phase, is shown in Fig. 2 and the system flow diagram for modeling two diesel-fueled trucks is presented in Fig. 3. The functional unit of the expanded system is 1 t transported good over a distance of 1 km (1 tkm).

The results of the impact categories (greenhouse gas emissions and mineral resource scarcity) are divided by the mileage and payload. The average value is formed according to the mileage of the diesel-fueled truck, respectively of the converted fuel cell truck, one third from the life cycle of the diesel truck and two thirds from the life cycle of the fuel cell truck.

For the use phase of the fuel cell trucks, two different provision pathways for the required hydrogen used as fuel are investigated. The hydrogen fuel is generated through electrolysis, utilizing both the European electricity mix and wind energy as a purely renewable source.

Converted fuel cell truck. Based on the assumption, that the converted fuel cell truck runs $1{\cdot}10^6$ km maintenance-free (for justification see above), only the supply of hydrogen is considered for the driving operation. The analysis encompasses solely the environmental effects arising from the production of hydrogen, as the transportation of hydrogen is minimal and characterized by significant uncertainties contingent upon the assumed storage and transport method (Halder et al., 2024). To perform this, the fuel consumption of the fuel cell truck is needed.

A conventional 40 t truck typically has a payload of 25 t (Schwarz, 2011). The mass utilization of a truck is 57 % on average, resulting in a payload of 14.3 t for a conventional diesel-fueled truck (Denimal et al., 2012). With 10.1 t, the converted fuel cell truck has a higher empty weight than a comparable diesel-fueled truck (7.3 t) (Schwarz, 2012). This results in a payload reduction of 2.8 t for the converted fuel cell truck and a payload weight amounting to 22.2 t. With an average mass utilization of 57 %, there is a remaining weight of 12.7 t (Denimal et al., 2012). Based on plans of the EU to increase the allowed total weight of heavy-duty trucks from 40.0 t to 44.0 t (Kulikowska-Wielgus, 2022), it is assumed that the converted fuel cell truck can be loaded with up to 4.0 t more than a typical diesel-fueled truck. To ensure comparability with the diesel truck, it is assumed that the payload weight of the converted fuel cell truck increases from 12.7 t to 14.3 t.

According to the manufacturer, the hydrogen consumption is 0.08

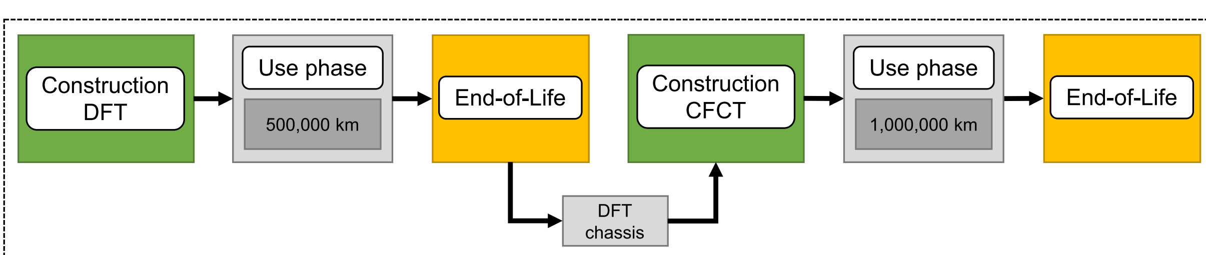

Fig. 2. Total analyzed system with the functional unit 1 tkm (DFT diesel-fueled truck; CFCT converted fuel cell truck).

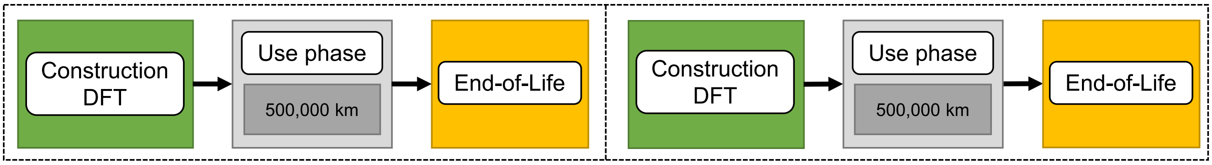

Fig. 3. Reference system with two diesel-fueled trucks with the functional unit 1 tkm (DFT diesel-fueled truck).

kg/km with a full load of 44 t (Clean Logistics, 2023). Due to the lack of extensive consumption tests of fuel cell vehicles in driving operation, it is assumed that the consumption decreases linear with decreasing overall weight. At the stated load factor, the total semi-trailer weight is 32.1 t.

Diesel-fueled truck. The utilization period of the diesel-fueled truck includes a driving phase over a distance of 500,000 km until the end of its life. This includes only the environmental impacts caused by the production and combustion of diesel fuel. To take care of this a modified Ecoinvent dataset was used developed for a vehicle meeting the latest EURO VI standard. In addition, the analysis was geographically limited to Europe (Wernet et al., 2016).

The average payload is 14.3 t (Denimal et al., 2012) resulting in a total vehicle mass of 29.3 t. For the determination of the average consumption, a *Scania G410* is assumed since extensive consumption tests for this truck type are available. In part-load operation (25.5 t), this truck consumes 26.2 L/100 km and in full-load operation (38.9 t) 32.9 L/100 km (Wildhage, 2014). Since 2014, there has been no significant reduction in the fuel consumption of EURO VI heavy-duty vehicles; i.e. these consumption data can still be considered as reliable (DESTATIS, 2019). Using linear interpolation, the consumption for the load operation considered here is 28.4 L/100 km (Hilgers, 2016). This value is 13 % lower compared the value given in the Ecoinvent database (Wernet et al., 2016). Therefore, the dataset has been modified. All the data is presented in Table 1.

3. Data and assumptions for life cycle inventory

The following section describes in detail material and energy flows for the construction and end-of-life treatment of the converted fuel cell truck and the newly fabricated hydrogen-powered fuel cell truck. Additionally, important assumptions for creating the life cycle inventory are presented. The difference between the converted fuel cell truck and the fuel cell truck is that the fuel cell truck is based on a newly built chassis. Further, data sources and assumptions for the diesel-fueled truck are described.

