World Electric Vehicle Journal

Article

Life-Cycle CO_2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems

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Abstract: As an important trend in the automotive industry, electrification of propulsion systems has potential to significantly reduce greenhouse-gas emissions of the transportation sector. Whereas electric vehicles do not produce exhaust emissions during driving, the impact of electricity provision for charging batteries, as well as the impact of vehicle production play an essential role in a holistic consideration of the carbon footprint. The paper introduces a comprehensive evaluation of greenhouse gas-emission-related factors of cars driven by different propulsion technologies, considering the entire product life cycle. This comprises vehicle production, including battery system, electric powertrain and other relevant components, the car's use phase under consideration of different electricity mixes and the end-of-life phase. The results of the study give insights of influencing factors on life-cycle-related carbon-dioxide-equivalent emissions of cars driven by combustion engines, hybrid powertrains and battery-electric propulsion systems. In addition, a comparison of actual mass-production cars is made and the total life-cycle carbon footprints are discussed under different boundary conditions of electric power supply. In this way, the article comprehensively introduces an automotive life-cycle assessment and provides fundamental information, contributing to an objective discussion of different propulsion technologies.

Keywords: greenhouse-gas emissions; life-cycle assessment; battery system; electric propulsion; hybrid powertrain; combustion engine; production technology; technology evaluation

Citation: Hirz, M.; Nguyen, T.T. Life-Cycle CO_2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems. *World Electr. Veh. J.* **2022**, *13*, 61. https://doi.org/10.3390/wevj13040061

Academic Editor: Michael Fowler

Received: 10 February 2022
Accepted: 23 March 2022
Published: 31 March 2022

1. Introduction

A comprehensive evaluation of products, systems and technologies under consideration of their entire life-cycle behavior is becoming increasingly important today. Especially in the automotive industry, the electrification of propulsion systems has been intensively discussed, and important decisions have to be made by governmental institutions, car manufacturers and in the supplier industry. The methodology of life-cycle assessment (LCA) provides a powerful tool for the holistic and objective evaluation of different technologies, and consequently delivers relevant information for decision-making processes.

In this context, the present article investigates CO_2-equivalent emissions as one relevant representative of greenhouse-gas impacts of cars driven by different propulsion technologies, including internal-combustion-engine vehicles (ICEV), hybrid vehicles (HEV) and battery-electric vehicles (BEV). Targets of the investigations include an introduction to standardized life-cycle-assessment processes in the automotive industry and a discussion of influencing factors and boundary conditions. In addition, the influences of main modules and materials on CO_2 equivalents are elaborated and debated for cars driven by the three different propulsion technologies. Finally, the methodology of LCA is applied onto actual mass-production cars with different powertrain systems, and their carbon footprints of both production and use phases are evaluated, compared and discussed. In this way, the article summarizes the state of the art of automotive life-cycle assessment and reflects the impacts of different propulsion technologies. Additionally, CO_2-equivalent emissions-related characteristics of selected mass-production cars are elaborated in detail and carbon-footprint-related factors of different powertrain technologies are highlighted and discussed.

The article focusses on aspects that are relevant for LCA-based evaluation and discussion. In this context, nontargets of the publication include a detailed description of propulsion- and vehicle technologies. In addition, the work focuses on technologies, which are available in the market on relevant mass-production scale to date. In this way, hydrogen fuel-cell electric vehicles (FCEV) and synthetic fuels are not considered. Biofuels, as they are used in some countries, e.g., Brazil, are also not considered in the present work, because of their limited relevance from the perspective of the worldwide market.

The applied research methodology is based on standardized LCA processes [1,2] and makes use of existing databases and procedures [3–5]. The research design includes literature study and representation of LCA-based impacts for the discussion of general characteristics of cars driven by different propulsion technologies (Section 3), and the actual application of LCA for the evaluation and discussion of selected mass-production cars with different powertrain technologies (Section 4).

2. Life-Cycle Assessment in the Automotive Industry

Life-cycle assessment is a standardized procedure that can be applied to evaluate products under consideration of their entire life cycle, including production, use phase and end-of-life phase. A holistic application of LCA represents a complex task that requires high effort and detailed investigations of the different sections in a life cycle. This includes raw-material extraction, manufacturing and assembling processes as sequences of production, aspects of the product's usage and service efforts, as well as dismantling, recycling and disposal in the final life-cycle phase. In the automotive industry, standardized LCA processes are typically conducted according to the ISO 14040 and the ISO 14044 [1,2]. In this way, the procedure of an LCA is classified into the following four main steps: *Goal and scope definition*, *Inventory analysis*, *Impact assessment* and *Interpretation*. Figure 1 shows the main phases of LCA and points to factors that are relevant for the assessment of automotive product life cycles.

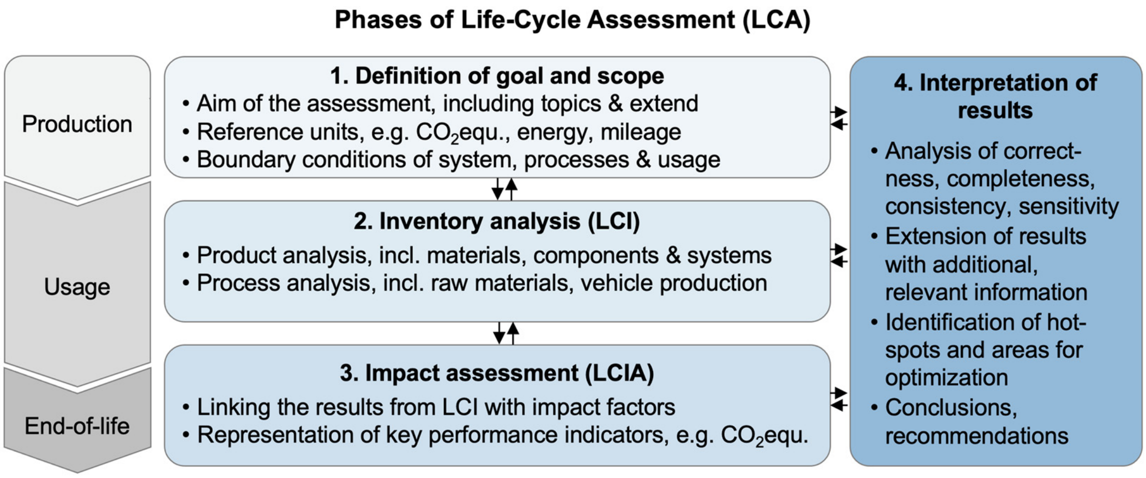

Figure 1. General procedure of an automotive LCA.

For conducting LCA of complex products, as is the case in the automotive industry, a comprehensive definition of boundary conditions, considered factors and limitations plays an important role, because these aspects influence the outcomes significantly. In addition, types and specifications of resulting parameters have to be defined carefully. Due to the broad applicability of LCA, different kinds of environmental or economic impacts can be represented, e.g., global warming potential, resource depletion, toxication potential, energy consumption. Due to the high importance of global warming today, the impact of greenhouse-gas emissions is often taken into consideration, e.g., in the form of carbon-dioxide (CO_2)-equivalent emissions. In this case, a broad range of influencing parameters is converted under consideration of their impact on global warming and represented in form of the corresponding CO_2 equivalents' factors. This approach has become very popular in the past years because it delivers one key performance indicator, which can be used for evaluation and discussion of different technologies. As a weakness, the reduction in data does not sufficiently allow consideration of all the different factors that might have an impact on a holistic LCA. Therefore, it is important to clearly specify the system boundaries as well as the assumptions and simplifications that have been made and to point out all influences, which cannot be represented by the CO_2 equivalents, e.g., land use, resource demand, environmental pollution, energy storage and system efficiency.

In the present publication, the greenhouse-gas-emission impacts of cars driven by different propulsion systems are evaluated and discussed based on comprehensive LCA, including combustion engines, hybrid powertrains and battery-electric cars. The equivalent CO_2 emissions are taken under consideration as a key indicator, and other influencing parameters are also considered to enable a holistic discussion of the technologies. Figure 2 shows an overview of the main phases of a car's product life cycle: *materials production, vehicle manufacturing, car usage, end-of-life phase*. In addition, the relevance of *energy and natural resources* as well as a potential backflow of materials and energy from recycling and recovering are indicated.

