



Life Cycle Assessment of a novel functionally integrated e-axle compared with powertrains for electric and conventional passenger cars

Michael Samsu Koroma^{a,*}, Daniele Costa^{a,b}, Stefano Puricelli^c, Maarten Messagie^a

^a Electric Vehicle and Energy Research Group (EVERGD), Mobility, Logistics and Automotive Technology Research Centre (MOBI), Department of Electrical Engineering and Energy Technology, Vrije Universiteit Brussel, 1050 Ixelles, Belgium

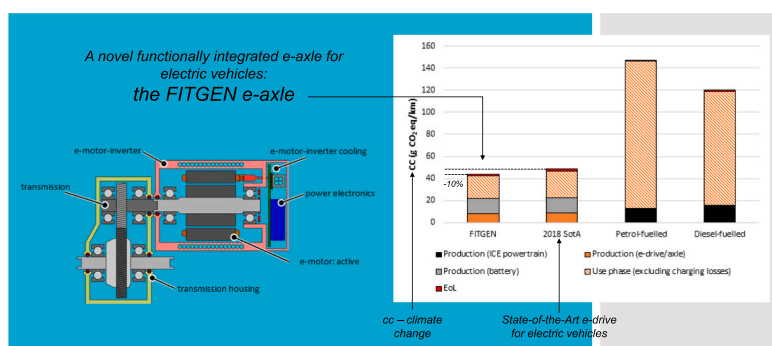
^b VITO – EnergyVille, Unit Smart Energy and Built Environment (SEB), Thor Park 8310, 3600 Genk, Belgium

^c AWARE - Assessment on WASTE and RESOURCES, Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy

HIGHLIGHTS

- Comparative LCA of alternative powertrain components of passenger cars is carried out.
- Powertrain environmental performance is strongly dependent on component efficiencies.
- The novel FITGEN e-axle excels in multiple impact categories, outperforming its 2018 counterpart.
- Reducing electronics usage and component integration improves environmental performance.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Jacopo Bacenetti

Keywords:

Powertrains
Electric axle
Electric vehicles
Electric motor

ABSTRACT

Road transport significantly contributes to climate change and air pollution. Efforts to reduce transport sector emissions include deploying battery electric vehicles and designing their powertrains for improved performance. The European H2020 funded Functionally Integrated E-axle Ready for Mass Market Third GENERation Electric Vehicles (FITGEN) developed a novel functionally integrated e-axle (the FITGEN e-axle) for electric vehicles. This paper presents the environmental performance of the FITGEN e-axle. Using the Life Cycle Assessment (LCA) methodology, the study compares the FITGEN e-axle to the 2018 State-of-the-Art (SotA) e-drive, besides diesel and petrol-fuelled powertrains. The FITGEN powertrain reduces climate impacts by 10 % and energy

Abbreviations: BEVs, Battery Electric Vehicles; CC, Climate Change; CO₂, Carbon dioxide; e-axle, Electric Axle; e-drive, Electric Drivetrain; EoL, End-of-Life; e-powertrain, Electric Powertrain; EU, European Union; EVs, Electric Vehicles; FITGEN e-axle, Functionally Integrated E-axle Ready for Mass Market Third GENERation Electric Vehicles; FRS, Fossil Resource Scarcity; FPM, Fine Particulate Matter; GHG, Greenhouse Gas; HTC, Human Carcinogenic Toxicity; HnCT, Human non-Carcinogenic Toxicity; ICE, Internal Combustion Engine; ICEVs, Internal Combustion Engine Vehicles; LCA, Life Cycle Assessment; LCI, Life Cycle Inventory; LCIA, Life Cycle Impact Assessment; LIB, Lithium-ion Battery; LU, Land Use; MRS, Mineral Resource Scarcity; Nd(Dy)FeB, Neodymium-dysprosium-iron-boron; NMC, Nickel Manganese Cobalt; OEMs, Original Equipment Manufacturers; PDU, Power Distribution Unit; ReCiPe, acronym name; RES, Renewable Energy Sources; SM, Supplementary Material; SotA, State-of-the-Art; UN, United Nations; WC, Water Consumption; WLTP, Worldwide Harmonised Light Vehicle Test Procedure.

* Corresponding author.

E-mail address: michael.samsu.koroma@vub.be (M.S. Koroma).

<https://doi.org/10.1016/j.scitotenv.2023.166860>

Received 4 June 2023; Received in revised form 1 September 2023; Accepted 3 September 2023

0048-9697/© 2023 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC license (<http://creativecommons.org/licenses/by-nc/4.0/>).

Climate change
H2020 FITGEN

consumption by 17 %, compared with the 2018 SoTA e-drive due to the efficiency improvements and components integration. It also outperforms the 2018 SoTA e-drive in several other impact categories, such as human toxicity (4–10 %), land use (19 %), and mineral depletion (8 %). However, the FITGEN powertrain only outperforms diesel and petrol powertrains in climate change and fossil resource scarcity impact categories. These findings imply that more efforts are required to improve the environmental profile of electric powertrains. Metal mining and production, especially for copper and aluminium, are critical for toxicity impacts. The sensitivity analysis demonstrates the robustness of the results, with no significant shift in their ranking order. The following aspects should be considered to improve the performance of electric powertrains from a life cycle perspective: improvement of components efficiency, reduced use of electronics and component integration, and use of low-carbon energy mix from their metal mining sites to production and use.

1. Introduction

The transport sector accounts for 57 % of global oil demand and 28 % of total energy consumption, producing approximately 25 % of anthropogenic greenhouse gas (GHG) emissions (UN, 2021). In that context, the environmental performance of automotive technologies has raised concerns, motivating the role of low-carbon technologies in reducing transport emissions. Governments worldwide are setting targets to ban the sale of fossil-fuel cars and accelerate the deployment of battery electric vehicles (BEVs) (Cui and Wappelhorst, 2020; Wappelhorst, 2021). Vehicle electrification is crucial to reduce anthropogenic GHG emissions, air pollutants, and the transport sector dependence on fossil fuels. However, technologies such as hybrid and plug-in hybrid electric vehicles (EVs) could still be in use in 2050, motivating the need for renewable petrol blends to reduce fossil oil consumption and transport emissions (Puricelli et al., 2022; Puricelli et al., 2021; Ricardo, 2020). In particular, biofuels and e-fuels are feasible. Biofuels are fuels produced from biomass that are already industrially established. Even though the carbon dioxide (CO₂) released from the combustion of biofuels is biogenic and climate-neutral, the production of their feedstocks might drive deforestation and compete with food crops (Puricelli, 2021; Puricelli et al., 2020). E-fuels are fuels produced using electricity-based hydrogen and captured CO₂. E-fuels could be economically sustainable when managing peaks of renewable electricity. However, compared to the direct use of electricity in EVs, they present higher energy losses during their production chain.

BEVs, on the other hand, do not release exhaust emissions, and their use stage impacts can be drastically reduced when charged with electricity from Renewable Energy Sources (RES) or a low-carbon electricity mix (Koroma et al., 2022; Koroma et al., 2020; Marmioli et al., 2018). Additionally, the efficiency and performance of their electric drivetrain (e-drive) components can be improved to reduce energy consumption and climate change (CC) impacts (Hernandez et al., 2015; Nordelöf et al., 2019b). The modularisation of components has enabled Original Equipment Manufacturers (OEMs) to optimise the ICEVs and reduce production impacts and costs (Christensen, 2011; Tatikonda and Stock, 2003). However, the mass production of BEV powertrains still involves non-established processes, as those from ICEVs cannot be easily adapted. With that in mind, OEMs are adopting modular production and integrating electric drivetrain (e-drive) components (Erriquez et al., 2020; Luccarelli et al., 2015; Sako and Murray, 1999).

The e-drive consists of three main components, i.e., the electric motor, the power electronics, and the transmission/gearbox. These components propel BEVs by delivering power from their battery to the wheels. The electric motor converts the electric energy into work used to propel the car and is coupled to the drive shafts connected to the wheels. The transmission system supports the motor by regulating its speed and torque while keeping the motor operating at its most efficient speed. Combining the electric motor, power electronics, and transmission system as a compact modular unit is referred to as an e-axle. The e-axle, when supplied with electricity, directly drives the BEV, reduces manufacturing costs, makes the BEV less complex, and improves overall efficiency and performance (Erriquez et al., 2020). In that context, the European H2020 funded Functionally Integrated E-axle Ready for Mass

Market Third GENERation Electric Vehicles (FITGEN) project delivered a fully functionally integrated e-axle for electric vehicles (Gennaro et al., 2020) – (hereafter FITGEN e-axle). The FITGEN e-axle was designed to deliver significant advances over the 2018 State of the Art (SoTA) e-drive (Gennaro et al., 2020). The technologies are organised into power electronics and chargers, electric motor and transmission systems, and cooling and control systems. Combining the e-drive/e-axle and the battery pack creates the electric powertrain (e-powertrain) system that powers BEVs and removes the need for an internal combustion engine powertrain.

