Sustainable Production, Life Cycle Engineering and Management
Series Editors: Christoph Herrmann, Sami Kara

Patricia Egede

Environmental Assessment of Lightweight Electric Vehicles

Springer

Sustainable Production, Life Cycle Engineering and Management

Series editors

Christoph Herrmann, Braunschweig, Germany
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Modern production enables a high standard of living worldwide through products and services. Global responsibility requires a comprehensive integration of sustainable development fostered by new paradigms, innovative technologies, methods and tools as well as business models. Minimizing material and energy usage, adapting material and energy flows to better fit natural process capacities, and changing consumption behaviour are important aspects of future production. A life cycle perspective and an integrated economic, ecological and social evaluation are essential requirements in management and engineering. This series will focus on the issues and latest developments towards sustainability in production based on life cycle thinking.

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Patricia Egede

Environmental Assessment of Lightweight Electric Vehicles

Springer

Patricia Egede
Institute of Machine Tools and Production
Technology
TU Braunschweig
Braunschweig
Germany

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Foreword

There is a need to reduce the environmental impact of passenger cars. Electric vehicles can be such a mean of low emission individual transportation. Applying lightweight strategies is common to reduce the environmental impact of conventional cars with internal combustion engines. The question remains if such strategies can also lead to an improvement in electric cars. However, this depends significantly on the terms of use such as the electricity mix, the ambient temperature and the use pattern. Hence, it is necessary to understand these influencing factors of the lightweight electric vehicle as a system. Such an understanding allows answering the question if the environmental performance of lightweight electric vehicles is better and allows identifying priorities for further research needs.

In her book, Patricia Egede presents the development and implementation of a concept to assess the environmental impact of a lightweight electric vehicle in comparison to a conventional vehicle and a reference electric vehicle. The concept considers the influence of the terms of use on the use phase of the vehicles. Furthermore, the focus lies on the addressees of the life cycle assessment (LCA) results who are often non-LCA experts like vehicle designers or policy makers. For the first time maps are introduced to convey LCA results. Overall, the work provides valuable input for decision making related to the environmental impact of lightweight electric vehicles in industry, legislation, and research.

With this published work as well as with her active role, Patricia Egede has strongly contributed to the build-up of the topic of Life Cycle Assessment of electric vehicles in Braunschweig and to the further development of the Joint German-Australian Research Group 'Sustainable Manufacturing and Life Cycle Engineering'.

Christoph Herrmann
Technische Universität Braunschweig

Sami Kara
The University of New South Wales

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This book was written during my work as a research associate at the Chair of Sustainable Manufacturing and Life Cycle Engineering of the Institute of Machine Tools and Production Technology at the Technische Universität Braunschweig.

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Finally, I wish to express my deep and sincere gratitude to my family and friends for their love and support: my family-in-law Gisela Telschow and Angelika and Martin Neuling, my best friends Lars Hunze and Christoph Schönau, my grandmother Elsa Egede, my sister Nathalie Egede, my husband Daniel Egede and my parents Annette and Sigurd Egede.

This book is dedicated to my husband—Danke für deine Geduld und Unterstützung—and to my parents—tak for jeres ubetinget kærlighed og støtte.

Braunschweig
February 2016

Patricia Egede

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Symbols and Abbreviations

Symbols

Δm	Mass saving due to lightweight measures (kg)
A	Vehicle frontal area (m²)
A	Acceleration (m/s²)
a_{lw}	Lightweight factor of a material in comparison to reference material (–)
c_{ER}	Reduction of energy consumption (kWh/km)
c_{erv}	Energy reduction value (kWh/km/kg)
$c_{\mathrm{erv,NEDC}}$	Energy reduction value for NEDC (kWh/km/kg)
c_{lw}	Energy consumption of lightweight vehicle (kWh/km)
c_{ref}	Energy consumption of reference vehicle (kWh/km)
c_w	Drag coefficient (–)
$E_{\mathrm{ref}}/E_{\mathrm{lw}}/E_{\mathrm{rest}}$	Total environmental impact of reference/lightweight/remaining vehicle in end-of-life phase
F	Rolling friction of tires (–)
F_A	Acceleration resistance (N)
F_{Ae}	Aerodynamic resistance (N)
F_D	Driving resistances (N)
F_R	Rolling resistance (N)
F_S	Road slope resistance (N)
G	Gravitational acceleration (m/s²)
i_e	Total environmental impact of electricity mix per kWh
$i_{\mathrm{E,lw}}/i_{\mathrm{E,ref}}$	Environmental impact of reference/lightweight material in end-of-life phase per kg
$i_{\mathrm{P,lw}}/i_{\mathrm{P,ref}}$	Environmental impact of reference/lightweight material in production phase per kg
$I_{\mathrm{ref}}/I_{\mathrm{lw}}/I_{\mathrm{rest}}$	Total environmental impact of reference/lightweight/ remaining vehicle over entire life cycle
m	Mass of the vehicle (including the load) (kg)