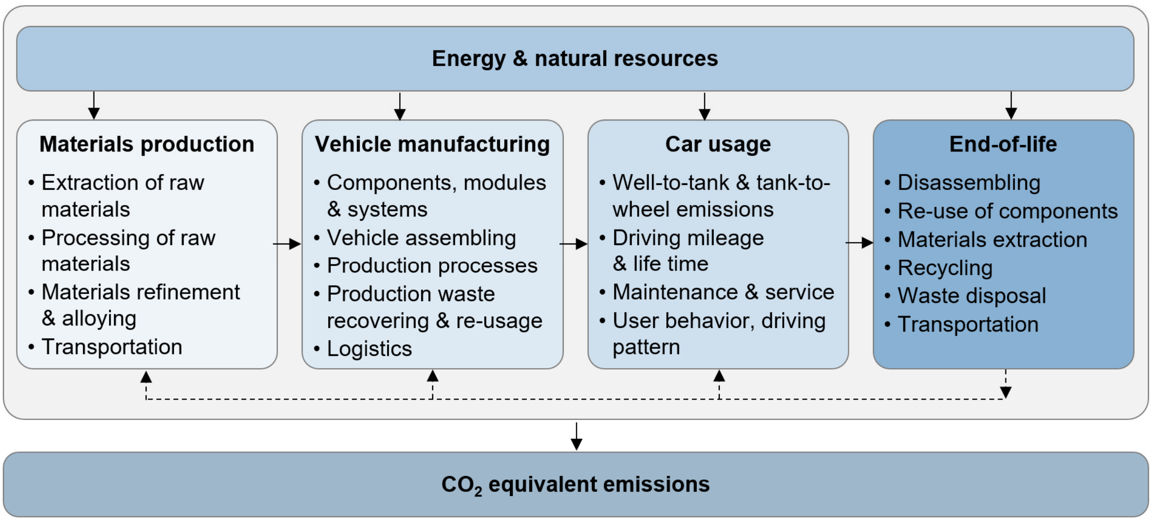

Figure 2. Main phases and influencing factors of a CO_2 equivalent-emissions-focused automotive LCA.

2.1. Aspects of Energy Provision and Natural Resources

The provision of energy and natural resources has an important impact on life-cycle behavior. This includes the electric and chemical energy that is required in all sections of the life cycle, as well as air, water and of course resources for materials production and vehicle manufacturing. In this way, impacts of raw-material sourcing and processing are explicitly investigated and material-related aspects are also considered in the sections of vehicle manufacturing, car usage and end of life. In the case of recycling, a certain share of materials can be extracted and returned to the previous sections of the vehicle life cycle to reduce the total carbon-equivalent impact.

Besides the consideration of natural resources, special attention has to be put on the provision of energy, which influences all four sections of the life cycle. Specifically, the provision of energy for material extraction and processing as well as vehicle manufacturing has a considerable impact on the one-time cost factor of CO_2-equivalent emissions. In addition, the energy effort for conducting processes of the end-of-life section have to be taken into account. In these industrial processes, energy is supplied in different ways, e.g., in form of heat, fluidic and of course electric energy. Processing heat is important for materials production, e.g., steel, and is typically provided by a combination of chemical energy carriers (e.g., natural gas) and electric energy.

Electric energy is required in a multifarious way throughout the sections of the product life cycle. In this way, the CO_2-equivalent impact of electricity provision is of high relevance for LCA considerations. It has to be considered that the four main phases of the life cycle of a car might be conducted with different boundary conditions of ecological impacts and energy provision in different countries around the world. This includes the use of land resources, environmental pollution and electricity supply. In this context, a comprehensive LCA considers the different factors that are valid in the specific regions where the corresponding processes take place. As an example, the resulting CO_2 equivalent factors for the production of steel might be different in selected Asian and European regions, because of the significantly different carbon footprint of electricity provision.

Figure 3 shows average values of carbon footprints of selected technologies of electricity production. So-called "renewable technologies" have a significantly lower impact because they do not use fossil-based resources. The large greenhouse-gas-emission output of fossil-based technologies is based on the conversion of hydrocarbons that release CO_2 emissions. A special case represents nuclear energy, because the CO_2 emissions are very low. However, there are other aspects to be considered, e.g., efforts for operation and nuclear-waste management, as well as risks of nuclear contamination. The diagram represents a holistic LCA-based view of the different technologies, including construction, service and maintenance of power plants, as well as the impact of electricity production. This is the reason why certain CO_2-equivalent emissions are also indicated for the renewable sources. For nuclear energy, the efforts for construction, service and maintenance are considered, but not for nuclear-waste deposition and risks of potential nuclear accidents.

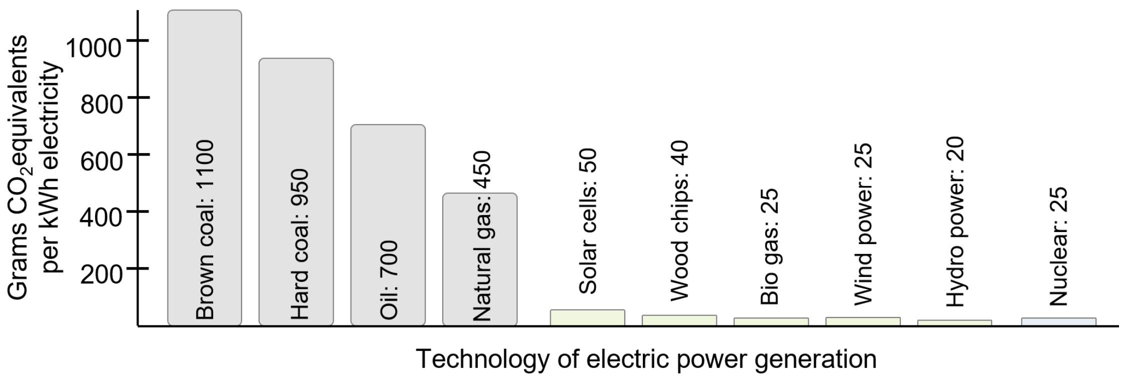

Figure 3. CO_2-equivalent-emission impacts of selected technologies of electric power generation [6–9].

Figure 4 shows the average life-cycle-based CO_2-equivalent emissions of electricity production in selected countries. The values consider the different shares of applied technologies for the production of electric energy—the so-called "electricity mix". A separation of regions within the countries is not shown here, but should also be considered in a detailed LCA. As an example, some manufacturers use dedicated energy sources with low CO_2 impact for vehicle manufacturing, e.g., [10], with the target of reducing the manufacturing-related carbon footprint of their products. In any case, Figures 3 and 4 indicate the importance of electric-energy provision for an objective and comprehensive LCA evaluation. This includes the production of cars, but also the use phase, especially in case of battery-electric vehicles.

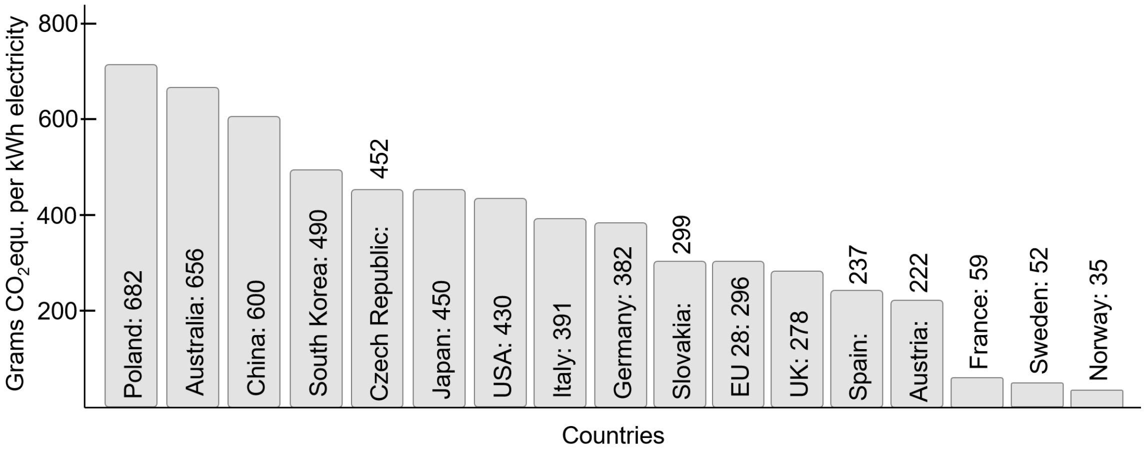

Figure 4. CO_2-equivalent-emission intensity of electricity production in selected countries [7–9,11–13].

2.2. Aspects of Materials Production and Vehicle Manufacturing

Vehicle production includes the sections of materials provision and vehicle manufacturing. The carbon footprint of car production is significantly influenced by vehicle type and size, powertrain technology as well as the vehicle's configuration and equipment. In addition, technologies of material sourcing and vehicle manufacturing as well as related processes of energy provision are to be considered. In this way, published results, e.g., by car manufacturers, suppliers and scientific institutions, may show certain dissimilarities of LCA-based results [14–18]. Due to the large number of influencing parameters and their wide range of variation, the following diagrams represent averaged numbers including ranges of extension of the corresponding factors. The diagrams are based on information from above-mentioned literature sources, which are enhanced and combined with own computations; see also Section 4.

