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Comparison of advanced fuels—Which technology can win from the life cycle perspective?

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ABSTRACT

Alternative drivetrains and advanced fuels are considered as promising methods for providing sustainable mobility. To understand the overall environmental impact of passenger vehicles on global warming potential (GWP) and primary energy demand (PED), a life cycle assessment (LCA) was conducted for currently popular sport utility vehicles (SUVs) and compared with that for compact cars. This LCA considered vehicle production as well as the use phase and fuel production; it is a well-to-wheel approach. To carry out this approach, different production processes of alternative vehicle types—plug-in hybrid (PHEV), hybrid (HEV), electric (EV), and fuel cell (FCEV) vehicles—were analyzed and compared with conventional internal combustion engine vehicles (ICEV). Furthermore, the emissions and PED due to the production and use of different advanced fuels, such as cellulosic bioethanol, biomass-to-liquid fuel, synthetic gases (methane and hydrogen) via power-to-X, and electricity from wind power, were compared with those of conventional gasoline, natural gas, steam-reforming hydrogen, and EU-28 electricity mix.

It was found that alternative drivetrains, especially those for FCEV and EV, show a higher GWP during production of up to 50%. However, EVs have a 45% and FCEVs a 35% lower GWP than that of ICEVs, based on a lifetime of 200,000 pkm if operated with traditional fuels. Furthermore, the LCA shows that PHEVs, operated by electricity from wind and cellulosic bioethanol, exhibited the lowest GWP (33 $g_{CO2,\ eq}$ per pkm) of all analyzed SUV types. However, compact cars presented a different conclusion. For compact cars, EVs had the lowest GWP with 28 $g_{CO2,\ eq}$ per pkm. In terms of PED, a similar behavior to that of GWP was found.

1. Introduction

In 2016, the transport sector was responsible for 33% of all the energy consumed in the European Union (EU) (Directorate-General for Energy (European Comission), 2019). Road transport was, by far, the mode with the largest energy consumption, with a share of 74% of the total energy demand for transport services in the EU. The EU transport sector depended almost entirely (93%) on crude oil products (European Environment Agency, 2018), accounting for 24% of the total greenhouse gas (GHG) emissions in the European Union (including international aviation) (Eurostat, 2018). Such a high share of fossil-based fuel must be reduced if the present climate is to be preserved.

To reach EU climate goals, several CO_2 saving measures are demanded. One option would be fuel savings by sustainable driving manners. According to (Ayyildiz et al., 2017) and (Lois et al., 2019) this could reduce fuel consumption by approx. 6%. Political actions that e.g. increase direct CO_2 emission taxes could further reduce the GWP of the transport sector (Yang et al., 2018). Furthermore, improvements in drivetrain technology itself are an important aspect. With a powertrain energy efficiency of 65%, electric vehicles are a promising alternative to conventional internal combustion engine vehicles (ICEV) (powertrain energy efficiency of 16–22%), as the efficiency of the electric motor is comparatively high (Ahman, 2001). With electric vehicles, either apply a battery system for electricity storage (EV) can be applied or a fuel cell can be placed in operation for electricity generation on-board, with hydrogen as potential energy carrier (FCEV). Utilized H_2 is, to a large extent, currently produced via steam methane reforming of natural gas but could also be produced from (renewable) electricity in water electrolysis (power-to-gas technology). Although electric vehicles have huge potential for the mitigation of global warming, GHG

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emissions over the entire life cycle strongly depend on the type of electricity that is utilized. For instance (Bauer et al., 2015), emphasize that the utilization of electricity from renewable sources is crucial for both battery-operated electric vehicles and hydrogen-powered fuel cell vehicles; otherwise, GHG emissions could be even higher than those from ICEV powered by conventional fossil fuels.

Another possible way to reduce the usage of liquid fossil-based fuels is to substitute them with gaseous or advanced fuels. The use of compressed natural gas (CNG) as gaseous fossil fuel could lead to CO_2 reductions of up to 50% (Lajevardi et al., 2018). Advanced fuels are considered an option because they can be climate neutral or have negative GHG emissions. In terms of this assessment, they are based on either biomass or renewable electricity. Both can be used to produce synthetic biofuels or renewable hydrogen. Electricity could also be used directly as a renewable energy carrier for mobility. Therefore, synthetic biofuels, as a substitution for fossil-based fuels, are considered as a viable option to mitigate GHG emissions in the transport sector, with the advantage of an easy adaptation process, as their utilization neither requires substantial changes to car engines nor to the refueling infrastructure (Fiorese et al., 2013). Considering these facts, policy targets have been formulated for the use of advanced fuels in the transport sector. In the context of the EU, the Renewable Energy Directive (RED, 2009/28/EC) as well as the Fuel Quality Directive (2009/30/EC) build upon the current legislative framework, containing the mandatory blending targets for biofuels (European Union, 2009). RED 2009/28/EC will be replaced by RED II 2018/2001/EU in 2021 (European Union, 2018).

As advanced fuels have huge mitigation potential for GHG emissions in the transport sector, some have already been evaluated in several life cycle studies (e.g. (Nordelöf et al., 2014), (Bauer et al., 2015), (Reiter and Lindorfer, 2015), (Morales et al., 2015), (Evangelisti et al., 2017), (de Souza et al., 2018), (Pero et al., 2018) and (Yu et al., 2018)). However, for an objective comparison of transport options, the observation of the entire life cycle from raw material extraction, vehicle manufacturing, fuel production, and utilization phase to end-of-life treatment is indispensable. Currently available studies mostly investigate only on one of the different aspects in detail or focus on one drivetrain system. This means that they either focus on a detailed use phase assessment by comparing different fuels or on a detailed assessment of the production phase by analyzing life cycle inventories of different drivetrain systems.

Bauer et al. concluded that reduction in climate change could be obtained by using electric vehicles in combination with renewable electricity, but it does not include a detailed production step assessment (Bauer et al., 2015). The same conclusion was stated in a study by Del Pero et al., which compared ICEVs with EVs (Pero et al., 2018). Nordelöf et al. present a review on 79 different LCA studies on electric vehicles and one of their synthesized conclusions is that the type of electricity generation has the strongest influence on the global warming potential of electric vehicles (Nordelöf et al., 2014). This also applies for H_2 production from electricity via water electrolysis, as described by Reiter and Lindorfer (2015). Negative environmental impacts of EV and FCV, e.g. in terms of toxicity or metal depletion, are particularly caused by the additional application of batteries or fuel cell systems and the related increase in material demand for vehicle manufacturing (Bauer et al., 2015; Evangelisti et al., 2017).

When it comes to biofuels, several LCA studies showed a decrease in global warming potential compared to fossil fuels. A review on more than 100 case studies by Morales et al. show that lignocellulosic ethanol always leads to a reduction in GHG emissions, but varying results are achieved for several other impact categories (Morales et al., 2015). Further, a study from de Souza et al. (de Souza et al., 2018) compared ICEVs, EVs and PHEVs with a strong focus on bioethanol and the Brazilian transportation system and showed a positive environmental performance of EVs and the bioethanol usage in conventional drivetrains. A similar study, comparing gasoline vehicles and EVs for the Chinese system, showed that EVs have a higher GWP compared to gasoline vehicles due to the high share of coal in the electricity mix of China (Yu et al., 2018).

The conclusion of most of the studies is, that advanced renewable fuels generally presume a lower environmental impact than fossil fuels, nevertheless no technology dominates performance in all environmental dimensions (Ashnani et al., 2015; Bicer and Dincer, 2018).

The presented life cycle assessment (LCA) combines an analysis of the production phase of conventional and alternative drivetrain vehicles and an assessment of the use phase of these systems using conventional and alternative energy carriers for mobility to provide a full environmental overview of individual mobility in terms of climate change. Therefore, this study focuses on the environmental impacts of global warming potential (GWP) and primary energy demand (PED) of mobility provision with a strong focus on advanced fuels, including the impacts of vehicle manufacturing, via a detailed life cycle inventory (LCI). The results could provide indications how different currently available fuels could be enhanced or substituted to improve the carbon footprint of the powertrain systems that they operate. Furthermore, currently popular sport utility vehicles (SUV) are compared with compact cars in terms of the energy demand and GHG emissions in the use phase for the identical drivetrain system.