3.1. *Converted fuel cell truck*

If required materials for the construction were not available in the Ecoinvent database, the materials were modeled separately. This data is contained in the Supplementary material (Tables S 1 and S 2).

The quantity and type of the converted fuel cell truck components were provided by the manufacturing company of the truck. Table 2 summarizes all components, arranged in order of their weight.

The assumptions and data for the two components with the highest relevance for the overall assessment are described below. Information about the other components is provided in the Supplementary material (Tables S 3). Of particular interest are the fuel cell modules and the heavy components of the hydrogen tank system accounting for a large proportion of the mineral resource scarcity.

Table 2
Components of the converted fuel cell truck.

No.	Component	Quantity	Weight
1	Chassis	1	5,296.0 kg
2	Hydrogen tank system	1	1,036.0 kg
3	Battery	1	760.0 kg
4	Tires and wheels	1	658.8 kg
5	Electric motor	2	472.0 kg
6	Axle beam	1	400.0 kg
7	Cooling system	1	173.0 kg
8	Fuel cell module	2	342.0 kg
9	Frame profiles	1	69.4 kg
10	Electric compressor	1	36.0 kg
11	DC/DC-converter LV[1]	2	20.9 kg
12	Control unit	2	13.7 kg
13	Air conditioning compressor	1	6.5 kg
14	Servo pump	1	3.2 kg
15	Heater	1	2.6 kg
Sum		19	10,138.7 kg

[1] LV: Low voltage.

Battery manufacturing. The battery technology, used in the converted fuel cell truck is lithium nickel manganese cobalt (NMC). This corresponds to many comparable vehicles (e.g. the *Hyundai Xcient Fuel Cell* and the *ESORO* truck) which are operated with NMC-batteries (Hirschi et al., 2020; Hyundai, 2020; Clean Logistics, 2023).

The battery of the converted fuel cell truck has a storage capacity of 93.2 kWh (Clean Logistics, 2023). It was modeled according to the data of Simons and Azimov (2021). The battery has a total weight of 760 kg (Clean Logistics, 2023). Since the Ecoinvent database (Wernet et al., 2016) does not contain all required materials, some materials had to be assessed separately. For this reason, Dai et al. (2019) lists alternatives adopted for the modeling process; lithium hexafluorophosphate ($LiPF_6$) is substituted with lithium chloride (LiCl) and polyvinylidene fluoride with 50 % polyethylene and 50 % tetrafluoroethane.

The energy demand for the final assembly of the battery within the production is taken from the GREET2 database (Argonne National Laboratory, 2020). It is assumed that the batteries will be produced in China, as around 70 % of global production capacity is located in China (Bernhart et al., 2019). Therefore, the respective data are adapted to Chinese conditions (e.g., related to the electricity mix etc.) (Wernet et al., 2016; Argonne National Laboratory, 2020). All information about the material quantities considered and the LCA data sets used in each case are listed in the Supplementary material (Tables S 3).

Table 1
Data about the trucks within the expanded system with one diesel-fueled truck and the converted fuel cell truck (DFT-CFCT) and the comparison system (two diesel-fueled trucks (DFT-DFT)).

	First Vehicle				Second Vehicle			
	Distance [km]	Payload [t]	Total weight [t]	Fuel Consumption [kg/tkm]	Distance [km]	Payload [t]	Total weight [t]	Fuel Consumption [kg/tkm]
DFT-CFCT	500,000	14.3	29.3	$16.6 \cdot 10^{-3}$	1,000,000	14.3	32.1	$4.1 \cdot 10^{-3}$
DFT-DFT					500,000	14.3	29.3	$16.6 \cdot 10^{-3}$

Hydrogen tank system. The hydrogen tank system consists of five cylindrical Type IV tanks and a supporting structure (Clean Logistics, 2023). The tank system has a total weight of 1.04 t (Table 3). The data are obtained from the manufacturing company of the CFCT (Clean Logistics, 2023). The regional classification for worldwide datasets is called rest of world (RoW) for older datasets and global (GLO) for newer datasets. In the further course of this work, German (DE), European (RER) and Chinese (CN) datasets are also used.

It is assumed that the production takes place in China. The origin of the electrical energy used is adjusted accordingly. The heat demand is modeled using a global supply process. Origin of heat and electricity demand are taken from a supplier for hydrogen storage systems (Worthington Cylinders, 2021). Table 4 shows the energy demand for the production of the hydrogen tank system.

According to the manufacturing company of the CFCT, the lifetime of the tank system is 15 years (Clean Logistics, 2023) which exceeds the lifetime of the converted fuel cell truck by 5 years (chapter 2). Considering it would be premature to discard the tank system, it is assumed that it will remain in use beyond the converted fuel cell truck's operational lifespan; i.e. only two third of the corresponding emissions are attributed to the truck.

Fuel cell module. The converted fuel cell truck has a fuel cell system operating with a proton exchange membrane fuel cell (PEMFC). The fuel cell system consists of two fuel cell modules with 120 kW power each. Due to the limited data provided by the supplier, the modeling is conducted using information obtained from literature sources. According to Simons and Azimov (2021), a fuel cell system is chosen, operating on the same scale and for which weight, power, and material composition details are available. The fuel cell system considered is then scaled up linearly from 100 to 120 kW power. One fuel cell module has a total weight of 342 kg. Since not all materials (carbon copy paper, perfluorosulfonic acid, polytetrafluoroethylene) listed in Simons and Azimov (2021) were available in the Ecoinvent database, some other materials were used instead based on information from Tahir and Hussain (2020).

In addition, the German plastics average is used (Wernet et al., 2016). The material composition of one fuel cell module is listed in Table 5.

The necessary electrical energy for assembling the fuel cell system is provided with 850 kWh by the supplier. The production site is located in China. The supply process *market group for electricity, medium voltage – CN* was used for the electrical energy. The operating time of the fuel cell system is 30,000 h. The operating time of the converted fuel cell truck is 20,000 h. This means that the fuel cell system exceeds the lifetime of the converted fuel cell truck by 50 % (chapter 2) (REFIRE, 2021). Given that recycling or disposal would be premature, it is assumed that the fuel cell system will continue to be used after the end of the fuel cell truck's service life. The allocation of the emissions and the mineral resource scarcity of the fuel cell system is carried out according to the operating time. This results in the converted fuel cell truck accounting for two thirds of the environmental impacts.

