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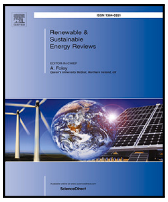

Total CO_2-equivalent life-cycle emissions from commercially available passenger cars

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ABSTRACT

The international passenger car market is undergoing a transition from vehicles with internal combustion engines to hybrid and fully electrified vehicles to reduce the climate impact of the transportation sector. To emphasize the importance of this needed change, this paper provides holistic comparisons of the total life-cycle greenhouse gas (GHG) emissions produced by a wide selection of commercially available passenger cars with different powertrains and energy sources. Simple analytical models are used to quantify the total life-cycle GHG emissions in terms of CO_2-equivalent values relative to the vehicle curb weight and the peak motor power. The production, utilization and recycling emissions are separately quantified based on the latest reviewed emission coefficient values. In total 790 different vehicle variants are considered. The results show that Battery Electric Vehicles have the highest production emissions. For example, the additional production emissions of a Tesla Model 3 Standard Plus approximately correspond to the driving emissions of a Volkwagen Passat 2.0 TSI after 18 000 km. Nonetheless, it is shown that conventional gasoline and diesel vehicles emit the highest amount of total life-cycle GHGs in comparison to vehicles powered by other available energy resources. When using green electricity, plug-in hybrid electric and fully electric vehicles can reduce the total life-cycle emission in comparison to combustion engine vehicles by 73 % and 89 %, respectively. A similar emission reduction is achieved by biogas powered vehicles (81 %). Fuel cell vehicles approximately reduce the GHG emission to a similar extent as electric vehicles (charged with conventional electricity) when using commercially available gray hydrogen (60 %).

1. Introduction

In 2019, the European Commission published the European Green Deal, as described and discussed in [1,2]. It comprises a strategy with the primary goal to increase the sustainability of the European Union's (EU) economy and to make Europe climate neutral in 2050. One of its major milestones is the significant reduction of Greenhouse Gas (GHG) emissions, such as CO_2, by a minimum of 50 % until 2030 in comparison to 1990 emission levels. Therefore, it is also planned to reach climate neutrality within the transportation sector, which can be essentially achieved by reducing passenger vehicles' GHG emissions [3].

Currently, different energy sources, such as liquid fuels, fuel gases or lithium-ion batteries, can be used to power passenger cars [4,5]. Typically, Internal Combustion Engine Vehicles (ICEV) constantly emit CO_2 while driving, whereas Battery Electric Vehicles (BEV) and Fuel Cell Electric Vehicles (FCEV) do not. Accordingly, consumer information brochures only describe passenger vehicles' driving emissions, which might mislead consumers to believe that Zero-Emission Vehicles (ZEV) do not emit any CO_2, since any other life-cycle emission aspects are omitted [6]. However, the primary energy sources of the electricity used to charge BEVs' batteries or to produce hydrogen, as well as the emissions created from vehicles' production, and to a lesser extent the disposal/recycling, must be considered when comparing passenger vehicles' total CO_2 emissions. Therefore, Life-Cycle Assessment (LCA) in terms of equivalent CO_2 emissions is a common approach to fairly compare the climate impact of different vehicles [7]. Although, due to the steady improvement of battery production/recycling techniques and local developments of green energy generation plants, LCA results involving BEVs can quickly become outdated. Furthermore, certain GHG aspects like the electricity carbon intensity [8] or the carbon emissions associated with the fuel transportation, such as crude oil shipping [9] or hydrogen transportation [10], do locally vary. Thus, as

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Abbreviations

BEV	Battery Electric Vehicle
CBG	Compressed Biogas
CNG	Compressed Natural Gas
DIN	German Institute for Standardization
EoL	End-of-Life
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
ICEV	Internal Combustion Engine Vehicle
LCA	Life-Cycle Assessment
LiDAR	Light Detection And Ranging
LPG	Liquid Petrol Gas
NEDC	New European Driving Cycle
PHEV	Plug-in Hybrid Electric Vehicle
RADAR	Radio Detection And Ranging
TtW	Tank-to-Wheel
UF	Utility Factor
USA	United States of America
WLTC	Worldwide Harmonized Light-Duty Vehicles Test Cycle
WLTP	Worldwide Harmonized Light-Duty Vehicles Test Procedure
WtT	Well-to-Tank
WtW	Well-to-Wheel
ZEV	Zero-Emission Vehicle

Nomenclature

a	Fitting coefficient
b	Fitting coefficient
c	Fitting coefficient
C_{bat}	Battery capacity
c_{WLTP}	Relative consumption during WLTP
D_{WLTP}	WLTP driving distance
$E_{\mathrm{CO_2,CD}}$	CO_2 emissions, charge depleting
$E_{\mathrm{CO_2,CS}}$	CO_2 emissions, charge sustaining
$E_{\mathrm{CO_2,tot}}$	Total CO_2 emissions
$E_{\mathrm{life,tot}}$	Total life-cycle emissions
$e_{\mathrm{prod,bat}}$	Battery production emissions
$e_{\mathrm{prod,body}}$	Body production emissions
$E_{\mathrm{prod,tot}}$	Total production emissions
$e_{\mathrm{recyc,bat}}$	Recycling emissions battery
$e_{\mathrm{recyc,body}}$	Recycling emissions vehicle body
$E_{\mathrm{recyc,tot}}$	Total recycling emissions
e_{ttw}	Tank-to-Wheel emissions
$E_{\mathrm{util,tot}}$	Total utilization emissions
e_{wtt}	Well-to-Tank emissions
e_{wtw}	Well-to-Wheel emissions
m_{veh}	Gross vehicle mass
$m_{\mathrm{veh,bat}}$	Gross vehicle battery mass
$m_{\mathrm{veh,body}}$	Gross vehicle body mass
$P_{\mathrm{veh,max}}$	Vehicle peak motor power
S_{lifetime}	Vehicle lifetime distance
ξ_{bat}	Battery specific energy

pointed out in [11] or [12], it is difficult to directly compare LCA results from different research papers.

For example, an LCA comparison between an ICEV and a BEV in China from 2018 is given in [13], which concludes that BEVs do not achieve any GHG emission reductions in comparison to similar ICEVs due to the carbon-intensive power generation in China, affecting the battery production and driving emissions. Similar conclusions are drawn in [14,15] for a BEV and ICEV comparison in Australia and for heavy-duty transports in Europe, respectively. In contrast, in [16] it is stated that the required emissions for the production of a Tesla size battery can correspond to the driving emissions of an ICEV after 8.2 years. In comparison to these publications, the research in [17] reveals that modern production techniques, as used for example in the United States of America (USA), can reduce the GHG emissions of Chinese battery manufacturing plants by about two thirds. Therefore, other LCA comparisons indicate that mid-size BEVs can reduce the life-cycle CO_2 emissions by 16 % to 46 % [18,19] in comparison to ICEVs, especially if renewable energy is available as a primary energy source for charging [20] and when including also the battery recycling process into the LCA [21]. Latest investigations show similar emission reduction tendencies for Plug-In Hybrid Electric Vehicles (PHEVs) [22], electric and hybrid buses [23], as well as electric trucks [24] in comparison to their combustion engine counterparts. In addition, as described in [25], the effect of the vehicle size and the battery capacity on the GHG emissions is less pronounced for EVs than for ICEVs. Moreover, as stated in [26], modern battery recycling techniques are under development and, thus, the climate impact of the recycling process is steadily improving as well. Nowadays, almost all battery materials can be recycled, as stated by [27], and the required energy amount is steadily decreasing [28].

However, the LCA investigations of the above mentioned research articles highlight only the role of a limited vehicle selection or partly pure hypothetical vehicles. Additionally, none of the research articles include vehicles' total lifetime emissions from the production to the recycling emissions considering the latest emissions coefficients, such as given in [28]. Hence, no holistic GHG emission comparisons of a large variety of commercially available vehicles with different kinds of energy sources can be found yet.

Therefore, the contribution of this paper is to give a comprehensive/holistic overview about the total CO_2 equivalent life-cycle emissions from a broad selection of commercially available passenger cars with different powertrains and energy sources. For this purpose, the latest emission parameters are extensively reviewed, a vehicle data base with 790 different car variants is created and, further, the production, utilization, including the Well-to-Wheel (WtW), and the recycling emissions are considered. Moreover, the life-cycle emissions are characterized relative to the vehicle curb weight and the peak motor power. Within the scope of this paper, the aspect of any kind of second-life battery utilization has not been taken into account.