2. Methods

The environmental impacts of advanced mobility options are examined with the LCA methodology according to ISO 14040 (International Organization for Standardization, 2006), including the four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. LCA methodology is described extensively in the literature (Finnveden et al., 2009; Guinee, 2002; Guinée et al., 1993; Klopffer, 1997; Reap et al., 2008; Rebitzer et al., 2004), and a further detailed description of the method is omitted here. However, the relevant applied methodologies and definitions for the conducted LCA of new mobility concepts and technologies are described below.

2.1. Goal and scope definition

The goal of this LCA is to examine the environmental impact of mobility provision with advanced fuels in comparison to reference fossil fuels. Advanced fuels include cellulosic ethanol, BtL fuel, and SNG from residual biomass, hydrogen from renewable electricity, and electricity from wind power. The investigated reference fuels are gasoline, electricity from the EU-28 mix, compressed natural gas (CNG), and hydrogen from natural gas steam reforming. The system boundaries of the LCA are shown in Fig. 1.

According to (Guinee, 2002), the ideal concept of LCA refers to a “cradle-to-grave” system boundary, which includes the entire product life cycle from extraction of raw materials and energy carriers to recycling or disposal. The LCA study is designed as a “well-to-wheel” LCA, including fuel production, and the manufacture and utilization of the vehicle (Jensen et al., 1998). The geographical system boundary strongly influences the mix of electricity generation and energy supply structure, as well as transport distances, and is determined by Europe (EU-28 countries). The year 2018 is set as the temporal reference point, as preference is given to the collection of up-to-date information

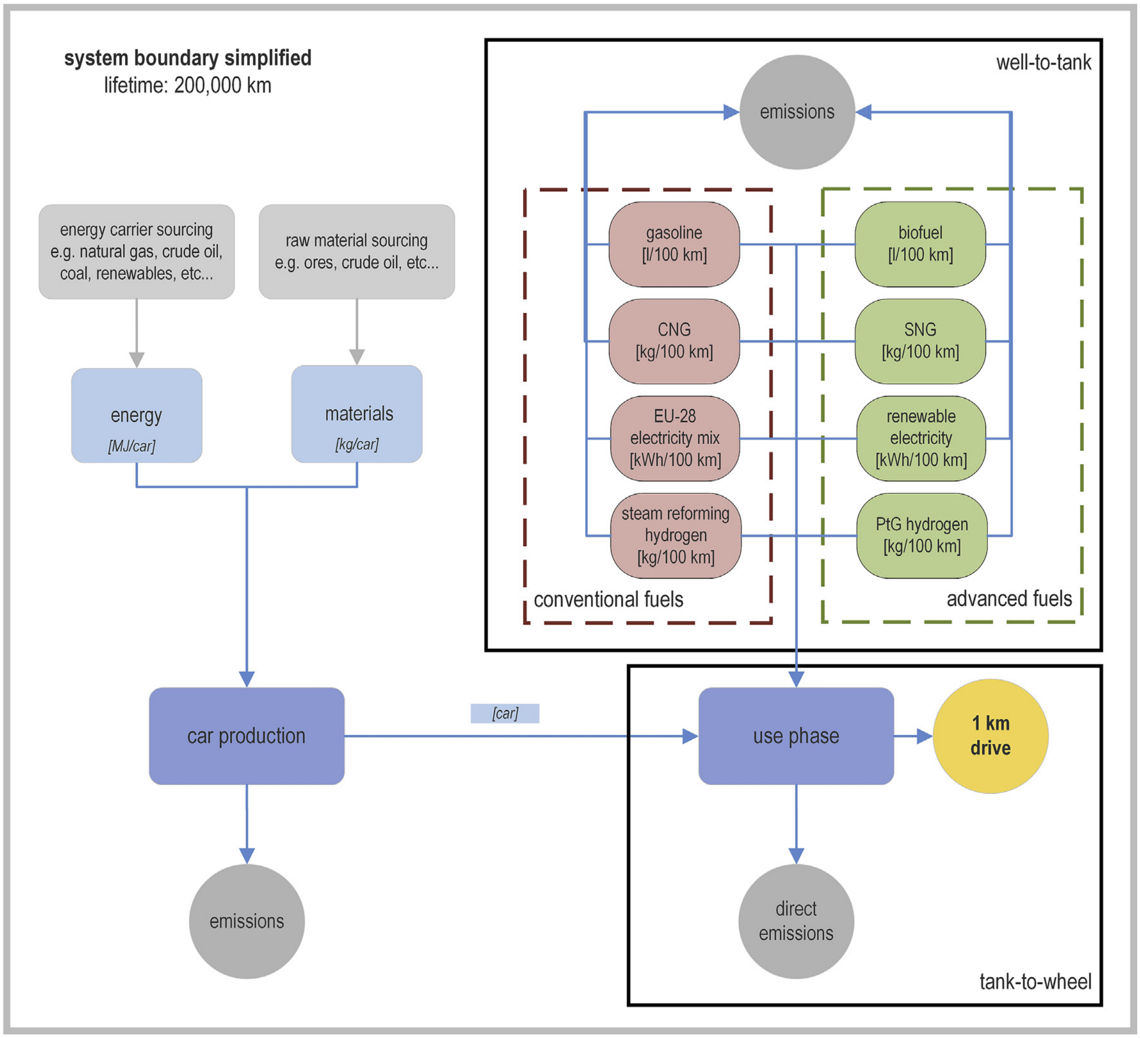

Fig. 1. System boundaries of the performed LCA.

relating to the process steps as well as the LCI.

The determination of process function and functional unit is important for an LCA study as it secures the comparability of the results as also concluded by (Cooper, 2003; Lagerstedt et al., 2003; Matheys et al., 2007; Sauer, 2012). The function of the studied processes is the provision of mobility; thus, the functional unit is defined to be 1 passenger kilometer (pkm) travelled by the vehicle in regard. This functional unit is based on a lifetime of 200,000 pkm, which is an assumption based on the 207,000 km lifetime in the GREET database (Argonne National Laboratory, 2018), 180,000 km lifetime by (Ellingsen et al., 2016), and the given warranty from different electric vehicle producers (i.e. Tesla Model X (Tesla Germany GmbH, 2019) and Hyundai IONIQ (Hyundai Import G.m.b.H., 2019)) of 200,000 km.

2.2. Inventory analysis and data collection

The LCI is defined as the compilation and quantification of inputs and outputs for the given product system throughout the entire life cycle (Suh et al., 2004), based on material and energy balance. Data availability is often lacking for novel process options; thus, the LCI often relies on information obtained from the literature. Furthermore, estimations based on stoichiometric equations as well as generic data are utilized for quantifying inputs and outputs. The presented LCA applies the GaBi ts 8 Professional database (thinkstep) (thinkstep AG, 2019). Further, the ecoinvent v 3.3 database, and the GREET LCA-model (Argonne National Laboratory, 2018) for data collection and life cycle modeling were used as well. The ecoinvent v 3.3 database was directly imported to the GaBi ts 8 Professional tool as extension database, while values from the GREET LCA database were manually added to the related process and linked with an associated process of the GaBi ts 8 Professional database or the ecoinvent v 3.3 database (see Supplementary material).

The system boundary is shown in Fig. 1. The level of detail in the LCI is high, in accordance with methodological guidelines (Del Duce et al., 2013; European Commission, 2010).

As already mentioned, the analyzed vehicles are based on the GREET LCA database. This database subdivides the vehicle into the following categories (Burnham, 2012):

- Chassis: includes braking system, wheels, tires, and cradle.
- Vehicle Body: includes body panels, glass, exterior, doors, and seating.
- Powertrain system: includes engine, fuel cell stack, and powertrain thermal and electrical system.
- Transmission system: includes gearbox, torque converter, and controls.