1.1. Related research activity

The trade-off between the advantages and challenges of producing and deploying transport technologies can be assessed using the life cycle assessment (LCA) methodology (Marmioli et al., 2018; Nordelöf et al., 2014; Peters et al., 2017). The scientific literature reveals that BEVs exhibit a higher potential to reduce transport emissions, specifically CC impacts, compared to ICEVs (EEA, 2016; Nordelöf et al., 2014; Ricardo, 2020). The electricity source for charging BEVs is the leading cause of their CC impacts. As a result, the scientific literature concludes BEVs can only reach their full potential to mitigate CC if the charging electricity mix is highly renewable with very low carbon emissions (Koroma et al., 2022; Koroma et al., 2020; Marmioli et al., 2018).

The majority of LCA studies on BEVs focused on either the charging electricity source (Marmioli et al., 2018), the traction batteries (Peters et al., 2017), or the complete vehicle (Nordelöf et al., 2014). Few studies have assessed the environmental performance of passenger BEVs powertrain components. Among the available studies, Hernandez et al. (2015) compared the life cycle environmental impacts of a permanent magnet-assisted synchronous reluctance motor equipped with neodymium-iron-boron or manganese-zinc ferrite magnets under different efficiency scenarios. The authors identified motor efficiency as the most critical parameter for environmental impacts in the use phase. In a later study, Hernandez et al. (2017) specifically assessed the resource depletion potential of the same motor and a power inverter, finding that energy resource depletion potential was the most significant, followed by metals and mineral resources. Nordelöf et al. (2019a, b) compared the life cycle environmental impacts of a permanent magnet synchronous machine for electric vehicles considering three different core designs: (1) neodymium-dysprosium-iron-boron magnet; (2) samarium-cobalt magnet; and (3) a permanent magnet-assisted synchronous reluctance motor with a strontium-ferrite magnet. The authors found global warming and human toxicity impacts as critical categories. Auer and Meincke (2018) did a comparative life cycle assessment of electric motors to understand the trade-offs between energy-efficient motors and the added efforts required to produce them. The authors found that increasing the efficiency of the motor pays off the extra environmental burden of production within the first few months of operation for energy-related indicators. However, there is a high possibility for environmental burden shifting between the use, production, and end-of-life stages.

For ICEVs, direct exhaust emissions from fossil fuel combustion are the dominant contributors to global warming or CC impacts (Ricardo,

2020). However, recent advances in ICEVs, especially their capacity to use partially renewable fuel blends, have shown promising results (Puricelli et al., 2022; Puricelli et al., 2021). In that regard, systematic comparisons between low-carbon powertrain technologies and conventional ones are necessary to inform decision-making within the transport sector.

1.2. Research contribution and novelty

The findings from related research suggest that the powertrain production and use phases are crucial for improving the life cycle environmental impacts of vehicles since the powertrain provides power to drive the vehicle and the average lifespan of cars can last from 8 to 35 years (Held et al., 2021) or from 150,000 to 300,000 km (Weymar and Finkbeiner, 2016). Besides, the performance of powertrain technologies significantly influences the environmental performance of a vehicle during its use phase (Auer and Meincke, 2018; Hernandez et al., 2015; Nordelöf et al., 2019c). However, as shown in Section 1.1, few studies have assessed the environmental impacts of the different passenger car powertrain components. To the authors' knowledge, only (Hernandez et al., 2017; Hernandez et al., 2015; Nordelöf et al., 2019c; Auer and Meincke, 2018) have studied the environmental performance of passenger BEVs powertrain components. Moreover, all the studies mentioned above have focused mostly on the electric motor and inverter units or power electronics and none assessed the full powertrain components. The lack of sufficient studies assessing the environmental impacts of e-drive components demonstrates a need for such studies in the scientific literature. In addition, the studies described above are relatively old, and their inventory data may not represent current advances in e-drive/e-axle SotA.

In that context, comparative LCA studies on the performance of alternative powertrain components for passenger cars have not yet been explored, let alone referencing a novel functionally integrated e-axle. Therefore, the present study is the first comparative LCA focused entirely on alternative passenger car powertrain components, giving precedence to the novel FITGEN e-axle. In that light, this paper aims to study the environmental performance of the novel FITGEN e-axle and compare its environmental impacts and trade-offs with its 2018 state-of-the-art counterpart (hereafter, the 2018 SotA e-drive) and the diesel-fuelled and petrol-fuelled ICEV powertrains. The findings can inform decision-makers in the transport sector before the novel FITGEN e-axle is widely adopted.

2. Materials and methods

This study assessed the life-cycle environmental impacts based on ISO 14040 and 14044 (ISO, 2020a, b) of the FITGEN e-axle to its 2018 counterpart and two ICEVs powertrains for passenger cars (described in Section 2.1). The LCA phases are described in Sections 2.2 to 2.4.

2.1. Passenger car powertrains components

A powertrain includes all the components that propel a car. The engine/e-motor, transmission, driveshaft, axles, differential, traction battery; basically, everything from the engine to the rotating wheels is part of the powertrain. A powertrain generates and transfers power from the engine/electric machine to the wheels. This study compares two e-drives (the FITGEN e-axle and the 2018 SotA) and two ICEV powertrains (diesel-fuelled and petrol-fuelled) for passenger cars. The diesel-fuelled and petrol-fuelled powertrain components consisted of an internal combustion engine (ICE), gearbox, cooling system, fuel system, starting system, exhaust system, and lubrication (Althaus and Gauch, 2010).

The FITGEN e-axle comprises a latest-generation buried-permanent-magnet synchronous machine driven by a silicon carbide inverter and a high-speed transmission system. A DC/DC converter complements it for high voltage motor operation in traction and enables super-fast charging

of the traction battery (120 kW-peak) plus an integrated AC/DC on-board charger. The FITGEN e-axle also includes a breakthrough cooling system that combines the water motor/inverter circuit with transmission oil. A simplified scheme of the FITGEN e-axle components is shown in Fig. 1.

The 2018 SotA e-drive is based on the performance of similar components from BRUSA, a provider of development services for all electronic and mechanical components of e-drives (BRUSA, 2019). The 2018 SotA e-drive includes a transmission system, converter, on-board charger, electric motor, inverter, and a power distribution unit (PDU).

To support a consistent comparison with the ICEV powertrains in this study, a lithium-ion battery pack is included in the system boundaries of the e-axle and the e-drive. The two electric powertrains differ in performance (see their relative mass and efficiency in Table 1) but also in integrating the PDU as part of the power electronics in the FITGEN motor-inverter-converter unit (see Fig. 1).

2.2. Goal and scope definition

An attributional and process-based LCA was performed. The goal was to assess the life cycle environmental impacts of the FITGEN e-axle for passenger cars compared to the 2018 SotA e-drive and ICEVs powertrains. The functional unit covers the primary function of the passenger car powertrains, i.e., to propel the cars over a defined distance. The functional unit is 1 vehicle-kilometre driven by a C-segment European Union (EU) passenger car. The C-segment was chosen as lower medium cars represented a significant share (18 %) of total EU car sales in 2020 (ACEA, 2022). It is assumed the vehicle mileage is 200,000 km over 12 years. The lifespan follows the average values for the EU fleet (ACEA, 2022), and the lifetime mileage follows Weymar and Finkbeiner (2016). The LCA follows a cradle-to-grave perspective, covering the production, use, and End-of-Life (EoL) phases of the powertrain options, including the distribution to the user and the collection at the EoL stage (Fig. 2).

2.3. Life cycle inventory analysis

The life cycle inventory (LCI) of the different powertrain technologies in this study was compiled based on the Nissan Leaf (for the BEVs in this study) and Ford Focus (for both the petrol and diesel ICEVs in this study) as exemplary cars of this segment (Ford, 2017; Nissan, 2015). Primary data for the foreground system and secondary data from multiple sources were obtained from the project partners. Background system data was retrieved from the ecoinvent v3.6 database (ecoinvent, 2019; Wernet et al., 2016). Tables 1 and 2 show the characteristics and weights of the representative vehicles in this study. The relevant ecoinvent datasets for components manufacture were based on the average European markets where available; otherwise, equivalent processes for global markets were used. An exception was made for permanent magnets (an alloy of neodymium, iron, and boron), for which average Chinese conditions were used as China has the largest reserves of rare-earths elements and is globally the leading supplier of rare-earths

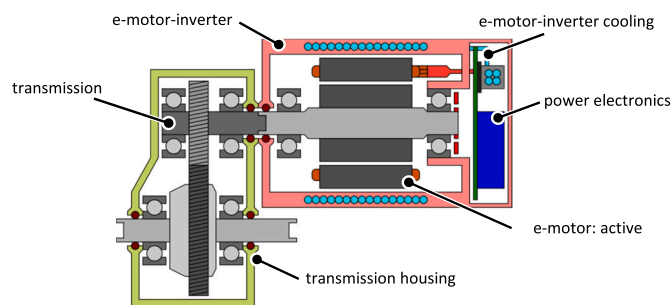


Fig. 1. Concept of the motor-inverter unit and the transmission (active parts for reference only, not to scale) (Fiumara and Primon, 2019).

Table 1
Key vehicle parameters used in this study.

