Chapter 2
Electric Vehicles, Lightweight Design and Environmental Impacts

This chapter provides the necessary theoretical background to understand the environmental impacts of LEVs. For this purpose, the chapter is divided into four parts. First, the relevant aspects of EVs and lightweight design are presented. Then, environmental impacts are discussed and Life Cycle Assessment, a method to evaluate these impacts, is introduced. Finally, the environmental impacts of LEVs are explained and the demand for a corresponding Life Cycle Assessment concept is derived.

2.1 Electric Vehicles

Within the following the term ‘electric vehicle’ is used to describe full battery electric vehicles. Relevant aspects of EVs are presented in the following sub-section. First the components and basic functioning of an EV are described. Then, the composition of the energy consumption of EVs is explained.

2.1.1 Components and Functioning of Electric Vehicles

Figure 2.1 shows the schematic picture of an EV consisting of the car body, wheels and tires, interiors, the steering, braking and suspension system, the non-propulsion electrical system and the drive train. The central element of EVs which distinguishes them from conventional vehicles is the electric drivetrain which has a battery as energy storage and uses an electric motor to turn the onboard energy into mechanical energy. The remaining components are not necessarily specific to EVs (although they can be adapted to fulfil specific requirements of an EV) (Hameyer et al. 2013). Hence, these components—electric motor and battery—are described in more detail after a brief explanation of the functioning of the EV.

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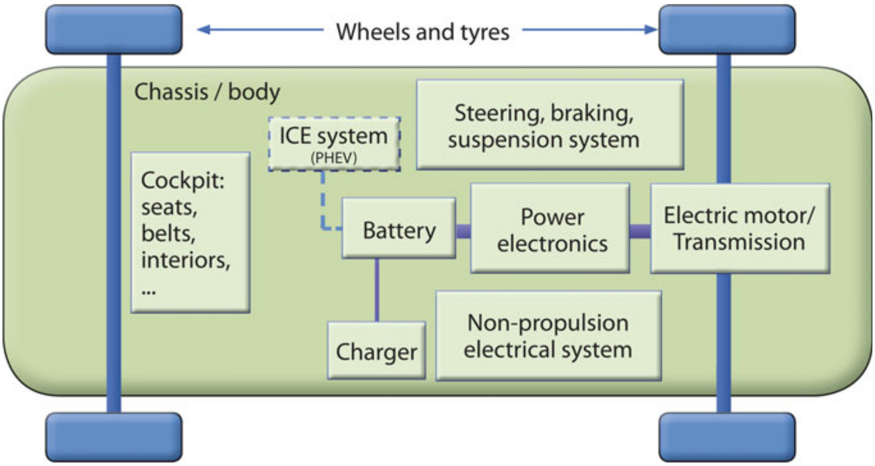

Fig. 2.1 Components of electric vehicle (Del Duce et al. 2013)

2.1.1.1 Functioning

The basic version of an electric drivetrain consists of the battery, an inverter (power electronics) and the electric motor. The battery provides a direct current which is passed on to the inverter. The inverter turns the direct current into an alternating current and provides it to the electric motor. Then the electric motor turns the electric energy into mechanical energy (i.e. into a torque with a specific rotational speed). This process can be turned around and the electric motor can serve as an electric brake. The electric motor then works as a generator and turns braking energy into electric energy which is stored in the battery via the inverter. This process is referred to as recuperation (Hameyer et al. 2013). For the non-propulsion electrical system a high voltage and a low voltage branch can be distinguished. Heating and cooling auxiliaries are connected to the high-voltage branch. The low voltage branch is supplied by a DC/DC converter. It ensures a sufficient charging of the 12 V battery as well as energy supply for all 12 V auxiliaries like light, radio and navigation (Wallentowitz and Freialdenhoven 2011; Hameyer et al. 2013).

2.1.1.2 Electric Motor

Electric motors commonly consist of a moving (i.e. rotor) and stationary (i.e. stator) component. They generate movement through the interaction of a magnetic field and conductors which carry current, using the so called Lorentz force (Leidhold 2015). Different types of electric motors exist: direct current (DC) and asynchronous and synchronous alternating current (AC) motors. The names are derived from the required input current. In DC motors the rotor carries the conductors and rotates in the magnetic field of a permanent magnet (stator). In AC motors the stator creates a rotating magnetic field in which the rotor moves. Due to their constructions, the rotor of synchronous motors moves with the speed of the magnetic field (synchronous), in asynchronous motors the rotor moves slower (asynchronous) (Stan 2012). Depending on the design, synchronous AC motors can contain permanent magnets (Wallentowitz and Freialdenhoven 2011). DC motors are simple and well-developed. Today's EVs are usually equipped with AC motors. Asynchronous AC motors are simpler and therefore less expensive than synchronous AC motors. However, the efficiency of the latter is higher (Achleitner et al. 2013; Leidhold 2015; Stan 2012). For more detailed descriptions and other special electric motors see Leidhold (2015), Achleitner et al. (2013), Stan (2012) and Wallentowitz and Freialdenhoven (2011).

2.1.1.3 Battery

Lithium-ion batteries are state of the art for EVs. The term describes a group of batteries which possesses a high specific power and a high specific energy (Scrosati and Garche 2010; Ecker 2015; Leidhold 2015) Depending on the vehicle seize the battery usually has a capacity of 15–25 kWh which provides a range of around 100–150 km (Sauer et al. 2013).

In general, a battery consists of cells, a battery management system, packing and a cooling system (Ellingsen et al. 2014). The basic build-up (battery system with modules and cells) and functioning of a battery are shown in Fig. 2.2. The cells are the most defining element of the battery. They are available in different forms: pouches, prismatic and cylindrical cells. The cell contains the anode (negative electrode), cathode (positive electrode), separator and electrolyte. The anode often consists of graphite. The cathode consists of a lithium-metal oxide or a metal phosphate. Common cathode materials are lithium cobalt oxide, lithium iron phosphate or lithium manganese oxide. The direction in which the lithium-ions cross the separator depends on whether the battery is being charged or discharged. The lifetime is mainly defined by two parameters: the time passing and the number of charging and discharging cycles. Typical life times range from 8 to 12 years and are close to 3000 cycles (Sauer et al. 2013).

2.1.2 Energy Consumption of Electric Vehicles in Use Phase

The range of EVs is determined by the state of charge of the battery and the energy consumption of the vehicle. Even though the state of charge of the battery is known at the beginning of each trip, the range of the vehicle is uncertain as it depends on the upcoming, uncertain energy consumption. The energy consumption depends on the vehicle itself and variables like the ambient temperature and the driving

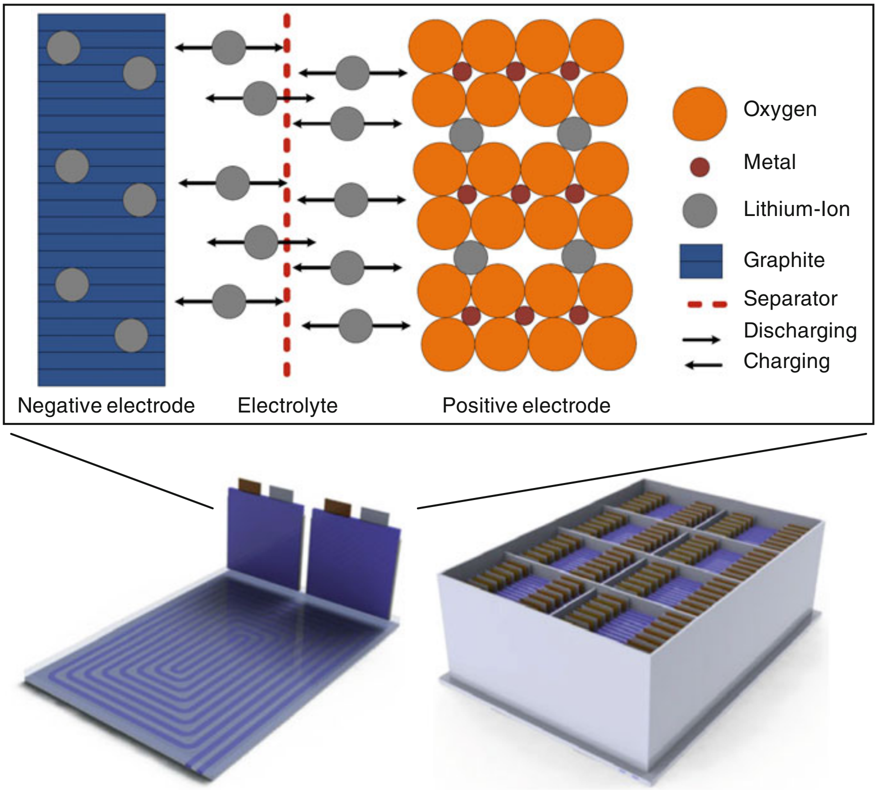

Fig. 2.2 Basic construction of a lithium-ion battery: battery pack with eight modules (*bottom right*), battery pouch cell (*bottom left*) (Schäper 2015), charging and discharging process in battery cell (*top*) (Ecker 2015)

behaviour. Therefore, it is variable. To understand which elements lead to the total energy consumption of EVs and what influences the final result, its composition is described in the following. As an aid to determine the energy consumption of vehicles, driving cycles are described subsequent to the description of the energy consumption.