- Generator
- Fuel cell auxiliaries/on board storage: includes hydrogen tank and water supply system.
- Traction motor
- Electronic controller
- Batteries
- Vehicle fluids
- Vehicle assembly

Adaptations of the GREET values were made in terms of the Li-ion battery capacity for EV, PHEV, and HEV. This was done, since most of the data sheets from currently available SUVs on the vehicle market (i.e. Audi eTron, Tesla Model X and Volvo XC60), have higher battery capacities. The capacities given in the GREET database were extended to 100 kWh for EV, 14 kWh for PHEV, and 10.4 kWh for HEV to reflect the current fleet. Furthermore, material flows according to the battery given in the GREET database were increased with a linear interpolation according to the assumption of a linear correlation.

2.3. Operation phase

Besides lifetime, other important values considered for the LCA were fuel consumption and exhaust gas emissions. Fuel consumption for provision of mobility is strongly dependent on the applied vehicle type. Furthermore, different assumptions were made as shown in Table 1. Fuel and energy consumptions for the vehicles are based on information from the manufacturer of Audi Q5 (Porsche Austria GmbH & Co OG, 2019a) and Volvo XC60 for the SUVs (Volvo Car Austria GmbH, 2019), and Hyundai IONIQ (Hyundai Import G.m.b.H., 2019) and VW Golf (Porsche Austria GmbH & Co OG, 2019b) for the compact car category, harmonized with literature data from the GREET database (Argonne National Laboratory, 2018) and Cavallaro et al. (2018).

Besides data for fuel and energy consumption, further assumptions were made. For fossil-based mobility the GWP of the use phase resulting from fuel ignition was accounted for. The assumed data are shown in Table 1. The emissions of the PHEV were assumed to be the lowest at 44 g CO_2-eq per pkm, while gasoline ignition in an ICEV was assumed to have the highest value with 177 g CO_2-eq, these values are based on Cavallero et al. (Cavallaro et al., 2018) and cross-checked via representative cars from Audi (Porsche Austria GmbH & Co OG, 2019a) and Volvo (Volvo Car Austria GmbH, 2019).

To provide better comparability with the GWP results, the SUV-sized vehicles are compared with smaller cars. For this, further assumptions of battery size, and electricity and fuel consumption for vehicles of the size of a compact car, such as VW Golf, were made. Table 2 shows the assumptions for this comparison.

It can be expected that small electric and hybrid vehicles use a battery with a significant reduction in capacity compared to SUVs. Based on sales information of different car manufacturers, such as Hyundai or VW, an EV battery capacity of approximately 36 kWh, a PHEV battery capacity of approximately 9 kWh, and an HEV battery capacity of approximately 2 kWh were assumed. The assumed reduction in energy consumption and exhaust gas emissions mostly varied between 25% and 40%. Besides material flows according to battery size, no changes to material flows in other parts of the car were made. This is an assumption based on the GREET database, and because many manufacturers deploy platforms that are built into different models, this simplification is close to practical reality. According to technical specifications provided by car manufacturers, such as Audi, there is no significant weight difference between a compact-sized car (Audi A3 with a weight up to 1.64 t) and an SUV (Audi Q5 with a weight up to 1.84 t) (Porsche Austria GmbH & Co OG, 2019a).

2.4. Impact assessment

A Life Cycle Impact Assessment (LCIA) encompasses the working steps of characterization and normalization of LCI results and is conducted with the LCA software program GaBi 8.7 (thinkstep) (Reap et al., 2008). The material and energy flows of the life cycle inventory are attributed to impact categories in the categorization step by the utilization of characterization factors (Guinee, 2002). The applied impact assessment method is CML 2001. CML is a problem-oriented approach using midpoint categories, which implements the ISO 14040 standard (Dreyer et al., 2003; Guinee, 2002). Further, its factors for characterization of the different LCA categories are applicable especially for an European point of view (Bach and Finkbeiner, 2017). The impact categories are global warming potential (kg CO_2-eq) and primary energy demand (MJ), which belong to the so-called key performance indicators (KPIs) in sustainability assessment.

3. Description of the advanced fuel production processes, reference systems, and vehicle powertrain systems

This section describes the advanced fuel production processes in detail and provides data on their material and energy balance. Furthermore, the applied vehicle technologies are characterized, and information on the material and energy demand for vehicle manufacturing, as well as fuel consumption in the utilization phase, is provided.

3.1. Data on advanced fuel production processes

Advanced fuels for non EVs are produced either via bio, thermo or electro chemical processes. Therefore, this article includes the advanced fuels: cellulosic ethanol produced in a biorefinery, biomass-to liquid fuel from gasification and hydrogen and SNG from electrolysis operated by renewable electricity. They were considered, since they are the classic and primarily discussed and promoted options for renewable fuels in each category (Chiaramonti and Goumas, 2019). As renewable electricity for the electrochemical process and as renewable energy carrier for EVs electricity from wind power was chosen.

These fuels are considered as advanced fuels because they are produced from renewable feedstock or renewable energy. Furthermore, GHG emissions during the driving process only occur in the case of the burned synthetic fuels (cellulosic ethanol, SNG, or fuel from BtL) and can be considered as CO_2-neutral, because the emitted carbon was used for plant growth or has come from

Table 1
Assumption of electricity and fuel consumption, and exhaust gas emission of SUVs (Cavallaro et al., 2018; Porsche Austria GmbH & Co OG, 2019a; Volvo Car Austria GmbH, 2019).

	Gasoline ICEV	NG ICEV	EV	FCEV	PHEV	HEV
Fuel consumption [MJ/pkm]	2.4	2.19	0	1.3	0.6	1.8
Electricity consumption [MJ/pkm]	0	0	0.7	0	0.6	0
Exhaust gas emissions [g CO_2-eq/pkm]	177	99	0	0	44	133

Table 2
Assumption of electricity, battery size, and fuel consumption and exhaust gas emission of small vehicles (Hyundai Import G.m.b.H., 2019; Porsche Austria GmbH & Co OG, 2019b).

	Gasoline ICEV	NG ICEV	EV	FCEV	PHEV	HEV
Li-Ion battery capacity [kWh]	0	0	35.8	0	8.9	1.6
Fuel consumption [MJ/pkm]	1.6	1.82	0	0.91	0.33	0.88
Electricity consumption [MJ/pkm]	0	0	0.48	0	0.38	0
Exhaust gas emissions [g CO_2-eq/pkm]	134	92	0	0	26	84

another renewable feedstock, e.g., air carbon capture. However, the technology readiness level (TRL) for these technologies is approximately 7. Thus, the TRL is in a range in which worldwide commercial availability is not a reality. R&D process optimization is required, particularly in the field of upscaling, energy efficiency, and process integration, resulting in uncertainties related to data availability for the conducted LCA.

3.1.1. Cellulosic ethanol production process

Cellulosic ethanol production in this paper refers to biochemical pathways, whereas the cellulolytic process consists of enzymatic hydrolysis of pretreated lignocellulosic materials and subsequent fermentation of sugars to ethanol, followed by downstream distillation. The utilization of cellulosic feedstock, such as grass, wood, and crop residues, is more challenging than the utilization of starch-based crops. Cellulosic ethanol is currently under commercialization in Europe, US, and Brazil (Ebadian et al., 2018).

The most important inputs for the biomass conversion process are listed in the supplementary material. Importance in this case is measured in terms of mass, in relation to the entire mass input to the process. There are additionally smaller amounts of chemicals used for processing, although they are not considered at this time. Further work is necessary to examine the share of these additives on the entire mass of inputs (measured in terms of mass). For all inputs with a share $\leq$5% of the total input mass, a cut-off rule is applied. This approach is acceptable according to LCA practice and literature.

3.1.2. Biomass-to-Liquids

For the production of synthetic BtL fuels, first, a synthesis gas is produced from the biomass by means of gasification. In the second stage, a synthetic fuel is produced out of this gas. A typical process is the Fischer-Tropsch synthesis, which results in a first-law efficiency in the range of 49.6–66.7% (Hannula and Kurkela, 2013), depending on the end-product and process conditions. In principle, a broad variety of biomass, including wood and cellulose or lignin-containing plant materials, can be used as feedstock (Gollakota et al., 2018). Although the individual steps for the production of BtL are well known and have been demonstrated successfully at the industrial scale, integrating the various technologies for commercial production of BtL has proven challenging in the past few years (Dimitriou et al., 2018). The inventory data of the electricity generation processes are taken from the ecoinvent v3.3 database and are shown in the supplementary Material.