Table 3
Materials of the hydrogen tank system (GLO global dataset; RoW rest of world dataset) (Clean Logistics, 2023).

Material	Percentage	Weight	Ecoinvent dataset
Aluminum alloy ($AlMg_3$)	35.0 %	363 kg	Market for aluminium alloy, $AlMg_3$ – GLO
Carbon fiber reinforced plastic	27.5 %	285 kg	Market for carbon fibre reinforced plastic, injection moulded – GLO
Unalloyed steel	14.8 %	153 kg	Market for steel, unalloyed – GLO
Epoxy resin	11.1 %	115 kg	Market for epoxy resin, liquid – RoW
Plastics	7.7 %	80 kg	Self-modeled
Stainless steel	3.9 %	40 kg	Market for steel, chromium steel 18/8 – GLO

Table 4
Energy demand for the hydrogen tank system (CN Chinese dataset; GLO global dataset) (Worthington Cylinders, 2021).

Flow	Value	Ecoinvent dataset
Electricity, medium voltage (China)	92.4 kWh	Market group for electricity, medium voltage – CN
Heat, natural gas	81.6 kWh	Market group for heat, district or industrial, natural gas – GLO

Table 5
Composition of one fuel cell module (GLO global dataset) (Tahir and Hussain, 2020; REFIRE, 2021; Simons and Azimov, 2021).

Material	Percentage	Weight	Ecoinvent dataset
Stainless steel	31.30 %	107.1 kg	Market for steel, chromium steel 18/8 – GLO
Low-alloyed steel	18.70 %	64.0 kg	Market for steel, low-alloyed – GLO
Aluminum, wrought alloy	16.80 %	57.5 kg	Market for aluminum, wrought alloy – GLO
Plastics	16.60 %	56.8 kg	Self-modeled
Synthetic rubber	6.50 %	22.2 kg	Market for synthetic rubber – GLO
Glass fiber reinforced plastic	2.60 %	8.9 kg	Market for glass fibre reinforced plastic, polyamide, injection moulded – GLO
Tetrafluoroethylene	2.60 %	8.9 kg	Market for tetrafluoroethylene – GLO
Carbon (copy paper)	2.40 %	8.2 kg	Market for carbon black – GLO
Copper	1.70 %	5.8 kg	Market for copper, cathode – GLO
Perfluorosulfonic acid	0.60 %	2.1 kg	Market for fleece, polyethylene – GLO
Cast iron	0.08 %	0.3 kg	Market for cast iron – GLO
Silicon	0.05 %	0.2 kg	Market for silicon, metallurgical grade – GLO
Platinum	0.02 %	0.1 kg	Market for platinum – GLO

As the converted fuel cell truck is a prototype, data on the end-of-life treatment of the vehicle are not yet available. Therefore, it was assumed that this fuel cell truck is dismantled at the manufacturing site at the end of its technical lifetime. The dismantled components are transported to appropriate recycling companies for further disassembly. At the respective site, the various components are disassembled into the respective materials. In this context, it is assumed that disassembling the component requires the same amount of energy as assembling it. Perfect separation as well as a complete recovery of all materials cannot be assured and therefore moderate recycling rates for metals (85 and 90 %), plastics (40 %) and glass (80 %) are assumed (European Commission, 2017). To maintain the mass balance, the remaining amounts is thermally treated based on the legal frame. Landfilling is not applied to any of the materials. The treatment processes for recycling and recovery are taken from the Ecoinvent database including the various transports to the respective reprocessing plant (Wernet et al., 2016). Recycling and disposal take place within the EU, except for electronic parts. Fig. 4 shows the flow diagram of the end-of-life modeling.

Furthermore, Fig. 4 shows that the recycling of materials results in credits; i.e. the recycling of materials and the resulting provision of secondary materials is associated with lower environmental impacts than the production of primary materials. The calculation of credits is explained in Chapter 2.2.2. For each component, the end-of-life was modeled individually.

3.2. Diesel-fueled truck

The dataset *lorry production, 16 metric ton – RER* from the Ecoinvent database is used in a modified form, following the approach outlined by Wernet et al. (2016) for modeling the construction of the diesel-fueled truck unit. This dataset includes the extraction of raw materials,