The energy consumption of EVs is influenced by five aspects (Del Duce et al. 2013):

- The driving resistances must be overcome to put the vehicle into movement.
- Energy is lost in the process of transforming the electric energy of the battery into mechanical energy at the wheels of the vehicle. Hence, each drivetrain has a specific efficiency.
- Auxiliaries on board the vehicle require energy. These are particularly the high voltage devices for heating and cooling but also low voltage auxiliaries such as light, radio or navigation.

- The charging process is affected of energy losses. In addition, the battery loses energy when in still stand.
- The electric motor can serve as a generator and charge energy into the battery while braking. Hence, recuperation recovers energy and reduces the total energy use.

2.1.2.1 Driving Resistances

The driving resistances F_D describe the physical resistances which must be overcome to move the vehicle. They are the rolling F_R, aerodynamic F_{Ae}, acceleration F_A and road slope F_S resistance (Ayoubi et al. 2013) as seen in Eq. (2.1).

$$F_D = F_R + F_{Ae} + F_A + F_S \tag{2.1}$$

These resistances are influenced by the mass of the vehicle (including the load) m, the gravitational acceleration g, the rolling friction of the tires f, the slope of the road β, the density of air δ, the size of the vehicle frontal area A, the drag coefficient of the vehicle c_w, the velocity v and the acceleration a (Ayoubi et al. 2013). The full equation for the driving resistances is shown in Eq. (2.2). The resistances are pictured in Fig. 2.3.

$$\mathrm{F_D} = \mathrm{m} * \mathrm{g} * \mathrm{f} * \cos\beta + \frac{\delta}{2} * \mathrm{A} * \mathrm{c_w} * \mathrm{v}^2 + \mathrm{m} * \mathrm{a} + \mathrm{m} * \mathrm{g} * \sin\beta \tag{2.2}$$

Subsequently, the necessary power P_D to propel the vehicle can be described as follows (Woll 2013):

$$P_D = (F_R + F_{Ae} + F_A + F_S) * v. \tag{2.3}$$

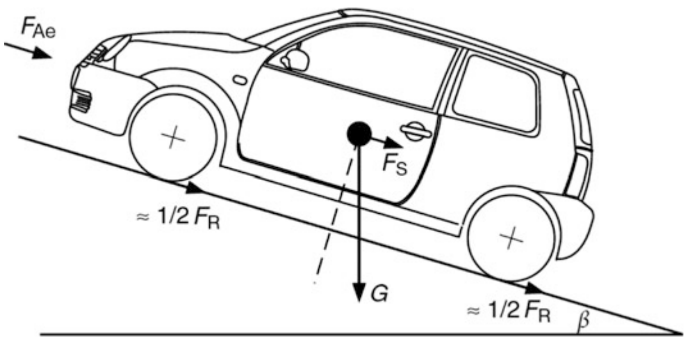

Fig. 2.3 Driving resistances (Ayoubi et al. 2013)

2.1.2.2 Drivetrain Efficiency

Depending on the operating point, the drivetrain of an EV can reach higher efficiencies than conventional vehicles. The efficiency of the drivetrain compares the power that is theoretically necessary under ideal conditions and the power that is actually needed to propel the vehicle. This means it expresses the effectiveness of all components (Pischinger and Adomeit 2013). The efficiencies of the single components battery (~99 %), inverter (~98 %), electric motor (~96 %) and transmission (~93 %) can lead to a global efficiency of around 87 %. Combustion engines only reach values around 30–40 % (Del Duce et al. 2013; Woll 2013). The efficiencies of the components are not static but depend on their operating points. For example, the battery efficiency depends on the internal resistance and the temperature. The efficiencies of the motor and the inverter depend on speed and torque (Faria et al. 2012; Del Duce et al. 2013). Figure 2.4 shows the example of an efficiency map of an electric drive train. Depending on the operation point (the combination of motor torque and motor speed) an efficiency of 85–95 % is achieved by the electric motor.

2.1.2.3 Auxiliaries

Auxiliaries can be connected to the low voltage as well as the high voltage branch of the drive train. Accordingly, their energy consumption has a lower or higher influence on the overall energy consumption. Devices such as lighting, radio, navigation or seat heating are set up to the low voltage branch and have power demands around 50–140, 20 and 30–70 W (Del Duce et al. 2013). Therefore, they play a secondary role for the energy consumption.

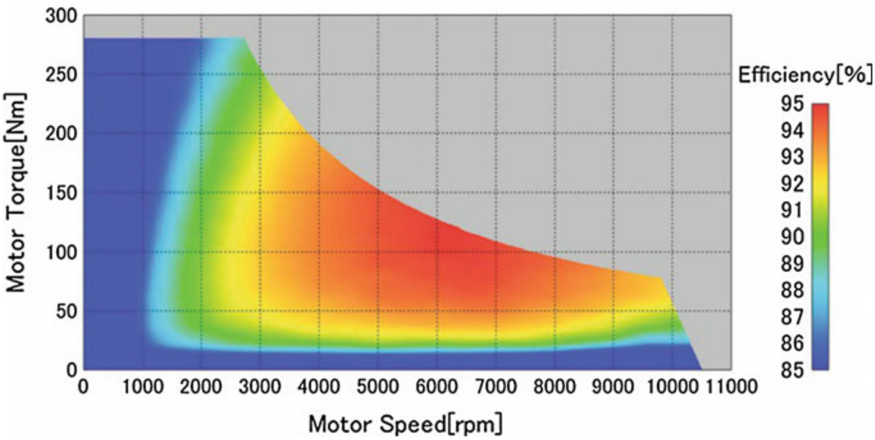

Fig. 2.4 Example of efficiency map for an electric motor (Sato et al. 2011)

Heating and air conditioning devices are fed by the high voltage branch. Whereas waste heat from the engine is used for heating in conventional vehicles, heat needs to be generated specifically in EVs. The most common solution is the use of positive temperature coefficient (PTC) heaters. The power demand for PTC heaters can be up to 5 kW (Hameyer et al. 2013). Air conditioning systems have a power demand of around 1 kW (Del Duce et al. 2013). The frequency of use of heating and cooling devices depends significantly on the ambient conditions like the temperature and the humidity but also on user preferences (Strupp and Lemke 2009; Konz et al. 2011). The high power demands in combination with frequent use have a significant influence on the total energy consumption and can reduce the range of an EV by up to 46 % (Konz et al. 2011; Ayoubi et al. 2013). Heat pumps are promising alternatives to reduce the energy consumption for heating as their energy demand is lower in comparison to PTC heaters (Hameyer et al. 2013). They can reduce the power demand to around 3 kW (Del Duce et al. 2013).

2.1.2.4 Battery and Charging Losses

Losses in the battery can occur in standstill and during the charging process. Battery still stand losses depend on the type and design of the battery as well as the use profile. A high number of cells leads to higher still stand losses. However, the losses in lithium-ion batteries are generally low. The efficiency of the charging process can vary significantly (80–90 %) and depends on the parameters of the charging system (e.g. the type of system such as wallbox or charging station) as well as on the battery itself (Del Duce et al. 2013; Roesky et al. 2015).

2.1.2.5 Recuperation

As described above, the electric engine can serve as a generator during the braking process and energy can be recuperated. While the energy used to overcome air and rolling resistance are irreversible, the energy used for acceleration and slope can be (partially) recovered by recuperation (Woll 2013). The rate of energy that can be recovered depends on the battery, the size of the electric motor and the power electronics. An algorithm controls the process to protect the battery from to high currents (Del Duce et al. 2013).

2.1.2.6 Driving Cycles

Driving cycles are predefined schedules to operate a vehicle under reproducible conditions and to achieve comparable results. These cycles are mainly used for the measurement of emissions and for type approval (Barlow et al. 2009). A cycle is defined by its speeds over time. They can cover urban and rural roads as well as highways (Neudorfer et al. 2006). A variety of different driving cycles exist like the

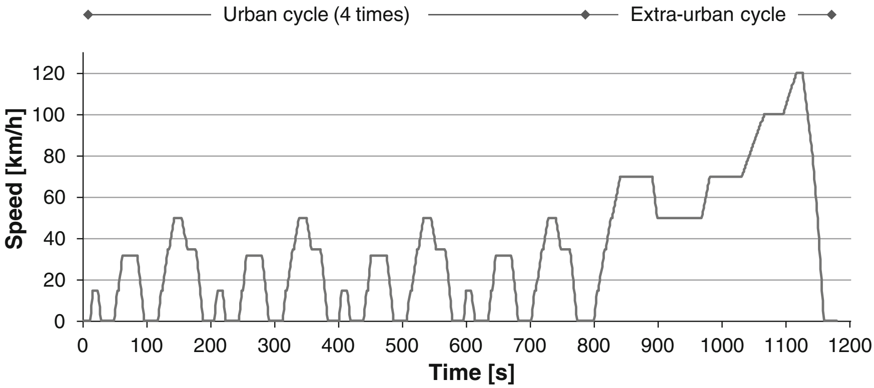

Fig. 2.5 New European driving cycle, own illustration with data from United Nations (2005)

EU legislative, the US and the Japanese testing cycles or the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) (Woll 2013). Figure 2.5 shows the example of the New European Driving Cycle (NEDC). The NEDC is a stylised driving cycle with constant speed and acceleration. It consists of four identical urban cycles and one extra-urban cycle. Currently, the NEDC is the standard driving cycle for type approval of passenger cars in Europe (United Nations Economic Commission for Europe 2014). Such a stylised type of driving cycle can underestimate the energy consumption achieved when driving in real traffic situations. In contrast, real-world cycles are derived from real data of one or multiple trips (Woll 2013).