In Figure 5, a comparison of relative CO_2-equivalent emissions of vehicle production is shown for ICEV, HEV and BEV. This diagram displays general mean characteristics and does not relate to a specific car. In this way, it can be applied for comparison of cars with different powertrain systems within similar vehicle characteristics, e.g., car type and size, performance and equipment. The diagram shows that the production of battery-electric cars has about a 50–100% higher carbon footprint than those of cars driven by conventional powertrains, which is mainly based on the battery system. In this representation, manufacturing efforts of charging units and thermal management systems are assigned to the carbon impact of the battery. The electric powertrain, comprising inverter, electric motor and transmission, shows a moderately lower carbon footprint than the combustion-engine-based powertrain, including the cooling system and transmission. Taking ICEV as a basis with 100%, the carbon footprint of BEV varies in a considerable range, as indicated by the vertical double arrow. This is based on the range of technical parameters and their influences on CO_2 equivalents, e.g., battery size and manufacturing technologies as well as the applied electricity mixes.

A general evaluation of hybrid cars is challenging because of their wide variation of electrification, see Section 3.2. Nevertheless, the diagram indicates an averaged behavior under consideration of the technology range. In typical hybrid cars, the combustion engine is smaller than in conventionally driven cars of similar performance classes, which is indicated in a moderately reduced CO_2-equivalent emissions footprint of the *ICE power train*. On top come the *electric power train* and the *battery system*, leading to an increase in the production-related carbon footprint of hybrid cars in the range of nearly zero for *mild hybrids*, about plus 25% for *full hybrids* and up to 50% plus for *plug-in hybrid* cars.

Considering comparable technologies of bodywork, chassis, exterior and interior modules, the CO_2-equivalent-emission impacts of the compared vehicles without powertrains are similar, with a slightly lower impact of the BEV because of the integration of the battery system into the bodywork.

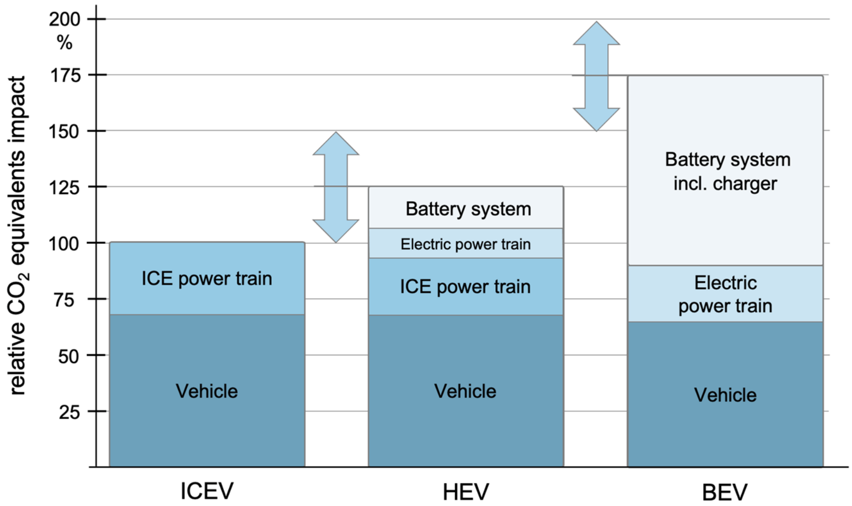

Figure 5. CO_2-equivalent-emission impacts of vehicle production in comparison.

Figure 6 shows a detailed breakdown of the contributions to CO_2-equivalent emissions in vehicle production. The representation is based on Figure 5 but displays a more specific view on the main modules' impacts and a segmentation of the different materials. The car's main modules are defined according to the classification made in Section 3. It has to be considered that for all three vehicle types, ICEV, HEV and BEV, the total size of each column indicates 100%. In this way, the percentages of contributions of the individual factors are shown for each vehicle powertrain technology separately.

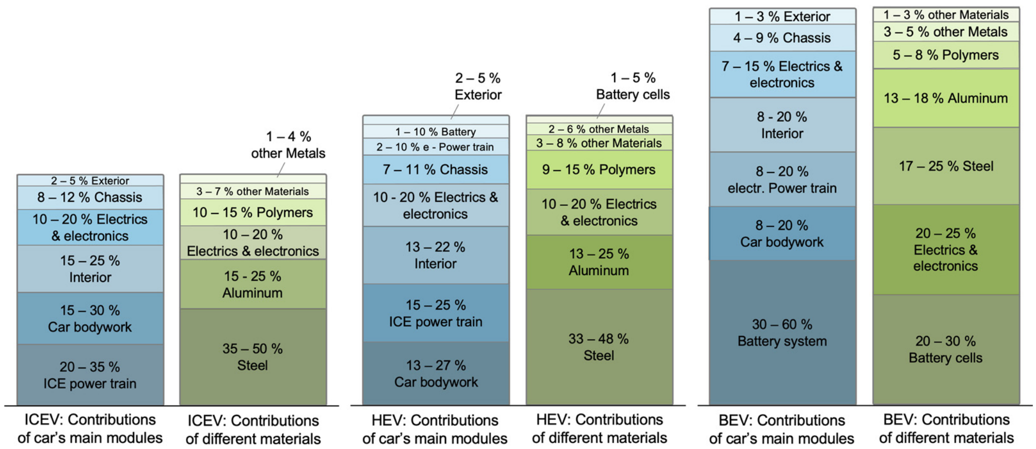

Figure 6. Contributions of main modules and different materials to CO_2-equivalent emissions of vehicle production.

Considering the main modules, it is visible that battery-system production has the largest carbon footprint, but also shows the largest variation extension, based on different battery sizes and the applied production technologies. The variation of carbon footprint of the other main modules is driven by their technical characteristics, e.g., bodywork dimension and weight, engine performance, level of electronic equipment, as well as of the applied materials, e.g., steel, aluminum or polymers. For HEV, the powertrain is split up into the combustion-engine-based unit (*ICE powertrain*) and the electric-drive unit (*e-Powertrain*), and the impact of the hybrid-system battery is shown separately.

Looking at the material-based effects on CO_2-equivalent emissions of ICEV, the main share is represented by the provision of steel and aluminum, and a considerable share by electrics and electronics. For BEV, battery-cell manufacturing as well as electric and electronics components are the source of about 40–55% of the entire carbon footprint. Preparation of steel and aluminum is still relevant for BEV but reduced in comparison to components of energy storage and electric powertrains. For HEV, the material-related impact on greenhouse-gas emissions is considerably defined by the actual powertrain configuration. In case of mild hybrids, the characteristics are similar to those of ICEV. In case of full hybrids and plug-in hybrids, the impacts of larger electric-drive units and battery systems have to be considered accordingly.

2.3. Aspects of the Car's Use Phase

Influencing factors on CO_2-equivalent emissions during the use phase of a car include the vehicle's driving resistances, powertrain efficiency and the type of fuel (energy) used for propulsion. In addition, user behavior and driving patterns, service and maintenance, including spare- and wear parts, have to be considered. A significant share of greenhouse-gas emissions that are generated during the use phase of a car are caused by the provision of chemical energy, in the form of fuel in the case of cars driven by combustion engines, or hydrogen in case of fuel-cell-electric vehicles. In case of battery-electric vehicles, electric energy is provided. In ICEV, gasoline or diesel fuel is converted in the engine, producing harmful emissions (such as hydrocarbons (HC), carbon-monoxide (CO), nitrogen oxides (NO_x), particulate emissions), and CO_2. In case of FCEV, hydrogen is converted in fuel cells to water (H_2O) to produce electric energy for propelling the car. In BEV, there are no exhaust emissions produced in the car, but upstream in the course of electric-energy generation.

In the following, the behaviors of ICEV and BEV are investigated, focusing on CO_2-equivalent emissions. FCEV are not considered further here, because this technology is not on a large-scale production level yet, which hinders a reasonable comparison in view of material production, vehicle manufacturing and the end-of-life phase.