m_{lw}	Mass of lightweight part(s) (kg)
m_{ref}	Mass of reference part(s) (kg)
P_D	Power to propel vehicle (W)
$P_{el.bat.out}$	Power taken from batter to propel vehicle (W)
$P_{recu,cycle}$	Possible recoverable power (W)
$P_{recu,max}$	Max. recovered power (W)
$P_{ref}/P_{lw}/P_{rest}$	Total environmental impact of reference/lightweight/ remaining vehicle in production phase
$P_{wheel.m.pos}$	Wheel power necessary to (W)
$U_{ref}/U_{lw}/U_{rest}$	Total environmental impact of reference/lightweight/remaining vehicle in use phase
v	Velocity (m/s)
x	Number of driven kilometres (km)
β	Slope of the road (–)
Δ	Density of air (kg/m³)

Abbreviations

AC	Alternating current
BOF	Basic oxygen furnace
C	Coal
CFRP	Carbon fibre reinforced plastics
CLEVER	Clean Vehicle Research: LCA and Policy measures
CML	Centrum voor Milieukunde
CO_2	Carbon dioxide
CO2-eq	Carbon dioxide equivalents
D	Diesel
DC	Direct current
EAF	Electric arc furnace
EF	Environmental Footprint
EIA	Environmental Impact Assessment
eLCAr	Guidelines for the LCA of electric vehicles
ELCD	European Reference Life Cycle Database
EMS	Environmental Management Systems
En	Energy Analysis
EUCAR	European Council for Automotive Research and Development
Euro	European electricity mix
EV	Electric vehicle
FDP	Fossil depletion potential
FEP	Freshwater eutrophication
FETP	Freshwater eco-toxicity
G	Gasoline
GDP	Gross domestic product

GFRP	Glass fibre reinforced plastics
GHG	Greenhouse gas
GWP	Global warming potential
HTP	Human toxicity
ICEV	Internal combustion engine vehicle
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
IOA	Input-Output Analysis
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEV	Lightweight electric vehicle
$LiFePO_4$	Lithium iron phosphate
LiNCM	Lithium nickel cobalt manganese
MDP	Mineral resource depletion
MFA	Material Flow Accounting
NEDC	New European Driving Cycle
NG	Natural gas
NOx	Nitrogen oxides
PM10	Particulate matter smaller than 10 μm
PMFP	Particulate matter formation
POFP	Photochemical oxidation formation
PTC	Positive temperature coefficient
RA	Risk Assessment
SEA	Strategic Environmental Assessment
SEEA	System of Economic and Environmental Accounts
SFA	Substance Flow Analysis
SO_2	Sulphur dioxide
SP	Service Provider
SPE	Society of Petroleum Engineers
TAP	Terrestrial acidification
TETP	Terrestrial eco-toxicity
TR	Technical report
TS	Technical specification
TTW	Tank-to-Wheel
US	United States
WTT	Well-to-Tank
WTW	Well-to-Wheel

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Chapter 1
Lightweight Electric Vehicles—A Good Environmental Choice?

1.1 Relevance and Environmental Burdens of Vehicles

The modes of transportation at our disposal are very important for the course of events in our everyday lives. The availability and costs of these transportation modes influence our choices in our private (e.g. shopping and leisure time activities) and professional environment (e.g. work place). Especially in more developed countries, the invention of motorized vehicles around 130 years ago lead to drastic changes not only of the transportation sector but also of the way we shape our lives. It increased our range of action significantly because individual mobility over long distances became available and affordable. Figure 1.1 shows the development of passenger transportation in Germany since 1825. First waggons were replaced by the railway at the end of the 19th century. Then, the railway was replaced by motorized vehicles. Today, 70 % of the kilometres travelled in Germany are covered by private vehicles while the rest is covered by bus and tram, railway and air traffic. Similar situations are present in other industrial nations like Australia, the United States and Canada (International Transport Forum 2010). This distribution shows the importance and necessity of motorized vehicles. At the same time the number of people living in urban areas has increased significantly. Whereas in 1950 only 30 % of the world's population lived in urban areas, the percentage has increased to around half today (United Nations 2015). This shift along with an increasing world population means that there exist increasingly more and larger areas in the world with a high population and vehicle density.