2. Modeling of estimated life-cycle CO_2-equivalent emissions

This chapter gives a brief but comprehensive description about the analytical models used within the scope of this paper to estimate and, consequently, to compare vehicles' total GHG emissions in terms of CO_2-equivalent (CO_2-eq.) emissions. LCA is an unbiased approach to compare the environmental impacts associated with all the stages of a product's life cycle [29]. It considers for instance a product's GHG emissions associated with the product's production and manufacturing process, utilization, maintenance, End-of-Life (EoL) treatment and final disposal [14,19]. Often, vehicles' total life-cycle emissions can be generally categorized into three distinct parts/phases: production, utilization and recycling emissions. Typically, GHG emissions are quantified in terms of CO_2-eq. emissions, which is a metric measure used to compare various greenhouse gases [22] in terms of their global warming

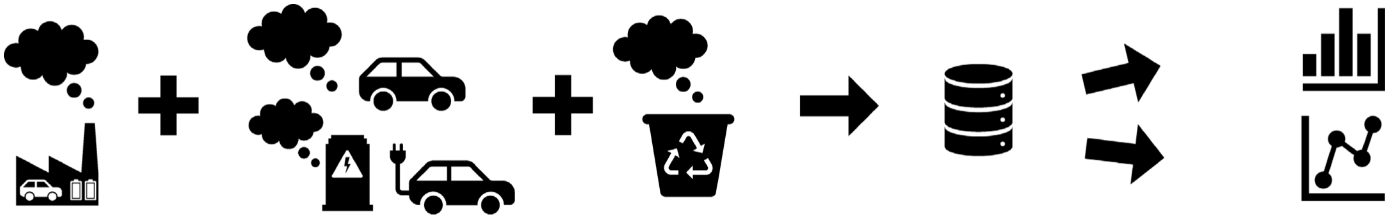

Fig. 1. Methodology of LCA: Accumulation of production, utilization and recycling GHG emissions in a database and systematic evaluation.

potential in relation to that of CO_2. Generally, a vehicle's total CO_2-eq. life-cycle emissions $E_{\mathrm{life,tot}}$ can be calculated as

$$E_{\mathrm{life,tot}} = E_{\mathrm{prod,tot}} + E_{\mathrm{util,tot}} + E_{\mathrm{recyc,tot}} \tag{1}$$

with $E_{\mathrm{prod,tot}}$, $E_{\mathrm{util,tot}}$ and $E_{\mathrm{recyc,tot}}$ being the total production, utilization and recycling emissions, respectively. In the following, the individual life-cycle emission parts are described in detail. Furthermore, simple analytical models are introduced to quickly quantify vehicles' life-cycle emissions relative to vehicles' curb weight, battery capacity, drive cycle emissions and life time in terms of the total traveled distance. The methodology used to calculate the total life-cycle GHG emissions is schematically illustrated in Fig. 1. At first, the production emissions of every vehicle are calculated according to Section 2.1. Then, the utilization emissions are estimated, as described in Section 2.2, before completing the GHG emission calculation with the recycling emissions, as explained in Section 2.3. Since the database includes several hundreds of different vehicle models, the equations are kept simple while accounting for a reasonable amount of uncertainties. The numerical values used for all calculations originate from literature as outlined in Section 3. The bibliographic references were surveyed based on their date of publication, favoring newer information, and on their depth of detail.

2.1. Production emissions

Even before a vehicle can be used to transport goods or passengers, a large amount of GHGs must be emitted to exploit a vehicle's raw materials and to manufacture the vehicle itself [17], referred to in here as production emissions. As similarly described in [14], a vehicle's total CO_2-eq. production emissions $E_{\mathrm{prod,tot}}$ can be estimated according to

$$E_{\mathrm{prod,tot}} = m_{\mathrm{veh,body}} \cdot e_{\mathrm{prod,body}} + C_{\mathrm{bat}} \cdot e_{\mathrm{prod,bat}} \tag{2}$$

with $m_{\mathrm{veh,body}}$ and C_{bat} being the vehicle curb weight in kg and the traction battery capacity (only for types of EVs) in kWh. Furthermore, $e_{\mathrm{prod,body}}$ and $e_{\mathrm{prod,bat}}$ are the relative CO_2-eq. emission for the vehicle body and the traction battery, given in $\mathrm{kg\ CO_2-eq./kg}$ and $\mathrm{kg\ CO_2-eq./\ kWh}$, respectively. The vehicle curb weight m_{veh} can be distinguished into the body mass $m_{\mathrm{veh,body}}$ and the battery mass $m_{\mathrm{veh,bat}}$ according to

$$m_{\mathrm{veh}} = m_{\mathrm{veh,body}} + m_{\mathrm{veh,bat}} = m_{\mathrm{veh,body}} + \frac{C_{\mathrm{bat}}}{\xi_{\mathrm{bat}}} \tag{3}$$

with C_{bat} and ξ_{bat} being the battery's nominal capacity in kWh and specific energy in kWh/kg, respectively.

2.2. Utilization emissions

After a vehicle is produced and delivered to the consumer, GHGs are constantly emitted when utilizing the vehicle and for its maintenance/repair, referred to in [7] as operational emissions. However, the emissions necessary for the production of expendable/spare parts, such as new tires, coolant fluids or lubricant oils, and vehicles' maintenance are very low in comparison to the emissions produced by the utilization of the vehicle [14,17]. Moreover, based on the user's driving profile and behavior, vehicles' actual service intervals strongly differ. Hence, the emissions associated with the production of spare parts and vehicles' maintenance are neglected within the scope of this paper. Therefore, the total CO_2-eq. utilization emissions $E_{\mathrm{util,tot}}$ can be calculated as

$$E_{\mathrm{util,tot}} = c_{\mathrm{WLTP}} \cdot e_{\mathrm{WtW}} \cdot S_{\mathrm{lifetime}} \tag{4}$$

with c_{WLTP} and S_{lifetime} being the relative energy/fuel consumption, based on the Worldwide Harmonized Light-Duty Vehicles Test Procedure (WLTP), for example given in L/100 km, and the expected vehicle life time in km, respectively. The relative CO_2-eq. WtW emissions e_{WtW} are for example given in $\mathrm{kg\ CO_2-eq./L}$. As schematically depicted in [7], the relative WtW emissions can be separated according to

$$e_{\mathrm{wtw}} = e_{\mathrm{wtt}} + e_{\mathrm{ttw}} \tag{5}$$

with e_{wtt} and e_{ttw} being the Well-to-Tank (WtT) and the Tank-to-Wheel (TtW) emissions. Considering the scheme in [7], the WtT emissions typically consider the processes of the energy source extraction, the energy carrier production and the energy carrier distribution, whereas the TtW emissions consider only the energy conversion process to actually propel the vehicle.

The second-life usage of vehicle batteries, such as described in [30], can reduce a vehicle's utilization emissions, but this effect is not considered within the scope of this paper.

2.2.1. Tank-to-wheel emissions during the worldwide harmonized light-duty vehicles test procedure

To estimate vehicles' relative fuel/energy consumption and the relative CO_2-eq. TtW emissions, standardized driving cycles are typically used. In 2017, the WLTP succeeded the New European Driving Cycle (NEDC) as the globally standardized test procedure to determine passenger vehicle's driving consumption and driving emissions. This driving cycle should produce more realistic results than the replaced NEDC by being approximately 50 % longer in time and it comprises higher absolute driving speeds [31,32]. In general, the WLTP consists of four parts, referred to as Worldwide Harmonized Light-Duty Vehicle Test Cycles (WLTC), with low, medium, high and extra-high driving speeds. Overall, the WLTP's time duration is 1800 s and its total driving range is about 23 km, as shown in [33]. The WLTP's speed profile is depicted in Fig. 2.

Typically, driving cycle tests are conducted in a laboratory environment and the test vehicle is only operated on a dynamometer test bench.

The emissions of conventional ICEVs can be directly measured from the exhaust gas emitted from the tail pipes. Thus, the relative CO_2 equivalent TtW emissions of ICEVs can be directly calculated according to

$$e_{\mathrm{ttw}} = \frac{E_{\mathrm{CO_2,tot}}}{D_{\mathrm{WLTP}}} \tag{6}$$

with $E_{\mathrm{CO_2,tot}}$ and D_{WLTP} being the measured total CO_2-eq. emissions and the WLTPs driving distance, respectively.