3.1.3. Electricity generation for utilization in electric vehicles

Electricity can be directly utilized for the provision of mobility in electric vehicles, with the advantages of an emission-free operation and high overall efficiency. However, the utilized type of electricity strongly influences the environmental performance of electric vehicles. Thus, this LCA study examines the EU-28 electricity mix and electricity from wind power as inputs. The inventory data from the electricity generation processes are taken from the GaBi ts 8.7 Professional database and are described in more detail in the supplementary Material.

3.1.4. Hydrogen and methane production via power-to-gas

Power-to-gas is an energy storage technology that utilizes surplus electricity from renewables to split water into hydrogen and oxygen in an electrolyzer (Stolten et al., 2016). The versatile technology system, thus, enables the increased implementation of fluctuating renewable power sources (wind power and photovoltaics) by providing long-term energy storage. Furthermore, the produced H_2 can be utilized for providing mobility by utilization of the energy carrier in fuel cell electric vehicles or in internal combustion engine vehicles. However, the application of H_2 for mobility purposes requires the establishment of a new infrastructure (e.g., H_2 pipelines, H_2 refueling stations). The synthesis of methane from H_2 and CO_2 is an optional step in the power-to-gas system and is considered as SNG in the LCA study, as it is very similar to natural gas. Therefore, the available infrastructure (gas distribution grid, CNG refueling stations, and CNG vehicles) could be utilized (Lindorfer et al., 2018).

The inventory data on hydrogen and methane production via power-to-gas systems have been described in detail by (Reiter and Lindorfer, 2015). The total efficiency of hydrogen and methane production from electricity was determined to be 58% based on the higher heating value of H_2. In this LCA study electricity from wind power is considered as inputs for the power-to-gas process.

3.2. Reference fuels for comparison

Reference processes are analyzed to provide a basis for the comparison of the advanced fuel production processes with existing technologies. Fossil fuels considered in this study are gasoline and natural gas, which are all utilized in internal combustion engines. Hydrogen produced from natural gas in the steam reforming process is considered as input for fuel cell electric vehicles. Renewable reference fuels include upgraded BtL biofuel, SNG, and cellulosic ethanol from wheat straw. These renewable fuels are also utilized in internal combustion engine and hybrid vehicles. Data on the reference processes are taken from the LCA databases GaBi ts 8.7 and ecoinvent v 3.3. Details on the applied processes and characteristics can be found in the supplementary Material.

4. Results

The results show the evaluation of the production processes of the vehicles according to the data gathered from the GREET database and the adaptations made, as mentioned in section 2.2. Furthermore, a comparison of the GWP is provided based on a lifetime of 200,000 km for the different drivetrains and fuels/electricity mixes. Finally, a comparison showing the differences between compact vehicles and the analyzed SUVs is presented.

4.1. Vehicle manufacturing

As mentioned in Section 2, vehicle manufacturing has a significant impact on the GWP of a vehicle during its lifetime. The vehicle technologies differ in components, material demand, and driving performance; thus, it is necessary to include their manufacturing and characteristics in the well-to-wheel analysis. The LCI includes the life cycle stages of the production of vehicle materials, part manufacturing and vehicle assembly, vehicle maintenance, repair, and end of life. Data have been taken from the GREET LCA-model and are given in detail in the supplementary Material.

Five vehicle types with a lifetime of 200,000 km are considered in the LCA study (see Section 2). Based on the information from the GREET LCA-model, the lead-acid batteries must be replaced twice during this lifetime. The Li-ion battery in the EV, PHV, and HEV, and the Ni-MH battery in the FCV do not need to be replaced within this lifetime.

ICEV utilizes conventional fuels such as gasoline, as well as biofuels, for mobility. Based on the compiled LCI, a typical SUV-sized passenger car with an internal combustion engine has an overall material demand of 1915 kg per vehicle, with steel accounting for half of that demand (55%). Vehicle production requires an input of 4452 MJ of electricity and 5759 MJ of thermal energy, which is anticipated from natural gas. It is further assumed that the vehicle assembly occurs in the EU-28.

At 2158 kg per vehicle, the material demand for the EV is higher than that for the ICEV, with steel accounting for 42%. The EV considered in the LCA study has a small lead-acid battery and a 100-kWh Li-ion battery. The vehicle manufacturing including assembly requires an energy input of 6524 MJ of electricity and 15,529 MJ of thermal energy. The fuel cell vehicle has a material demand of 1812 kg and consists of 57% steel. Vehicle assembly, battery, and fuel cell production require 4478 MJ electricity and 5802 MJ thermal energy. The higher energy demand results from the battery production for the EV. In particular, the electrode-drying process is energy intensive (Schmitt et al., 2015). Furthermore, the EV has the highest share of aluminum-based products and the lowest share of steel-based products. This results from the high weight of the battery combined with the high share of aluminum-based products that are used during production.

The PHEV is expected to have a material demand of 2198 kg during its lifetime while the HEV has a demand of 2078 kg. In both cases, the steel share is expected to be about 50% of the total material demand. In terms of energy usage during production (including assembly), the electricity demand for the PHEV is 5028 MJ, while the demand for the HEV is 4741 MJ. The same behavior is found for thermal energy demand—8525 MJ for PHEV and 7180 MJ for HEV. The difference between electricity and thermal energy demand mainly results from the different battery sizes. A more detailed material share overview for the production of these vehicles can be found in Fig. 2 or in the supplementary Material. The higher energy demand during the production of the hybrid vehicles results from the same factor as in EV. However, the battery size is much smaller in hybrid vehicles than that in EV. Furthermore, the energy demand is also smaller.

In terms of FCEV, the material demand is 1560 kg, with an electricity demand of approximately 4480 MJ and a thermal energy demand of approximately 5800 MJ for the assembly of the car or one of the building parts. As shown in Fig. 2, FCEVs have the highest share of carbon fiber. This mainly results from the hydrogen tank, which is made of carbon fiber.

The total energy demand during production is shown in Fig. 3. It can be seen that the vehicle assembly maintains the same value regardless of vehicle type. Furthermore, the battery production for all vehicle types, except ICEV, is the only other influencing assembly factor.

An analysis of the global warming potential (GWP) of the different vehicle types (see Fig. 4) revealed that for all vehicle types, except the EV, the category vehicle *without drivetrain components*, including the chassis, vehicle body, vehicle fluids, and vehicle assembly, has the highest amount of climate active emissions, nearly the same value (varying between 2940 and 3380 kg CO_2-eq) for all vehicle types. In comparison with the drivetrain system (excl. battery or fuel cell auxiliary system), it was found that EV has the smallest impact on GWP with 876 kg CO_2-eq, while the FCEV has the highest impact with approximately 2300 kg CO_2-eq. The fuel cell stack is mainly the cause, as it is included in the drivetrain system. Combined with the fuel cell auxiliary system, which includes the fuel cell tank and piping, the drivetrain accounts for nearly 3200 kg CO_2-eq in FCEVs.

The GWP resulting from the battery is dependent on the battery size. For ICEVs, the battery has no significant impact, as it only includes the lead-acid battery (which is also included in the battery category of all the other vehicle types). However, depending on the size, the importance of battery grows from the FCEV to the HEV, to the PHEV, and especially for the EV. In terms of the EV, the battery has the largest impact of all analyzed categories and vehicles. This is due to the material demand resulting from the capacity. For instance, the PHEV has a battery capacity of 14 kWh, while the EV has a capacity of 100 kWh. Furthermore, the large amount of energy that is necessary during production, as well as the usage of nickel, manganese, and cobalt (NMC), which has the most significant impact in terms of the battery at approximately 1700 kg CO_2-eq, significantly affects the GWP of the vehicle. The carbon footprint could be reduced during the production process by reducing the amount of NMC necessary for the same capacity. Furthermore, a production location in China was assumed, which affects the GWP of production in terms of the higher share of hard coal in the energy mix and even higher CO_2 emissions. Consequently, a battery production location shift, e.g., from China to Europe, or the extension of renewable energies in the Chinese energy mix could possibly have a significant positive impact on the production process in terms of GWP.