Figure 7 shows the different sequences of energy provision and conversion for vehicle propulsion as well as their influencing factors on CO_2-equivalent emissions. The so-called "well-to-tank" (WTT) emissions are generated in the course of energy-, respectively fuel provision. For gasoline and diesel fuel, this includes production of crude oil, refinery processes, transportation and distribution. For electricity, different technologies of electricity production, transfer, transformation and distribution are to be considered. The so-called "tank-to-wheel" (TTW) emissions stem from the conversion of energy in the vehicle. For ICEV, this comprises the combustion process of fuel, resulting in exhaust emissions. BEV do not produce exhaust emissions, leading to zero TTW emissions. The sum of WWT and TTW emissions is defined as "well-to-wheel" (WTW) emissions and represents the actual CO_2-equivalent-emission impact when operating a car.

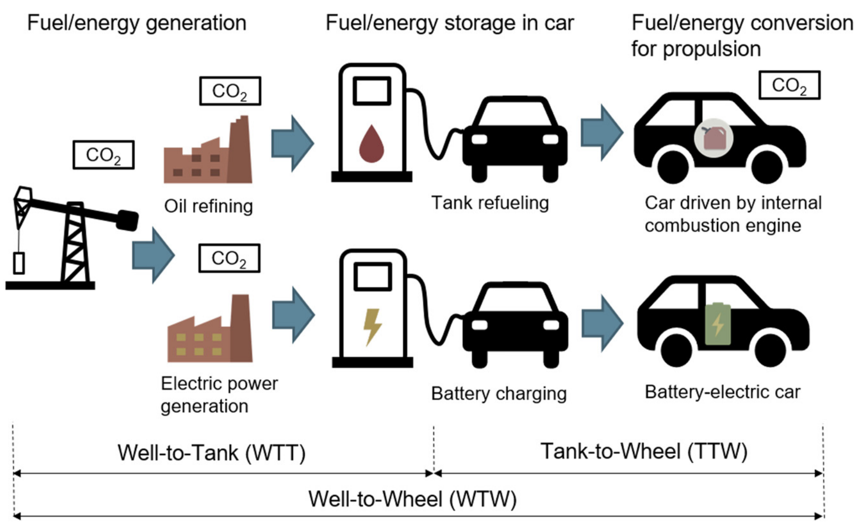

Figure 7. Sequences of energy provision and conversion for vehicle propulsion.

For BEV, the electricity mix in the corresponding countries and regions has a significant impact on greenhouse-gas-emission behavior (cf. Figures 3 and 4). In addition, losses of energy transport and of charging the battery have to be considered. In a modern electricity grid, the average transportation and transformation losses can be estimated in a range of about 5% [19]. Charging losses of the battery are strongly influenced by the specific charging power. In this way, low-power charging takes longer, but enables high efficiency of the charging process of up to 95%. High-power charging—so-called "supercharging"—is able to reduce the charging time considerably, but can lead to electrical losses of more than 30%, which requires specific cooling of the charging system and battery [20,21]. In conclusion, the resulting WTW emissions of BEV are defined by the technology of electricity production, losses of electricity transfer and storage as well as the energy consumption of the observed vehicle in the considered driving pattern.

For ICEV, there are several factors to be considered in the calculation process of WTT emissions, including type and quality of crude oil, upstream technologies of fuel production, transportation and distribution. In this way, WTT emissions are in the range of 10% to 20% of the TTW emissions for conventional fuel, with a lower impact for diesel and higher impact for gasoline fuel [22]. In the combustion engine, hydrocarbons of fuel are burned by use of aspirated air. Considering the average content of hydrogen and carbon and assuming perfect combustion [23], the TTW emissions can be calculated directly from the fuel consumption with linear factors:

$$\textit{fuel consumption in liters per 100 km} * \psi = CO_2 \textit{ emissions in grams per km} \tag{1}$$

The factor ψ varies for gasoline and diesel because of their slightly different ratio of hydrogen and carbon content, with ψ = 23.2 for gasoline and ψ = 26.2 for diesel fuel.

The specific user behaviors, including driving pattern and style, driven mileage, and in case of BEV also the charging patterns, significantly influence the CO_2-equivalent emissions. User-related factors are very complex to consider and are the topic of different investigations, e.g., [24]. In the present work, the standardized driving cycle WLTC (World harmonized Light vehicles Test Cycle, [25]) and averaged user-behavior schemes are taken under consideration.

In relation to the greenhouse-gas-emission impact of vehicle manufacturing and propulsion, the effects of service, maintenance and spare parts are relatively low. In general, ICEV have a higher demand of service and wear parts, e.g., filters, clutches, oil changes and brakes. BEV have a higher mass due to the battery system and consequently a slightly higher tire wear, but significantly lower effort for powertrain and brake-system maintenance.

2.4. End-of-Life Phase

The end-of-life phase of a car includes vehicle dismantling, separation of materials and recycling processes as well as thermal and energetic recovery. Due to the high relevance on environmental pollution, different legislative boundary conditions regulate the handling of old cars in this sequence, e.g., [26,27]. Focusing on the impact of the end-of-life phases on the LCA-related carbon footprint, the relevance of recycling is relatively small. A certain share of materials can be recycled and fed back to earlier sequences, which has potential to reduce the total carbon footprint (see Figure 2, dotted arrows). On an actual industrial scale, recycling is well-introduced for steel and aluminum, on a lower level for plastic parts, and on a minor level for other materials [28]. A special case represents the battery systems of electrified or electric vehicles, because of the very valuable materials, which would make sense to apply recycling processes. Unfortunately, automotive lithium-ion batteries are not designed for recycling and as of yet there are no effective dismantling and recycling processes defined on an industrial scale [29–31]. In addition, there are plans to use the (still valuable) cells of old batteries in so-called "second-life" applications in stationary electric-storage systems. In the present work, effects of the end-of-life phase and of recycling are considered for steel and aluminum, which reduces the carbon footprint of vehicle production, but due to the above-mentioned uncertainties, they are not considered for the battery system.

3. Vehicle Inventory Analysis

As an important section of LCA, the inventory analysis includes a breakdown of systems, modules and components of a car and the corresponding investigation of product structure and related processes for materials preparation and vehicle manufacturing.

3.1. Main Modules of a Car

In many cases, the inventory analysis is conducted in form of a top-down breakdown, which targets the definition of main modules. In subsequent steps, the main modules are fragmented into various submodules and components, which for each the required data for the LCA are generated. This includes a detailed analysis of materials and the chain of manufacturing-related processes. Figure 8 shows an exemplary top-level structure of a car, including the main modules. Depending on vehicle type and size, implemented technologies, powertrain system and equipment, each module influences the results of an LCA in different ways.

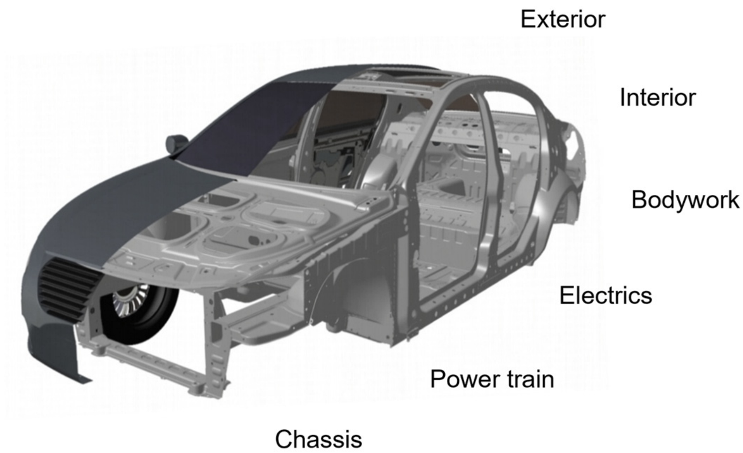

Figure 8. Main modules of a car.

The main module, *bodywork*, includes the vehicle body as well as doors and closures. Different material combinations are applied in modern cars, mainly based on steel sheets combined with aluminum and synthetic components. Aluminum bodies have a great potential for weight reduction but require higher effort (and consequently produce higher CO_2-equivalent emissions) in the manufacturing phase. Carbon-fiber bodies have the uppermost weight-reduction potential, but are rarely used in larger-scale mass production due to the high manufacturing efforts [32].

Exterior components include plastic parts for bumpers, styling and outer components, but also supplementary parts that complement the vehicle body. The exterior module typically has a low carbon footprint in relation to the bodywork.

Interior includes seats, inner panels, dashboards, air-conditioning systems and comfort-related equipment. As well as the seats, the comfort equipment has a large impact on both manufacturing-related greenhouse gas emission balance and vehicle weight.

The *electrics* module includes electric standard components, wiring and the power supply of electric and electronics systems on different voltage levels. This module differs greatly for conventional, hybrid and battery-electric cars.