In contrast, the measurement of PHEVs' emissions is more difficult, since PHEVs can be propelled by both the electric motor (which does not locally emit any CO_2) or the internal combustion engine. Therefore, a strategy for calculating PHEVs' overall emissions was elaborated and appointed in the Amendment 4 of the United Nations Global

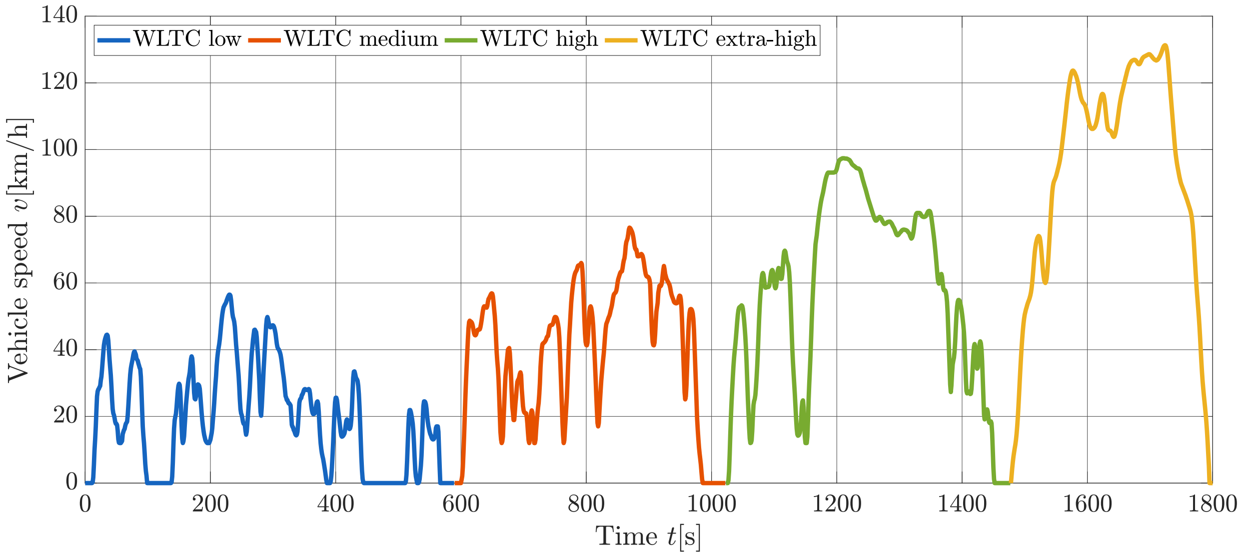

Fig. 2. Speed profile of the WLTP, consisting of Low (blue), Medium (orange), High (green) and Extra-high (yellow) speed part.

Technical Regulation on Worldwide Harmonized Light-Duty Vehicles Test Procedures (ECE/TRANS/180/Add.15) [34]. In a nutshell, PHEVs' battery energy and fuel consumption during the WLTP must be fairly distinguished. Therefore, a Utility Factor (UF) shall be used, which is defined as the ratio between the distance driven in battery 'charge depleting' mode divided by the WLTP's total distance [35,36]. With the measured emissions in each cycle and the calculated UF, the amount of the total CO_2 emissions corresponds to

$$E_{CO_2,\mathrm{tot}} = UF \cdot E_{CO_2,\mathrm{CD}} + (1 - UF) \cdot E_{CO_2,\mathrm{CS}} \tag{7}$$

with $E_{CO_2,\mathrm{CD}}$ and $E_{CO_2,\mathrm{CS}}$ being the CO_2 emissions associated with the 'charge depleting' and 'charge sustaining' mode, respectively. The relative CO_2-eq. TtW emissions of PHEVs can similarly be calculated as given in (6). Nonetheless, when assessing PHEVs' WtT emissions, the relative electrical and the fuel consumption must be separately considered.

In comparison, BEVs' and FCEVs' CO_2 emissions during driving are defined to be zero, since they do not locally emit any CO_2. Their fuel or electricity consumption, however, must be measured. Typically, vehicles' TtW emissions are issued by manufacturers' sales divisions, since they are important for vehicles' taxation according to current regulations.

2.2.2. *Uncertainty of well-to-tank emissions*

As mentioned before, the TtW emissions only cover a part of the total utilization emissions. Therefore, to fully assess the utilization emissions, the WtT emissions must be considered as well. These should include all emissions from the production, the storage and, further, the shipping/transportation of the used fuel or transmission of the electric energy. However, the WtT emissions cannot be estimated or quantified using standardized test procedures, since these can differ based on different aspects. As investigated and stated in [37,38], the WtT emissions significantly vary depending on the considered location. For example in [9], the authors analyze the shipping emissions per liter of crude oil when shipped along various trade lanes. When shipped from the Arabian Gulf to North America, the maritime transport would account for up to 11 % of the WtT emissions. In contrast, when shipped from the Arabian Gulf to Southeast Asia, the maritime transport corresponds only to 3 %. Therefore, it must be taken into account that the LCA comparisons, such as given in [17,19,23,24], are to a certain extent only locally valid.

2.3. *Recycling emissions*

The last GHG emission in a vehicle's life are associated with the recycling after decommissioning. Normally, the final recycling process [39,40] actually reduces vehicles' CO_2-eq. emission footprint, since the recycled material from scrapped cars can be reused to a great extent. As described in [41], the production of traction batteries is often controversially discussed to be very carbon intensive, but the proper recycling can significantly reduce BEVs' total life-cycle CO_2-eq. emissions.

The total CO_2-eq. recycling emissions $E_{\mathrm{recyc,tot}}$ are calculated as

$$E_{\mathrm{recyc,tot}} = m_{\mathrm{veh,body}} \cdot e_{\mathrm{recyc,body}} + C_{\mathrm{bat}} \cdot e_{\mathrm{recyc,bat}} \tag{8}$$

with $e_{\mathrm{recyc,body}}$ and $e_{\mathrm{recyc,bat}}$ being the relative recycling coefficients for vehicles' bodies, given in $\mathrm{kg\ CO_2 - eq./kg}$, and batteries, given in $\mathrm{kg\ CO_2 - eq./kWh}$, respectively.

3. Vehicle database and review of life-cycle assessment parameters

For the life-cycle emission comparisons, a database of vehicles was created, which should fairly represent the majority of all commercially available passenger cars, such as Volkswagen Passat, Audi A4, Tesla Model 3, Toyota Mirai, Mercedes-Benz C 300 d, etc. The main goal was to include as many different vehicle models as possible, considering various manufacturers, which is quite cumbersome when considering all commercially-available vehicle variants. For this reason only one chassis variant with the most basic equipment was considered for each vehicle model and only two drivetrain variants per vehicle were selected, representing the vehicle's lowest and highest possible peak motor power. Moreover, different publicly accessible energy sources were considered, such as gasoline, diesel, liquid petrol gas (LPG), compressed natural gas (CNG), compressed biogas (CBG), hydrogen (H_2) and electricity. When energy sources other than gasoline and diesel were possible to order for a specific vehicle, corresponding drive train variants for each energy source were additionally added. In total, 790 different vehicle variants were considered.

The values of vehicles' curb weight m_{veh}, relative WLTP energy consumption c_{WLTP} and battery gross capacity C_{bat} were obtained from official product specification sheets, major car journals or review information websites, such as given in [42].

As described in [43], vehicles' production emissions can differ locally. For example, according to [43], the production emissions of a compact car ($m_{\mathrm{veh}} = 1292.8\,\mathrm{kg}$) correspond to $9596.9\,\mathrm{kg}$ CO_2 − eq. in China, whereas in the US these are only $6241.2\,\mathrm{kg}$ CO_2 − eq. Within the scope of this paper, only one value should be chosen for each of the relative production emission coefficients $e_{\mathrm{prod,body}}$ and $e_{\mathrm{prod,bat}}$. This approach should simplify the LCA, but still allows to fairly compare different vehicle variants. The study in [44] compared different variants of Volkswagen's vehicle model Golf, such as its gasoline, diesel, CNG and BEV variant. The relative production emissions $e_{\mathrm{prod,body}}$ (excluding the BEV's lithium-ion battery) based on the values given in [44] correspond to $4.56\,\mathrm{kg}$ CO_2 − eq./kg for the gasoline model, $4.73\,\mathrm{kg}$ CO_2 − eq./kg for the diesel model and $4.16\,\mathrm{kg}$ CO_2 − eq./kg for the CNG model. As similarly described in [43,45], the relative production emissions for a gasoline compact car ($m_{\mathrm{veh}} \approx 1300\,\mathrm{kg}$) produced in the USA range from $4.17\,\mathrm{kg}$ CO_2 − eq./kg to $4.82\,\mathrm{kg}$ CO_2 − eq./kg. Nevertheless, as described in [44], it is unclear which fraction of the BEV's production emissions originate from the battery pack. Based on [14,17,43,45], a similar production emission coefficient $e_{\mathrm{prod,body}}$ can be concluded for BEVs' body. With the help of BEVs' nominal battery capacity C_{bat} and batteries' specific energy ξ_{bat}, the weight of a vehicles traction battery can be estimated according to (3). As listed in [46], batteries' specific energy ξ_{bat} can be assumed to be about $200\,\mathrm{Wh/kg}$. Furthermore, according to [27,47], the most recent studies estimate batteries' production emissions coefficient $e_{\mathrm{prod,bat}}$, ranging from $61.6\,\mathrm{kg}$ CO_2 − eq./kWh up to $106.0\,\mathrm{kg}$ CO_2 − eq./kWh. within the scope of this paper, a production emission coefficient $e_{\mathrm{prod,body}}$ of $4.56\,\mathrm{kg}$ CO_2 − eq./kg was selected for vehicles' bodies (corresponding to that of the gasoline model in [44]). Furthermore, an emissions coefficient $e_{\mathrm{prod,bat}}$ of $83.5\,\mathrm{kg}$ CO_2 − eq./kWh, which corresponds to the average value of the before mentioned range, was selected for EV batteries.