In total, it can be stated that alternative drivetrain systems, i.e., EV and FCEV, have the highest GWP during production, while the conventional ICEV has a GWP approximately 50% lower. However, this could change in the near future, owing to the larger market penetration of alternative drivetrain systems and their high potential for process optimization. Further, in terms of the battery and the fuel cell stack, improvements in alternative technologies and in production of conventional ones, could reduce the GWP in its production phase. E.g. Mahmoudzadeh Andwari et al. (Mahmoudzadeh Andwari et al., 2017) mentioned lithium air battery as promising alternative to lithium-ion technology, which could increase the range of a same sized battery significantly. According to Jamesh (2019), further future alternatives could be Na-ion and Li—S batteries due to their high energy density.

In terms of the primary energy demand, a similar behavior from the vehicle production emissions was found (see Fig. 5). As mentioned, battery production is an energy intensive process. In addition, the primary energy demand is the highest for the EV. From the primary energy demand of 116,200 MJ, 50% is attributable to the battery production process. This energy intensive production process is the main reason for the higher primary energy demand of the hybrid vehicles.

In terms of the FCEV, which has the 2nd highest primary energy demand, its high value results from the fuel cell auxiliary system, or more specifically, from the carbon production for the hydrogen tank.

4.2. Fuel economy and use phase

With the assumptions from Table 1, it was possible to analyze the specific GWP over a lifetime of 200,000 km for a combination of different vehicle types with different conventional and alternative fuels. The results of this analysis are shown in Fig. 6.

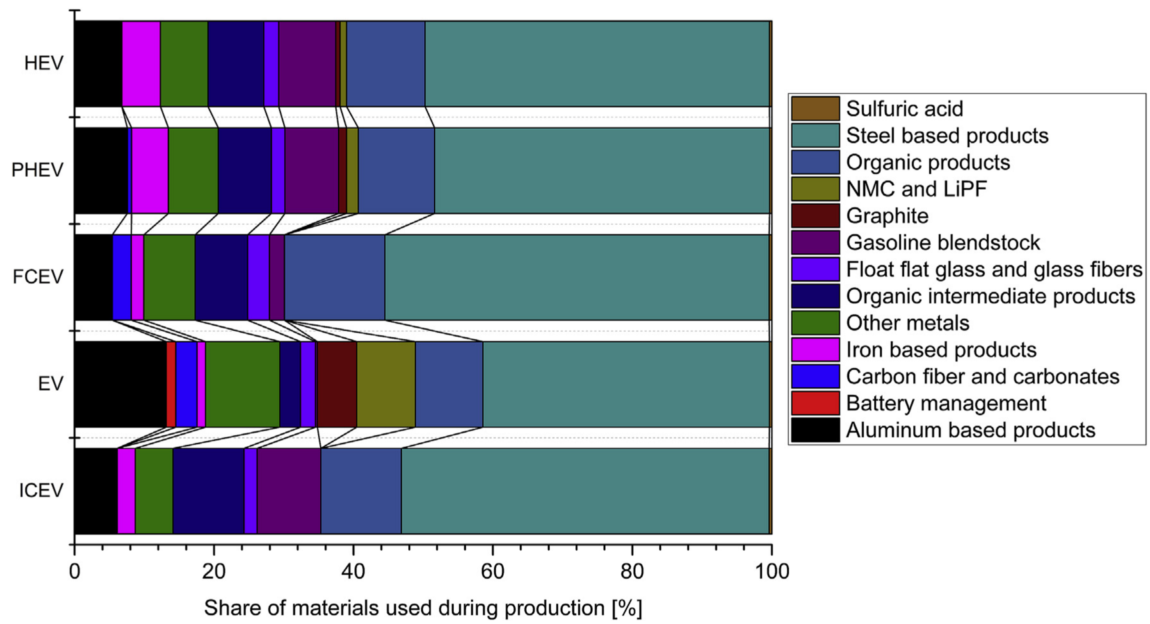

Fig. 2. Share of materials during the production process of the different vehicle types.

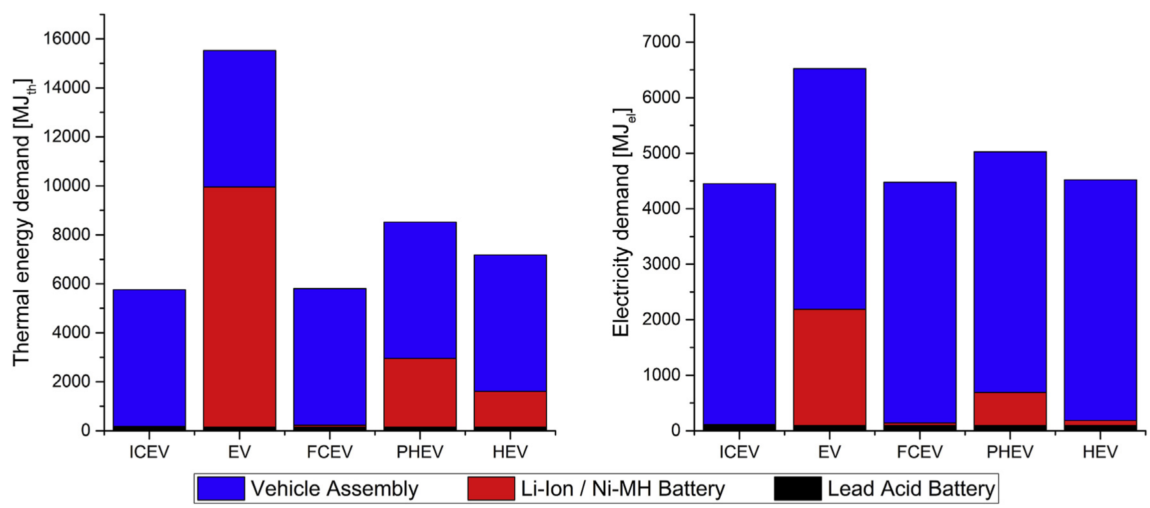

Fig. 3. Thermal energy (EU-28 mix: thermal energy from natural gas) (left) and electricity (EU-28 mix) (right) demand during production process of a vehicle. Comparison of the different vehicle types.

Fig. 6 shows an overview of the expected specific GWP, given in g CO_2-eq per pkm, for the different driving technologies on a well-to-wheel perspective. It also shows the comparison of the global warming potential between conventional energy carriers (i.e., gasoline, steam-reforming hydrogen, CNG, and EU28-mix electricity) and green energy carriers (i.e., cellulosic ethanol, hydrogen from power-to-gas, BtL-fuel, SNG, and wind-power electricity).

The first result that can be seen in Fig. 6 is the comparatively small share of vehicle production on the GWP of the conventionally operated vehicles. Except for alternative fuel concepts, the share of vehicle production on the lifetime GWP is below 35%.

As shown in Fig. 6, PHEVs are the only conventional technology with emissions below 100 g CO_2-eq per pkm. With values between 100 and 150 g CO_2-eq per pkm, EVs and FCEVs operated by conventional fuels have an up to 50% higher GWP, originating mainly from energy carrier production. For EVs, the lifetime GWP of electricity is 81 g CO_2-eq per pkm. This GWP results from the usage of fossil energy carriers in electricity production. In the case of FCEVs, the global warming potential of hydrogen production is significantly higher with 115 g CO_2-eq per pkm. This effect is caused by the steam-reforming process, which is used for hydrogen production from fossil natural gas.

ICEVs operated by CNG exhibit a similar performance to conventional hydrogen-operated FCEVs. This follows from the advanced development of the drivetrain system, and fuel production. This high development rate comes from the fact that CNG drivetrains barely differ from gasoline drivetrains and from the well-developed natural gas infrastructure. The main driving factor for the GWP of CNG ICEVs is exhaust gas emissions. With a value of 99 g CO_2-eq per pkm, the share of the GWP is about 65%. The small amount of electricity included in the results for CNG ICEVs comes from the compression of natural gas to CNG.