Powertrain type	ICEV - Petrol	ICEV - Diesel	BEV
Energy carrier	Petrol	Diesel	Electricity
Type of drive	Front	Front	Front
Number of cylinders	4	4	–
Emissions standard	Euro 6	Euro 6	–
Transmission type	Manual	Manual	Single speed
Number of gears	6	6	–
Engine capacity (cm ³)	1499	1997	–
Max power	110 kW @ 6000 rpm	110 kW @ 3750 rpm	110 kW @ 6000 rpm
Max torque	240 Nm @ 1600–4000 rpm	370 Nm @ 2000–3250 rpm	310 Nm
Kerb weight (kg)	1350	1433	1580
Gross vehicle weight (kg)	1900	2050	1995
Li-ion battery energy capacity (kWh)	–	–	40
Frontal area (m ²)	2.3	2.3	2.3
Rolling resistance coefficient	0.009	0.009	0.009
Aerodynamic drag coefficient	0.29	0.29	0.29

magnets (Schreiber et al., 2021).

2.3.1. Production phase

The detailed bill of materials to produce the FITGEN e-axle is confidential due to legal agreements among project partners. However, a simplified list of principal components and their efficiencies are shown in Table 3 and compared to the 2018 SotA. The total energy required to manufacture the main components of the FITGEN e-axle is shown in Table 4, calculated for their respective weights. These values were derived from the scientific literature (Nordelöf, 2019; Nordelöf et al., 2019a; Nordelöf and Tillman, 2018; Nordelöf et al., 2018) and the ecoinvent database.

A lithium-ion battery (LIB) pack is added to the e-drive/e-axle components to carry out a consistent comparative LCA among the electric and conventional powertrains. A 40 kWh LIB is chosen to match the performance of the 2018 Nissan Leaf, an exemplary BEV of the C-segment. The battery pack contains Nickel Manganese Cobalt (NMC)111 cells based on Dai et al. (2018) and Winjobi et al. (2020), with battery pack components based on Ellingsen et al. (2014). Detailed inventory data are shown in the Supplementary Material (SM) (Table S1). The inventory data for manufacturing the diesel-fuelled and petrol-fuelled drivetrain components were derived from Althaus and Gauch (2010), as modelled in the ecoinvent v3.6 database. The characteristics of the

ICEV drivetrains are shown in Table 5.

2.3.2. Use phase

The electricity supply to charge e-powertrains is based on the average low-voltage mix for 2020 according to the “Stated Policies Scenario” for the EU (IEA, 2019). The conversion from high-voltage to medium- and low-voltage electricity accounted for associated losses and

Table 2
Mass of the different powertrain components in this study.

Components	Mass (kg)	Reference
Petrol-fuelled powertrain	331.5	ecoinvent (2019); Ford (2017)
Diesel-fuelled powertrain	407.4	ecoinvent (2019); Ford (2017)
2018 SotA e-drive	100.9	ecoinvent (2019); BRUSA (2019)
FITGEN e-axle	109.8	FITGEN (2020)
Traction battery pack	239.0	Dai et al. (2018); Winjobi et al. (2020)

Table 3
Weights and efficiencies of the e-drive components in this study.

Components	2018 SotA e-drive ^b		FITGEN e-axle ^a	
	Mass (kg)	Efficiency	Mass (kg)	Efficiency
Transmission	23.8	0.97	20.2	0.98
Motor-inverter unit	–	–	58.0	0.95
Converter	4.5	0.97	–	–
Cooling system-DC/DC converter unit	–	–	25.4	0.99
On-board charger	6.2	0.95	6.2	0.95
Motor	53	0.95	–	–
Inverter	9.5	0.97	–	–
Power distribution unit	3.9	–	–	–

Sources: ^a(Fiumara and Primon, 2019); ^b(BRUSA, 2019; ecoinvent, 2019).

Table 4
Energy requirement for FITGEN e-axle components manufacture.

Components	Energy carrier	Value
Transmission	Electricity (kWh)	15.5
	Heat (MJ)	164
Motor-inverter	Electricity (kWh)	24.7
	Heat (MJ)	337.5
Neodymium permanent magnet	Electricity (kWh)	21.1
	Heat (MJ)	0.24
DC-DC converter	Electricity (kWh)	0.11
	Heat (MJ)	293.4

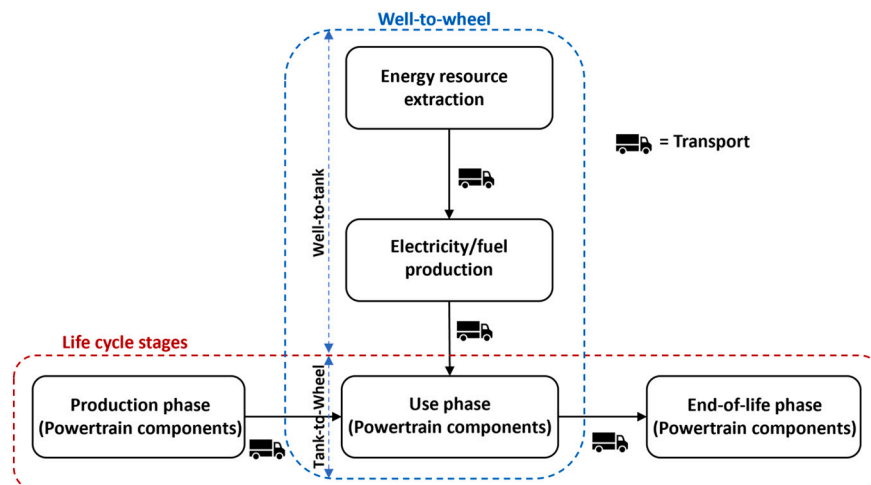


Fig. 2. System Boundary.

Table 5
Characteristics of the internal combustion engines vehicles drivetrains.

Type	1.5-L EcoBoost petrol engine		2.0 L TDCi diesel engine		Reference
	Inline three-cylinder turbo petrol direct fuel injection and Ti-VCT, transverse		Inline four-cylinder turbocharged diesel, transverse		
Engine efficiency	0.3		0.4		Ben-Chaim et al. (2013) Ford (2017)
Displacement (cm ³)	1499		1997		
Bore (mm)	79.02		85		
Stroke (mm)	76.4		88		
Compression ratio	10:01		16:01		
Max power (kW)	110		110		
Max torque (rpm)	6000		3750		
Max torque (Nm @ rpm)	170	At 1600 - 4000	370	at 2000 - 3250	
Transmission	Durashift 6-speed (B6G5d) manual		Manual 6-speed (MMT6)		
Transmission efficiency	0.95		0.95		Ben-Chaim et al. (2013) Ford (2017)
Gear ratios	6th	0.690	6th	0.790	
	5th	0.821	5th	0.970	
	4th	1.032	4th	0.870	
	3rd	1.357	3rd	1.240	
	2nd	2.048	2nd	1.290	
	1st	3.727	1st	3.580	
	Reverse	3.820	Reverse	1.420	
	Final drive	4.070	Final drive	3.933	
Emission level	Euro 6		Euro 6		

emissions based on European conditions as modelled in the ecoinvent database. As a result, the carbon intensity of the charging electricity mix was estimated as 346 g CO_{2eq}/kWh. Likewise, inventory data for petrol

and diesel to conventional power powertrains were derived from the ecoinvent database.

The BEV electricity consumption was calculated using the driving cycle defined by the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) (EC, 2017). The use phase follows a similar approach to Nordelöf et al. (2019a, b). The energy consumed in the e-powertrain lifetime was estimated by considering the vehicle dynamics, the average efficiencies of the powertrain components (Table 1), and the WLTP drive cycle parameters (EC, 2017).

To account for the variable efficiency of the electric motor at different operating (due to changes in traffic conditions) points in the driving cycle, the efficiency maps of the FITGEN e-axle without the transmission system were used in the model (see Fig. 3); whereas, the efficiency map of the neodymium-dysprosium-iron-boron permanent magnet synchronous machine in Nordelöf et al. (2019a, b) was used as a proxy for the 2018 SotA e-drive. As a result, the study considered the expected variations in BEVs efficiency as traffic conditions change while driving in real-life environment (Jonas et al., 2022).

The vehicle mass, rolling resistance, aerodynamic drag, speed, and acceleration were used to calculate the mechanical energy at the wheels required to follow the WLTP cycle (see Table 2 and Table 3). This assessment focuses on the electricity needed to overcome the e-powertrains losses and energy required to carry their weights. This electricity was estimated by subtracting the BEV energy consumption when including the e-powertrains' weights and losses from the same consumption when excluding their weights and losses. The equations applied in the consumption model are described in an earlier study (Koroma et al., 2022).