2.2 Lightweight Design for Vehicle Engineering

The aim of this sub-chapter is to give an overview on the topic of vehicle lightweight design. For this purpose the chapter starts with an introduction on lightweight design and continues with a detailed description of lightweight materials because of their relevance to the environmental impact of vehicles.

2.2.1 Lightweight Design

The weight of vehicles has increased continuously in the past four decades. Three examples are shown in Fig. 2.6. The weights of the Volkswagen models Passat, Golf and Polo have increased by an average of 50 % since the 1970s. Drivers for the weight increase are higher demands—of customers or legislation—on safety, performance, comfort, reliability and other vehicle characteristics. These demands lead to additional and more complex parts in each new vehicle generation.

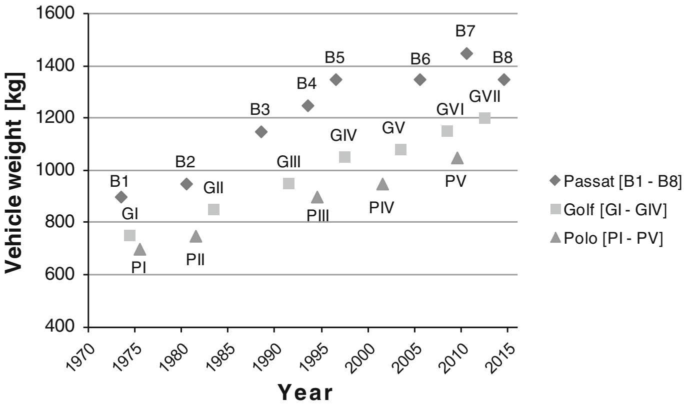

Fig. 2.6 Development of vehicle weight of Volkswagen models Passat, Golf and Polo in the past four decades (based on Eckstein et al. 2010; Volkswagen 2009, 2015a, b)

Furthermore, a spiral effect pushes up the weight even higher. Because the components can be mutually dependent on each other, secondary weight increases can occur. Weight increases lead to the demand for a more powerful and heavier motor or engine. This increases the load on the chassis and the demands on the drivetrain making reinforcements and therefore weight increases necessary. To maintain the driving range a larger energy storage is needed. Consequently, the stiffness of the vehicle body must be revised which again could lead to the demand for a more powerful motor or engine. The added weight resulting from this spiral effect is called secondary weight effect (Eckstein et al. 2010). In the reverse case, general weight reductions turn the spiral effect around and lead to secondary weight reductions (Ellenrieder et al. 2013).

Against this background lightweight design is a widely applied concept in vehicle engineering with a range of advantages (Niemann et al. 2005). Lightweight design

- reduces costs and environmental impacts in the use phase and for distribution processes,
- achieves a higher performance (e.g. speed or payload) with the same total weight or achieves the same performance with a smaller total weight,
- allows easier handling of the affected parts,
- enables characteristics which would not have been possible otherwise (e.g. particularly in aerospace engineering),
- reduces weight of other parts because their load is reduced (secondary effects).

The increased weight of vehicles in the past does not contradict the relevance of lightweight design. Much more it is a result of the fourth argument in the list above. The saved weight is often compensated by new features (i.e. parts) which would not have been added otherwise. Figure 2.7 shows the vehicle body of the Golf VI (left) and the Golf VII (right). The lightweight measures lead to a weight reduction of

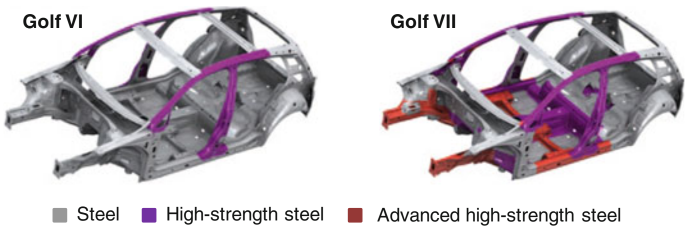

Fig. 2.7 Vehicle body of Golf VI and Golf VII (Ellenrieder et al. 2013)

12 kg (Ellenrieder et al. 2013). It can be assumed that the total weight increase of around 50 kg (see Fig. 2.6) would have been even higher without these changes.

The example of the Golf is an application of lightweight design via material substitution. In addition lightweight design can be achieved by a number of other principles. In general five forms can be distinguished: material, production, functional, form and conditional lightweight design (Ellenrieder et al. 2013; Kopp et al. 2011; Klein 2013). Production lightweight design aims at reducing the required joining processes and material demand. Form lightweight design considers the load which rests on the components and restricts material use to where it is required. Functional lightweight design chooses either a strategy of integrating several functions into one component or of separating the functions to achieve a lower weight. Conditional lightweight design considers how the product is used (e.g. the life time) and adapts the design accordingly. Material lightweight design substitutes a material with one of lighter density (e.g. replacement of steel with plastic) or with a material of better properties. These properties can be the strength, a smaller distortion or a reduced wear (e.g. replacement of conventional steel with high strength steel) (Niemann et al. 2005). Often the strategies are not applied separately but at the same time. Hence, their impact cannot always be traced back to a specific strategy as they depend on each other. Often the functional lightweight design defines the goal of the design (e.g. minimal cost or environmental impact). The other design options are then applied to achieve this goal (Ellenrieder et al. 2013; Kopp et al. 2011).

Material lightweight design portrays a special case of lightweight design as it does not focus on the mere reduction of material but on the substitution of materials. As each material has unique environmental impacts, new and unknown parameters are brought into the equation of the environmental impacts of vehicles. Therefore, material lightweight design is described in more detail in the following.

2.2.2 Material Lightweight Design

Steel is the standard material for vehicles of large-scale production. Its good performance regarding strength and ductility, its widespread availability, low production costs and well-established infrastructure for recycling make steel a very suitable material for vehicles. Today, 60 % of an average vehicle is made of steel (Evertz et al. 2013). However, due to higher lightweight goals, standard steel is increasingly being replaced by other materials. Relevant replacement materials in automotive engineering are (Ellenrieder et al. 2013; Klein 2013):

- (Advanced) High-strength steel,
- light metals like aluminium, magnesium and titanium,
- composite materials like carbon or glass fibre reinforced plastics (CFRP/GFRP),
- other hybrid materials combining metal, textiles and plastics.

Steel and light metals are combined with other metallic and non-metallic materials (e.g. chromium, molybdenum, copper or titanium) to create a large variety of alloys with designed characteristics. New alloys are developed continuously (Weidenmann and Wanner 2011; Weißbach 2012). Composite materials consist of at least two different materials or at least two different phases (Hornbogen et al. 2008). Fibre reinforced materials are a type of composite materials. The fibres carry the mechanical load and the matrix provides support and keeps the fibre in place. Both fibre and matrix can be of metals, (bio-) polymer and ceramic materials (Hornbogen et al. 2008). Recycling is often more difficult for lightweight materials particularly for composite materials (Schuh et al. 2013). For more information on lightweight materials see Henning and Moeller (2011), Friedrich (2013), Klein (2013) and Fischer et al. (2014).

Due to the wide variety of materials, a selection process is necessary. Ashby (2012) defines this material selection as a four step process of translation, screening, ranking and documentation. First, the design of the product must be translated into constraints (e.g. non-toxic, optically transparent, stiffness and strength) and objectives (e.g. costs, mass, volume). In the screening process materials are selected which meet the constraints. Then the materials are ranked according to their ability to meet the objectives. Finally, in the documentation step the possible materials are analysed in detail. This step prevents the selection of a material with a major draw-back not perceived in the previous steps.