As described in [48], vehicles' WtW emissions e_{wtw} approximately correspond to $2.83\,\mathrm{kg}$ CO_2 − eq./L for gasoline, $3.18\,\mathrm{kg}$ CO_2 − eq./L for diesel, $1.83\,\mathrm{kg}$ CO_2 − eq./L to $2.16\,\mathrm{kg}$ CO_2 − eq./L for LPG and $2.39\,\mathrm{kg}$ CO_2 − eq./kg to $2.96\,\mathrm{kg}$ CO_2 − eq./kg for CNG. The value for CBG from municipal waste is given with $0.749\,\mathrm{kg}$ CO_2 − eq./kg by [49] and the value for commercially available hydrogen (the majority is gray hydrogen [50]) is given with $9.13\,\mathrm{kg}$ CO_2 − eq./kg by [51]. Within the scope of this paper, two different WtW emission values are considered for electricity. First, the carbon intensity of the German power generation is considered, which corresponds to $0.401\,\mathrm{kg}$ CO_2 − eq./kWh according to [52]. Second, the carbon intensity of electricity produced only from renewable energy sources is considered, which corresponds to $0.003\,\mathrm{kg}$ CO_2 − eq./kWh to $0.068\,\mathrm{kg}$ CO_2 − eq./kWh according to [53]. For the LCA comparisons the average value of the carbon intensity range is chosen, which corresponds to $0.036\,\mathrm{kg}$ CO_2 − eq./kWh. Since BEVs' TtW emissions e_{ttw} are zero, the WtT emissions e_{wtw} correspond to that of the electricity supply. Furthermore, to assess the total life-cycle utilization emissions, vehicles' lifetime must be specified. In 2019, the average distance German car drivers traveled per year was about $14\,610\,\mathrm{km}$ according to [54]. As issued by the German Federal Motor Transport Authority in [55], about 3.6 million cars were newly registered in 2019 and the total amount of registered passenger vehicles increased from 47.1 million to about 47.7 million. Thus, with the values from [54,55] it is valid to suggest an average vehicle lifetime S_{lifetime} of about $230\,000\,\mathrm{km}$, which corresponds to about 15.7 years.

In [56,57], the relative recycling emissions of vehicles' body $e_{\mathrm{recyc,body}}$ are approximated for a mid-size car, corresponding to $-2.33\,\mathrm{kg}$ CO_2−eq./kg and $-3.52\,\mathrm{kg}$ CO_2−eq./kg, respectively. This corresponds to an average recycling coefficient $e_{\mathrm{recyc,body}}$ of $-2.93\,\mathrm{kg}$ CO_2 − eq./kg. The relative battery recycling emissions $e_{\mathrm{recyc,bat}}$ of the BEVs reviewed in [56,57] approximately correspond to $-41.1\,\mathrm{kg}$ CO_2−eq./kg and $-55.7\,\mathrm{kg}$ CO_2 − eq./kg, respectively. Thus, the average value of the recycling coefficients presented in [56,57] is chosen in here, corresponding to $-48.4\,\mathrm{kg}$ CO_2 − eq./kg. In Table 1, the emission coefficients reviewed before are given.

4. Results and discussion

This section presents and discusses the obtained total CO_2-eq. life-cycle emissions of the 790 vehicle variants based on the modeling approaches introduced in Section 2, including the emission parameters reviewed in Section 3, and the vehicle database itself. Furthermore, it discusses this study's results, problems and practical implications.

4.1. Total life-cycle emission comparison of mid-size car selection

At first, within this subsection, only a small selection of vehicles from the database is considered. Furthermore, the vehicle production, utilization, including the WtW, and recycling emissions are separately quantified and compared. These small comparisons should transparently illustrate the chosen methodology before introducing the entire results of the 790 vehicle variants in the subsequent subsections. For this purpose, an example selection of several vehicles from the mid-size sedan sector (D-segment) is chosen. This vehicle class offers all included energy sources, apart from LPG, and the vehicle chassis as well as the peak motor power ratings are comparable. Moreover, the selected vehicle variants give a good general representation of vehicles' life-cycle GHG emissions relative to different powertrains and energy sources. The selected vehicle variants and their required parameters for the emission calculations are given in Table 2. With these values, the overall GHG emissions can be calculated as described before in Section 2. The bar chart in Fig. 3 depicts the obtained total CO_2-eq. life-cycle emissions and, as can be seen, it is distinguished between the production, utilization and recycling emissions.

Considering the production emissions of the selected gasoline vehicle, a Volkswagen Passat 2.0 TSI, as a baseline, it can be noticed that the selected diesel vehicle, Mercedes-Benz C 300 d, and the CNG/CBG vehicle, Audi A4 40 g-tron, are characterized by a similar amount of production emissions. Their production emissions differ from the baseline by $-1.1\,\%$ and $0.7\,\%$, respectively, due to the vehicles' mostly similar body and drivetrain. The obtained production emission values for the selected electrified vehicles, such as the FCEV (Toyota Mirai), gasoline PHEV (VW Passat 1.4 TSI GTE) and diesel PHEV (Mercdes-Benz C 300 de) are increased by $17\,\%$, $15\,\%$ and $35\,\%$, respectively. Since the FCEV is equipped with only a small Li-Ion battery and the fuel cell system is not considered in detail, its production emissions are relatively low compared to other EVs. The gasoline PHEV's small increase in production emissions compared to the similarly sized ICEV can be explained by the fact that although an emission-intensive Li-Ion battery is included, the conventional internal combustion engine is replaced by a smaller, lighter and less powerful version. Since the diesel PHEV's internal combustion engine is the same as the diesel ICEV's, the production emission surplus is significantly higher in comparison. Comparing the BEV (Tesla Model 3 SP) to the baseline vehicle, its production emissions are increased by $49\,\%$. This difference equals about $1294\,\mathrm{L}$ of fuel. With this amount, the gasoline car could travel about $18\,000\,\mathrm{km}$ (one year and three months). Due to the battery system, the GHG emissions required for the production of the selected BEV are typically higher than those of the combustion engine, hydrogen and PHEV vehicles depicted in Fig. 3. The influence of the battery capacity on the production emissions can be recognized, because PHEVs have smaller batteries than BEVs and, thus, emit less GHG during production.

In contrast, the combined share of the selected BEV's production and utilization emissions is significantly reduced in comparison to that of the Volkswagen Passat 2.0 TSI (gasoline), Mercedes-Benz C 300 d (diesel) or the Audi A4 40 g-tron (CNG). From Fig. 3 it becomes clear that the largest amount of the GHG emissions results from the vehicle utilization in almost all cases. Only the utilization emissions from the CBG vehicle and the BEV, when recharged with renewable energy exclusively, are relatively small compared to their production emissions.

Table 1
Reviewed values used for equivalent CO_2 emission calculations.

Emission source	Coefficient	Value	Unit	Reference
Production emissions vehicle body	$e_{\mathrm{prod,body}}$	4.56	kg CO_2 − eq./kg	[44]
Production emissions battery pack	$e_{\mathrm{prod,bat}}$	83.50	kg CO_2 − eq./kWh	[27,47]
Gasoline - WtW	e_{wtw}	2.83	kg CO_2 − eq./L	[48]
Diesel - WtW	e_{wtw}	3.18	kg CO_2 − eq./L	[48]
LPG - WtW	e_{wtw}	2.00	kg CO_2 − eq./L	[48]
CNG - WtW	e_{wtw}	2.68	kg CO_2 − eq./kg	[48]
CBG - WtW	e_{wtw}	0.749	kg CO_2 − eq./kg	[49]
H_2 - WtW	e_{wtw}	9.13	kg CO_2 − eq./kg	[51]
Conventional electricity - WtW	e_{wtw}	0.401	kg CO_2 − eq./kWh	[52]
Renewable electricity - WtW	e_{wtw}	0.036	kg CO_2 − eq./kWh	[53]
Recycling emissions vehicle body	$e_{\mathrm{recyc,body}}$	−2.93	kg CO_2 − eq./kg	[56,57]
Recycling emissions battery pack	$e_{\mathrm{recyc,bat}}$	−48.4	kg CO_2 − eq./kWh	[56,57]
Total lifetime traveled distance	S_{lifetime}	230 000	km	[54,55]
Energy density	ξ_{bat}	0.200	kWh/kg	[46]

Table 2
Relevant modeling parameters of mid-size car selection and obtained total CO_2-eq. life-cycle emissions.