The same approach in Nordelöf et al. (2019a, b) was used to model the use phase of the ICEV powertrains since the focus was on the fuel needed to overcome energy losses due to the inefficiency of the ICEV powertrain and that required to carry its weight. Thus, the energy for each ICEV powertrain was estimated by deducting the ICEV fuel consumption when including the powertrain weight and energy losses (due to engine and transmission system inefficiencies) and the same

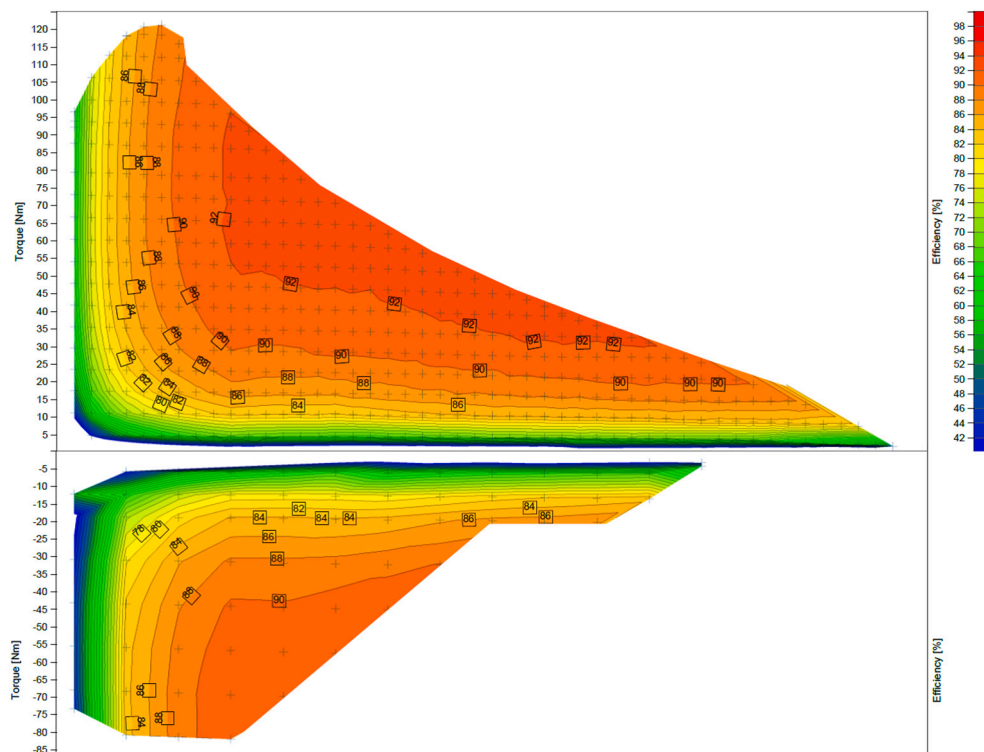


Fig. 3. Efficiency map of the FITGEN e-axle without transmission in Quadrant one (Q1) (top) and Quadrant two (Q2) (bottom). Q1 is measured in acceleration mode and Q2 is in recuperation mode. The highest measured efficiency was 94,89 % at 8400 rpm and 56 Nm (Sierra et al., 2022).

consumption when excluding the powertrain weight and energy losses. Using the WLTP driving profile, Eqs. (1) and (2) adopted from Ben-Chaim et al. (2013) were used to calculate the energy required by an ICEV to overcome the forces of resistance (E_r in [J/100 km]) and the kinetic energy needed for intermittent accelerations (E_k in [J/100 km]).

$$E_r = \frac{1}{\eta_T} \sum_{i=1}^{I_2} \int_{T_i} \frac{1}{\eta_i(P, n, t)} \left(m^* g^* C_r^* \frac{v_i(t)}{3.6} + 0.5^* \rho^* C_d^* A_f^* \left\{ \frac{v_i(t)}{3.6} \right\}^3 \right) dt \quad (1)$$

$$E_k = \frac{m^* \lambda}{2} \sum_{i=1}^{I_2} \int_{T_i} \frac{a_i(t)}{\eta_i(P, n, t)} dt \quad (2)$$

The engine efficiency ($\eta(P, n)$) varies during the ICEV operation and depends on the maximum efficiency of the engine at optimal mode (η_o), the power utilisation coefficient (μ_p), and the engine speed mode coefficient (μ_n), as shown in Eq. (3) (see Table 5 for the relevant data). The relationship for estimating the coefficients (μ_p and μ_n) is reported in Ben-Chaim et al. (2013). The coefficient values and their share in the WLTP drive cycle are shown in Table 6 – adapted from Ben-Chaim et al. (2013) and Kneba et al. (2021). Lastly, the fuel consumption (L/100 km) is given by Eq. (4).

$$\eta(P, n) = \eta_o^* \mu_p^* \mu_n \quad (3)$$

where: P_i = the instantaneous engine power; P_e = the maximum engine power; n_i = the instantaneous engine speed; n_p = the speed corresponding to engine-rated power; μ_p = the degree of power utilisation coefficient; and μ_n = the engine speed mode coefficient.

Lastly, the fuel consumption (L/100 km) is given by Eq. (4):

$$F_c = \frac{E_r + E_k + P_{aux}}{H_l} \quad (4)$$

Where: H_l = the lower calorific value of one litre of fuel (J/L); T_i = the acceleration subinterval duration (s); λ = the mass factor of the ICEV; $a_i(t)$ = the instantaneous vehicle acceleration (m/s²); $v_i(t)$ = the instantaneous vehicle speed (km/h); m = vehicle mass (kg); g = gravitational acceleration (m/s²); C_r = coefficient of rolling resistance; ρ = air density (kg/m³); C_d = aerodynamic drag coefficient; and A_f = vehicle frontal area (m²).

2.3.3. End-of-life phase

The EoL stage was modelled considering the treatment and disposal of the powertrain components. EoL treatment and disposal include several steps: collection, decontamination, dismantling, shredding, and recycling (Edwards et al., 2006). However, recycling was excluded even though most materials (such as aluminium, steel, and copper) used to manufacture the different drivetrains are recyclable. The decision to exclude recycling from the scope of the study was based on the uncertainty of data and the variability of recycling e-drive components in practice (Andersson et al., 2017). Nevertheless, the benefits of material recycling were accounted for by utilising a share of recycled materials

Table 6
Proposed operation points and coefficient of the engine speed mode (Ben-Chaim et al., 2013).

Operation point	Share in test (%) ^a	$P_i/P_e, n_i/n_p$ (%)	μ_p , Petrol	μ_p , Diesel	μ_n
P1	20.54	0.2	0.47	0.54	0.87
P2	22.28	0.3	0.59	0.68	0.92
P3	20.50	0.4	0.71	0.75	0.96
P4	15.03	0.5	0.82	0.86	0.98
P5	10.74	0.6	0.9	0.92	0.99
P6	6.74	0.7	0.97	0.97	1
P7	4.17	0.8	1	1	0.99

^a Authors estimate adapted from Kneba et al. (2021).

burden-free following the cut-off system approach adopted in the ecoinvent database (Wernet et al., 2016).

2.4. Life cycle impact assessment and sensitivity analysis

The ReCiPe 2016 life cycle impact assessment (LCIA) method was used in this study (Huijbregts et al., 2016). The midpoint environmental impact categories for global warming potential (GWP), mineral resource scarcity (MRS), fossil resource scarcity (FRS), fine particulate matter formation (FPMF), water consumption (WC), land use (LU), human non-carcinogenic toxicity (HnCT), and human carcinogenic toxicity (HCT) are discussed in detail in Section 3. These impact categories are considered by the authors the most critical for vehicles. Results for other impact categories (stratospheric ozone depletion, ionising radiation, ozone formation, acidification, eutrophication, and ecotoxicity) are reported in the SM (see Tables S2). In addition, a sensitivity analysis of selected parameters was conducted to test their impact on the reliability of the LCIA results. Table 7 shows the variation of selected parameters for the sensitivity analysis.

Biofuels and electrofuels (e-fuels) have shown promising results in reducing the carbon emissions of passenger cars (Puricelli et al., 2022; Puricelli et al., 2021). With that in mind, three innovative fuels blended with petrol streams (fuel B, C and D) were used for a sensitivity test on the petrol-fuelled powertrain. Fuel B contains 7 % v/v bionaphtha, 8 % v/v bioethanol, and 85 % v/v petrol; fuel C contains 21.8 % v/v bio-ETBE and 78.2 % v/v petrol; and fuel D contains 4.8 % v/v bio-ethanol, 2.7 % v/v of either methanol, biomethanol or e-methanol, and 92.5 % v/v petrol. The detailed inventories for modelling the production and use phases of these innovative fuels were derived from Puricelli et al. (2022).

3. Results and discussion

3.1. Use phase energy demand of the powertrain options

Fig. 4 shows the total use phase energy demand specified over the lifetime mileage for all powertrain options (see Section 2.3.2 for the calculation method). In Fig. 4a, the 2018 SotA e-drive consumed more electricity (97,154 kWh) than the FITGEN e-axle (7172 kWh); this difference is linked to the FITGEN e-axle efficiency improvements. This finding is consistent with the literature shown by Auer and Meincke (2018) and Hernandez et al. (2015) for energy-efficient traction motors. The total contributions of the charger (1112 kWh) and battery pack (4474 kWh) are the same for both the e-powertrains. For the FITGEN e-axle, the charging losses (9 %) and the battery pack (35 %) accounted for almost half (45 %) of the total electricity demand. Thus, the efficiencies of the various e-powertrain components are critical in improving the energy demand for BEVs.

In comparison, the energy demand for conventional powertrains is driven by the engine and transmission efficiencies (Fig. 4b). Fig. 4b also shows that the diesel-fuelled powertrain is more efficient (consuming

Table 7
Selected parameters for sensitivity analysis.