Vehicles operated by gasoline (HEV, MHEV, and ICEV) cause the highest GHG emissions. In all three cases, the emissions show the

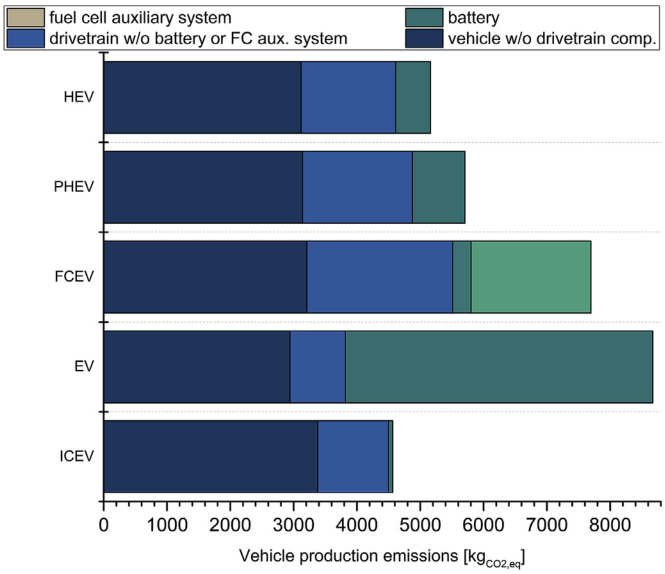

Fig. 4. Global warming potential per vehicle of the production for different drive technology.

largest share of the global warming potential owing to the combustion of gasoline during the use phase.

Evidently, substitution of conventional energy carriers by renewables reduces GHG emissions significantly. In the case of EV, the usage of electricity from wind power reduces the global warming potential of the electricity supply from 81 to 1.2 g CO_2-eq per pkm, which is a similar effect as reported by Bauer et al. (2015). Furthermore, the total global warming potential of EV decreases from 112.9 to 33.1 g CO_2-eq per pkm, which is, in this case, mainly caused by vehicle production. The same effect can be observed in the case of FCEVs. Here, the global warming potential of the fuel production is reduced from 115 to 6.2 g CO_2-eq per pkm, which means a total reduction from 147.7 to 38.9 g CO_2-eq per pkm. The reduction of GWP in fuel production is comparable to the findings of Reiter and Lindorfer (2015).

This reduction effect can also be observed by replacing conventional fuels with advanced fuels in the case of PHEV, HEV, and ICEV. For PHEV, the reduction comes from replacing gasoline with BtL fuel and EU-28 electricity mix with electricity from wind power. In this case, the GWP is reduced from 80 to 39 g CO_2-eq per pkm. When using cellulosic ethanol from wheat straw, the GWP reduces to 33 g CO_2-eq per pkm. The same behavior, but with a more significant reduction, was found by replacing gasoline with BtL-fuel in an HEV. Meanwhile, gasoline-operated vehicles exhibit a GWP of 166 g CO_2-eq per pkm, while the GWP is reduced to 53 g CO_2-eq per pkm through BtL-fuel operation. Replacing BtL-fuel with cellulosic ethanol from wheat straw lowers the GWP (35 g CO_2-eq per pkm) even further.

For ICEV, the GWP reduction potential of BtL compared to gasoline is about 134 g CO_2-eq per pkm (from 224 to 90 g CO_2-eq per pkm). Cellulosic ethanol from wheat straw increases the GWP performance even further, decreasing the overall value to 53 g CO_2-eq per pkm. In the case of gas-operated ICEVs, this reduction effect is not as high as that for the replacement of gasoline with advanced fuels. The utilization of SNG instead of CNG decreases the GWP from 146 to 85 g CO_2-eq per pkm.

Consequently, it can be stated that so-called “green” vehicles (EV and FCEV) can only achieve their full potential in terms of GHG reduction by using environmental-friendly fuels (e.g., electricity from wind, photovoltaic, wind power, and bio-hydrogen) because of the strong impact of the vehicle use phase over the entire

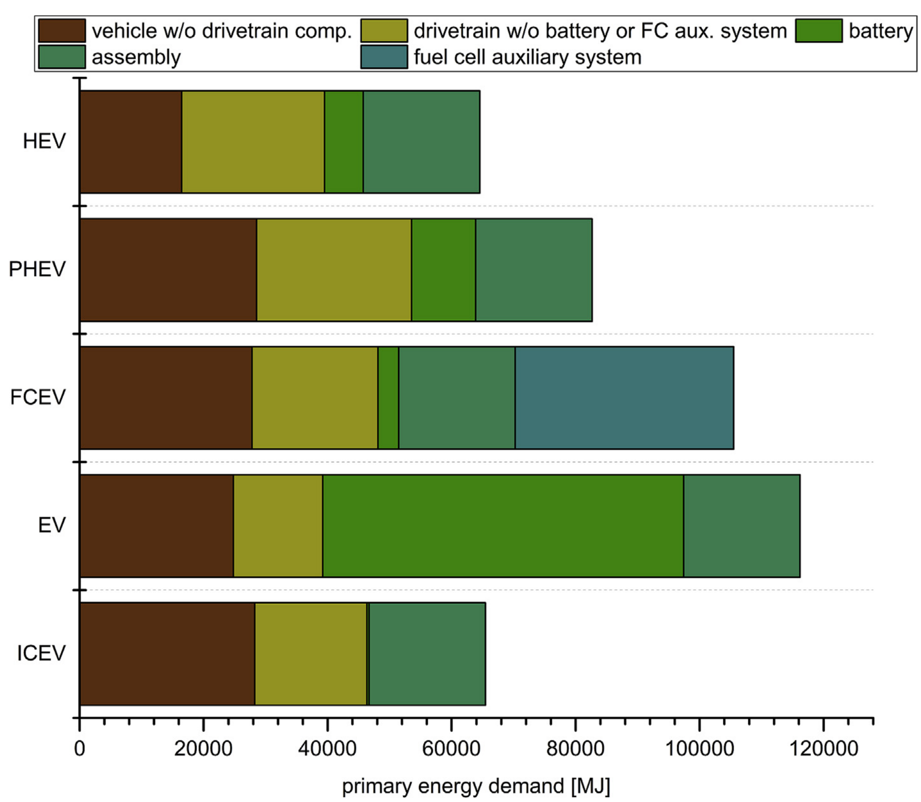

Fig. 5. Primary energy demand during the production phase.

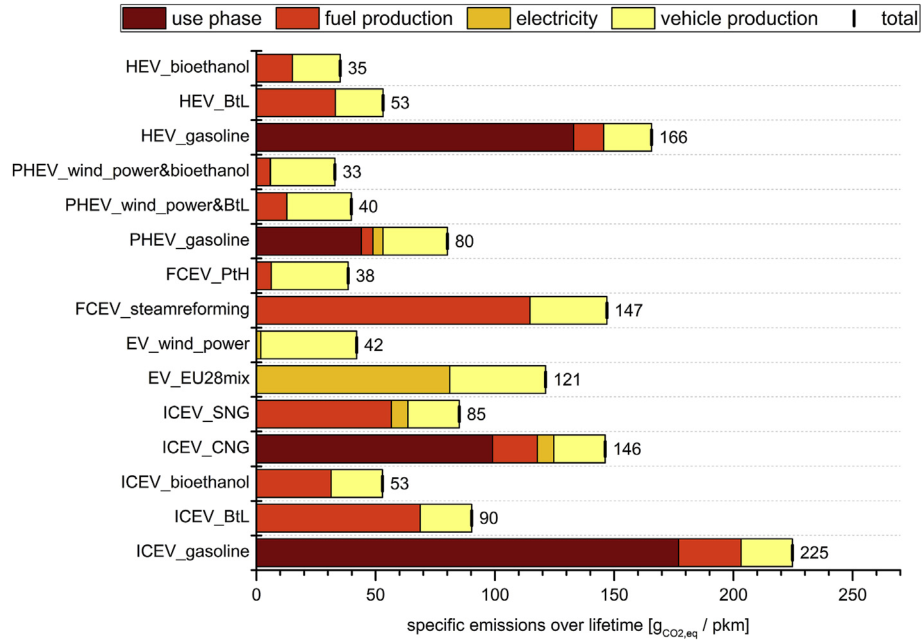

Fig. 6. Global warming potential of different drive technologies over the lifetime based on 200,000 pkm.

lifetime. Furthermore, it is possible to state that advanced fuels can enhance the GWP performance of conventional-combustion-based drive train systems significantly.