However, the invention of motorized vehicles has not only contributed benefits. The resulting use of fossil fuels has negative impacts particularly on the environment. Current environmental issues due to traffic are foremost related to the use of crude oil. Crude oil is a fossil and therefore finite resource used for the production of diesel and gasoline. The production and combustion of these fuels lead to two major environmental challenges: the emission of greenhouse gases (GHGs) and local air pollution especially in large cities (Gruden 2008). In fact, transportation is

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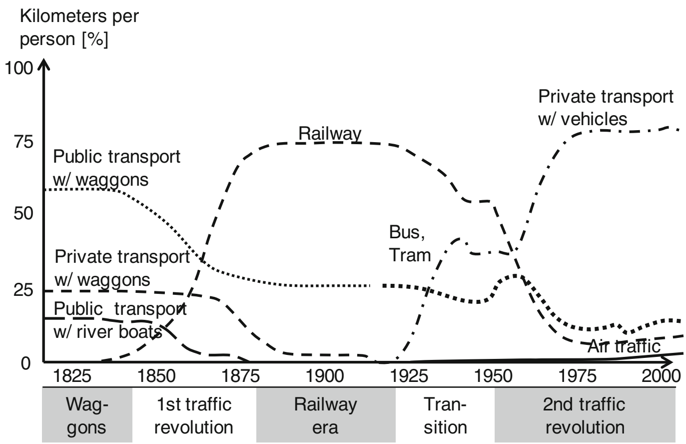

Fig. 1.1 Development of passenger transportation in Germany since 1825 (Burgert et al. 1996, translated)

a main reason for anthropogenic GHG emissions. Figure 1.2 shows the contribution of the transportation sector in reference to the sectors of electricity and heat, industry, residences and others. 22 % of the world's anthropogenic GHG emissions can be attributed to transportation. The majority of these emissions originates from road transportation while the rest comes from water-borne transportation, aviation and others. At the same time, traffic leads to major air pollution particularly in large cities. Particulate matter, a form of air pollution, can have negative effects on human health like cardiovascular diseases or lung cancer (Straif et al. 2013). Estimates suggest that in 2010 around 3.2 million people died prematurely due to the exposure to particulate matter (Lim et al. 2012). Metropoleis like Dhaka, Beijing and New Delhi suffer from this negative repercussion (Gurjar et al. 2008; Cassiani et al. 2013).

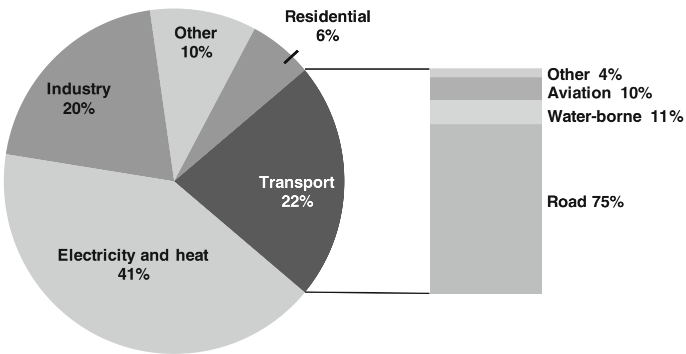

Fig. 1.2 Anthropogenic greenhouse gas emissions by sector in 2010 [data from IEA (2012)]

In the future, we can expect these challenges to become more and more severe (Creutzig 2015). The availability of vehicles in a country is closely related to the nation's economic growth (Hansen 2013). Figure 1.3 shows the relation of the gross domestic product (GDP) per capita and the number of vehicles per 1000 inhabitants for selected countries. A larger income makes travellers shift to modes of transportation that are faster and more energy intensive (Kahn Ribeiro et al. 2007). Whereas the countries on the upper right (i.e. developed countries) have reached a point near saturation of vehicle ownership, the countries on the bottom left (i.e. emerging countries) possess a strong growth potential. Hence, the number of vehicles and their environmental impacts will increase as the GDP of the world's developing and emerging nations like China, India and Brazil rises.