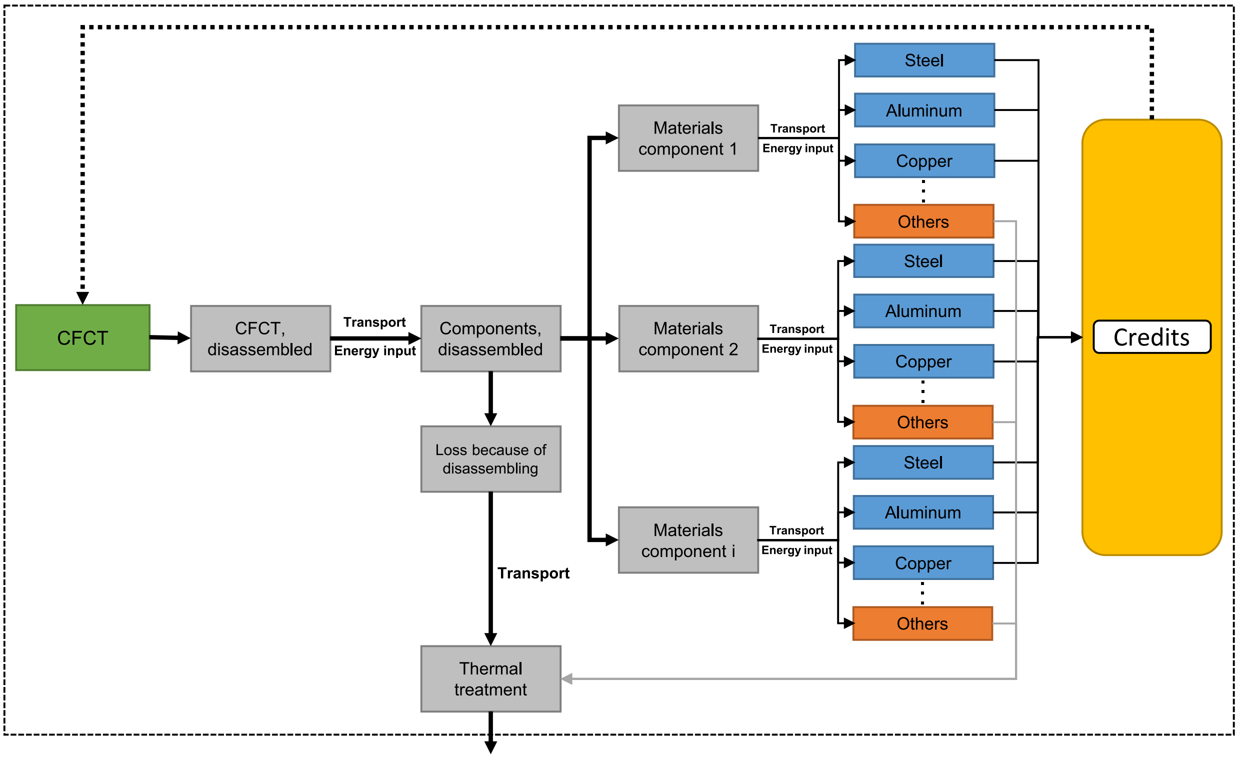

Fig. 4. End-of-life modeling of the converted fuel cell truck (CFCT).

manufacturing of components, assembly of the truck and its disposal. Since the trucks considered to have a total permissible mass of 18 t, material and energy inputs are scaled up by a factor of 1.1. In addition, the disposal of the truck unit is removed from the dataset and end-of-life modeling is performed similar to the converted fuel cell truck. However, no secondary use of components at the end-of-life is assumed (i.e., only disposal and recycling).

4. Impact assessment results

Below, the impact assessment results in the categories greenhouse gas emissions and mineral resource scarcity are presented. The outcomes are examined individually for the construction and disposal phases, as well as for the entire life cycle, encompassing the utilization phase.

4.1. Truck construction

The results of the greenhouse gas emissions and of the mineral resource scarcity of the diesel-fueled truck and the converted fuel cell truck are shown in Table 6.

Table 6
Results of greenhouse gas emissions and mineral resource scarcity of the diesel-fueled truck and the converted fuel cell truck.

	Diesel-fueled truck	Converted fuel cell truck
Greenhouse gas emissions		
Construction	50,361 kg CO_2-eq	58,052 kg CO_2-eq
End-of-life	7,421 kg CO_2-eq	7,268 kg CO_2-eq
Credits	–3,100 kg CO_2-eq	–4,538 kg CO_2-eq
Sum	54,682 kg CO_2-eq	60,782 kg CO_2-eq
Mineral resource scarcity		
Construction	1,391 kg Cu-eq	2,080 kg Cu-eq
End-of-life	51 kg Cu-eq	51 kg Cu-eq
Credits	–157 kg Cu-eq	–421 kg Cu-eq
Sum	1,286 kg Cu-eq	1,710 kg Cu-eq

Greenhouse gas emissions. Table 6 shows that the greenhouse gas emissions of the diesel-fueled truck are lower compared to the converted fuel cell truck. The share of emissions of the construction phase is roughly 89 % for the converted fuel cell truck and around 87 % for the diesel-fueled truck (without considering credits). The construction phase of the converted fuel cell truck can be broken down into material production and the energy input required for assembly. The part material production causes 90 % of the GHG emissions of the converted fuel cell truck's construction phase. As the provision of materials accounts for a significant part of the impact categories, Fig. 5(a) shows the shares of various materials related to the GHG emissions. Thus, the materials glass and carbon fiber reinforced plastics, steel and aluminum significantly contribute to the overall GHG emissions. Platinum, exclusively utilized in the fuel cell system, exhibits a relatively high contribution, accounting for approximately 12 %.

The shares of the most important components of the converted fuel cell truck concerning GHG emissions are shown in Fig. 5(b). Following this graph, the components chassis, hydrogen tank system, and fuel cell system account for the largest shares of the overall emissions.

Mineral resource scarcity. As listed in Table 6, the construction part is responsible for 96 % of the diesel-fueled truck's mineral resource scarcity and 98 % for the converted fuel cell truck's MRS (without considering credits). Analogously to the greenhouse gas emissions, the supply of materials accounts for a significant part of the MRS. Fig. 6 shows the shares of the various materials indicating that platinum is dominating the material consumption with a share of around 38 %, followed by a 32 % contribution of steel.

The shares of mineral resource scarcity of the different components are shown in Fig. 6(b). With around 50 %, the fuel cell system has a high share of the components, which is due to the high influence of platinum only used within the fuel cell system. This is followed by the electric motor and the chassis, each contributing 12 %.

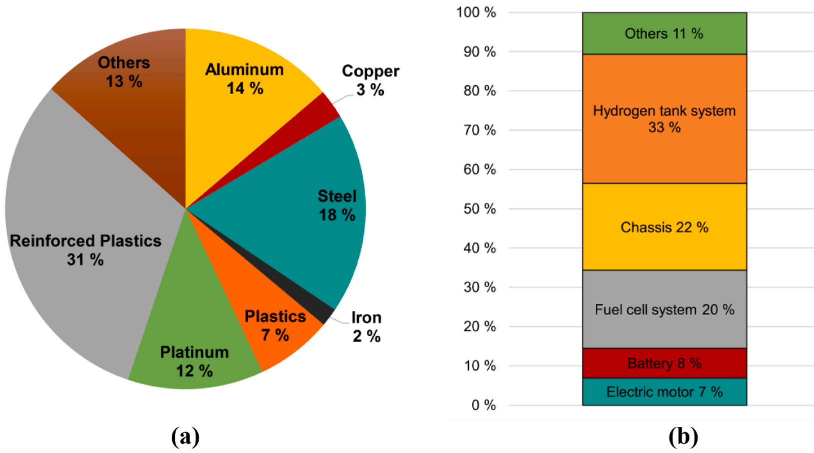

Fig. 5. Distribution of greenhouse gas (GHG) emissions of different materials (a) and different components (b) of the converted fuel cell truck.