Parameter	Sensitivity scenario		
Electricity source	High share of RES (Norwegian electricity mix)	High share of fossil fuel (Polish electricity mix)	–
Partially-renewable petrol blends for ICEV	Fuel B	Fuel C	Fuel D
Lifetime mileage (km)	–25 %	+25 %	–
Efficiency of powertrain components	–1 %	+1 %	–
Powertrain mass	–10 %	+10 %	–

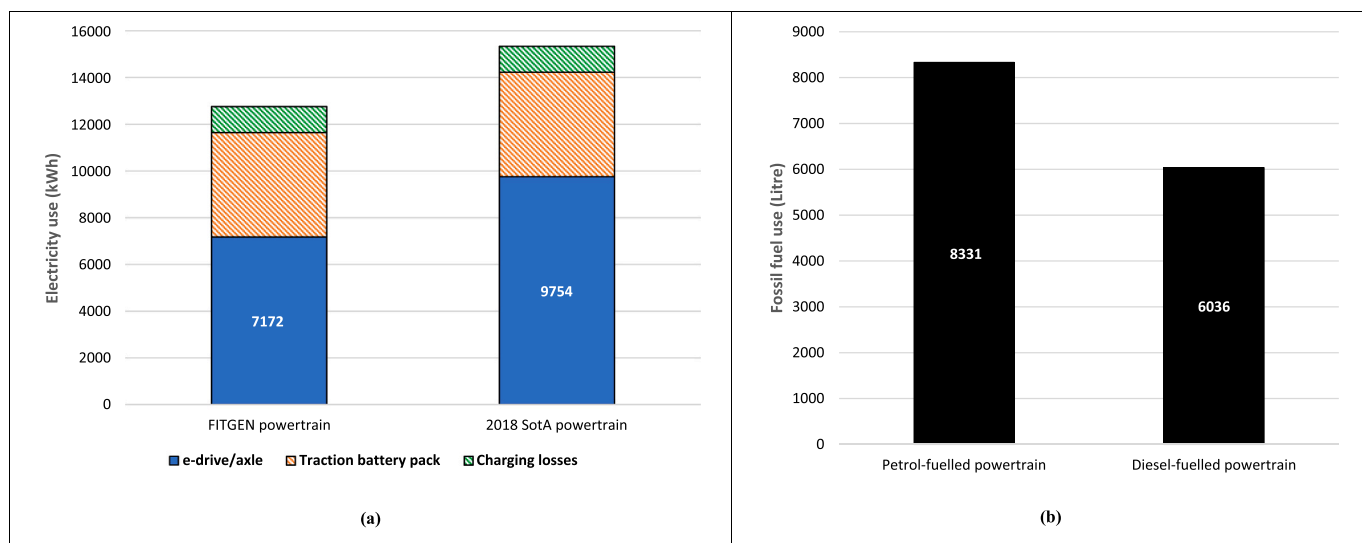


Fig. 4. Use phase energy demand for e-powertrains (a) and conventional powertrains (b).

about 28 % less fossil fuel) than its petrol-fuelled counterpart. These results suggest that increasing the energy efficiency of powertrain components will continue to be an important ecodesign lever since it can reduce fuel/energy consumption, emissions, and resource use, among others. This improvement could make BEVs more practical and directly translate to the increased driving range and optimised performance while achieving regulatory compliance, boosting economic benefits, and fostering technological progress in the transportation sector.

3.2. Environmental and human health impacts of the powertrain options

Overall, conventional powertrains emitted a larger share of lifetime GHG emissions than the e-powertrain (Fig. 5a). The FITGEN powertrain generated the lowest CC impact at 10 %, 163 %, and 222 % less than the 2018 SotA, the diesel-fuelled, and the petrol-fuelled powertrains, respectively. The e-powertrains production phase contributed to higher CC impacts (around 44 % of their total) than the conventional powertrains (ranging from the total contribution from 20 to 30 %). The results are consistent with the scientific literature and are mainly explained by the added burden of producing the traction battery (Peters et al., 2017).

The results also show that the CC impacts of LIB production are significant (around 27 % - 30 %) of the e-powertrain total compared to around 17 %–18 % for producing the other e-powertrain components. The manufacturing of metals and electronics mainly drove the e-powertrain production phase CC impacts. A detailed process contribution analysis found that using fossil fuels at mine sites and in materials/components manufacturing factories accounted for a significant share of production phase CC impacts. The battery production phase is also critical; the energy source and the total electricity consumed for manufacturing the battery cell are also significant contributors. Thus, the energy source and efficiency of the manufacturing plants are critical to improving the impacts of e-powertrain technologies on CC. Decision-makers should prioritise renewable energy sources and efficiency improvement along the supply chain to minimise the carbon footprint of powertrain technologies.

The FITGEN e-axle production CC impact is 2 % lower than the 2018 SotA e-drive, although the FITGEN e-axle is 9 kg heavier. Fewer electronics usage by functionally integrating the PDU in the power electronics and integrating the inverter and e-motor in one housing drives its lower production phase CC impact than the 2018 SotA e-drive. The

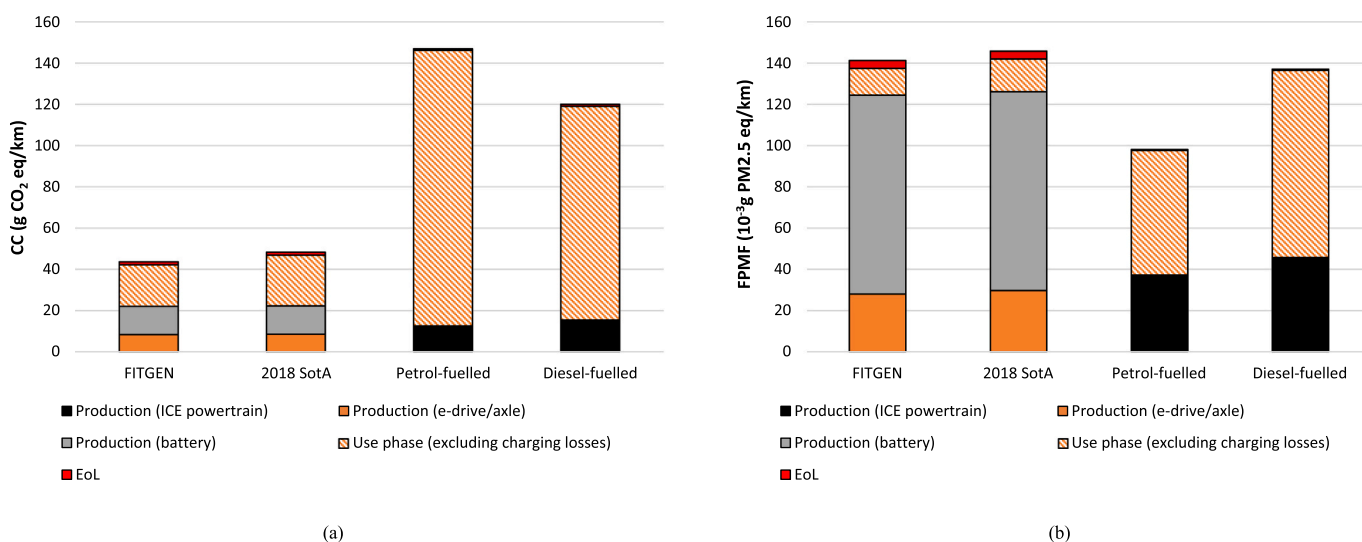


Fig. 5. Life cycle impact assessment results for the impact categories climate change (CC) (a) and fine particulate matter formation (FPMF) (b), specified per kilometre driven.

impact on CC of the FITGEN e-axle converter is about two times higher than the 2018 SotA converter. This increase is linked to the integrated housing of the cooling system. However, introducing the cooling system enables a higher motor-inverter efficiency in the FITGEN than in the 2018 SotA. As a result, the added burden of producing the cooling system is made up for during the use stage of the energy-efficient FITGEN e-axle.

The use phase electricity/fuel consumption contributed significantly to the total GHG emissions from each powertrain option. The most significant impacts on CC were associated with the conventional powertrains (corresponding to 85 % of their total) due to their dependence on fossil fuel and relatively low efficiencies. The relative share of use phase CC impacts is lower in the e-powertrains due to their relatively higher efficiency and the lower carbon content of their use phase energy. Similarly, this confirms the findings of Hernandez et al. (2015) that the efficiencies of powertrain components are critical for reducing use phase energy consumption and, consequently, the environmental damage from e-drive technologies.

Fig. 5b shows that the FITGEN powertrain emitted 3 % fewer FPM pollutants than the 2018 SotA powertrain, and emitted around 3 % and 31 % more than diesel and petrol-fuelled powertrains. Although it is worth stating the ±3 % difference between the FITGEN and the diesel and 2018 SotA powertrains, it can be considered negligible in this study due to the inherent uncertainty associated with the inventory data and the LCA modelling database. The production phase FPM is mainly due to coal- and lignite-based energy for battery cell manufacture and metal production, specifically copper, aluminium, electronics, and iron. The share of the production phase of FPM impact was higher for the e-powertrains than for the conventional powertrains. The production phase contributed over 85 % of the e-powertrains total FPM compared to around 35 % in the conventional powertrains. However, the e-powertrains share of use phase FPM is lower than their conventional alternative due to the source of the charging electricity mix. This reduction is driven by the use of renewable electricity in the EU mix, which has a lower share of FPM pollutants than the production and burning of fossil fuel to propel conventional powertrains.