Chassis includes the lower vehicle structure, suspension, brakes and wheels. Electric cars often have a changed vehicle architecture in comparison to conventionally powered cars, which comprises a large, flat battery below the passenger cabin. In this case, chassis and car body design differs from those of conventional cars, which has to be considered in the course of the inventory analysis.

3.2. Powertrain System

Of course, the powertrain system represents the most important module when it comes to a comparison of ICEV, HEV and BEV. This is caused by the very different approach of energy conversion for propelling the car, influencing the use phase. In addition, effects of the different powertrain technologies have to be considered in course of the manufacturing-related investigations of an LCA. There are several works that introduce the technologies of automotive powertrain systems, e.g., [33–35]. In the present article, the focus is put on aspects that are relevant in view of LCA and a corresponding evaluation of the carbon footprints of the investigated propulsion technologies.

The powertrain structure of cars driven by internal-combustion engines is characterized by a considerable number of mechanical components of high complexity (Figure 9). This comprises the combustion engine with pistons, valves, a number of shafts and bearings, as well as cylinder heads, crankcases, housings and covers. Driving power is transferred to the wheels via a manual or automated shiftable transmission system in combination with one or several clutches, differential gears and drive shafts. The main materials applied in the powertrain include different types of steel for shafts and moveable components, cast iron for some shafts, cylinder liners and housings, as well as aluminum for housings and covers. Fuel is supplied via a tank system including fuel pump and filters, and the exhaust gases are concerned to after-treatment in the exhaust system by use of highly effective catalytic converters and filters.

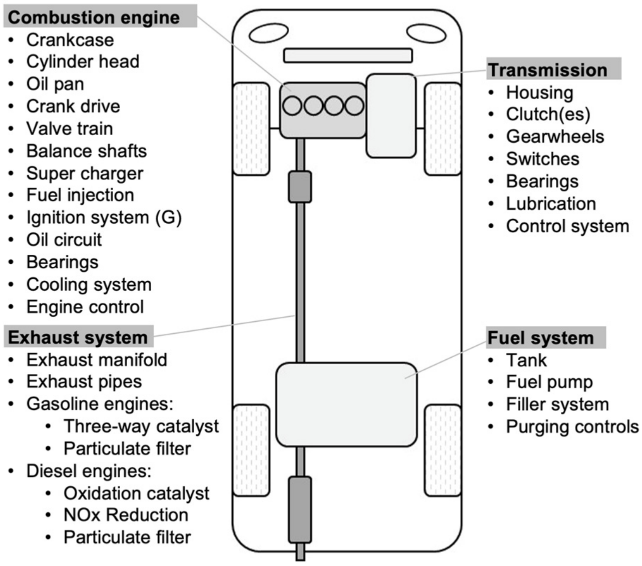

Figure 9. Powertrain structure of conventionally driven cars.

The powertrain structure of electric cars is simpler considering the mechanical parts but includes a higher share of electrical components and the complex high-voltage battery system for electric-energy storage (Figure 10). This comprises an electric motor, holding stator and rotor, power electronics as well as high-voltage charging system. Depending on the applied electric-motor technology, magnetic materials might be used (e.g., in permanent magnet-synchronous motors), which requires high effort for the provision of the corresponding resources [36]. In addition, copper and semiconductor-based components are applied in various components, e.g., inverter, converter and battery.

The high-voltage system requires efforts for electric protection, and the thermal management of BEV has to be designed more complex than those of ICEV because of the different operating-temperature levels of the inverter, electric motor and battery system. The carbon footprint of mechanical components of an electric powertrain is considerably lower than those of a conventional powertrain because there is a lower number of mechanical parts and the transmission system is much simpler. Most electric cars are equipped with a nonshiftable gearbox without a clutch.

Hybrid propulsion systems are defined by a combination of combustion engine and electric powertrain. There are different architectures of hybrid powertrains available, which differ according to the arrangement of combustion engine and electric-drive unit, Figure 11.

In the *serial hybrid configuration*, the combustion engine is not mechanically connected to the wheels, but drives an electric generator that supplies the electric-drive unit with energy. In this way, serial hybrids have a similar electric-drivetrain configuration as battery-electric cars, but with the extension of a combustion-engine-based power supply. In another configuration (not shown here), fuel-cell-electric vehicles are also serial hybrids, whereby a hydrogen fuel-cell system provides electric power for driving the car. In *parallel hybrid configurations*, both the combustion engine and electric motor are mechanically connected with the wheels. Different configurations can be defined according to the position of the electric motor in the powertrain system: *P0* (electric motor/generator connected to the crankshaft via a belt drive), *P1* (electric motor/generator directly at the crankshaft, typically at the flywheel), *P2* (electric motor separated from the crankshaft by an additional clutch), *P3* (electric motor at the output shaft of the gearbox) and *P4* (one axle of the car is driven by the combustion engine, the other one is driven by an electric-axle drive). Due to the high variability of the powertrain setup, parallel hybrids are applied in very different configurations according to the actual requirements of a specific car model. *Combined hybrid configurations*, also called "power-split" hybrids, are characterized by a central transmission system, which combines the combustion engine and one or several electric motor/generator units. In this way, the drive system can be controlled very flexibly according to the actual driving situations.

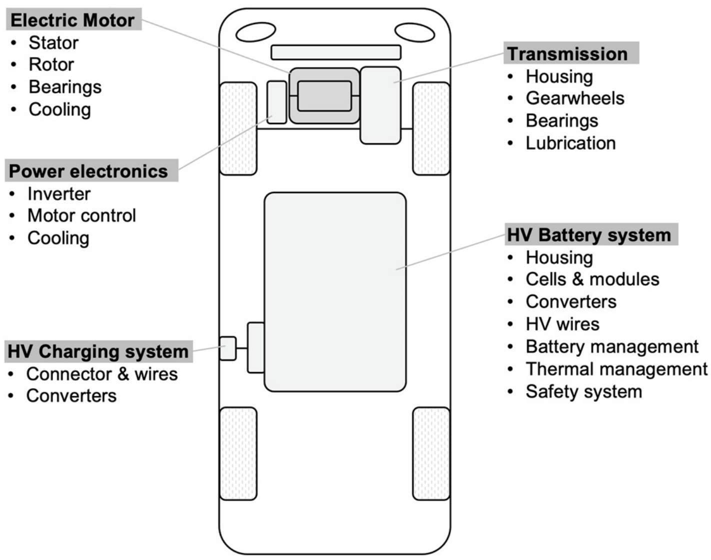

Figure 10. Powertrain structure of electric cars.

Besides their architecture, hybrid powertrains can be distinguished according to the degree of electrification, which defines the electric-performance capability. In this way, so-called *mild hybrids* are typically equipped with relatively small electric motors (less than 15 kilo Watts (kW) power) and small low-voltage battery systems (less than 1 kilo Watt hour (kWh) energy capacity). The electric unit serves as a starter/generator and eventually enables a certain share of brake-energy recuperation. Electric drive is not possible for *mild hybrids*. *Full hybrids* are equipped with powerful electric motors (depending on the vehicle class with more than 100 kW), but relatively small battery systems with a capacity of typically up to 5 kWh. The propulsion system of *full hybrids* allows electric drive for short distances and—depending on the drivetrain architecture—can provide effective brake-energy recuperation. Finally, so-called *plug-in hybrids* are equipped with powerful electric motors with up to more than 100 kW power output, depending on the vehicle class, and significantly larger battery systems (capacity between 8 and 30 kWh), which optionally can be charged externally from the electric power grid. In this way, *plug-in hybrids* provide electric-driving ranges from 30 to more than 60 km [37].

Concerning the life-cycle assessment of the different technologies, hybrid powertrain systems are characterized by a wide range of carbon-footprint characteristics. This is related to all sections of the life cycle. In the production phase, the degree of electrification plays an important role, because it defines the types and quantities of materials and the technologies of production. In this way, *mild hybrids* have a very similar production-related carbon footprint as comparable to conventional cars. Depending on their architecture and degree of electrification, *full hybrids* are characterized by a 5 to 10% higher production-related carbon footprint. Due to the larger battery system, *plug-in hybrids* can have up to a 25% higher carbon footprint than conventional cars of similar size and performance. Own measurement series have shown that the reduction potential of fuel consumption is in the range of 0–5% for typical *mild hybrids* and up to 15% for *full hybrids*. In the case of *plug-in hybrids*, the evaluation of potential reduction of fuel consumption (respectively carbon footprint) during the use-phase is much more complex, because it is significantly influenced by the actual driving pattern and user behavior. If *plug-in hybrid* cars are frequently charged from the grid, and the driving distances are below the maximum electric range, the combustion engine is not in operation, leading to zero fuel consumption. On the other hand, if the car is not charged from the grid, it is operated like a *full hybrid*, and the potential benefits of external electric power supply are not taken.