The actual weight reduction achieved by a lightweight material depends on each individual case. The specific requirements (e.g. load on the part, use case and life time) define the weight reduction which is realised in the final design. However, estimates for each material are possible. Figure 2.8 shows the comparison of two studies on the weight reduction potential of lightweight materials. Ellenrieder et al. (2013) and Mayyas et al. (2012) suggest reduction potential values for (advanced) high-strength steel, aluminium, magnesium and different types of fibre reinforced plastics. The authors provide similar values for lightweight metals. High-strength steel components achieve a weight of around 90 % of the regular steel alternative, for aluminium the values range around 50–60 %, for magnesium around 37–51 %. The result is less clear-cut for fibre reinforced plastics for which the values range from 24 to 80 %. An explanation is the variety of fibre reinforced material which makes estimates on the weight reduction potential more difficult. Furthermore, the

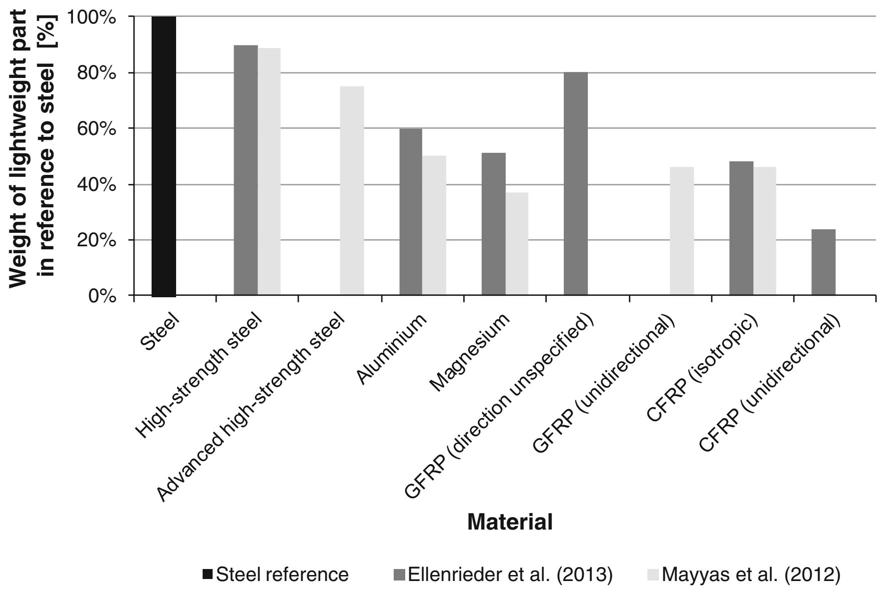

Fig. 2.8 Weight reduction via material substitution (Ellenrieder et al. 2013; Mayyas et al. 2012)

degree of application could influence the prediction. Today, high-strength steel and aluminium are applied more often in vehicle engineering than fibre reinforced plastics.

2.3 Environmental Impacts

All of our activities stand in relation to the environment surrounding us. Along the entire life cycle of a product like a vehicle, flows of material and energy lead to environmental impacts. Hence, this subsection discusses the topic of environmental impacts and their assessment. First, the life cycle of EVs is described. Then, sustainable development, the main driver for the assessment of environmental impacts, is discussed and the field of environmental system analysis tools is introduced. Finally, the basic principles of Life Cycle Assessment—a well-established method to quantify the environmental impacts of products over their entire life cycle—are described.

2.3.1 Life Cycle of Electric Vehicles

Vehicles are long lasting products with a lifetime of around 10–15 years and a total driving distance of 100,000–250,000 km (Hawkins et al. 2012). A generic life cycle

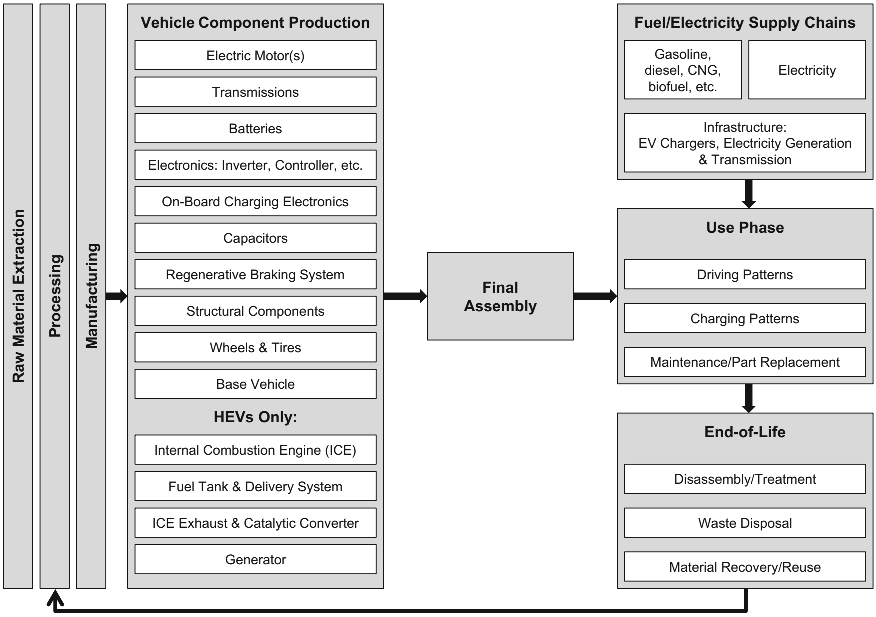

Fig. 2.9 Life cycle of electric vehicle (Hawkins et al. 2012)

divided into eight stages is pictured in Fig. 2.9. After their extraction the raw materials are processed and sent to further manufacturing. The materials are then used for the production of the vehicle components. These are the electric motor, the transmission, the battery, electronics, capacitors, the braking system, structural components, wheels and tires and the base vehicle. These parts are assembled to the final product. The use phase includes the electricity supply chain and maintenance of the vehicle. It is characterized by the driving and charging patterns of the user. At the end-of-life the vehicle is disassembled and the resulting parts are either brought to waste disposal, material recovery or reuse to enter a new life cycle (Fig. 2.9).

Today, most automotive companies have a low in-house production depth. This means that the accomplished processes of the vehicle on the site of the manufacturer are mainly restricted to the areas moulding, paint shop, body construction and assembly. Most components are manufactured and delivered by suppliers (Klug 2010). The recycling process of the vehicle consists of several steps. First a dismounting is conducted. It separates reusable parts as well as materials and parts that require special recycling treatment like the battery from the residual car body. The residual car body is then shredded and the material mix is separated. Some materials are recycled (e.g. metal scrap) whereas other materials are brought to waste treatment. The reusable parts are reconditioned if necessary (Del Duce et al. 2013). The battery requires a special treatment to recover the valuable materials that it contains. Currently, different processes (e.g. hydrometallurgical or pyrometallurgical) are tested and evaluated. Depending on the specific composition of the lithium-ion battery, different recycling processes can be suited to achieve the best material recovery results (Buchert et al. 2011; Treffer 2011). In many countries, recycling quotas are defined by regulations. For example, in the European Union the Directive 2000/53/EG regulates the recycling of end-of-life vehicles. From January 1st 2015, the recycling rate must reach at least 95 %. Of this share 10 % may be energy recovery (European Parliament). However, this does not mean that every vehicle that reaches the end of its life in the EU is recycled according to these standards. Due to economic reasons vehicles are exported to developing countries with much lower recycling standards and technologies (Zoboli et al. 2000).

Overall, this means that both the production and the recycling of vehicles are complex processes that involve a large number of different stakeholders. Subsequently, the information on the life cycle of EVs is large and widely dispersed among these participants and an assessment of the environmental impacts requires a methodological approach as described in the following.

2.3.2 Sustainable Development and Environmental System Analysis Tools

A development that is sustainable "meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development 1987). The three pillars of sustainability—environment, economy and society—form a network as depicted in Fig. 2.10. Bearable, equitable and viable relations of these three pillars are the foundation of a sustainable development.

The environment stands out for its often very slow reactivity to impacts. This makes the environment vulnerable because it means that negative repercussions of human actions can take a long time to be noticed and therefore remain undetected. But it also means that the environment can require a long time to recover once negative activities have been stopped (e.g. the recovery of the ozone layer after the banning of chlorofluorocarbons). Too avoid strong environmental burdens and ensure a stable and continuously healthy environment, several aspects must be addressed. Functional equivalents should be available for non-renewable resources and renewable resources should only be used in their rate of regeneration. An overloading of the environment with substances must be prevented and the environment should be given sufficient time to recover once substances have been entered. Unjustified risks should be avoided (Herrmann 2010).