Fig. 6 shows that the production phase of the powertrains drives the human toxicity impact categories. This phase contributed over 74 % across all powertrain options for both human carcinogenic toxicity (HCT) (Fig. 6a) and human non-carcinogenic toxicity (HnCT) (Fig. 6b). Overall, the FITGEN powertrain outperformed the 2018 SotA powertrain by 4 % in HCT (which can be considered negligible) and 10 % in HnCT but underperformed in both HCT and HnCT compared to the conventional powertrains. The contribution analysis showed that the

toxicity of the FITGEN e-axle production primarily comes from treating sulfidic mine tailings related to metals, specifically from copper and aluminium production chains. These findings agree with the literature (Hernandez et al., 2015; Nordelöf et al., 2019b). Spoils disposing from hard coal and lignite mining for fossil-based electricity production (primarily used in mines and metal processing factories) also contribute to human toxicity. The extra consumption of copper, aluminium, and other precious metals like gold for electronics and e-powertrain production accounted for higher non-carcinogenic toxicity than their conventional counterpart.

3.3. Impact on resource depletion

Life cycle impacts on MRS (Fig. 7a) and FRS (Fig. 7b) are shown in Fig. 7. The production phase dominated the MRS impact category, contributing over 85 % across all powertrain options. The contribution of the production phase is explained by the need for metals (such as gold, silver, aluminium, copper, and steel) for manufacturing powertrain components and electronics. The FITGEN powertrain outperformed the 2018 SotA by using 8 % fewer minerals (i.e., scarce minerals) despite being 9 kg heavier. Compared to the ICEV powertrains, the FITGEN e-axle consumed 12 % and 24 % more scarce minerals than the diesel- and petrol-fuelled powertrains.

The use phase impacts dominate fossil resource scarcity, primarily driven by using fossil fuels for ICEVs and in electricity generation for BEVs. As expected, the potential of FRS is significant for the conventional powertrains use phase due to their dependence on fossil fuels for energy. Overall, the FITGEN powertrain used the smallest amount of fossil fuel, consuming 11 %, 191 %, and 225 % less than the 2018 SotA, the diesel-fuelled, and the petrol-fuelled powertrains, respectively. The impacts on land use (LU) and water consumption (WC) are shown in Fig. 8. The e-powertrains have the most impact on LU and WC. The LU impact of the FITGEN powertrain is over 80 % more than the conventional powertrains but 17 % less than the 2018 SotA.

The e-powertrains use phase dominated the LU impact category, primarily driven by land use for installing renewable electricity-producing technologies such as onshore wind and photovoltaic systems. The transformation of land into mining sites for mineral and fossil resource extraction also drove the impacts of LU. Water use for nuclear power, combined heat and power plants, and hydroelectricity production dominated the impacts of the e-powertrains use phase for the WC impact category. Likewise, WC for material processing is responsible for the production phase impact of all powertrain options.

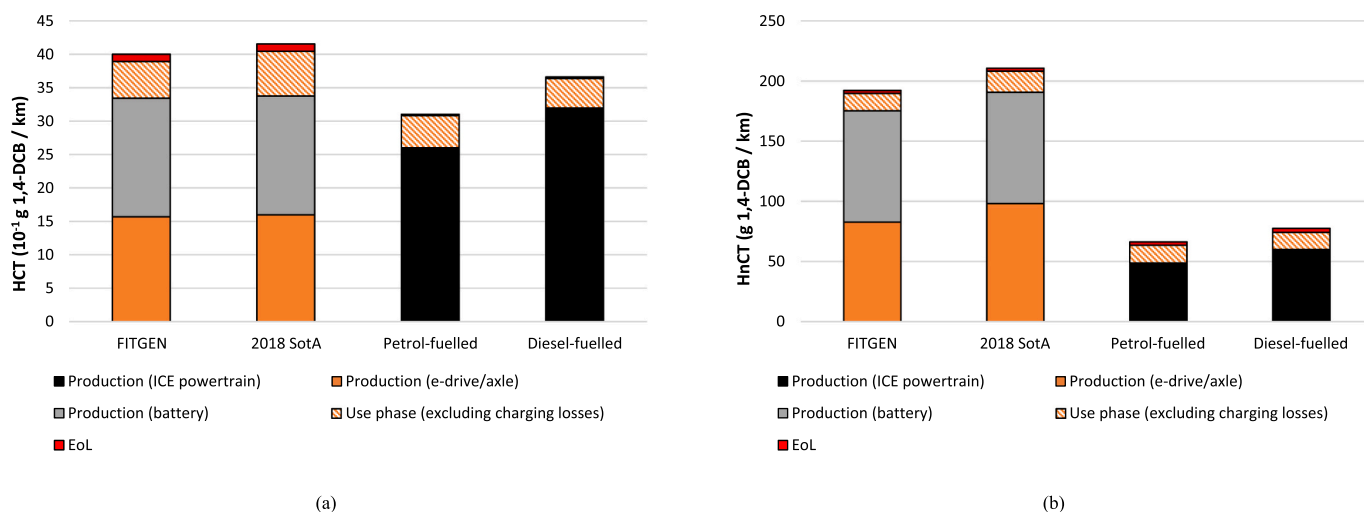


Fig. 6. Life cycle impact assessment results for the impact categories human carcinogenic toxicity (a) and human non-carcinogenic toxicity (b), specified per kilometre driven.

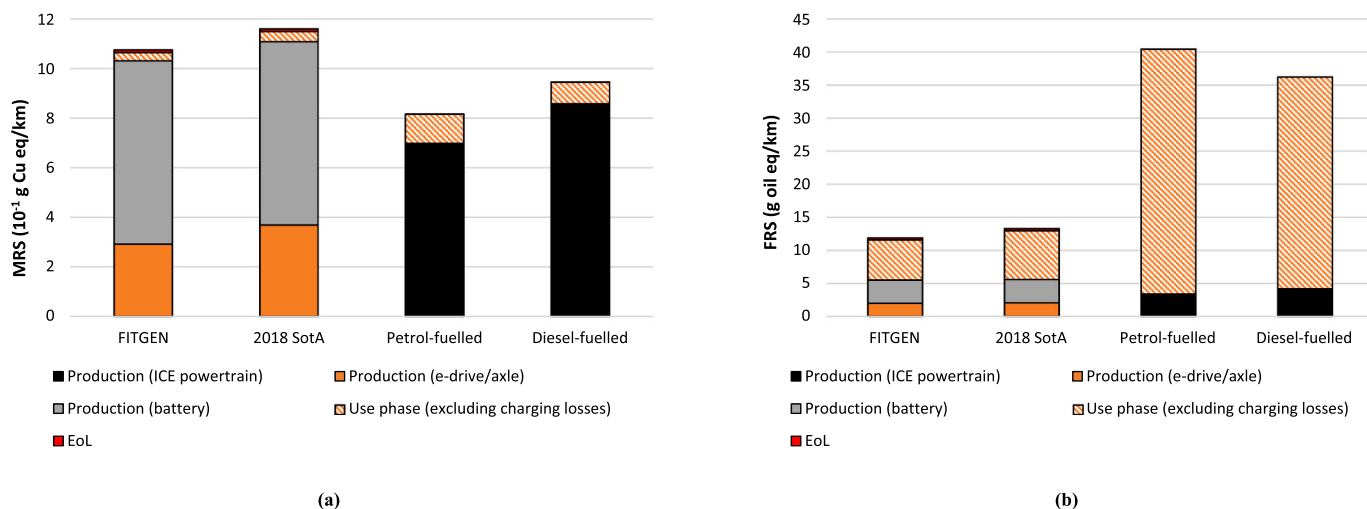


Fig. 7. Life cycle impact assessment results for the impact categories mineral resource scarcity (a) and fossil resource scarcity (b), specified per kilometre driven.

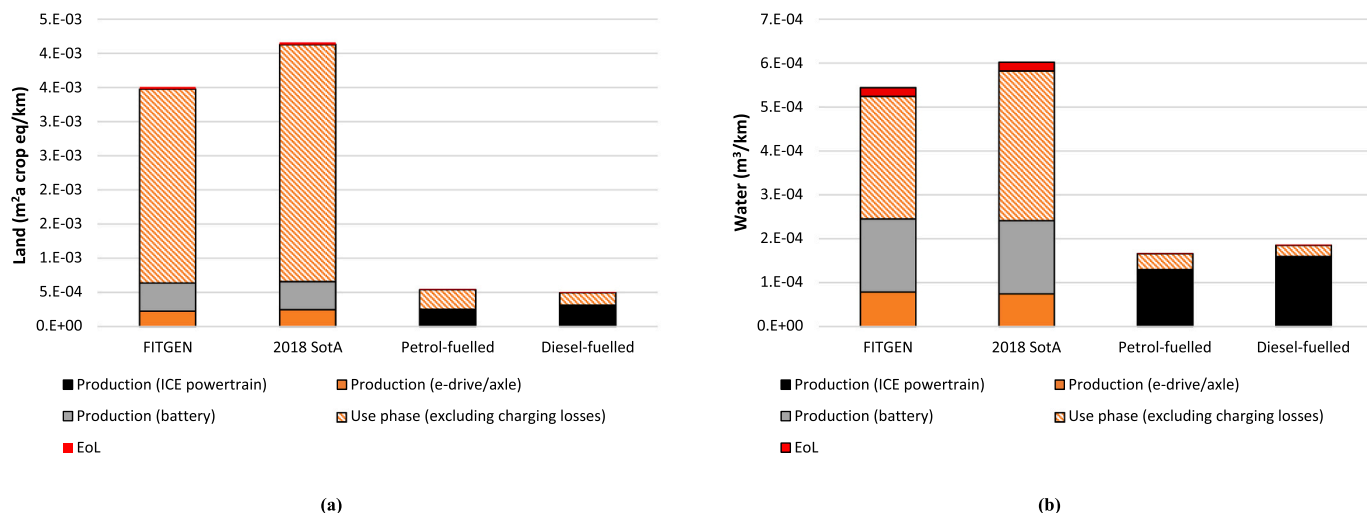


Fig. 8. Life cycle impact assessment results for land use (a) and water consumption (b), specified per kilometre driven.