Energy source	Vehicle model	Peak motor power	Curb weight	Fuel consumption	Electricity consumption	Battery gross capacity	Total CO_2-eq.
Gasoline	Volkswagen Passat 2.0 TSI	206 kW	1653 kg	7.2 L/100 km	0 kWh/100 km	0 kWh	49 559 kg
Diesel	Mercedes-Benz C 300 d	180 kW	1635 kg	4.9 L/100 km	0 kWh/100 km	0 kWh	38 504 kg
CNG	Audi A4 40 g-tron	125 kW	1665 kg	3.9 kg/100 km	0 kWh/100 km	0 kWh	26 754 kg
CBG	Audi A4 40 g-tron	125 kW	1665 kg	3.9 kg/100 km	0 kWh/100 km	0 kWh	9 432 kg
H_2	Toyota Mirai	135 kW	1900 kg	0.79 kg/100 km	0 kWh/100 km	2 kWh	19 740 kg
Gasoline PHEV Conv.	Volkswagen Passat GTE	160 kW	1730 kg	1.4 L/100 km	11.5 kWh/100 km	13 kWh	22 889 kg
Gasoline PHEV Renew.	Volkswagen Passat GTE	160 kW	1730 kg	1.4 L/100 km	11.5 kWh/100 km	13 kWh	13 235 kg
Diesel PHEV Conv.	Mercedes-Benz C 300 de	225 kW	2060 kg	1.4 L/100 km	18.7 kWh/100 km	13.5 kWh	31 208 kg
Diesel PHEV Renew.	Mercedes-Benz C 300 de	225 kW	2060 kg	1.4 L/100 km	18.7 kWh/100 km	13.5 kWh	15 510 kg
BEV Conv.	Tesla Model 3 Standard Plus	239 kW	1684 kg	0 L/100 km	14.3 kWh/100 km	58 kWh	17 497 kg
BEV Renew.	Tesla Model 3 Standard Plus	239 kW	1684 kg	0 L/100 km	14.3 kWh/100 km	58 kWh	5 492 kg

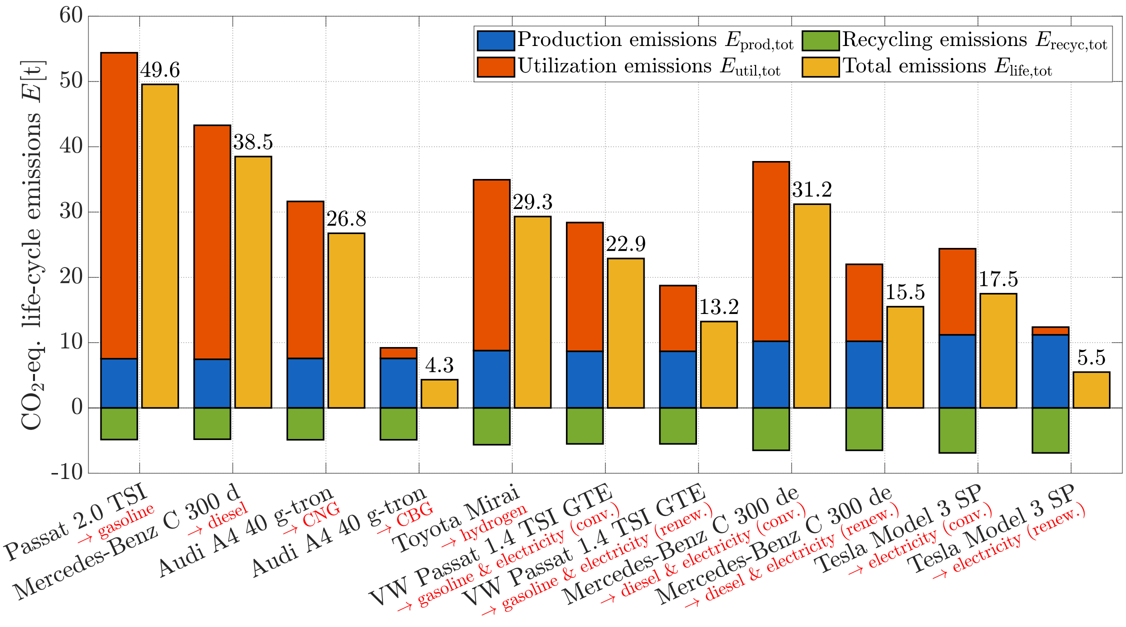

Fig. 3. Total life-cycle emissions of mid-size car selection, including production, utilization and recycling emissions.

In general, the results show that ICEVs using fossil fuels emit more GHG during driving than vehicles utilizing renewable energy sources, including CBG. In addition, the comparison shows that hybrid and fully electrified vehicles significantly reduce the utilization emissions.

The recycling emissions differ between the vehicles in a similar relation as the production emissions. For example, in addition to the recycling of the vehicle chassis and body parts, the recycling of PHEVs' or BEVs' batteries results in a large amount of extra GHG savings. Since battery recycling is currently not as efficient as the recycling of other vehicle parts, the emission savings at vehicle recycling relative to the production emissions are smaller for EVs.

4.2. Total life-cycle emissions relative to vehicle curb weight

Due to the rolling and drag resistance forces, it is clear that heavier and larger vehicles consume more energy/fuel than lighter ones, which in turn results in higher driving emissions [58]. Additionally, since more material is needed for producing heavier vehicles, the

Table 3
Coefficients for normalized life-cycle emission estimation relative to the vehicle curb weight according to (9).

Energy source	a	b	c
Gasoline	$3.701 \cdot 10^{-5}$	$3.953 \cdot 10^{-2}$	51.28
Diesel	$1.049 \cdot 10^{-5}$	$7.874 \cdot 10^{-2}$	7.834
LPG	0	$1.087 \cdot 10^{-1}$	6.439
CNG	0	$5.320 \cdot 10^{-2}$	30.45
CBG	0	$1.997 \cdot 10^{-2}$	8.509
Gasoline PHEV Conv.	$2.759 \cdot 10^{-5}$	$-2.253 \cdot 10^{-2}$	65.98
Gasoline PHEV Renew.	$1.323 \cdot 10^{-5}$	$-5.429 \cdot 10^{-3}$	30.07
Diesel PHEV Conv.	0	$6.343 \cdot 10^{-2}$	1.226
Diesel PHEV Renew.	0	$-8.232 \cdot 10^{-3}$	88.26
BEV Conv.	0	$4.510 \cdot 10^{-2}$	9.892
BEV Renew.	0	$1.614 \cdot 10^{-2}$	−2.970

production emissions are increased as well. The increased emission savings through the vehicle recycling cannot counterbalance the before mentioned aspects. To illustrate this effect, Fig. 4 depicts the total life-cycle emissions of the 790 vehicle variants relative to their vehicle curb weight. The mid-size cars selected in Section 4.1 are indicated by arrow labels. All emissions values are purposefully normalized ($E_{\text{life,tot}} / S_{\text{lifetime}}$ [g/km]), because relative emissions values are commonly used for consumer information materials and the assessment basis for vehicle emission regulations. To illustrate the influence of the production emission deviation, for example due the location, the semi-transparent areas mark the possible best (61.6 kg CO_2 – eq./kWh) and worst case (106.0 kg CO_2 – eq./kWh) scenarios. Moreover, for each individual energy source category, an emission function relative to the vehicle curb weight m_{veh} is mathematically fitted, so that the distinct trends are easily visible. For the curve fitting, a quadratic equation with the form according to

$$E_{\text{life,tot}}(m_{\text{veh}}) = a \cdot m_{\text{veh}}^2 + b \cdot m_{\text{veh}} + c \tag{9}$$

is used, with a, b and c being the coefficients to be estimated/fitting coefficients. In Table 3, the parameterized values of the coefficients for each individual energy source can be found. From Fig. 4, it can be seen that ICEVs generally emit more GHG than electrified vehicles. Especially, heavy gasoline vehicles, such as Sport Utility Vehicles, have a very high individual impact on the overall emissions of vehicle fleets. LPG vehicles show a similar relation, whereas diesel and CNG vehicles generally produce slightly less emissions than gasoline vehicles. Nevertheless, when refueling CNG vehicles with CBG, the total lifetime emissions can be reduced by about 65 %. Electrified vehicles such as FCEVs, PHEVs and BEVs emit significantly less GHGs during their lifetime than their respective ICEV counterparts even if recharged with conventional electricity. When recharging with renewable electricity only, additional emission savings of up to 70 % over the entire vehicle's life-cycle can be achieved. When comparing FCEVs to ICEVs, a significant reduction in CO_2-eq. emissions can be seen, despite the nature of hydrogen's production from natural gas.