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The battery system is composed of modules that include a number of cell elements, which represent the basic units of electric-energy storage (Figure 12). Cells and modules are electrically connected in serial and parallel order to provide a certain voltage and current level via so-called "bus bars" and high-voltage connectors. A rigid housing including stiffener elements protects the battery against mechanical deformation, e.g., in case of a crash. Lithium-ion batteries are sensitive against high and low temperatures, which requires accurate management of the temperature in the cells. This is provided by a complex thermal-management system, including sensors and controllers. The battery-management system comprises several cell-management controllers on module level as well as the general battery management that controls the battery during charging, discharging as well as in case of error and crash scenarios.

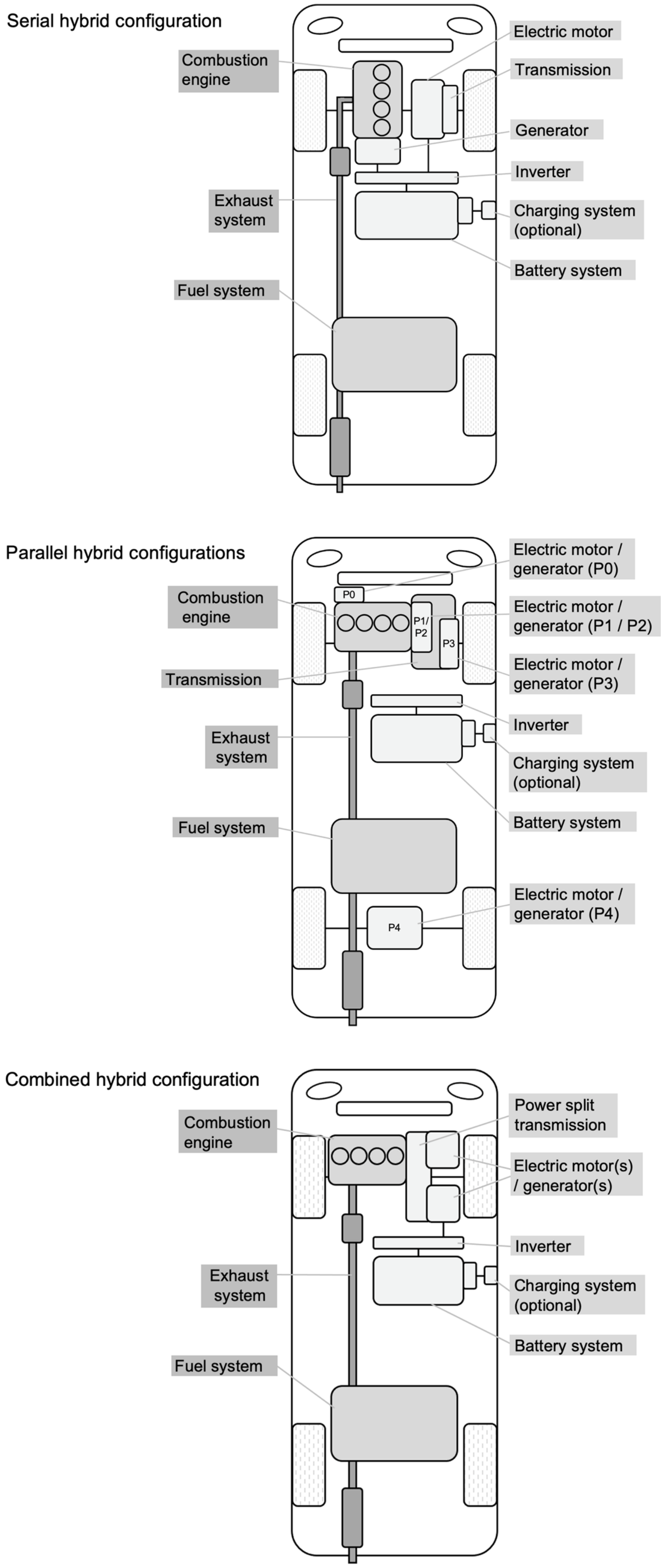

Figure 11. Powertrain architectures of hybrid cars.

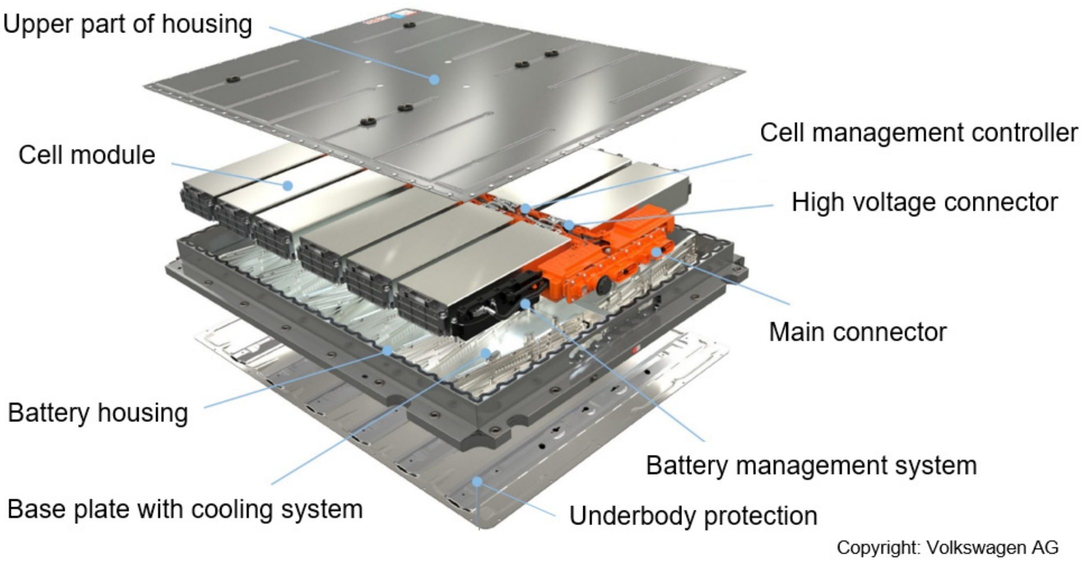

Figure 12. Configuration of a modern battery system for BEV, modified from [38].

In an inventory analysis of the battery system, the different materials used and the various manufacturing processes have to be investigated and analyzed. In general, automotive-battery manufacturing can be separated into the production of cells and the production of the battery unit, including assembling of cells to modules, adding conductors, sensors and controllers, as well as integration of the entire battery with a thermal system, battery management and housing. In most cases, the cells are produced at cell-supplier factories in China, South Korea or Japan and shipped to the battery-system-manufacturing plants located near the car manufacturer's vehicle-assembly lines. Some car manufacturers integrate the entire battery-manufacturing chain in large, so-called "gigafactories", e.g., [39].

Cell manufacturing is a very complex process that includes the preparation of active materials for anodes and cathodes as well as separators and electrolytes, surfacing technologies for electrode production and foil slitting-, winding- and stacking processes. Due to the high sensitivity of electrochemical reactions, initial charging processes, so-called "formation", has to be conducted with high accuracy and control effort. Finally, all cells are checked before delivery and a certain share of potentially defective cells are sorted out, which has a considerable impact on the LCA [40]. Typical materials for anodes are graphite and silicon–graphite combinations. At the cathode, lithium-metal oxides come to use, integrating e.g., lithium, cobalt, manganese, nickel, aluminum and iron phosphate. The actual material mixtures are designed specifically and may vary between different car manufacturer and vehicle types. The carrier foils of the electrodes are made of aluminum and copper, and the separator is typically a polymer membrane.

The entire cell-manufacturing process is related to high demands on accuracy and cleanliness. Extraction and processing of active materials in the cells, as well as manufacturing processes, require high effort, which significantly influences the life-cycle balance. In an average consideration, about the half of production-induced CO_2-equivalent emissions of an automotive-battery system stem from cell production and the other half from battery-system manufacturing and transportation. Figure 13 shows the distribution of CO_2-equivalent emissions of battery manufacturing. It is visible that the high electric-energy demand represents the most important factor, followed by materials extraction, processing and the production of electrodes [41]. The figure also shows that due to the high energy impact of battery production, the application of low-carbon electricity sources plays an important role to reduce the life-cycle carbon footprint of electric cars. In a comprehensive LCA, the electricity mixes of both cell production and battery-system manufacturing have to be considered. In this context, it makes a relevant difference if the battery is produced in a country with high CO_2-equivalent-emission impacts or in a country with a large share of renewable energy sources (see also Figure 4).