To understand the environmental implications of our activities, an environmental assessment of these activities is necessary. Different methods and tools which analyse and assess the use of resources and impacts on the environment are available. These are referred to as environmental system analysis tools (Baumann and Tillman 2009). They can be categorized according to their object in focus

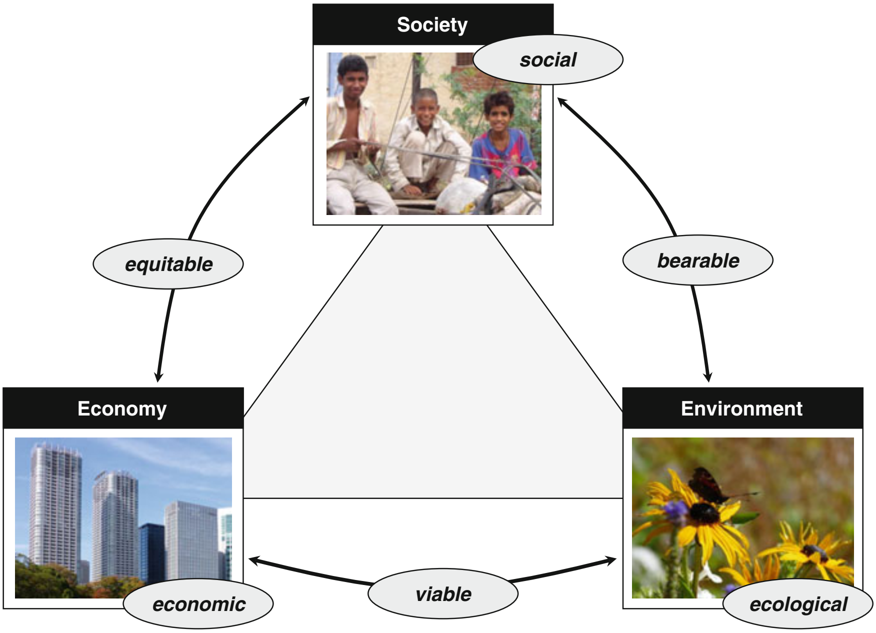

Fig. 2.10 Triangle of sustainability (Ohlendorf 2006, photos replaced)

(policies, plans, programmes and projects, regions and nations, organisations, products and functions or substances) and their studied impacts (natural resources and/or environmental impacts). A categorization of environmental system analysis tools is presented in Fig. 2.11.

Energy Analysis (En), Environmental Footprint (EF) and Material Flow Accounting (MFA) are suited to analyse the use of natural resources of all objects. En and MFA focus on energy or material flows (with a focus on input flows) in energy or physical units (European Communities 2001). EF provides a result in units of square measure expressing the land size required for a sustainable development (Bilitewski et al. 1998). Risk Assessment (RA) focuses on the probability of certain damages. Substance Flow Analysis (SFA), a method of the MFA group, traces single substances and evaluates its environmental impacts. For the assessment of natural resources as well as environmental impacts a range of methods is applied depending on the object of interest. Policies, plans, programmes and projects can be assessed with Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA). EIA is mainly applied to projects. SEA is a more strategic tool which is suited for policies, plans and programmes. System of Economic and Environmental Accounts (SEEA) and Input-Output Analysis (IOA) are suited for the assessment of regions and nations on the basis of economic activities. An Environmental Management System (EMS) implements procedures into companies which ensure environmentally sound practices (Calantone et al.

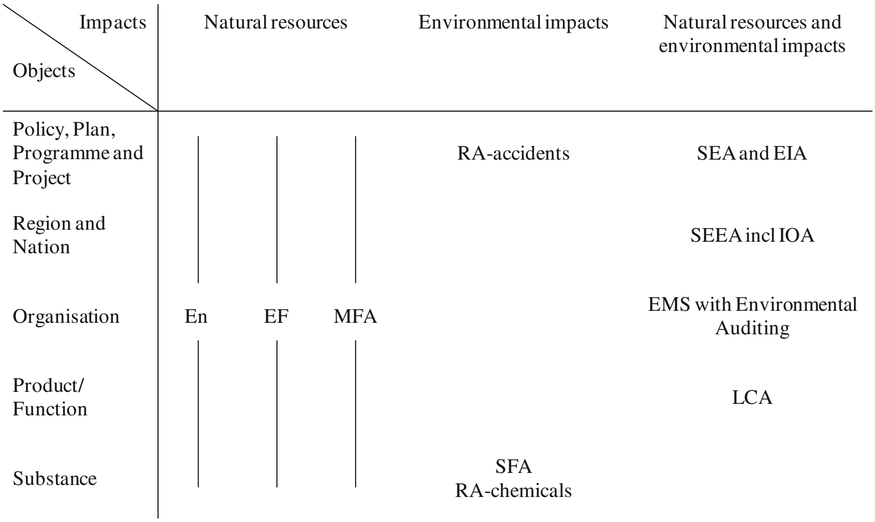

Fig. 2.11 Environmental system analysis tools categorized according to object of interest and impacts studied (Cf. Finnveden and Moberg 2005); energy analysis (*En*), environmental footprint (*EF*), material flow accounting (*MFA*), risk assessment (*RA*), substance flow analysis (*SFA*), environmental impact assessment (*EIA*), strategic environmental assessment (*SEA*), system of economic and environmental accounts (*SEEA*), input-output analysis (*IOA*), environmental management system (*EMS*)

2004). For more detailed descriptions on the tools mentioned see Bilitewski et al. (1998), Finnveden and Moberg (2005), European Communities (2001), Wackernagel and Rees (1996), Melnyk et al. (2003).

The method LCA is suited for the assessment of the use of natural resources and environmental impacts of products (Finnveden and Moberg 2005). When the purpose of the study is the assessment of a product over its entire life cycle, an LCA is the only method to choose. By definition, an environmental assessment of a product is an LCA (Finnveden 2000). Because LEVs are a product and the goal is to assess their environmental impact, the method LCA is described in detail in the following.

2.3.3 Life Cycle Assessment

An LCA analyses the potential environmental impacts of a product or service along its entire life cycle. The life cycle includes the raw material extraction, the production, use and any end-of-life-treatment including recycling (ISO 14040:2006).

The first LCAs were completed in the United States and Europe around 1970 where different types of beverage packaging were compared. Increasing problems with packaging as well as the oil crisis seem to have contributed to the development of these environmental assessments. The interest faded at the beginning of the 1980s but increased again at the end of the decade (Klöpffer and Grahl 2009; Hunt et al. 1996). This lead to the development of the first international methodological framework Guidelines for Life Cycle Assessment—A Code of Practice by the Society of Environmental Toxicology and Chemistry (Consoli et al. 1993). Further efforts resulted in the development of standards by the International Organization for Standardization (ISO). Today, the method LCA is defined in two international standards. In addition, two technical reports and a technical specification provide further guidance:

- ISO 14040:2006 Life cycle assessment—Principles and framework.
- ISO 14044:2006 Life cycle assessment—Requirements and guidelines.
- ISO/TR 14047:2012 Life cycle assessment—Illustrative examples on how to apply ISO 14044 to impact assessment situations.
- ISO/TS 14048:2002 Life cycle assessment—Data documentation format.
- ISO/TR 14049:2012 Life cycle assessment—Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis.

The international standards ISO 14040:2006 and ISO 14044:2006 are the most important references for the LCA method. ISO 14040:2006 contains the general frame but no binding instructions. These instructions are part of ISO 14044:2006 (Klöpffer and Grahl 2009). 'ISO/TR 14047 Illustrative examples on how to apply ISO 14042', 'ISO/TR 14048 Data documentation format', 'ISO/TR 14049 Examples of the application of ISO 14041 to goal and scope definition and inventory analysis' provide more detailed guidance and examples but again have no binding character.

With the intend to be more specific than the ISO standard to increase consistency and quality of LCA studies, the Institute for Environment and Sustainability (Joint Research Centre—European Commission) has derived the International Reference Life Cycle Data System (ILCD) Handbook from the ISO standard. The ILCD Handbook consists of a set of documents and a data network. A large number of international experts, relevant stakeholders and the public participated to complete this handbook (European Commission 2011).

The methodological framework for an LCA is shown in Fig. 2.12. The method consists of four steps linked in an iterative process: goal and scope definition, inventory analysis, impact assessment and interpretation. LCAs are used for product development or improvement, strategic planning, policy making, marketing or other purposes. The iterative process allows the adaptation and adjustment of previous steps due to findings in latter phases of the LCA. The method LCA is based on six principles. These are (1) the consideration of the entire life cycle, (2) the focus on the environment, (3) the relative aspect referring to the functional unit, (4) the iterative approach of the method, (5) transparency of all parts of the LCA and (6) the consideration of all impacts on the environment, human health and resources (ISO 14040:2006).

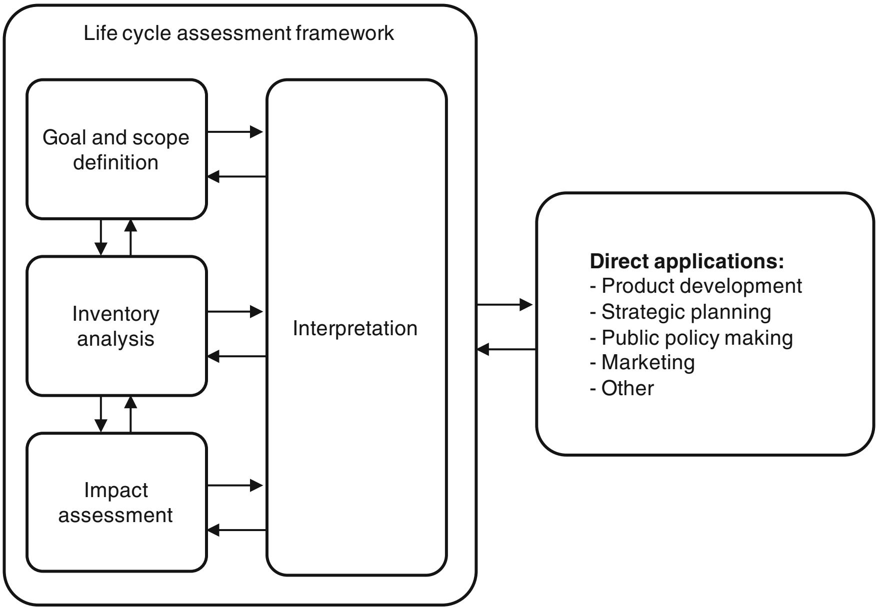

Fig. 2.12 Methodological framework of LCA (ISO 14040:2006). ("Reproduced by permission of DIN Deutsches Institut für Normung e.V. The definitive version for the implementation of this standard is the edition bearing the most recent date of issue, obtainable from Beuth Verlag GmbH, Burggrafenstraße 6, 10787 Berlin, Germany.")