Based on the obtained results, a conclusion can be drawn that BEVs and CNG/CBG vehicles achieve the lowest total life-cycle emissions when exclusively charged with green electricity and refueled only with biogas, respectively. Despite the fact that electrified vehicles, in general, are heavier than conventional vehicles due to the extra weight of the Li-Ion batteries and, in the case of PHEVs, the additional electric motors, these typically achieve higher life-cycle emission savings than ICEVs. Only when comparing light, and thus small, ICEVs with heavy EVs or PHEVs, no emission savings can be achieved if renewable electricity is not available.

4.3. Total life-cycle emissions relative to peak motor power

Generally, heavier vehicles require an increased peak motor power to reach dynamic driving characteristics similar to city, small or compact cars. Therefore, vehicle manufacturers equip heavier vehicles with more powerful drivetrains, as illustrated in Fig. 5 showing the rated peak motor power $P_{\text{veh,max}}$ of the 790 vehicle variants relative to the vehicle curb weight m_{veh}. The mid-size cars selected in Section 4.1 are indicated by arrow labels. It can be seen that none of the commercially available vehicles with a curb weight of less than 1000 kg has a power rating of more than 100 kW. All vehicles with a higher power rating than 200 kW have a vehicle curb weight of at least 1400 kg. Additionally, there are no vehicles with a lower power than 100 kW that have a higher curb weight than 1800 kg. The vast majority of vehicles weighs more than 2000 kg and has a peak motor power of more than 200 kW. Furthermore, it can be seen that gasoline vehicles have the highest power-to-weight ratio as long as the curb-weight does not exceed 2000 kg. For higher curb weights, the power-to-weight ratio of BEVs and PHEVs is comparable to that of gasoline vehicles.

Table 4
Coefficients for normalized life-cycle emission estimation relative to the peak motor power according to (10).

Energy source	a	b	c
Gasoline	$3.934 \cdot 10^{-6}$	$5.981 \cdot 10^{-1}$	100.3
Diesel	0	$5.260 \cdot 10^{-1}$	96.05
CNG	0	$3.858 \cdot 10^{-1}$	70.14
CBG	$-1.335 \cdot 10^{-3}$	$3.663 \cdot 10^{-1}$	14.96
Gasoline PHEV Conv.	$-3.628 \cdot 10^{-4}$	$4.318 \cdot 10^{-1}$	56.38
Gasoline PHEV Renew.	$-2.012 \cdot 10^{-4}$	$2.449 \cdot 10^{-1}$	29.32
BEV Conv.	$-1.296 \cdot 10^{-4}$	$2.000 \cdot 10^{-1}$	63.75
BEV Renew.	$-1.209 \cdot 10^{-4}$	$1.058 \cdot 10^{-1}$	13.60

Considering these results, it can be seen that vehicles with a higher peak motor power have an increased curb weight and, hence, these consume more fuel/energy [58]. Thus, it becomes obvious that commercially available vehicles with a high power rating emit more GHG than those with a lower power rating. To depict this relation, Fig. 6 shows the normalized CO_2-eq. life-cycle emissions $E_{\text{life,tot}} / S_{\text{lifetime}}$ of the 790 vehicle variants relative to the peak motor power $P_{\text{veh,max}}$. Similar to (9), for each individual energy source category, an emission function relative to the peak motor power with the form according to

$$E_{\text{life,tot}}(P_{\text{veh,max}}) = a \cdot P_{\text{veh,max}}^2 + b \cdot P_{\text{veh,max}} + c \tag{10}$$

is determined, with a, b and c being the coefficients to be estimated/ fitting coefficients. In Table 4, the parameterized values of the coefficients for each individual energy source are listed.

It can be seen that the emission-power effect is more pronounced (derivative of $E_{\text{life,tot}}(P_{\text{veh,max}})$ is higher) for ICEVs than for BEVs. For example, the coefficient b shows that the derivative of the emission-power ratio of gasoline vehicles is about three to six times higher than that of BEVs when recharged with conventional and renewable electricity respectively. Furthermore, Fig. 6 shows that the GHG emissions of BEVs, when recharged with conventional electricity, correspond to half (for $P_{\text{veh,max}} < 100\,\text{kW}$) down to a third (for $P_{\text{veh,max}} \approx 500\,\text{kW}$) of those of ICEVs. When exclusively recharged with green electricity, the emissions are even reduced by a factor of 10 (for $P_{\text{veh,max}} < 100\,\text{kW}$) to 15 (for $P_{\text{veh,max}} \approx 500\,\text{kW}$). This relation can be explained by the fact that ICEVs in comparison to BEVs and PHEVs do not have the possibility to utilize regenerative braking, which converts the kinetic energy of the vehicle back to electrical energy. Additionally, the WLTP efficiency of a combustion engine (≈30 % [59]) is significantly lower than that of an electric drivetrain (>90 % [60,61]).

4.4. Problems in data acquisition and comparability

During the acquisition of the vehicle data, several problems were encountered, which are described in the following paragraphs. For the calculation of the production and recycling emissions, the vehicle curb weight and the battery gross capacity have been primarily used. However, manufacturers often do not provide the data in a globally standardized form. Thus, they either provide the German Institute for

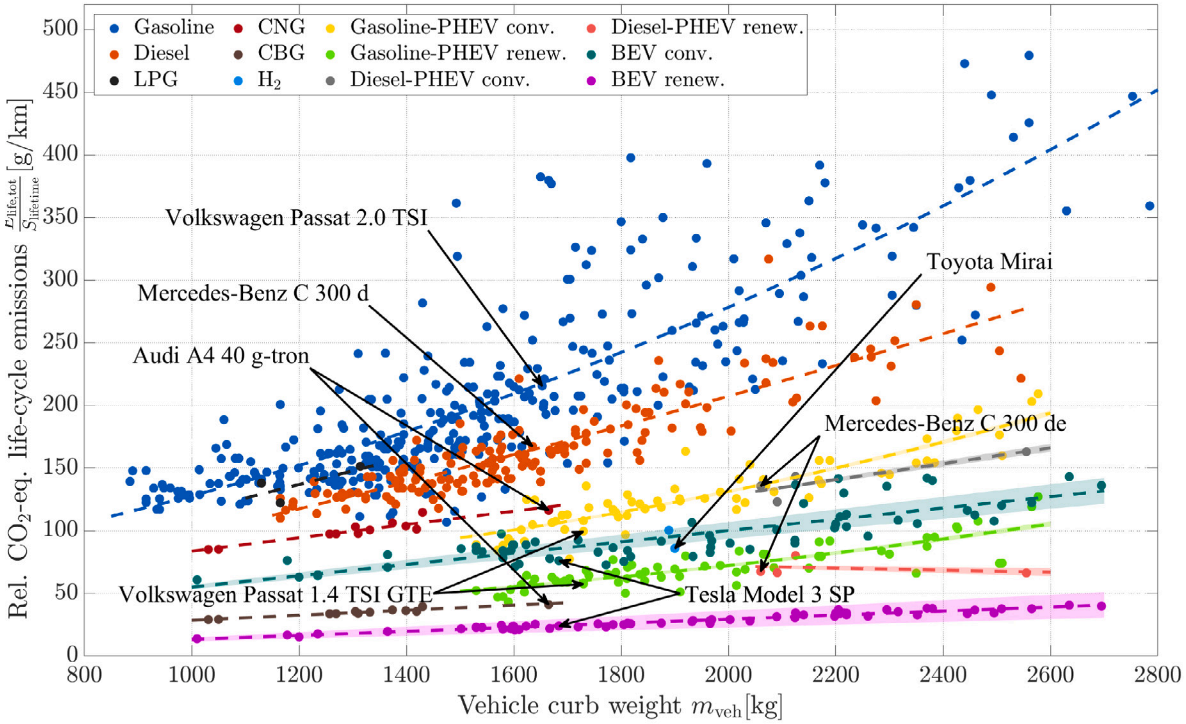

Fig. 4. Normalized CO_2-eq. life-cycle emissions relative to the vehicle curb weight.