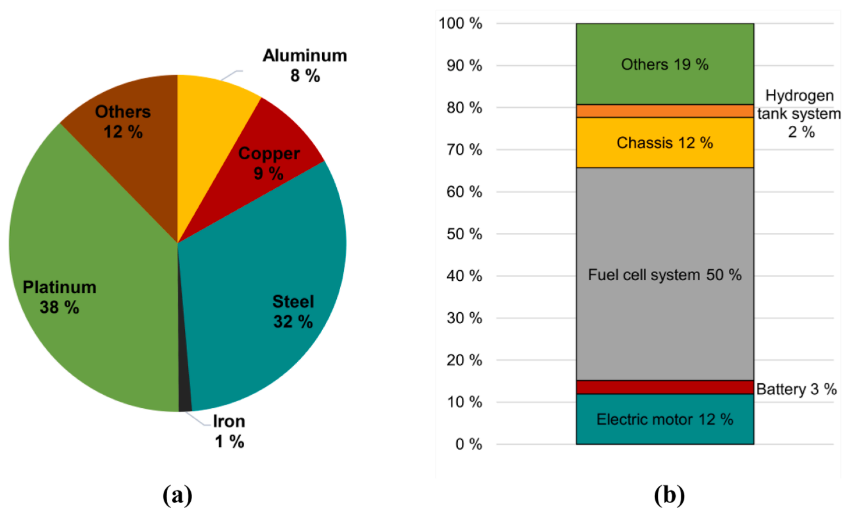

Fig. 6. Distribution of the mineral resource scarcity (MRS) for different materials (a) and different components (b) of the converted fuel cell truck.

4.2. Total life cycle

Within this chapter, the results of the impact assessment for the following two systems are presented.

- The expanded system with one diesel-fueled truck (DFT) and the converted fuel cell truck (CFCT) with driving phases (called *DFT-CFCT*).
- The reference system with the usage of two diesel-fueled trucks (DFT) with driving phases (called *DFT-DFT*).

Table 7 shows the results of greenhouse gas emissions and mineral resource scarcity for both systems. To evaluate the influence of the chassis, the newly designed fuel cell truck (FCT) will be considered as an alternative to the converted fuel cell truck in the reference system (called *DFT-FCT*) (Table 7).

Greenhouse gas emissions. Table 7 shows that if the conventional electricity mix is assumed (share of 46 % renewable energy) for hydrogen supply via water electrolysis, the diesel-fueled truck shows clearly lower GHG emissions. If only renewables energies (here wind and photovoltaic) are used to provide the electricity for the electrolyzer, the GHG emissions of the converted fuel cell truck are much lower compared to the GHG emissions of the diesel-fueled truck. The total emissions of the FCT are slightly higher compared to the CFCT.

Fig. 7 shows the shares of greenhouse gas emissions of the respective life phases of the system diesel-fueled truck and converted fuel cell truck (DFT-CFCT) for the two investigated options to operate an electrolyzer (with electrical energy from the public power grid and with electricity from wind energy). In addition to the expected high contribution of the diesel operation to the overall GHG emissions, a high share of hydrogen operation becomes visible. The operation phase with hydrogen causes almost three quarter of all GHG emissions when the hydrogen is generated using electrical energy from the European electricity grid (i. e., the European fuel mix). If renewable energies are used, in this case wind energy, the share of the converted fuel cell truck driving phase drops to about one third.

Mineral resource scarcity. In contrast to the results of the greenhouse gas emissions, the diesel-fueled truck has in every case a lower mineral resource scarcity compared to the converted fuel cell truck – with no matter if the electricity mix or renewable energies are used to provide electricity for the hydrogen. When using renewable energies, the MRS is slightly higher compared to using electricity from the grid. Fig. 8 shows that the use phase has the highest share if the hydrogen is supplied by renewable energies. This is due to the relatively high resource intensity of wind power plants and photovoltaic cells. In particular, the construction of the towers for the wind power plants is the most important factor determining the high mineral resource scarcity.

Fig. 9 compares the results of greenhouse gas emissions and mineral resource scarcity per tkm for the complete life cycles of the converted

Table 7
Results of greenhouse gas (GHG) emissions and mineral resource scarcity (MRS) for the systems diesel-fueled truck and the converted fuel cell truck (DFT-CFCT), diesel-fueled truck and newly constructed fuel cell truck (DFT-FCT) and two diesel-fueled trucks (DFT-DFT).

		DFT-CFCT	DFT-FCT	DFT-DFT
Greenhouse gas emissions				
Extended life cycle [t CO_2-eq]	Hydrogen from electricity[2] mix	1,983	1,990	1,079
	Hydrogen from renewable energies[3]	699	706	
Per FU [g CO_2-eq/tkm]	Hydrogen from electricity mix	93	93	76
	Hydrogen from renewable energies	33	33	
Mineral resource scarcity				
Extended life cycle [t Cu-eq]	Hydrogen from electricity mix	4.8	4.9	2.8
	Hydrogen from renewable energies	5.4	5.5	
Per FU [g Cu-eq/tkm]	Hydrogen from electricity mix	0.22	0.23	0.19
	Hydrogen from renewable energies	0.25	0.26	

[2] German electricity mix 2021 from Wernet et al. (2016) and Fraunhofer ISE (2021).
[3] Wind and Photovoltaic, based on the shares in the German electricity mix 2021 from Fraunhofer ISE (2021).

fuel cell truck (CFCT) and the diesel-fueled truck (DFT), taking different options of hydrogen supply into account.