Along with the GWP, an analysis of the primary energy demand during the use phase was conducted (see Fig. 7). As shown in Fig. 7, the primary energy demand of vehicle production typically has the smallest share of the total specific primary energy demand. This results from the high energy demand during the production of the fuels based on thermochemical conversion (BtL) or electricity (PtG). Furthermore, with the exception of cellulosic ethanol, all other advanced fuels exhibit a higher demand for primary energy during its production. BtL has an approximately three-fold higher energy demand when used in an HEV or ICEV and an approximately two-fold higher demand in a PHEV, compared with gasoline. In an FCEV, the demand for the advanced fuels is double that of conventional fuels. This is exactly the opposite in an EV, for which wind power exhibits 50% that of the EU-28 electricity mix. The most significant difference involves an ICEV operated by SNG vs. CNG, in which SNG has an approximately four-fold higher primary energy demand than that of CNG.

The main reason for the varying primary energy demand comes from the different efficiencies during production. While conventional fuels (except EV) can be produced with high efficiencies, the production of advanced fuels is always connected with losses

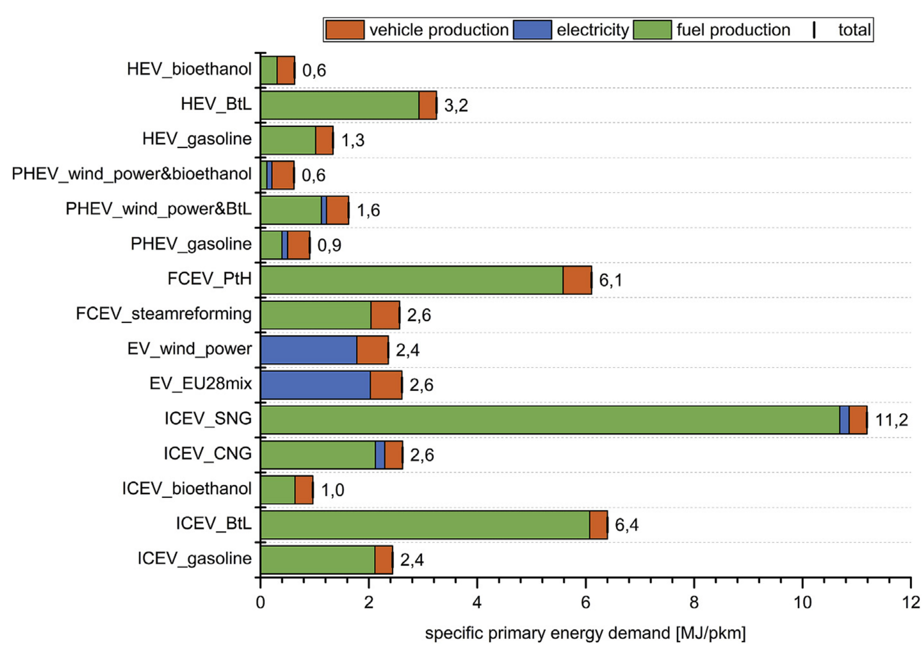

Fig. 7. Primary energy demand of different drive technologies over the lifetime based on 200,000 pkm Comparison to compact cars.

during production because of electrolysis, methanation, gasification, or other processes that convert electricity or biomass into chemical energy. This can be seen by comparing the primary energy demand of the wind-power-operated EV, the hydrogen from the power-to-hydrogen-operated FCEV, and the SNG-operated ICEV. In the first case, electricity can be used with nearly 100% efficiency, while for the hydrogen-operated FCEVs, electricity initially must be converted to hydrogen via electrolysis. This conversion process results in a higher energy demand. When expanding the process through methanation, the primary energy demand is even higher (as mentioned below for SNG). The only exception to this higher energy demand is cellulosic ethanol from wheat straw. This results from the comparable low temperatures of the process and the lack of direct electric conversion as in electrolysis.

The values for the SUVs shown in section 4.2 were compared to the GaBi results for compact vehicles (see Fig. 8).

For PHEV and EV, a reduction in battery capacity has an impact on the GWP as well as a reduction in energy demand during the use phase. In the case of PHEV, battery capacity reduction results in a reduced GWP of 1.3 g CO_2-eq per pkm, which represents a reduction of 5%. For EV, the difference is more significant with a reduction of 14 g CO_2-eq per pkm, corresponding to a reduction of 34%. In terms of the different energy sources, traditional PHEV have a reduction potential of 23 g CO_2-eq per pkm (reduction from 80 to 57 g CO_2-eq per pkm). For alternative fuels, the reduction potential was 1.3 g CO_2-eq per pkm, which results from the reduced battery capacity. In terms of the total EV use phase, traditional operation by the EU-28 mix would result in a reduction from 121 to 72 g CO_2-eq per pkm, when using a compact vehicle instead of an SUV. For a wind-power-operated EV, the reduction potential corresponds to 14 g CO_2-eq per pkm, based on the smaller battery.

The comparison of compact vehicles with SUV-sized vehicles indicates that, particularly when using traditional fuels, the usage of compact vehicles leads to a significant reduction in vehicle GWP. This significant difference becomes smaller with the use of advanced fuels.

In terms of primary energy demand, a small reduction in the energy demand from compact vehicles compared to SUVs was observed (see Fig. 9). This reduction was found to be about the same as the reduction in GWP and, therefore, not further discussed.

5. Conclusions

The LCA of five different types of vehicles, operated by nine different types of fuels or electricity sources, is conducted.

It is found that the GWP and primary energy demand during

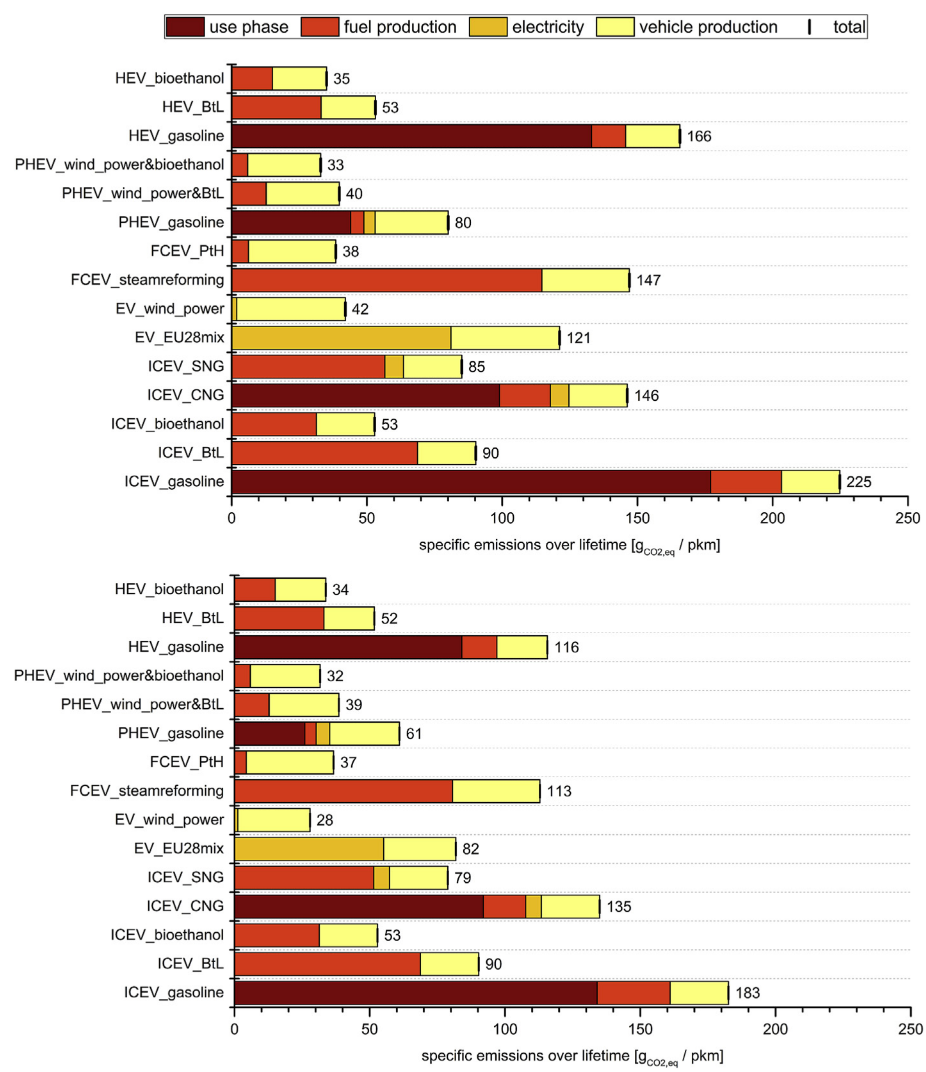

Fig. 8. Comparison of specific emissions over lifetime for SUVs (top) and compact vehicles (bottom).