2.3.3.1 Goal and Scope Definition

The goal and scope definition establishes the cornerstones of each study. The goal definition contains four elements: (1) the purpose, (2) the reasons, (3) the intended audience of the study and (4) the classification whether or not a comparison is done. The scope definition describes the product system and its system boundaries as well as function, functional unit and reference flow. Furthermore, methodological choices are made for allocation procedures, impact categories and data requirements. Also, review and reporting procedures are described (ISO 14040:2006).

Function, functional unit and reference flow describe the performance of the product system. A system might have several functions. Hence, the goal of the study determines the selection of the relevant function(s) (e.g. the function of transportation). Then, the functional unit quantifies the function (e.g. transportation from A to B for one year). The reference flow describes the unit to which all other flows in the inventory relate. It describes the element of the product which is necessary to fulfil the function (e.g. bicycle or passenger vehicle). Whereas function and functional unit in comparative studies always have to be the same, the reference flow can differ (ISO 14040:2006; European Commission 2011).

The completeness of scope demands the consideration of the entire life cycle. The focus on the environmental impact of the use phase of vehicles has lead to the development of extracts of LCAs based on their scope. An analysis which focuses on the use phase is called Well-to-Wheel (WTW) analysis. This approach can be divided into the two parts: Well-to-Tank (WTT) and Tank-to-Wheel (TTW). WTT covers the environmental impact of the production of the energy carrier and includes storage and distribution. TTW covers the energy conversion in the vehicle (Nordelöf et al. 2014).

2.3.3.2 Life Cycle Inventory Analysis

In the phase of the Life Cycle Inventory Analysis (LCI) the data collection of all input and output flows takes place. These are energy and material inputs, products, waste, emissions to air and discharges to water or soil (ISO 14040:2006). The result of the inventory analysis is a balance sheet with all incoming and outgoing flows. Due to the extensive data collection, the inventory analysis usually portrays the most resource-intensive step of the LCA. The life cycle phases are broken down into unit processes for which the elementary flows[1] are available. Both primary and secondary data can be used. Primary data is collected from the specific life cycle. Secondary data is taken from databases. These databases offer predefined, standard data sets (Klöpffer and Grahl 2009). Examples for commercial databases are Ecoinvent 3.1 (Ecoinvent 2015) and GaBi (Thinkstep 2015). Free solutions are ProBas (Umweltbundesamt 2015), ELCD 3.2 (European Commission—Joint Research Center 2015) and GEMIS (Internationales Institut für Nachhaltigkeitsanalysen und -strategien 2015).

Depending on the type of process, the input and outputs can be more or less complex. In case of co-production or other relevant multi-input/multi-output process, multi-functionalities of processes occur. These multi-functionalities must be solved to calculate the inventory. For this different approaches exist. The ISO standard proposes a three step hierarchy. First, it demands to divide the unit process further if possible. In case this is not possible, the product system should be expanded and include the provided co-function. Finally, the flows should be assigned by allocation. Allocation assigns the flows to the multiple functions of a process. Allocation according to physical properties is to be favoured over economic properties (ISO 14040:2006). A very relevant case of multi-functionality is caused by energy recovery, reuse and recycling. The use of energy, material or components which originate from other life cycles as well as end-of-life treatments which enable energy, material or components to re-enter a new life cycle causes multi-functionality. A variety of methods is available to solve these cases (Dubreuil

[1]An elementary flow is an "material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation" ISO (14044:2006).

et al. 2010; Ekvall and Tillman 1997; Frees 2008; Nicholson et al. 2012; European Commission 2011). For each study it is necessary to find the method most suited to reflect the given system.

2.3.3.3 Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) uses the inventory results to assess the potential environmental impact. It translates the inventory results into values of impact categories. This step contains mandatory and optional elements. The mandatory part consists of three steps. The first step is the selection of impact categories, category indicators and characterisation models. Impact categories represent groups of environmental effects to which the different inventory elements are assigned. Examples for impact categories are climate change, acidification, eutrophication, human or eco-toxicity[2] (Klöpffer and Grahl 2009; Hauschild and Huijbregts 2015). Category indicators describe the effect which quantifies each impact category (e.g. radiative forcing quantifies climate change). Characterisation models express a specific scenario (e.g. the baseline for 100 years). The second step is the assignment of the inventory results to one or more impact categories. This is called classification. In the third and final step called characterization the category indicators are calculated. For this purpose characterisation factors are derived from the category indicators and the characterisation model. For example, to quantify climate change the global warming potential (GWP) of carbon dioxide (CO_2) is defined as 1. Based on this reference the GWP of other substances can be defined (e.g. the GWP of methane is 25 because 1 unit of methane is 25 times stronger than CO_2 regarding GWP). This scheme allows expressing the impact category climate change in CO2-equivalents (CO2-eq). The optional elements of the impact assessment are the normalization (i.e. relating results to a reference value), grouping (i.e. sorting and ranking of results) and weighting (i.e. aggregating several categories, e.g. to a single score) (Baumann and Tillman 2009; Curran 2012). Single scores allow the aggregation of impact categories into a single value which at first appears to ease comparisons. However, this simplification erases important information which is why LCA practitioners are often opposed to using single scores (Klöpffer and Grahl 2009). Impact assessment methods (e.g. Ecoindicator'99, CML 2002 or ReCiPe) (Curran 2012) combine the elements above and allow LCA practitioners to focus on the other steps of the LCA. These methods combined with LCA software solutions make the impact assessment easy and fast.

Figure 2.13 shows an example of LCIA results of a gasoline and diesel vehicle for the category climate change. In general around 80 % of the GHG emissions are associated to the use phase. The rest is almost entirely linked to the production phase while the impact of the end-of-life phase is minor.

[2] Detailed descriptions of the most common impact categories can be found in Baumann and Tillman (2009) and Hauschild and Huijbregts (2015).

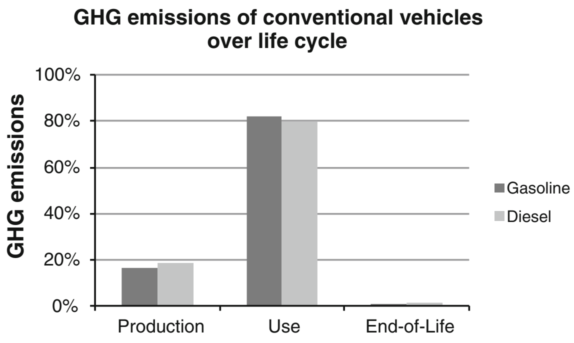

Fig. 2.13 Example of LCIA results from conventional vehicles, own calculation and illustration with data from Hawkins et al. (2013)

2.3.3.4 Interpretation

The interpretation is the final step of an LCA. It allows the identification of hot spots derived from the inventory analysis and impact assessment. Also, the results are checked for completeness, sensitivity and consistency. Furthermore, limitations are described. Finally, conclusions and recommendations can be derived (ISO 14040:2006). One type of analysis is the break-even analysis. It is used to analyse trade-offs between products and calculate the point where the products have the same impact in an impact category. At this point the preference changes from one product to the other (Baumann and Tillman 2009). Figure 2.14 shows a simple, schematic break-even analysis of a electric and conventional vehicle along the kilometres driven during their lifetimes. The break-even point is reached around mid-term. The EV has a higher environmental impact for the production than the conventional vehicle. However, its impact per kilometre is lower.

The LCA method leads to a vast collection and calculation of data foremost in the phases LCI and LCIA. As the complexity of the product increased, the amount of generated data becomes more extensive as well. Even though tables contain all

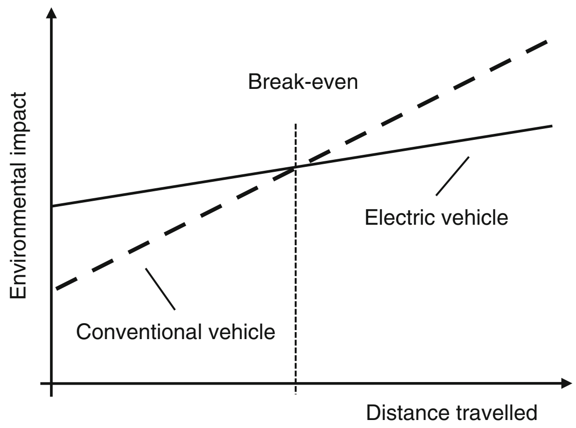

Fig. 2.14 Simple break-even analysis of an electric and a conventional vehicle

required information, graphs are much easier to understand than the presentation of mere numbers. The use of different colours, shapes and textures simplifies the processing of data (Otto et al. 2003b). Therefore, good visualization is essential when conveying LCA results (Otto et al. 2003a; Heijungs 2014). Particularly because the generated results are relevant for non-LCA experts like politicians and decision makers in companies, it is important to translate the numerical data into helpful charts that support the message and ease the access to the topic and results.