Sensitivity analysis: Renewable energies within the electricity mix. According to Fig. 9, the influence of an increasing share of renewable energies on the two impact categories assessed here are to be determined. Thus, the life cycle impacts of the converted fuel cell truck (after conversion from diesel to hydrogen operation) per functional unit were determined for different shares of renewable energies within the electricity mix used for hydrogen production. In the baseline scenario, the German electricity mix (data from the year 2021) was used. This dataset includes a share of renewable energies of 46 % (Wernet et al., 2016; Fraunhofer ISE, 2021; IEA, 2021). In addition, the provision of hydrogen based on electricity coming from 100 % renewable sources of energy is considered. Renewable energies were modeled using wind energy and photovoltaic, reflecting their respective shares in the German electricity mix in 2021 (Fraunhofer ISE, 2021). Fig. 9(a) shows that the exclusive use of electricity from renewable sources of energy for hydrogen supply reduces the greenhouse gas emissions throughout the overall life cycle. A linear interpolation is realized to determine the required share of renewable energies within the electricity mix, at which the greenhouse gas emissions per functional unit of the converted fuel cell truck are lower than for the diesel-fueled truck. The threshold is a share of 61 % renewable energies within the electricity mix. Fig. 10 shows the greenhouse gas emissions per functional unit for different shares of renewable energies in the grid mix.

As already shown in Fig. 9(b), the mineral resource scarcity increases with an increasing share of electricity from renewable energies within the electricity mix. The linear increase of the MRS is shown in Fig. 10 analogously to the linear decrease of the GHG emissions. As mentioned before, one main reason is the high share of wind energy within the assumed electricity provision based on renewable sources of energy. This is attributed to the comparatively resource-intensive utilization of wind power plants.

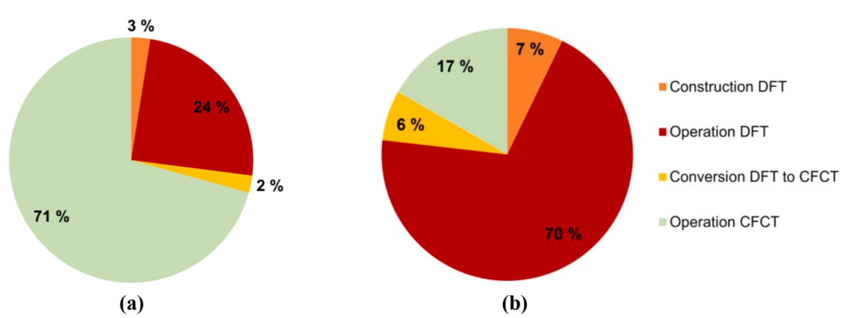

Fig. 7. Shares of greenhouse gas emissions of the system DFT-CFCT with hydrogen provision through the electricity mix (a) or renewable energies (b) (DFT diesel-fueled truck; CFCT converted fuel cell truck).

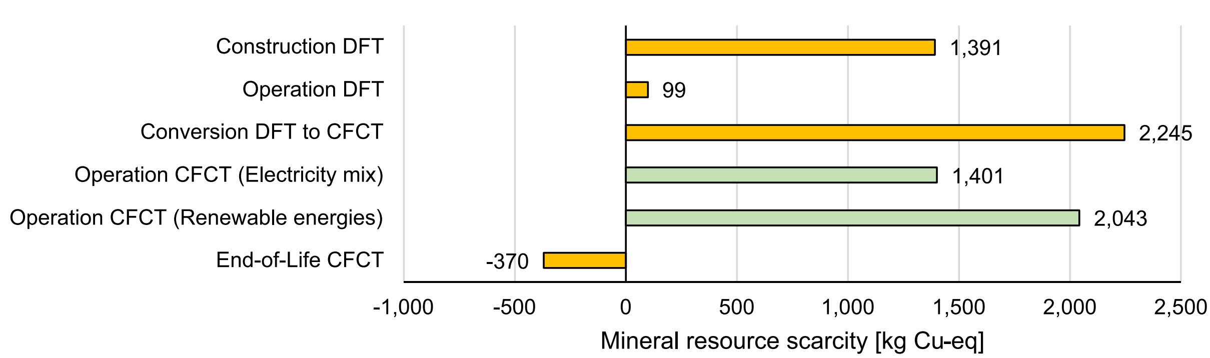

Fig. 8. Results of mineral resource scarcity (MRS) within the different life phases (DFT diesel-fueled truck; CFCT converted fuel cell truck).

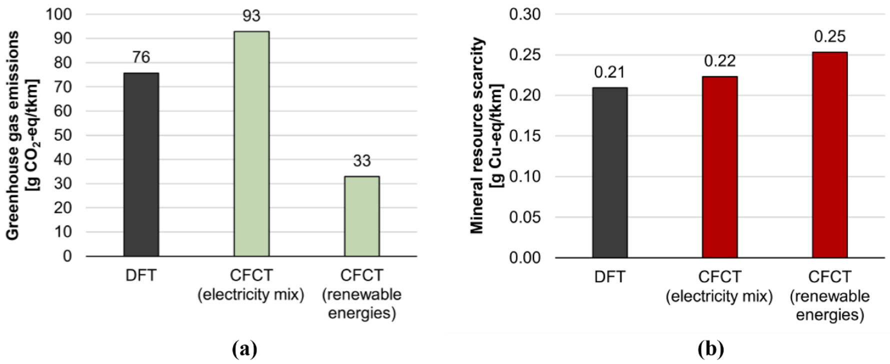

Fig. 9. Greenhouse gas emissions (a) and mineral resource scarcity (b) of the system with two diesel-fueled trucks (DFT-DFT) and of the system with one diesel-fueled truck and the converted fuel cell truck (DFT-CFCT).