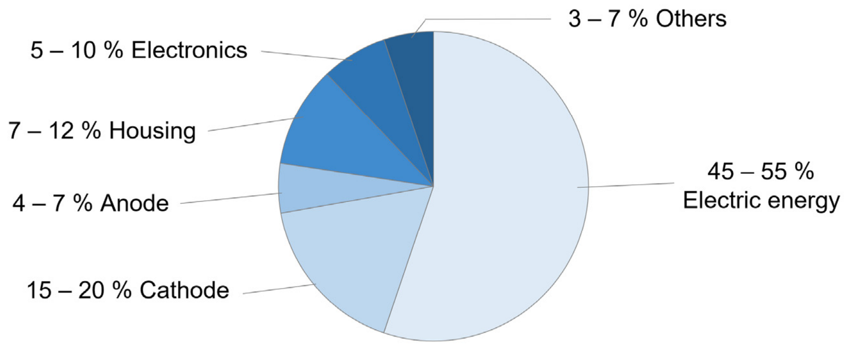

Figure 13. CO_2-equivalent-emission impacts of battery-manufacturing-related factors.

The end-of-life phase of lithium-ion batteries provides great potential in general because of the valuable materials [42], but recycling processes are not introduced on a large industrial scale yet. Reasons are the highly complex processes of battery disassembling and materials extraction and the relatively low volume of available exhausted automotive high-voltage batteries today. In addition, there are alternative business models coming up, which could make use of old automotive batteries in so-called "second-life" applications in stationary power-storage systems. Studies show that in case of recycling, a reduction in the carbon footprint of battery manufacturing in the range of 5–10% is feasible [41,42].

Another issue to be considered in an LCA is the lifetime of lithium-ion batteries. In the initial years of BEV, the battery system was concerned with relevant aging effects, which often made replacement of the battery within the lifetime of a car necessary. However, battery technology has improved significantly in view of energy-storage capability and degradation behavior during the past years. In modern electric cars, the battery system is designed for the entire lifetime of the car, which does not require replacements. Usually, car manufacturers provide warranty of 8–10 years and a mileage of 150,000–200,000 km for the battery, considering a reduction in energy storage capability of a maximum of 20–30% [43,44].

Due to the fact that a major share of the carbon footprint of BEV is caused by the production of the battery system, the size and energy storage capability significantly influences the total CO_2-equivalent emissions characteristics. In today's cars in the markets, the storage capability varies widely, depending on vehicle type, class and variant. Small, low-cost BEV are equipped with batteries of about 10 to 20 kWh energy-storage capacity; compact and midsize cars with about 20 to 75 kWh; and large and premium-class cars with about 60 to more than 100 kWh. Hybrid cars are equipped with smaller battery-storage capacities, ranging from less than 1 kWh in mild hybrids to up to 30 kWh in plug-in hybrids. Considering a direct influence of the energy-storage capacity on the CO_2-equivalent-emission impact, the actual battery size has to be included carefully in the course of LCA-based evaluations and discussions.

4. Results and Discussion

The introduced procedure of LCA has been applied to evaluate the CO_2-equivalent-emission impact of electric cars in comparison with hybrid and conventionally driven cars under consideration of the above-mentioned boundary conditions and influencing factors. The following three sections represent results of the investigations, divided into vehicle-manufacturing-related sequences, the phase of car usage and a consideration of the behavior in the total life cycle. The underlying LCA has been conducted according to the referred ISO standards [1,2] under consideration of large databases [3–5]. Table 1 shows the main characteristics of the investigated cars with different propulsion technologies.

Table 1. Main characteristics of investigated cars with different propulsion technologies.

	ICEV	HEV	BEV
Car type:	Compact car (C-class)	Compact car (C-class)	Compact car (C-class)
Vehicle mass:	1400 kg	1450 kg	1800 kg
Propulsion:	Gasoline engine	Comb. full hybrid, gasoline engine	Permanent magnets synchr. Motor
Max. power	90 kW	90 kW	110 kW
Fuel/energy consumption:	6 liter/100 km	4.5 liter/100 km	20 kWh/100 km incl. charging losses
Battery capacity:	-	1.3 kWh	60 kWh
Country of battery cell production:	-	China	China
Country of vehicle manufacturing:	Germany	Japan	Germany
Car body main material:	Steel	Steel	Steel
Vehicle comfort equipment level:	Standard	Standard	Standard
Total carbon footprint of production:	7.5 tonnes CO_2 equivalents	9.0 tonnes CO_2 equivalents	14.0 tonnes CO_2 equivalents

In the present study, vehicle characteristics of the compact car class (C-segment) are taken under consideration, because this vehicle class is very popular in the European market. The investigated cars represent selected actual vehicles of comparable size and performance, driven by different propulsion technologies including combustion-engine-based powertrains (ICEV and HEV) as well as battery-electric propulsion systems. The fuel- and electric-energy consumptions are based on the standardized WLTP-driving cycle. The hybrid car (HEV) is a typical power-split full hybrid driven by a combination of gasoline engine, automated transmission system and a configuration of two electric motors. For the BEV, the electric-energy consumption considers 16 kWh per 100 km for propulsion in the standardized driving cycle plus 10% energy demand for passenger-cabin climatization and auxiliaries (e.g., for heating/cooling the car in winter/summer). In addition, charging losses are included for an assumed charging behavior of 75% slow charging and 25% high-power charging.

4.1. Vehicle Production

Figure 14 shows the LCA-based production-related CO_2-equivalent-emission impacts of the investigated cars. For cars with internal combustion engines, the main contributions stem from the *car bodywork*, *ICE powertrain*, *interior* and *electrics and electronics* modules. With 9.0 tonnes of CO_2 equivalents, the investigated hybrid car shows a 20% higher production-related carbon footprint than the conventionally driven car. Whereas the *car bodywork*, *interior*, *chassis* and *exterior* modules display the same masses of CO_2 equivalents, the impact of the *ICE power-train* is slightly lower for the hybrid car, which is caused by a smaller (and moderately less-performant) combustion engine. Additional modules of the hybrid car, relevant for the production-related carbon footprint, are the *e-powertrain* and the *battery*. Together, they contribute to about 1.5 tonnes, respectively 17 % of CO_2 equivalents.

The battery-electric car has a significantly higher production-related carbon footprint with 14.0 tonnes. Here, the *battery system* acts as a main contributor with 7.0 tonnes. Due to a high integration of the battery housing into the vehicle structure and a larger share of plastic exterior parts, the *car bodywork* module shows a slightly lower CO_2-equivalent mass impact than those of the ICEV and the HEV. The considered BEV has relatively simple comfort equipment in comparison to the two other cars, resulting in a slightly reduced carbon footprint of the *interior* module. Relevant is the *electric powertrain* module with 10% of the total CO_2-equivalent impact. The impact of the *electrics and electronics* module considers only low-voltage components, as all high-voltage elements are included in the CO_2-equivalent balance of the *battery system*.

4.2. Use Phase

The LCA-based evaluation of the car's use phase includes CO_2-equivalent emissions during driving, as well as the impacts of maintenance, service and wear parts. A relevant share of carbon footprint is caused by vehicle propulsion, which comprises well-to-tank emissions (WTT) for preparation of electric energy, respectively fuel, and tank-to-wheel emissions (TTW) caused by combustion of fuel. As mentioned in Section 2.3, BEV do not produce TTW emissions. For cars with combustion engines, production and provision of fuel (WTT) has to be considered.

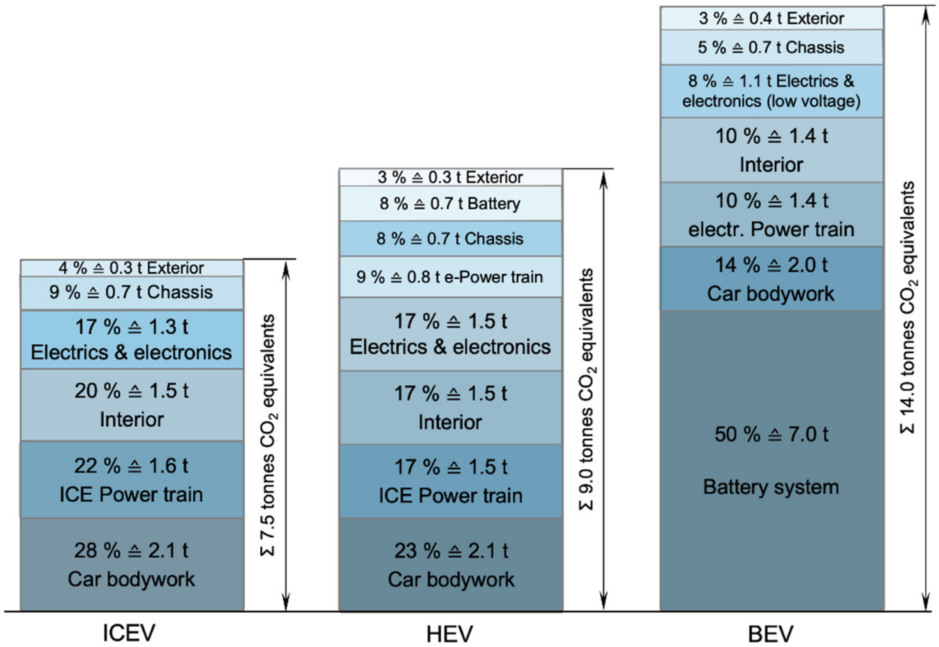

Figure 14. LCA-based production-related CO_2-equivalent-emission impacts of selected compact cars, equipped with different propulsion technologies.