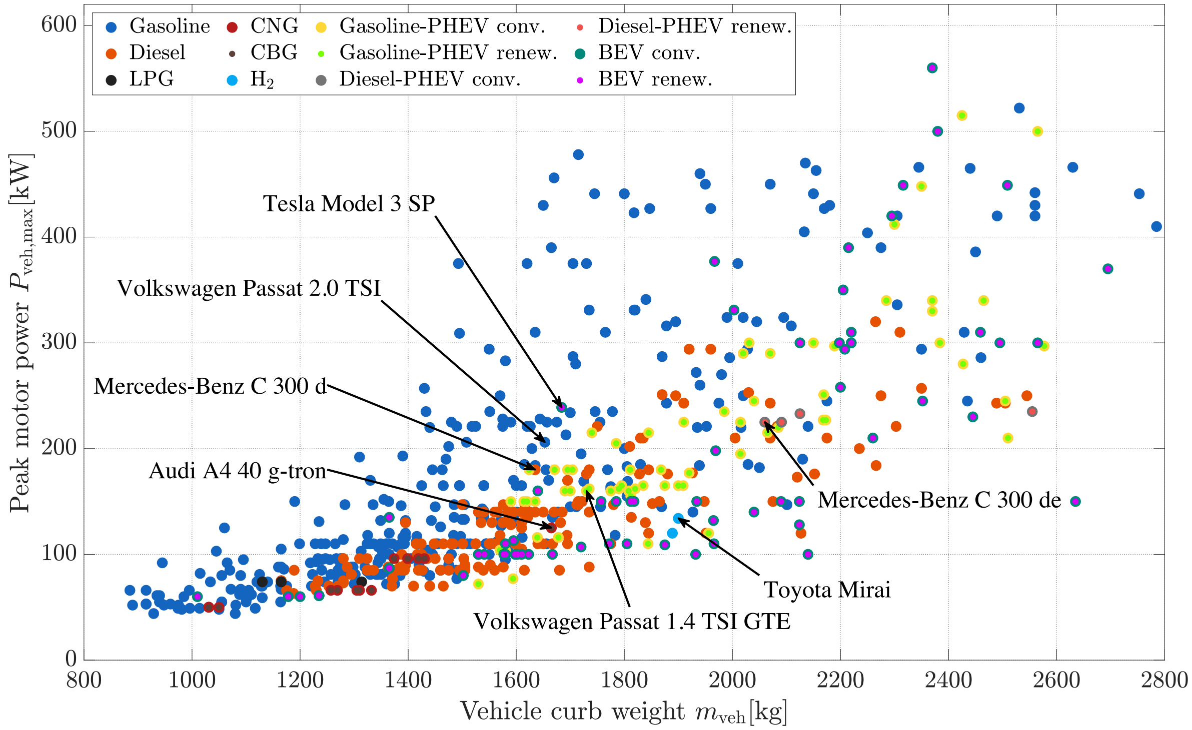

Fig. 5. Peak motor power relative to the vehicle curb weight.

Standardization (DIN) (car with all the fluids necessary for operation, including a 90 % full tank of fuel) or EU standard value (DIN figure plus 75 kg for the driver) for the vehicle curb weight. Furthermore, vehicle manufactures might publicly use the battery net instead of the gross capacity, since it is of more interest for the consumer. Therefore, inadequate and missing vehicle data had to be adapted or accumulated from sources like car magazines', websites or online forums. Additionally, it is not clear how the supply chains differ between vehicle manufacturers and different vehicles produced by the same car brand. Moreover, the actual manufacturing location of each vehicle as well as the origin of the battery cells and raw materials can have an impact on vehicles of the same type. Since only the most basic configuration of each vehicle has been considered for the comparisons, all additional equipment was neglected. For example, this means that the production emissions of

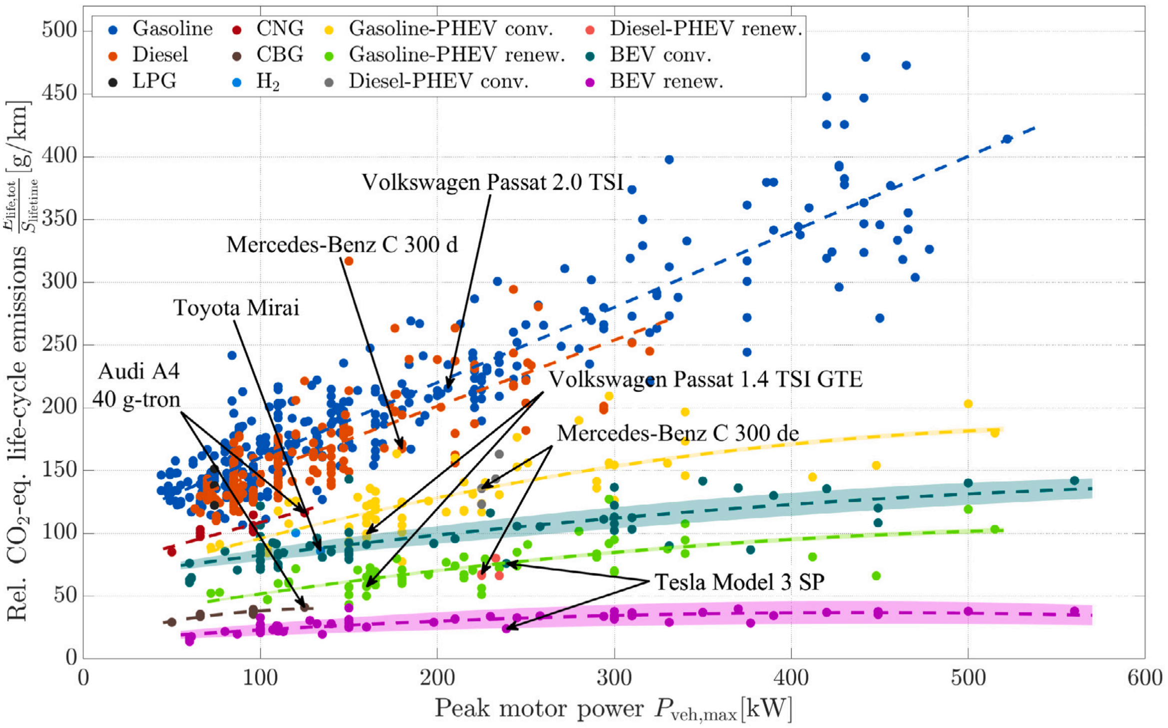

Fig. 6. Normalized CO_2-eq. life-cycle emissions relative to the peak motor power.

luxury vehicle versions' leather seats, cameras, Radio Detection And Ranging (RADAR) and Light Detection And Ranging (LiDAR) sensors, different transmission options, all-wheel-drive systems, etc. were not necessarily included in the calculations.

Furthermore, the emissions associated with the fuel production and provisioning can strongly differ depending on the location. Especially, the emissions values for CBG or hydrogen in comparison to fossil fuels can significantly differ. This is due to the reason that there are multiple profitable production techniques for CBG and hydrogen, which have different climate change impacts. Similarly to these alternative fuels, the WtT emissions of gasoline and diesel caused by crude oil production, shipping and refining are subject to the location of the processes. Since most countries obtain their fuels from a variety of different locations, an averaged value is used in this study. Further detailing of each individual fuel's WtT emissions exceeds the scope of this paper.

Generally, the large-scale availability of certain energy sources was also not extensively considered within the scope of this paper. For instance, CNG/CBG fueling stations are available in most parts of Europe, but these are still rare in comparison to LPG stations. Both LPG and CNG vehicle types are usually suitable for bivalent usage, which means that they have an additional gasoline tank to extend their driving range. However, the utilization of small amounts of gasoline has not been taken into account for these vehicles within the study presented here. Although CBG powered vehicles produce significantly less GHG emissions in comparison to ICEVs, the sustainable supply of biogas is limited to the available amount of manure, waste, etc. Moreover, the emissions produced by cattle farming, from which the manure partially originates for biogas production, are not included in this calculation since only the waste products are used.

Due to the usage of the UF for PHEVs, the WLTP energy consumption values are potentially more inaccurate compared to the real-world consumption of other vehicle types. The WLTP values suggest that PHEVs are recharged almost daily, because of their limited electric driving range, which is not possible for many vehicle owners/drivers. Additionally, manufacturers typically provide the fossil fuel consumption of PHEVs, whereas the electric energy consumption might be omitted because it is not part of any CO_2 emission regulations. However, for this study, this aspect was crucial for the proper calculation of the WtW emissions from PHEVs.

Currently, only two different FCEVs are available for purchase on the market. Reliable studies on fuel cells' production emissions are yet to be published. Especially, since the effects of mass production cannot be foreseen at the moment, the production emissions associated with the fuel cell itself are neglected within the scope of this paper. However, the emissions caused by the small traction battery used in FCEVs are included in the calculations underlying the vehicles' production emissions.