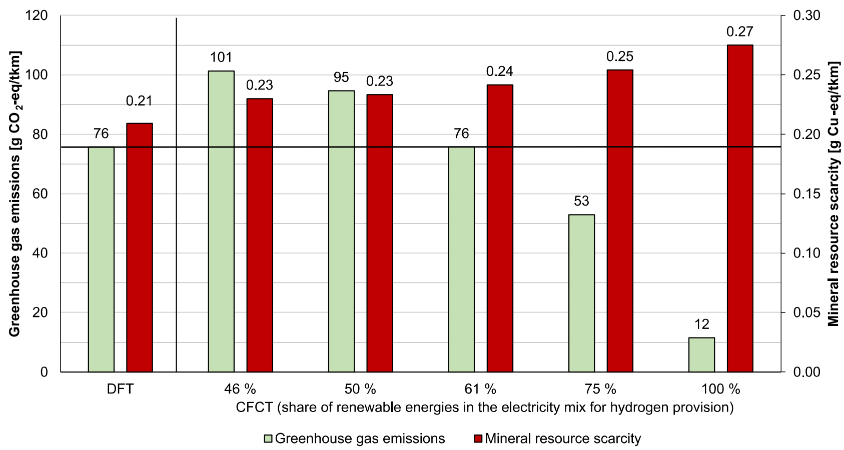

Fig. 10. Results of greenhouse gas (GHG) emissions and mineral resource scarcity for increasing renewable energies in the electricity including one diesel-fueled truck (DFT) and the converted fuel cell truck (CFCT).

5. Discussion

Given the emphasis on data in the field of fuel cell-driven heavy-duty trucks, the data quality is assessed below. Additionally, a comparison is drawn with relevant studies in the field of life cycle assessment of fuel cell-driven vehicles in the heavy-duty sector.

5.1. Data quality

Data for modeling in this study was obtained from the following sources:

- suppliers and manufacturer of the converted fuel cell truck,
- Ecoinvent database (version 3.9), and
- scientific literature and other public available sources.

In case of average or implausible data from suppliers, data from literature or from the Ecoinvent database were used. When relying on literature data, a preference is given to the most recent publications. Furthermore, in some instances, literature data had to be adjusted to fit the system under consideration through scaling. Moreover, materials had to be substituted if they were unavailable within the database and could not be accurately modeled. Table 8 summarizes the data quality for all components. Components are ranked in descending order of mass. If no ingredient data were provided by suppliers (X), it is indicated whether the data were provided via the Ecoinvent database (E) or whether other literature data (L) were used. Even with detailed data from suppliers, materials and energy requirements were modeled using Ecoinvent, with limited knowledge of data quality.

Table 8
Data quality of the components of the converted fuel cell truck (LV low voltage).

Component	Materials		Energy	
	Supplier	Literature (L)/ Database (E)	Supplier	Literature (L)/ Database (E)
Chassis		L		L
Hydrogen Tank System	X		X	
Battery	X			L
Tires and Wheels		L		L
Electric Motor	X			L
Axle beam	X			E
Cooling System	X			L
Fuel Cell System		L	X	
Frame Profiles	X			E
Electric Compressor		E		E
DC/DC-Converter LV	X		X	
Control Unit		E		E
Air Conditioning Compressor		E		E
Heater	X		X	

Data on energy requirements were only available from a few components. For some components, energy requirements and materials were estimated using literature data due to insufficient information.

- The chassis and fuel cell system are particularly worth of mention; data from the Ecoinvent data base might be already older (for example, from before 2017) (Wernet et al., 2016).
- The diesel-fueled truck was modeled using an Ecoinvent dataset. The quality of the dataset can be classified as medium, as the data are from 2004.
- The data for the driving phase is sourced from Ecoinvent and is qualitatively labeled as medium, as minimal modifications were necessary; however, it has to be noted that these data date back to 2005 (Wernet et al., 2016).
- The data of energy and water demand in electrolysis of hydrogen as well as data on impact indicator values for the provision of hydrogen via wind energy are from Mehmeti et al. (2018) from 2018 and thus are relatively recent. The data can be declared as good.

In conclusion, while the data can be deemed largely comprehensive, it is prone to significant uncertainties, particularly in the production of components, given the reliance on extensive literature data.

5.2. Comparison with other studies

Since the converted fuel cell truck is a prototype, the comparison with the results from other studies and assessments is difficult. Below, the results for the converted fuel cell truck are compared with fuel cell trucks of other investigations. Many studies only address the impact category of greenhouse gas emissions, while there are few studies, especially in the category of mineral resource scarcity, which is additionally considered in this work. For this reason, only studies that specifically investigate greenhouse gas emissions were employed for comparisons.

In Hill et al. (2020), extensive life cycle assessment studies were carried out on vehicles with different size classes and different propulsion technologies. Semitrailer trucks in the 40 t range with fuel cell drive systems were also considered. A lifetime mileage of 800,000 km was assumed for the vehicles, and the European electricity mix for 2020 was used for the hydrogen provision. The system boundaries of the study correspond to that of the total life cycle of this work. The hydrogen truck (orig.: articulated lorry) from Hill et al. (2020) achieves a value of 129 g CO_2-eq/tkm. The result of the converted fuel cell truck of this work per functional unit is with 101 g CO_2-eq/tkm using the assumed German electricity mix around 22 % lower than in Hill et al. (2020). This is presumably due to the significantly different composition of the electricity mixes.

In the paper from Simons and Azimov (2021), only different propulsion technologies for heavy-duty trucks and the utilization phases were considered. Here, the comparison shows that when the data is adjusted to the case considered here, the values of the diesel-fueled truck are 52 % higher than that of a diesel-fueled truck in the reference system. But, exact utilization and size of the truck used in Simons and Azimov (2021) are not known. Compared to the converted fuel cell truck in this paper, the fuel cell truck from Simons and Azimov (2021) emits 69 % higher GHG emissions when hydrogen is supplied by the electricity mix of the United Kingdom and 51 % higher GHG emissions when using electricity from wind energy (Simons and Azimov, 2021). The deviation may be due to the fact that in this work the renewable energies were modeled by means of photovoltaics and wind. The comparison of the results of this work with the results from Simons and Azimov (2021) for the hydrogen supply, depending on the type of electricity provision for the overall driving phase of the fuel cell trucks are shown in Fig. 11(a). Fig. 11(b) compares additionally the converted fuel cell truck's life cycle per tkm from this work with the fuel cell truck from Hill et al. (2020).

In summary, the results presented in this paper, which were included in the comparison, are within a similar order of magnitude as those reported in other studies.