The diagram in Figure 15 shows the well-to-wheel (WTW) CO_2 equivalent emissions of the investigated compact cars with different propulsion systems and varied carbon footprint of electricity production. It is visible that hybrid propulsion technology has the potential to reduce the carbon footprint by about 25% in comparison to conventional combustion engines. Considering the behavior of electric cars, the importance of low-carbon electricity production is clearly demonstrated (c.f. Figures 3 and 4). In this way, a modern hybrid car can have a lower use-phase-related greenhouse-gas-emission impact than an electric car that is charged in a country or region with highly carbon-intensive electric-power generation. It is interesting to see in Figure 15 that in most of the exemplarily considered countries, the usage of BEV leads to a significantly lower carbon footprint than those of ICEV and HEV. In countries with very low carbon-intensive electric-power generation, the well-to-wheel CO_2-equivalent-emission impact can be reduced to 7.5% (France) or even 4% (Norway) in comparison to those of the ICEV.

4.3. Total Life Cycle

Combining the carbon footprints of production and those of the use phase, Figure 16 illustrates the life-cycle CO_2-equivalent emissions of the investigated compact cars with different propulsion systems and varied carbon footprints of electric-power generation. In the present consideration, the vehicle production was assumed to be in Germany (ICEV and BEV) and Japan (HEV), and the battery-cell production in China. In this way, the results represent exemplary behavior that might be different in specific cases under dissimilar boundary conditions. Anyway, the impact of electricity provision to the total carbon footprint is clearly visible.

The high CO_2-equivalent emissions of BEV production are compensated relatively quickly in case that the cars are operated in countries with low-carbon electricity production, e.g., Norway. Considering the average EU 28 electricity mix, the break-even point with

ICEV is reached at about 65,000 km. In the case of high-carbon electricity production, e.g., in Poland, the break-even point will not be reached within the considered mileage range of 200,000 km. HEV are characterized by about a 20% higher carbon footprint production than ICEV, but have considerably lower CO_2 emissions during operation, which leads to significant advantages of the lifetime CO_2-equivalent-emission behavior. However, the potentials of BEV that are charged with low-carbon electricity can clearly not be reached with combustion-engine-based technologies.

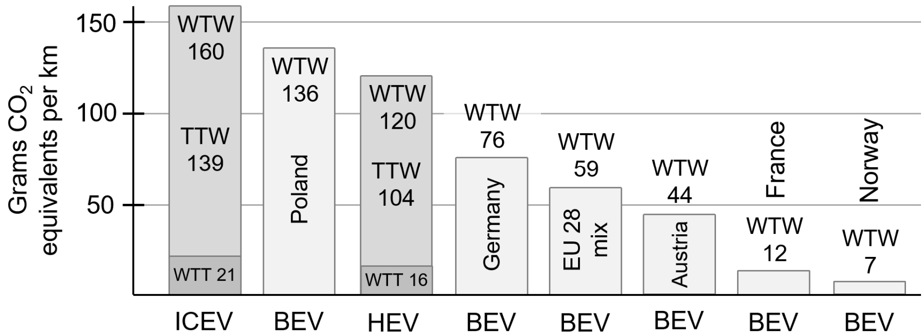

Figure 15. Well-to-wheel CO_2-equivalent emissions of selected compact cars with different propulsion systems and varied carbon footprint of electricity production.

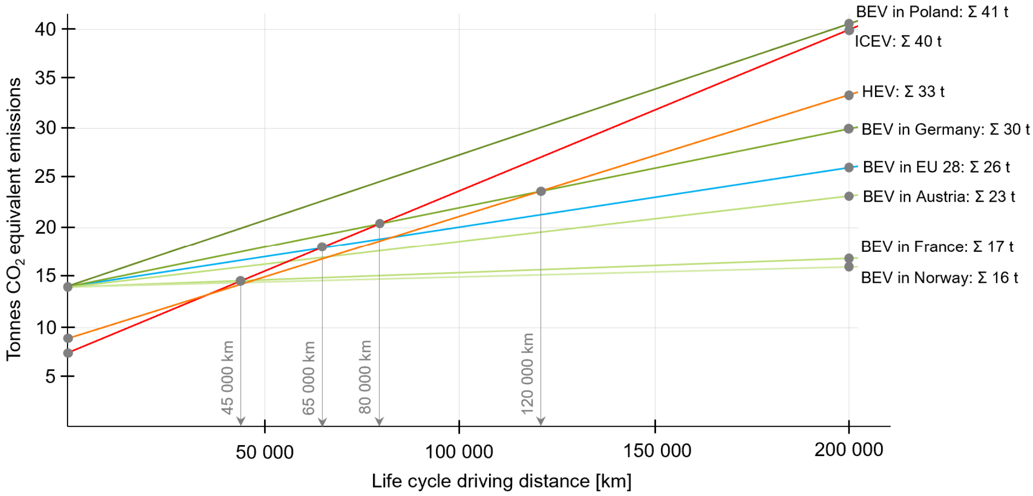

Figure 16. Life-cycle CO_2-equivalent emissions of compact cars with different propulsion systems and exemplarily varied carbon footprints of electric-power generation.

5. Conclusions

A holistic evaluation and comparison of cars driven by different propulsion technologies requires the application of extensive life-cycle assessment. Due to the high complexity of modern vehicles and the related manufacturing and supply-chain processes, comprehensive investigations integrate energy provision, materials production, vehicle manufacturing, car usage and end-of-life treatment.

The article introduces processes and influencing factors of life-cycle assessment in the automotive sector and discusses modern propulsion technologies in view of their CO_2-equivalent-emission impacts. Based on a literature study, the ranges of CO_2-equivalent-emission impacts are shown for the main modules of modern cars driven by combustion engines, hybrid cars and battery-electric cars. Subsequently, the standardized methodology of life-cycle assessment is applied on actual mass-production cars of the C-segment and the impacts of the investigated powertrain technologies are evaluated for the vehicle's production phase and the use phase. Focusing on the production phase including materials processing and recycling, battery-electric cars are characterized by a 50 to 100%

higher carbon footprint than comparable cars driven by combustion engines. In the case of hybrid cars, the wide range of powertrain architectures makes a clear definition regarding hybrid drive configuration and the degree of electrification necessary. In this context, the production-related carbon footprint of hybrid cars can be up to 50% higher than those of comparable conventionally driven cars. In the phase of usage, the technology of electric-power generation significantly influences the carbon footprint of electric cars. In the case of low-carbon electric-energy supply, battery-electric cars are characterized by remarkably low carbon footprints. In the case of fossil-based electricity production, the level of CO_2-equivalent emissions is comparable with those of cars driven by combustion engines. In total consideration, the higher carbon footprint of electric-car production can be compensated by the lower carbon impact during the use phase, but only if there is a low-carbon electric-power supply for charging available. Hybrid cars can reduce the life-cycle-related CO_2-equivalent-emission impacts considerably in comparison with conventionally driven cars, and seem to be an attractive alternative to battery-electric cars in the case that low-carbon electric energy is not available in a certain region.

Considering future trends of increasing implementation of electricity production with low CO_2-equivalent emissions and the introduction of low-carbon manufacturing technologies, battery-electric cars have a large potential to contribute to a reduction in greenhouse-gas emissions in the transportation sector.

Author Contributions: M.H., conceptualization, methodology, validation, formal analysis, investigation; T.T.N., resources, data curation, validation; M.H. and T.T.N., writing—original draft preparation, review, editing and visualization; M.H., supervision, project administration, funding acquisition. All authors have read and agreed to the published version of the manuscript.

Funding: The publication of this article was supported by TU Graz Open Access Publishing Fund.

Acknowledgments: Open Access Funding by the Graz University of Technology.

Conflicts of Interest: The authors declare no conflict of interest.

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