3.4. Sensitivity analysis

A sensitivity analysis of the selected parameters in Table 7 was conducted to test the robustness of the LCIA results (Table S3 in the SM shows the sensitivity analysis results). Overall, the results were robust and showed no significant shifts in ranking order for all the impact categories discussed relative to the main study, except for PMF when the lifetime mileage was varied by +25 % (see the red cells in Table S3). The sensitivity analysis on lifetime mileage showed that increasing the lifetime mileage of passenger cars benefits all powertrain options and all impact categories discussed. Varying the efficiency of the powertrain components by ± 1 % showed no change in the ranking order of the impact categories discussed relative to the main study. Increasing the powertrain efficiency by +1 % indicated significant reductions in environmental burden for e-powertrains in impact categories driven by use phase electricity consumption.

Likewise, varying the powertrain mass by ± 10 % showed no change in the ranking order of the impacts. Reducing the powertrain mass by 10 % showed a reduction across all impact categories. However, improving the powertrain efficiency showed more significant potential for reducing the environmental burden of passenger car powertrains relative to reducing the powertrain mass. A sensitivity analysis on the use phase electricity mix confirmed that e-powertrains could significantly reduce

CC impacts when charged with a high share of the renewable electricity mix, such as the Norwegian electricity mix. Similarly, the use of innovative fuels to power the petrol-fuelled powertrain showed a reduction in several impact categories. Their impact and ranking order vary across the impact categories considered, with fuel B (containing bionaphtha and bioethanol) the most beneficial for reducing CC. However, their impacts on land use and water consumption were significantly higher than in the referenced results (see Table S3).

4. Final remarks

The results of this study highlight vital conclusions. Firstly, the FITGEN e-axle powertrain, characterised by its high level of component integration, shows a notable decrease in the environmental impacts of BEVs compared to the 2018 state-of-the-art e-drive. It is anticipated that future vehicles equipped with the FITGEN e-axle would exhibit a reduction of roughly 17 % in energy consumption during the use phase, as well as a decrease of 10 % in climate change impact over their lifetime, compared to vehicles equipped with the 2018 state-of-the-art e-drive. These results could be improved further if the performance of the traction battery is improved, considering the climate change impact associated with the production and use of BEVs' traction batteries is significant. Therefore, improving the battery manufacturing process by

integrating more renewable or low-carbon energy sources during production is imperative. Likewise, continuous efforts to optimise the energy efficiency of traction batteries to significantly reduce losses during the use phase are necessary to enhance the total environmental efficacy of electric powertrains.

The study also demonstrates that the FITGEN powertrain exhibits superior performance compared to the 2018 state-of-the-art powertrain across multiple impact categories, including freshwater ecotoxicity, human carcinogenic toxicity, marine ecotoxicity, freshwater eutrophication, land usage, and water consumption. This highlights the potential of energy-efficient powertrain technologies to improve the life cycle environmental performance of BEVs. The results further demonstrate that integrating electric powertrain components into a compact unit can reduce the use of scarce metals and minerals, potentially enhancing resource efficiency and mitigating extra environmental impacts along the material supply chain.

However, added efforts to reach higher efficiency shifted the environmental burden from energy-related indicators to toxicity and mineral resource depletion indicators, i.e., from use to the manufacturing stage. Likewise, despite the advances made regarding the FITGEN e-axle efficiency and compact size, the conventional powertrains outperformed the e-powertrains in all the impact categories discussed, except for climate change and fossil resource scarcity. These results imply that more efforts are required to improve the total environmental profile of e-powertrains. For instance, as most toxicity-related impacts are linked to the metal mining supply chain, practical strategies to improve waste management in mines could reduce the unwanted effect of BEVs and renewable energy technologies on toxicity-related indicators. Additionally, improving recycling rates and recycling facilities for car materials can minimise metal mining activities. Therefore, manufacturers, decision-makers and policymakers should adopt life cycle approaches to inform and outline clear directions towards efficient, compact, and fully integrated e-drives to reduce further BEVs life cycle impacts.

CRedit authorship contribution statement

Michael Samsu Koroma: Conceptualization, Methodology, Data curation, Software, Validation, Formal analysis, Investigation, Writing – original draft, Visualization. **Daniele Costa:** Methodology, Validation, Writing – review & editing, Supervision. **Stefano Puricelli:** Methodology, Validation, Writing – review & editing. **Maarten Messagie:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

All data is reported in the manuscript and supporting materials.

Acknowledgements

The authors thank the European Commission for supporting this research conducted within the European H2020 project FITGEN (Grant Agreement 824335).

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2023.166860>.

References

ACEA, 2022. Vehicles in Use Europe 2022. Available online at: URL: <https://www.acea-auto/> (accessed 4.4.22).

- Althaus, H., Gauch, M., 2010. Vergleichende Ökobilanz individueller Mobilität : Elektromobilität versus konventionelle Mobilität mit Bio- und fossilen Treibstoffen Marcel Gauch Life Cycle Assessment & Modelling Group, Technologie & Gesellschaft. Zürich. <https://doi.org/10.13140/RG.2.1.4191.8482>.
- Andersson, M., Ljunggren Söderman, M., Sandén, B.A., 2017. Are scarce metals in cars functionally recycled? Waste Manag. 60, 407–416. <https://doi.org/10.1016/j.wasman.2016.06.031>.
- Auer, J., Meincke, A., 2018. Comparative life cycle assessment of electric motors with different efficiency classes: a deep dive into the trade-offs between the life cycle stages in ecodesign context. Int. J. Life Cycle Assess. 23, 1590–1608. <https://doi.org/10.1007/s11367-017-1378-8>.
- Ben-Chaim, M., Shmerling, E., Kuperman, A., 2013. Analytic modeling of vehicle fuel consumption. Energies 6, 117–127. <https://doi.org/10.3390/en6010117>.
- BRUSA, 2019. BRUSA Elektronik AG. Available online at: URL: <https://www.brusa.biz/en.html> (accessed 3.19.19).
- Christensen, T.B., 2011. Modularised eco-innovation in the auto industry. J. Clean. Prod. 19, 212–220. <https://doi.org/10.1016/j.jclepro.2010.09.015>.
- Cui, H., Wappelhorst, S., 2020. Growing Momentum: Global Overview of Government Targets for Phasing out Sales of New Internal Combustion Engine Vehicles. Int. Counc. Clean Transp. Available online at: URL: <https://theicct.org/blog/staff/global-ice-phaseout-nov2020> (accessed 11.4.21).
- Dai, Q., Kelly, C.J., Dunn, J., Benavides, T.P., 2018. Update of Bill-of-Materials and Cathode Materials Production for Lithium-ion Batteries in the GREET Model. U.S. Department of Energy, Chicago.
- EC, 2017. Commission regulation (EU) 2017/1151. Off. J. Eur. Union 60, 732.
- ecoinvent, 2019. ecoinvent v3.6. Available online at: URL: <https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-6/>.
- Edwards, C., Coates, G., Leaney, P.G., Rahimifard, S., 2006. Implications of the End-of-Life Vehicles Directive on the vehicle recovery sector. Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 220, 1211–1216. <https://doi.org/10.1243/09544054JEM473SC>.
- EEA, 2016. Electric Vehicles from Life Cycle and Circular Economy Perspectives, EEA Report No 13/2018, EEA Report No 13/2018. European Union, Copenhagen.
- Ellingsen, L.A.W., Majeau-Bettez, G., Singh, B., Srivastava, A.K., Valøen, L.O., Stromman, A.H., 2014. Life cycle assessment of a lithium-ion battery vehicle pack. J. Ind. Ecol. 18, 113–124. <https://doi.org/10.1111/jiec.12072>.
- Erriquez, M., Schäfer, P., Schwedhelm, D., Wu, T., 2020. How to Drive Winning Battery-Electric-Vehicle Design: Lessons from Benchmarking Ten Chinese Models. McKinsey Co.
- FITGEN, 2020. Functionally Integrated E-Axle Ready for Mass Market 3rd Generation Electric Vehicles. Available online at: Fitgen. URL: <https://fitgen-project.eu/> (accessed 6.23.21).
- Fiumara, A., Primon, A., 2019. FITGEN Project Deliverable 3.1: E-Axle Specification Input. Brussels.
- Ford, 2017. Ford | Technical Specifications: Performance and Economy. Michigan, United States.
- Gennaro, M. De, Buechel, P., Primon, A., Bertini, O., Pescetto, P., Page, J.H., 2020. Interim Results of the H2020 Project FITGEN: Design and Integration of an e-Axle for the Third-Generation Electric Vehicles 1–10.
- Held, M., Rosat, N., Georges, G., Pengg, H., Boulouchos, K., 2021. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. Eur. Transp. Res. Rev. 13 <https://doi.org/10.1186/s12544-020-00464-0>.
- Hernandez, M., Messagie, M., Hegazy, O., Marengo, L., Winter, O., Van Mierlo, J., 2015. Environmental impact of traction electric motors for electric vehicles applications. Int. J. Life Cycle Assess. 22, 54–65. <https://doi.org/10.1007/s11367-015-0973-9>.
- Hernandez, M., Messagie, M., De Gennaro, M., Van Mierlo, J., 2017. Resource depletion in an electric vehicle powertrain using different LCA impact methods. Resour. Conserv. Recycl. 120, 119–130. <https://doi.org/10.1016/j.resconrec.2016.11.005>.
- Huijbregts, M., Steinmann, Z.J.N., Elshout, P.M.F.M., Stam, G., Verones, F., Vieira, M.D.M., Zijp, M., van Zelm, R., 2016. ReCiPe 2016 - A Harmonized Life Cycle Impact Assessment Method at Midpoint and Endpoint Level. Report I: Characterization, National Institute for Public Health and the Environment. Bilthoven.
- IEA, 2019. World Energy Outlook 2019, World Energy Outlook Series. OECD Publishing, Paris. <https://doi.org/10.1787/caf32f3b-en>.
- ISO, 2020a. ISO - ISO 14044:2006/Amd 2:2020 - Environmental Management — Life Cycle Assessment — Requirements and Guidelines — Amendment 2. ISO, Int. Organ. Stand. Available online at: URL: <https://www.iso.org/standard/76122.html> (accessed 7.12.22).
- ISO, 2020b. ISO - ISO 14040:2006/Amd 1:2020 - Environmental Management — Life Cycle Assessment — Principles and Framework — Amendment 1. ICS 13.020.10 Environ. Manag. Available online at: URL: <https://www.iso.org/standard/76121.html> (accessed 7.12.22).
- Jonas, T., Hunter, C.D., Macht, G.A., 2022. Quantifying the impact of traffic on electric vehicle efficiency. World Electr. Veh. J. 13, 985–990. <https://doi.org/10.3390/wevj13010015>.
- Kneba, Z., Stepanenko, D., Rudnicki, J., 2021. Numerical methodology for evaluation the combustion and emissions characteristics on WLTP in the light duty dual-fuel diesel vehicle. Combust. Engines 3–11. <https://doi.org/10.19206/ce-143334>.
- Koroma, M.S., Brown, N., Cardellini, G., Messagie, M., 2020. Prospective environmental impacts of passenger cars under different energy and steel production scenarios. Energies 13, 6236. <https://doi.org/10.3390/en13236236>.
- Koroma, M.S., Costa, D., Philippot, Maeva Cardellini, Hosen, G., Coosemans, Md Sazzad, Thierry Messagie, M., 2022. Life cycle assessment of battery electric vehicles: implications of future electricity mix and different battery end-of-life management. Sci. Total Environ. 831, 1–26. <https://doi.org/10.1016/j.scitotenv.2022.154859>.