6. Conclusions

The goal of this work is the life cycle assessment (LCA) of a truck converted from diesel to fuel cell operation in comparison with a conventional diesel truck. Thereby the trucks should be considered within two different systems. This is true on the one hand for the exclusive consideration of the life cycle of a tractor unit and on the other hand for the consideration of two consecutive trucks including the driving phases. Within the second system, the objective was to compare the usage of one diesel-fueled truck followed by either another diesel truck or a converted fuel cell truck. In contrast to many other life cycle studies, this work is characterized by a good data situation, since a substantial amount of data was directly supplied by the manufacturer of the converted fuel cell truck or obtained from the suppliers.

The results for the assessment of the greenhouse gas (GHG) emissions can be summarized as follows.

- When focusing solely on the life cycle of the truck, the converted truck emits 60.8 t CO_2-eq and the diesel truck 50.3 t CO_2-eq. In a more detailed breakdown of the results for the converted fuel cell truck, the supply of materials is the main driver of the overall GHG emissions; in particular, the materials aluminum (15 %), steel (20 %) and glass fiber, or carbon fiber reinforced plastics (26 %) are noteworthy. The reinforced plastics are used in the hydrogen tank system and are poorly recyclable. As a result, the hydrogen tank system accounts for the largest share of GHG emissions within the components at 27 %, followed by the chassis (24 %) and the fuel cell system

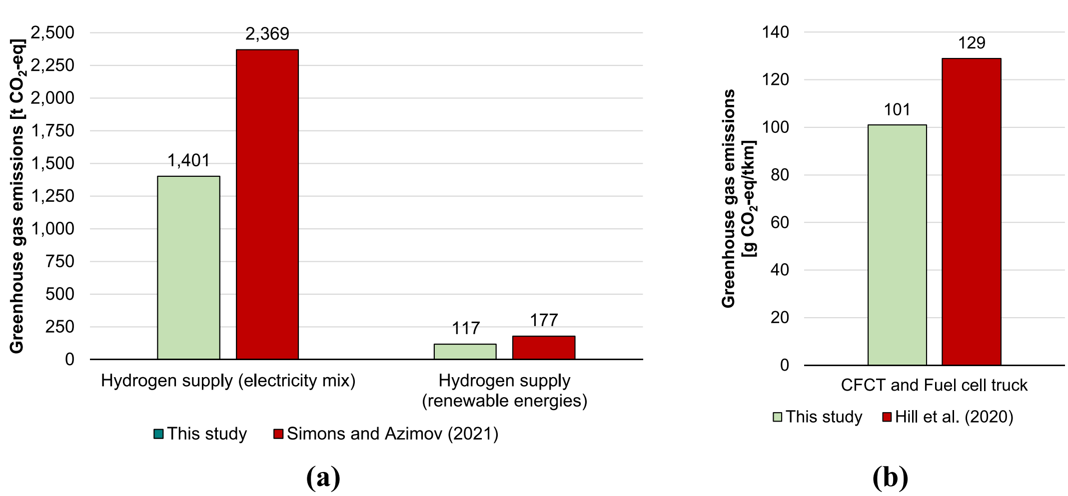

Fig. 11. Comparison of this work with other studies (CFCT converted fuel cell truck) (Simons and Azimov, 2021; Hill et al., 2020).

(22 %). Lower GHG emissions can be achieved by reducing the used carbon fiber and glass fiber reinforced plastics, due to the poor recyclability.
- In the context of the second system under consideration, involving the driving phase and the consecutive use of two trucks, a distinction must be made between hydrogen supply via the German electricity mix and via purely renewable energies. Using two diesel trucks results in 76 g CO_2-eq/tkm per functional unit. If the German electricity mix is used for the provision of hydrogen for the converted fuel cell truck, this results in 93 g CO_2-eq/tkm, and if electricity from purely renewable sources (e.g. wind energy and photovoltaic) is used for hydrogen provision via electrolysis, the result is 33 g CO_2-eq/tkm. To achieve at least the same value as that of the diesel truck, the share of renewable energies in the electricity mix must be at least 61 %, considering just the life cycle of the CFCT without the DFT.

The results for the mineral resource scarcity (MRS) compiled within this study can be summarized as follows.

- When considering the truck's life cycle alone, 1.7 t Cu-eq is consumed by the converted fuel cell truck and 1.4 t Cu-eq by the diesel truck. Analogously to the results for the GHG emissions, material supply is of high importance. Platinum (38 %) and steel (32 %) in particular have high shares of the MRS. The high proportion of platinum is primarily attributed to the fuel cell system, which clearly dominates the overall system with a 51 % share. An improvement in fuel cell technology most likely in the years to come will lead to a clear reduction in platinum demand and thus in the MRS value.
- In the context of the second system considered, with the inclusion of the driving phase and two trucks used in succession, also for the MRS a distinction is necessary between hydrogen supply via the German electricity mix and via electricity from purely renewable sources of energy. When using two diesel trucks, the resource consumption accounts for 0.19 g Cu-eq/tkm. If one diesel-fueled truck followed by the converted fuel cell truck is used the resource consumption accounts for 0.22 g Cu-eq/tkm when using the electricity mix and 0.25 g Cu-eq/tkm when using pure renewable energies. A MRS reduction through renewable energies is not possible due to the need for relative resource-intensive wind power plants.

In addition to the aforementioned results, this work also modeled almost all components in detail. In addition to the exact material composition of the components, the energy used to build and to assemble the components (including the various transport processes) was included, as well as an estimation for the final transport from the final production of the components to the completion of the converted fuel cell truck. Therefore, the results outlined above are seen to be quite reliable.

The future prevalence of converting diesel-powered vehicles to fuel cell-powered ones or adopting new fuel cell vehicles hinges not only on the outcomes of this study but also on the extent of progress in establishing a sustainable hydrogen economy. Additionally, the expansion of corresponding infrastructure, such as charging facilities for vehicles, will play a crucial role in determining the widespread adoption of these technologies and should be the subject of further research efforts.

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CRediT authorship contribution statement

Chris Drawer: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Anne Rödl:** Conceptualization, Methodology, Writing – review & editing, Supervision. **Martin Kaltschmitt:** Methodology, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Supplementary data is available.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2024.101020.

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