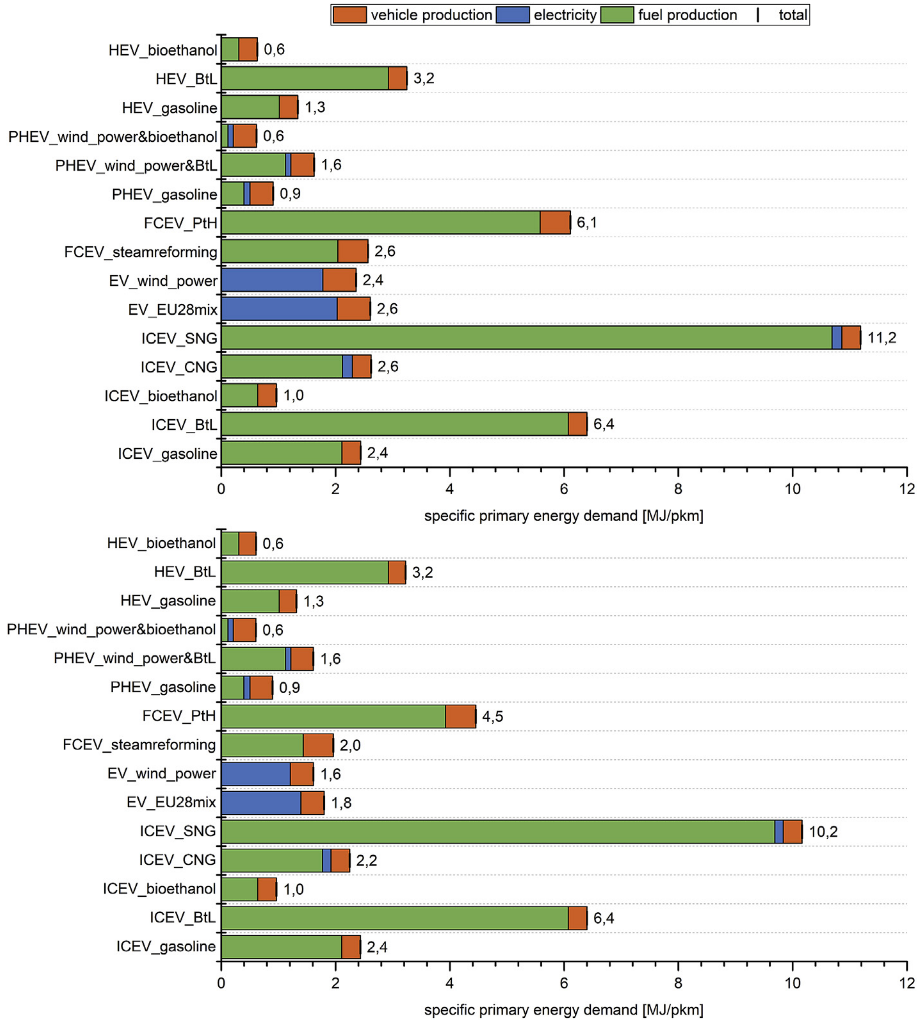

Fig. 9. Comparison of the primary energy demand of SUV-sized vehicles (top) and compact vehicles (bottom).

vehicle production is the highest for alternative drivetrains with values between 8000 and 9000 $kg_{CO2,\ eq}$ for EV and FCEV. This effect is caused by the comparatively high carbon footprint during the production process of Li-ion batteries, fuel cell auxiliary systems, and fuel cell stacks, which results from its high primary energy demand. Furthermore, hybrid vehicles have a 25–30% higher GWP and primary energy demand compared to ICEVs. As a result, it can be stated that further improvements, which should reduce the primary energy demand as well as the environmental impact of production, are necessary to lower the GWP of new drivetrain technologies. Therefore, future research has to investigate alternatives to currently available fuel cell stacks and batteries, especially with a focus on the environmental performance during the production phase.

However, based on the overall lifetime, the highest share of GHG emissions originate from the use and/or production of the energy carrier. As mentioned, different types of fuels and electricity sources were analyzed to provide an overview of different advanced fuels compared to traditional ones. Advanced fuels have been found to exhibit high potential for reducing the GWP over the total lifetime of a vehicle. Furthermore, EV and FCEV were found to require operation with advanced energy carriers from renewable resources to impart a positive impact on mobility compared to traditional drivetrains. Another result was that advanced fuels in traditional drivetrains, e.g., ICEV, can help to reduce mobility emission by 75%. However, to demonstrate this positive effect, further research is necessary, considering the large amount of resources necessary to produce a sufficient amount of advanced fuels to operate a large share of traditional drivetrain-based vehicles.

For the primary energy demand, a different behavior was found. Most advanced fuels have a significantly higher primary energy demand owing to higher losses during production. This effect can be partly offset if renewable energy is utilized in the production process to a maximum extent. An exception to this is EV operated by wind power, because electricity from wind power contains no conversion losses, unlike other advanced fuels.

In terms of vehicle size, a significant reduction (up to 30%) in GHG emissions was found when using a compact vehicle instead of an SUV, particularly during the use phase with traditional energy carriers, resulting mainly from lower fuel use and electricity consumption. This effect gets smaller if advanced fuels are used. In addition, smaller batteries could affect the GWP of EVs and PHEVs positively.

In total, as a result of the comparatively low emissions due to fuel production and carbon neutral emissions, PHEVs operated by cellulosic ethanol and wind power have the lowest GWP per km of SUV-sized vehicles (33 $g_{CO2,\ eq}$ per pkm). In terms of compact cars, EV profit from smaller batteries and, therefore, from lower emissions due to manufacturing. Therefore, EV operated by wind power have the lowest GWP per km of all compact cars (28 $g_{CO2, eq}$ per pkm). The demonstrated potential for CO_2 reduction via assessed renewable mobility options strongly supports cleaner production of vehicle and fuels enabling a potential decoupling of road vehicle traffic and associated constantly increasing carbon dioxide emissions.

To summarize the following list of findings can be drawn:

- it was concluded that alternative drivetrains have a significantly higher GWP and primary energy demand during production
- based on the overall lifetime, the vehicle use phase was identified to be the most significant impact category
- compact cars have shown a significantly lower GWP compared to SUV sized ones
- PHEVs were identified to have the lowest specific GWP of all compared SUVs
- EVs have shown the lowest specific GWP of the compared compact cars
- primary energy demand of alternative fuel production was analyzed to be higher compared to conventional fuels

Future work should focus on including technological trajectories for the years 2030–2050. This should ensure the representation of future improvements of the mentioned technologies in all phases of the life cycle.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.117879.

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Nomenclature

BtL: biomass-to-liquids
CNG: compressed natural gas
EV: electric vehicle
FCEV: fuel cell electric vehicle
GHG: greenhouse gas
GWP: global warming potential
HEV: hybrid electric vehicle
ICEV: internal combustion engine vehicle
KPI: key performance indicator
LCA: life cycle assessment
LCI: life cycle inventory
LCIA: life cycle impact assessment
NG: natural gas
PHEV: Plug-In hybrid electric vehicle
SNG: synthetic natural gas
TRL: technology readiness level
TTW: tank-to-wheel
WTW: well-to-wheel
WTT: well-to-tank