2.4 Environmental Impact of Lightweight Electric Vehicles

Both EVs and the use of lightweight materials have the potential to reduce the environmental impact in comparison to the currently used conventional vehicles. Combining both options can improve the environmental performance even further. However, at the same time both technologies also bring additional environmental burdens. The following chapters highlight these environmental trade-offs and draw five main conclusions.

2.4.1 Environmental Impact of Electric Vehicles

EVs offer a range of environmental advantages in comparison to conventional vehicles. Hence, they can reduce negative impacts of vehicles on the environment and improve living conditions especially in large cities.

- The propulsion energy comes from electric energy which is transformed into mechanical energy. Therefore, EVs emit no emissions at their place of use. This makes them attractive for large cities which suffer from severe air pollution.
- EVs can use electricity generated from renewable sources. This leads to a low environmental impact of the use phase and relieves the pressure on fossil resources.

However, the use of EVs is not only connected to environmental advantages. At the same time EVs have environmental disadvantages.

- The production of the vehicle components usually has higher environmental impacts than of conventional vehicles. Especially the battery contributes to this effect.
- The environmental impact of the use phase is very volatile. Both the environmental impact of the electricity mix as well as the energy consumption can vary significantly.

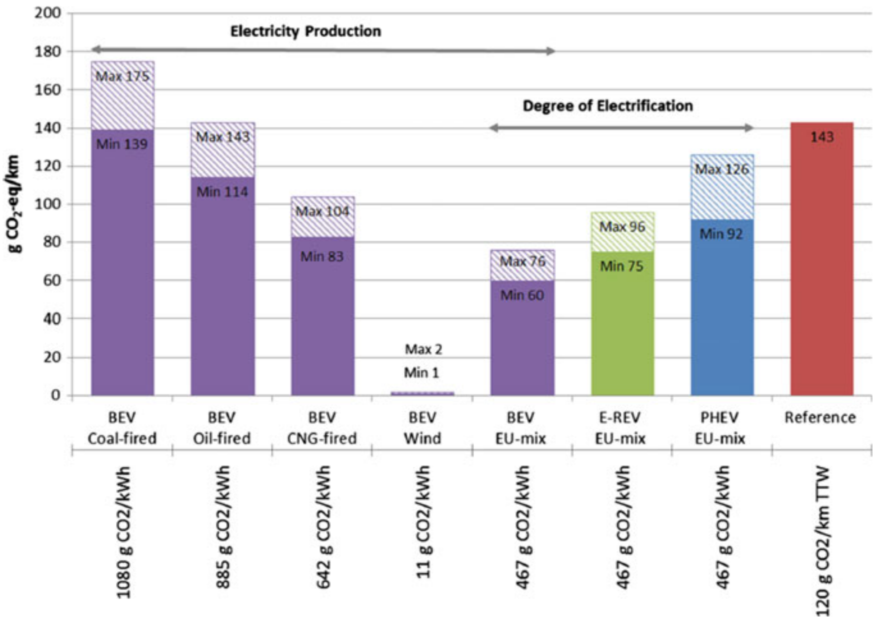

Fig. 2.15 GHG emissions for different types of electricity production and different vehicle types (Nordelöf et al. 2014); battery electric vehicle (*BEV*), extended range electric vehicles (*E-REV*), plug-in hybrid vehicle (*PHEV*)

The electricity mix used for the charging of the battery is one of the most relevant factors for the environmental impact of EVs. Figure 2.15 shows the ranges of GHG emissions per km (g CO2-eq/km) for different electricity mixes applied to the use of EVs. The GHG emissions of the electricity mix are displayed below each bar. A coal based electricity mix leads to the highest results, a wind based electricity mix to the lowest results. The impact is found to be in between 1 and 175 g CO2-eq/km. This reflects the general opinion that EVs only provide a satisfactory environmental advantage when they are charged with renewable energy (Nordelöf et al. 2014). Hence, the selection of the electricity mix for an LCA is crucial for the outcome and should be well considered and argued for. Particularly the selection of a very advantageous electricity mix based on renewable energy sources should be justified.

Although an EV has a higher overall efficiency than a conventional vehicle, it has a significant disadvantage. Figure 2.16 shows the visualisation of the energy flows for on EV (left) in comparison to a conventional vehicle (right) for the NEDC. Whereas only around 10 % of the input power is used for acceleration in a conventional vehicle, the value reaches around 35 % in the EV. About two thirds of this power can be recovered. However, the energy consumption of an EV can vary significantly due to the demand for heating and cooling as described in Sect. 2.1.2. Conventional vehicles and EVs have a significantly different use pattern of

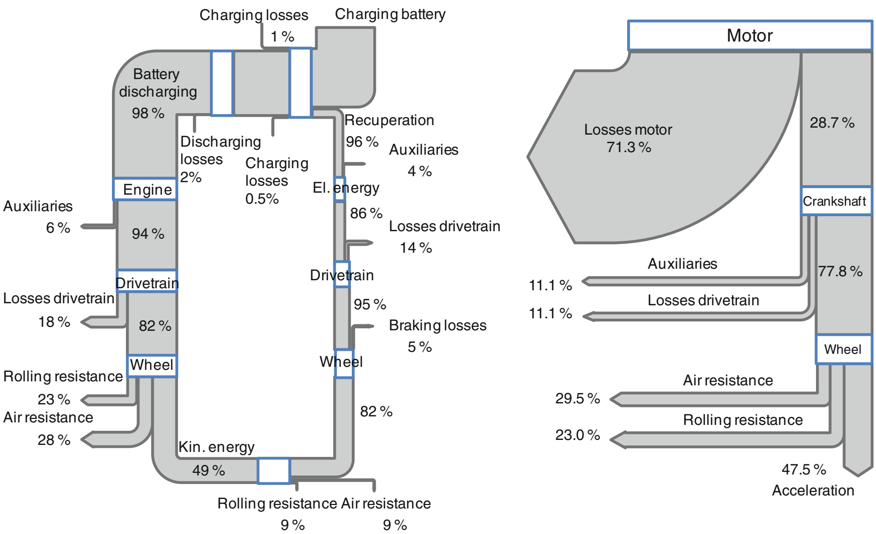

Fig. 2.16 Energy flows of conventional and electric vehicles for new European driving cycle translated from Woll (2013)

auxiliaries which the NEDC does not consider. Hence, due to its stylised nature also regarding speed and acceleration, the NEDC is often criticized for delivering unrealistic, too optimistic results (Mock et al. 2012; Samuel et al. 2002). While the NEDC does cover all aspects of the energy consumption (the driving resistances, the drivetrain efficiency, charging losses and recuperation), it does not cover the energy demand for both low and high voltage auxiliaries because these can be turned off during the measurement according to the approval provisions (United Nations 2005). Therefore, the energy demand for auxiliaries is very low in the two Sankey diagrams as only small units are turned on which are necessary for the operation of the vehicle. However, depending on the ambient conditions the share of the energy consumption of heating in EVs can reach values of almost 50 % (Konz et al. 2011; Ayoubi et al. 2013). In conventional vehicles the considerable amount of access heat (as seen in Fig. 2.16) from the engine is used to heat the vehicle cabin. This imbalance concerning heating and cooling should therefore be weighed out. In many LCA studies the use of high voltage auxiliaries is not considered because the NEDC is applied. Consequently, the impact of ambient conditions is not considered in these studies.

For a given vehicle the environmental impact of the use phase can vary significantly depending on the use case. The break-even analysis in Fig. 2.17 illustrates the unknown outcome of the comparison and shows the necessity of a detailed analysis of the use phase. Both outcomes depend on the use case (i.e. origin of fuel, electricity mix, ambient temperatures and resulting demand for heating and cooling). Therefore, both the conventional vehicle and the EV could be the better choice from an environmental point of view.