4.5. Discussion and practical implications

The results obtained from this study show that although electrified vehicles produce more GHG during their production due to the energy intensive production of the Li-Ion batteries, their overall lifetime GHG emissions are lower compared to conventional vehicles. When used with renewable energies, their emissions can be further reduced. As expected, the total life-cycle GHG emissions are strongly dependent on the vehicles' curb weight. As shown in Fig. 4 this dependence can be described as a quadratic function for ICEVs and as a linear function for EVs, respectively. This can be explained by EVs' ability to regenerate some of the energy used to accelerate the vehicle when braking. While with ICEVs the production emissions as well as the fuel consumption increase with weight, this is only the case for production emissions with EVs. A similar phenomenon can be experienced with the emissions dependent on peak motor power. Here, the dependence is mostly linear for ICEVs while it is negatively quadratic for EVs. This can be explained by the fact that EVs with higher peak motor power tend to be more sporty and aerodynamic vehicles which therefore use less energy and produce less GHG emissions during utilization. The sensitivity analysis for different battery production emissions additionally shows that battery production only has a small impact on the total life-cycle GHG emissions of a vehicle.

Comparing these results to other recent studies, similarities can be noticed. Comparing the production emissions from the single vehicle comparison to the results obtained from [14], it can be seen that there are hardly any deviations within the results. The total life-cycle emissions are lower for the ICEV in [14], because only 200.000 km of total traveled distance until decommissioning were included into the calculation. However, the BEV's total GHG emissions are lower in this study since it was assumed that the battery pack can be used until the vehicle's EoL. The results on vehicle production emissions obtained by [17] are also similar to this study. The relative difference between the BEV's and the ICEV's production emissions is 59 % compared to 49 % in this study. As stated by [26], the production emissions contribute to vehicles' total GHG emissions by 10 % in the case of an ICEV and by 40 % in the case of a BEV, respectively. These values are similar to this study's results for ICEVs, which are 15 to 19 %. BEVs, however, emit 58 % of their life-cycle emissions during production if conventional electricity is used. The differences can be explained mainly by the used drive cycles and total traveled distance as well as the electricity's composition. Comparing the findings in [5] to this study, it becomes clear that the results in the single vehicle comparison are realistic. Although a different vehicle category and total distance traveled was considered, BEVs generally emit the lowest amount of GHG. PHEVs and vehicles with alternative fuels are comparable to each other while gasoline and diesel ICEVs emit the highest amount of GHG. Since the total distance traveled was presumed to be only 150.000 km in [5], the emissions per km are overall higher compared to this study.

Generally, the obtained results can be used to approximate the individual GHG emissions from a certain passenger car compared to other vehicles. This is possible for most of the currently, commercially available vehicles in Europe but also for similar vehicles in other markets. The results from this study can help consumers to choose the right vehicle for their personal use if GHG emissions are an important influence on the decision. Furthermore, companies can estimate the impact on their GHG emissions when changing their vehicle fleet from conventional vehicles to vehicles with alternative powertrains. However, the calculations within this study only apply to the chosen values for the specific emissions, fuel consumption measured in the WLTP cycle and for 230.000 km of total traveled distance until decommissioning. The real-world emissions strongly depend on these parameters and need to be adapted to the vehicles' specific application case. Furthermore, vehicles with hybrid powertrains or multiple possible fuels such as CNG/CBG/LPG vehicles produce a variable amount of GHG during utilization dependent on the actually used fuel or energy source.

5. Conclusion and future outlook

This paper has dealt with the modeling and quantification of the total CO_2-eq. life-cycle emissions from a broad selection of commercially available passenger cars with different powertrains and energy sources. In total, 790 different vehicle variants are considered. The total life-cycle emissions are divided into the production, utilization and recycling emissions. Thus, this paper provides comprehensive and holistic comparisons of vehicles' GHG emissions.

The results show that the combined sum of the production and recycling emission values (absolute) of gasoline, diesel and CNG vehicles are small in comparison to the utilization emissions ($<33\,\%$). For example, the obtained utilization emissions of a Volkwagen Passat 2.0 TSI (gasoline) correspond to $46\,865\,\mathrm{kg}$ CO_2-eq., whereas the production and recycling emissions are about $7538\,\mathrm{kg}$ CO_2-eq. and $-4843\,\mathrm{kg}$ CO_2-eq., respectively. The additional production emissions of similarly sized PHEVs compared to classical combustion engine vehicles vary from 15 % to 37 %, while for BEVs, the production emissions are increased by about 49 %. For example, the additional production emissions of a Tesla Model 3 SP approximately correspond to the driving emissions of a Volkwagen Passat 2.0 TSI after 18 000 km. Similar results have been obtained for the vehicle recycling emissions, which have a positive climate change impact (emission saving). These counterbalance the climate change impact of the production emissions by a large extent (60 % to 65 %). Compared to gasoline powered cars, diesel vehicles can reduce the utilization emissions by 24 %, CNG vehicles by 49 %, FCEVs by 65 %, gasoline PHEVs by 58 %, diesel PHEVs by 41 % and BEVs by 72 %, when using conventional electricity (Germany; $0.401\,\mathrm{kg}\ CO_2-\mathrm{eq./kWh}$). When exclusively refueling with CBG or recharging with green electricity, the emissions savings are 86 % for the CBG vehicle, 79 % for the gasoline PHEV, 75 % for the diesel PHEV and 97 % for the BEV.

Overall, it has been shown that vehicles with higher curb weight produce more GHG emissions both during production and utilization (as well as in total). For vehicles with combustion engines, this correlation can be approximated with a quadratic function while it is rather linear for electrified vehicles. Considering the total vehicle life-cycle emissions relative to the peak motor power, a linear correlation has been observed. Nonetheless, the observed gradients for ICEVs is larger than those for BEVs. For example, the GHG emissions of BEVs in comparison to ICEVs are reduced by a factor of 10 (for $P_{\mathrm{veh,max}} < 100\,\mathrm{kW}$) to 15 (for $P_{\mathrm{veh,max}} \approx 500\,\mathrm{kW}$), when exclusively recharged with green electricity.

Summarizing the key-results; it has been shown that BEVs produce the lowest amount of total life-cycle emissions, especially when using electricity produced from renewable energy sources. Up until today, the majority of commercially available hydrogen is produced from natural gas, which worsens the actual climate change impact of FCEVs in comparison to BEVs (using green electricity). The GHG emissions emitted by FCEVs are lower than those of CNG vehicles. Nevertheless, when fueled with CBG, the utilization emissions of CNG vehicles can be significantly reduced.

Based on the mentioned results, the following major conclusions can be drawn. Fully electrified vehicles, such as BEVs and FCEVs, and biogas powered gas vehicles should be the favored solutions for vehicle owners. It is important that the used electricity, hydrogen and biogas is produced in sustainable and environmentally friendly ways, which might be economically difficult for biogas and hydrogen when considering a larger scale.

Since fossil energy sources will likely lose parts of their current market share, in a future work updated emission values need to be used for all calculations. This could lead to a larger production of biofuels and, thus, ICEVs could become more competitive to EVs again, as for example shown by CBG vehicles in this study. A future version of this study could also increase the complexity of the acquired data. Through a potential usage of the official vehicle registration statistics, the number of different vehicles can be increased. Potentially, emissions caused by vehicle development could be estimated by the sales figures as well as the country's energy mix in which the development took place. In Addition to an overall larger quantity of different vehicles, the production locations could be used to estimate the GHG emissions of the respective supply chains. In the course of this, for each EV, the production location of the batteries can be used to determine the exact production emissions. All the necessary data can be acquired by governmental organizations like the German Kraftfahrt-Bundesamt. Since the real-world fuel consumption or real driving emissions of every vehicle must be provided by vehicle manufacturers in the future, the accuracy of the results, especially for PHEVs (no UF would be required any longer), could be improved.

As previously mentioned in 4.4, there were some problems to be faced by this study which can be solved within future works. LCA generally has its limitations as stated by [62]. Accordingly, energy and exergy analyses can be used as an alternative to LCA in future publications. Especially exergoenvironmental analyses, such as performed in [63] on different bioenergy systems, could be performed on passenger vehicles and their individual energy sources.

CRediT authorship contribution statement

Johannes Buberger: Concept, Methodology, Formal analysis, Data curation, Visualization, Writing – original draft. **Anton Kersten:** Methodology, Formal analysis, Visualization, Supervision, Writing – original draft, Writing – review & editing. **Manuel Kuder:** Methodology, Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Richard Eckerle:** Methodology, Writing – review & editing, Project administration. **Thomas Weyh:** Supervision, Writing – review & editing, Project administration, Funding acquisition. **Torbjörn Thiringer:** Writing – review & editing, Funding acquisition.

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.

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