- Luccarelli, M., Matt, D.T., Russo Spena, P., 2015. Modular architectures for future alternative vehicles. *Int. J. Veh. Des.* 67, 368–387. <https://doi.org/10.1504/IJVD.2015.070412>.
- Marmiroli, B., Messagie, M., Dotelli, G., Van Mierlo, J., 2018. Electricity generation in LCA of electric vehicles: a review. *Appl. Sci.* 8 <https://doi.org/10.3390/app8081384>.
- Nissan, 2015. 2015 Leaf 1–22.
- Nordelöf, A., 2019. A scalable life cycle inventory of an automotive power electronic inverter unit—part II: manufacturing processes. *Int. J. Life Cycle Assess.* 24, 694–711. <https://doi.org/10.1007/s11367-018-1491-3>.
- Nordelöf, A., Tillman, A.M., 2018. A scalable life cycle inventory of an electrical automotive traction machine—part II: manufacturing processes. *Int. J. Life Cycle Assess.* 23, 295–313. <https://doi.org/10.1007/s11367-017-1309-8>.
- Nordelöf, A., Messagie, M., Tillman, A.M., Ljunggren Söderman, M., Van Mierlo, J., 2014. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *Int. J. Life Cycle Assess.* 19, 1866–1890. <https://doi.org/10.1007/s11367-014-0788-0>.
- Nordelöf, A., Grunditz, E., Tillman, A.M., Thiringer, T., Alatalo, M., 2018. A scalable life cycle inventory of an electrical automotive traction machine—part I: design and composition. *Int. J. Life Cycle Assess.* 23, 55–69. <https://doi.org/10.1007/s11367-017-1308-9>.
- Nordelöf, A., Alatalo, M., Söderman, M.L., 2019a. A scalable life cycle inventory of an automotive power electronic inverter unit—part I: design and composition. *Int. J. Life Cycle Assess.* 24, 78–92. <https://doi.org/10.1007/s11367-018-1503-3>.
- Nordelöf, A., Grunditz, E., Lundmark, S., Tillman, A.M., Alatalo, M., Thiringer, T., 2019b. Life cycle assessment of permanent magnet electric traction motors. *Transp. Res. Part D Transp. Environ.* 67, 263–274. <https://doi.org/10.1016/j.trd.2018.11.004>.
- Peters, J.F., Baumann, M., Zimmermann, B., Braun, J., Weil, M., 2017. The environmental impact of Li-ion batteries and the role of key parameters – a review. *Renew. Sust. Energ. Rev.* 67, 491–506. <https://doi.org/10.1016/j.rser.2016.08.039>.
- Puricelli, S., 2021. Effects of the Use of Innovative Fuels and Biofuels on the Reduction of Air Pollution and the Climate Change. *Politecnico di Milano / Vrije Universiteit Brussel*.
- Puricelli, S., Cardellini, G., Casadei, S., Faedo, D., van den Oever, A.E.M., Grosso, M., 2020. A review on biofuels for light-duty vehicles in Europe. *Renew. Sust. Energ. Rev.* 137, 110398 <https://doi.org/10.1016/j.rser.2020.110398>.
- Puricelli, S., Casadei, S., Bellin, T., Cernuschi, S., Faedo, D., Lonati, G., Rossi, T., Grosso, M., 2021. The effects of innovative blends of petrol with renewable fuels on the exhaust emissions of a GDI Euro 6d-TEMP car. *Fuel* 294, 120483. <https://doi.org/10.1016/j.fuel.2021.120483>.
- Puricelli, S., Costa, D., Rigamonti, L., Cardellini, G., Casadei, S., Samsu, M., Messagie, M., Grosso, M., 2022. Life Cycle Assessment of innovative fuel blends for passenger cars with a spark-ignition engine: a comparative approach. *J. Clean. Prod.* 378, 134535 <https://doi.org/10.1016/j.jclepro.2022.134535>.
- Ricardo, 2020. Determining the Environmental Impacts of Conventional and Alternatively Fuelled Vehicles through LCA. Luxembourg, European Commission. <https://doi.org/10.2834/91418>.
- Sako, M., Murray, F., 1999. *Modules in Design, Production and Use: Implications for the Global Automotive Industry*, International Motor Vehicle Program Annual Meeting. Oxford.
- Schreiber, A., Marx, J., Zapp, P., 2021. Life Cycle Assessment studies of rare earths production - findings from a systematic review. *Sci. Total Environ.* 791, 1–21. <https://doi.org/10.1016/j.scitotenv.2021.148257>.
- Sierra, A., Alvarez, F., Pescetto, P., Lacher, H., Kapeller, H., 2022. FITGEN D5.2 - Integration of the Components and Bench Qualification. Available online: <https://www.fitgen-project.eu/>.
- Tatikonda, M.V., Stock, G.N., 2003. Product technology transfer in the upstream supply chain. *J. Prod. Innov. Manag.* 20, 444–467. <https://doi.org/10.1111/1540-5885.00042>.
- UN, 2021. Fact Sheet Climate Change. Available online at: United Nations. URL: https://www.un.org/sites/un2.un.org/files/media_gstc/FACT_SHEET_Climate_Change.pdf.
- Wappelhorst, S., 2021. Update on Government Targets for Phasing out New Sales of Internal Combustion Engine Passenger Cars. Available online at: Int. Council. Clean Transp. URL <https://theicct.org/> (accessed 11.4.21).
- Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. *Int. J. Life Cycle Assess.* 21, 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Weymar, E., Finkbeiner, M., 2016. Statistical analysis of empirical lifetime mileage data for automotive LCA. *Int. J. Life Cycle Assess.* 21, 215–223. <https://doi.org/10.1007/s11367-015-1020-6>.
- Winjobi, O., Dai, Q., Kelly, J.C., 2020. Update of Bill-of-Materials and Cathode Chemistry Addition for Lithium-ion Batteries in GREET 2020. Chicago.