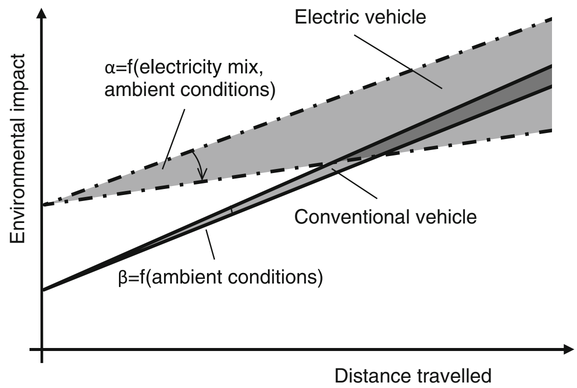

Fig. 2.17 Environmental impact of EVs in comparison to conventional vehicles

2.4.2 Environmental Impact of Lightweight Materials

The use of lightweight materials offers several advantages as described in Sect. 2.2.1 like new design options and a higher performance. Regarding the environmental impact, the benefits of interest are the reduced energy consumption in the use phase as well as secondary weight savings. However, lightweight materials generally require a higher effort for their extraction and material production than the heavier materials which they replace. This causes their environmental impacts to be higher in these early life cycle phases. They can also require more complex recycling processes or not be recyclable at all. Figure 2.18 shows the relation of the Young's modulus and the mass of CO_2 per cubic meter. Materials on the bottom left have low CO_2 emissions but they also have an inferior material quality. Materials with a higher quality are found on the upper right meaning they have higher CO_2 emissions. Hence, it can be concluded that in general a lighter (because stronger) material has a higher environmental impact for its production. The figure includes three lines referred to as 'Guidelines for minimum CO_2 design'. These lines mark an equal ratio of mass of CO_2 per cubic meter and stiffness for different geometries (tie, beam and panel). Depending on the desired stiffness, a line—parallel to the ones displayed as examples—can be drawn to identify materials with equal properties (Ashby 2012).

As a result, a lightweight vehicle does not necessarily have a lower environmental impact than a heavier vehicle. Whether a lighter vehicle performs better from an environmental point of view depends on its ability to outweigh the higher impact of production and possible end-of-life with a lower consumption in the use phase. The trade-off effect and the break-even point are shown in Fig. 2.19. For a given use case (i.e. fixed energy source) lightweight design I is not able to achieve a break-even in comparison to the reference vehicle. However, design II does perform better than the reference vehicle. This depends on the environmental impact of the

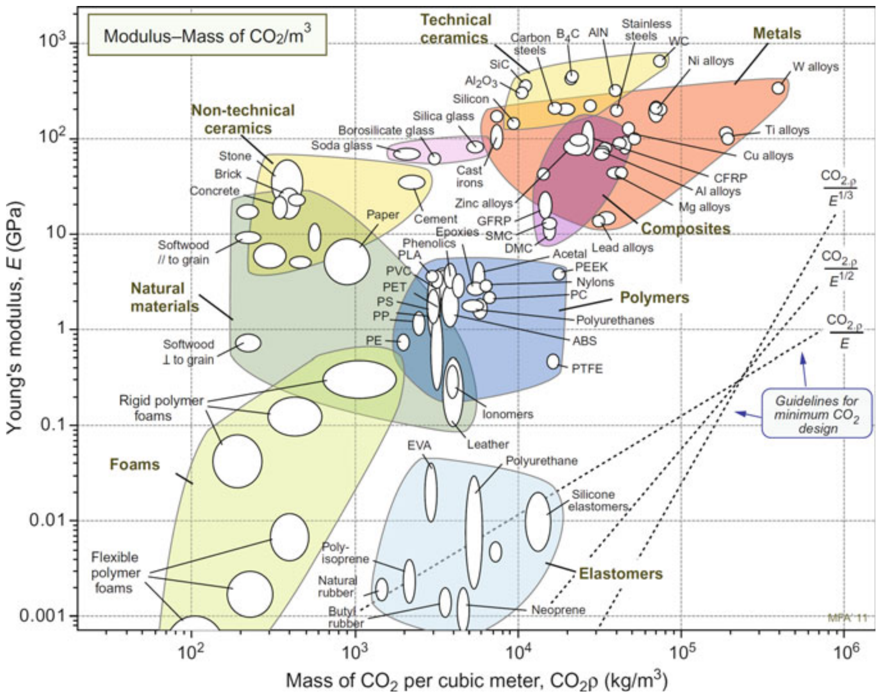

Fig. 2.18 Relation of Young's modulus and mass of CO_2 per cubic meter (Ashby 2012)

material (i.e. y-intercept), the weight saving (and following energy saving) in the use phase (i.e. slope of line) and the recycling process at the end-of-life which is often more complex for lightweight materials.

2.4.3 *Environmental Impact of Lightweight Electric Vehicles*

LEVs are of interest because they can combine the advantages of both EVs and lightweight vehicles. A lighter weight increases the range of an EV for which the range is still a critical issue. Secondary weight savings can augment this effect even further. However, when EVs are charged with electricity from renewable sources, the additional impact of the production of the lightweight material cannot be outweighed with savings in the use phase. The questions must be answered whether an EV in general is a better choice than a conventional vehicle and whether the LEV has a better environmental performance than the reference EV or not. The answer is not universally valid as it depends on the use case (i.e. source of energy, ambient conditions, etc.).

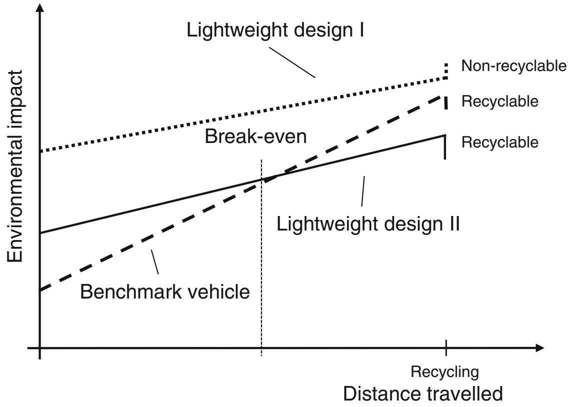

Fig. 2.19 Break-even analysis of reference vehicle and two lightweight vehicles

Figure 2.20 shows the break-even analysis of a conventional vehicle, a (reference) EV and two LEVs. For reasons of clarity the end-of-life processes are not displayed. Depending on the use case, various outcomes of the assessment are possible. In no case does LEV II portray a useful solution. In this example the (reference) EV has the potential to be the best option. It is important to note that there is a relation between the outcomes of each vehicle type and that not all outcomes are possible. For example, in case an electricity mix with a high environmental impact is used, the results for the EV and the LEV will both be in the

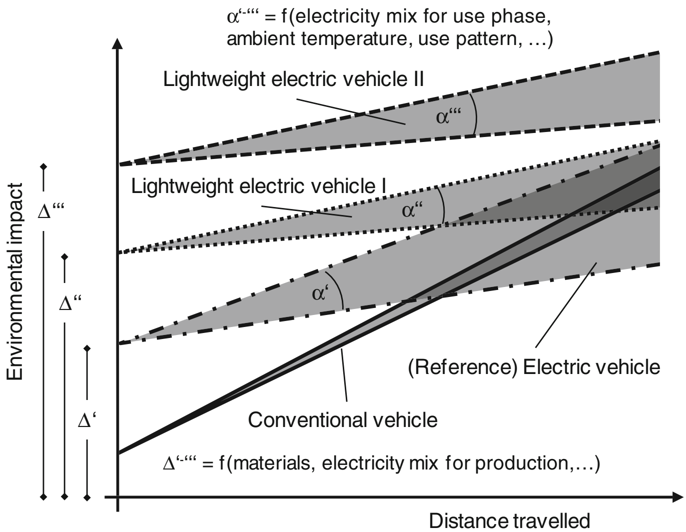

Fig. 2.20 Break-even analysis of conventional, electric and lightweight electric vehicle

upper range. However, the results are not entirely proportional. For example the ambient temperature plays a very important role for (L)EVs but only a minor for conventional vehicles. The environmental impact of the production depends on the materials used and their production process. Using electricity from renewable sources to produce lightweight materials can reduce their environmental impacts significantly.

Finally, five main conclusions for the environmental assessment of LEVs can be drawn:

1. (L)EVs are complex technical products. The calculation of an environmental assessment over the entire life cycle—a LCA—is necessary to determine the environmental viability of a specific LEV.
2. LEVs usually have higher environmental impacts in the production and end-of-life phase than the conventional solutions. These higher impacts have to be outweighed in the use phase. Two conclusions can be derived from this fact.
   a. To decide whether LEVs propose an environmentally sound choice, they must not only be compared to a reference EV. It is also necessary to check whether EVs are a meaningful choice in comparison to conventional vehicles in general.
   b. The environmental impact of LEVs in the use phase depends on the terms of use (e.g. the electricity mix, the ambient temperature, the frequency of use). Hence, the terms of use should be considered in the calculation of an LCA. Consequently, there is not a universally valid value for the entire world and the LCA of LEVs is regional and use case specific.
3. To comply with the requirements of an LCA it is important that the assessment is not covered by a single comparison for one impact category. The comparison for a variety of different impact categories is necessary to cover the entire spectrum of the environmental impact of LEVs.
4. Due to the large amount of data that is needed and created when conducting an LCA, a good visualization is essential to convey the results. Particularly when non-LCA experts are involved. Each outcome requires a tailored portrayal that passes on the right message.

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