Considering the importance and growth potential of motorized vehicles as well as their environmental issues, it becomes evident that there is a need for measures which reduce the environmental impact of these vehicles. Two options which can offer advantages in comparison to conventional vehicles are the introduction of electric vehicles (EVs) and lightweight design (Kahn Ribeiro et al. 2007). EVs solve the challenge of local vehicle emissions. This is particularly important for urban areas. Furthermore, electric drive trains consisting of an electric motor and a battery can reach higher efficiencies than the drive train of conventional vehicles. Also an electric drivetrain enables the use of electricity from renewable sources with low environmental impacts in comparison to fossil fuels. Lightweight solutions reduce the energy demand (i.e. the environmental impact) of the vehicle in the

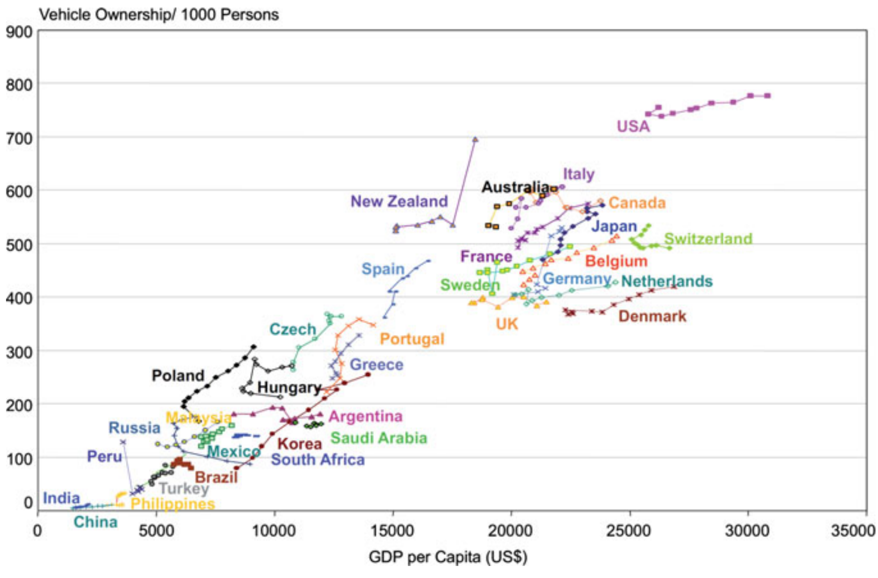

Fig. 1.3 Vehicle ownership as a function of per capita income. *Note* plotted years vary by country depending on data availability. *Data source* World Bank (2004). Kahn Ribeiro et al. (2007) (Fig. 5.2, page 332 in original source)

use phase (Hameyer et al. 2013). The combination of both measures—the manufacturing of lightweight electric vehicles (LEVs)—potentially leads to even higher savings of environmental impacts in comparison to the conventional solutions. However, aspects like the use of different materials and more energy-intensive production processes in comparison to conventional vehicles can also lead to higher environmental impacts. The production of the components for the electric drive train—particularly the battery—is energy-intensive and uses assemblies which demand complex recycling processes (Buchert et al. 2011; Ellenrieder et al. 2013). Similarly, lightweight materials are usually more energy-intensive than the conventional material steel and can be less suitable for recycling (Das 2011; Henning and Moeller 2011). These additional impacts have to be outweighed by savings in the use phase. The environmental assessment over the entire life cycle—a Life Cycle Assessment (LCA)—calculates these trade-offs (ISO 14044:2006).

However, for a given vehicle the environmental impact of the use phase is not a globally valid value. The product of the driven kilometres, the environmental impact of the energy source per unit and the energy consumption of the vehicle mainly determines the environmental impact of the use phase. These parameters are influenced by the terms of use (Del Duce et al. 2013; Hawkins et al. 2013). For example, the energy consumption for heating and cooling of an EV depends on the ambient temperature. The ambient temperature depends on the type of climate as well as the time of day and year. The time of driving depends on the use pattern. Consequently, it is necessary to consider the terms of use—regional influencing factors and use patterns—to answer the question whether (L)EVs are a good environmental choice and to identify areas of priority to turn (L)EVs into future means of low emission individual transportation.

1.2 Research Objective and Structure

The goal of this book is the development of a concept for the environmental assessment of LEVs which considers the terms of use. This concept shall allow an LCA practitioner to conduct site and user-specific LCAs which reflect the prevailing conditions and individual use patterns. For this purpose this book is divided into six chapters. The structure is presented in Fig. 1.4.

Following this introduction, Chap. 2 presents the basics on Life Cycle Assessment, EVs and lightweight design. The goal of the chapter is to analyse the two technologies and highlight their environmental burdens. Based on these three sections the environmental implications of using lightweight materials in EVs is described. In Chap. 3 the current state of research is evaluated. Relevant guidelines and studies on Life Cycle Assessment of EVs and lightweight components are compared. A set of criteria is defined to classify the stage of research. On the basis of this comparison the further research demand for a concept on the Life Cycle Assessment of LEVs is derived. The concept is developed in Chap. 4. First, the objective of the concept and the requirements are described in detail. Then its four

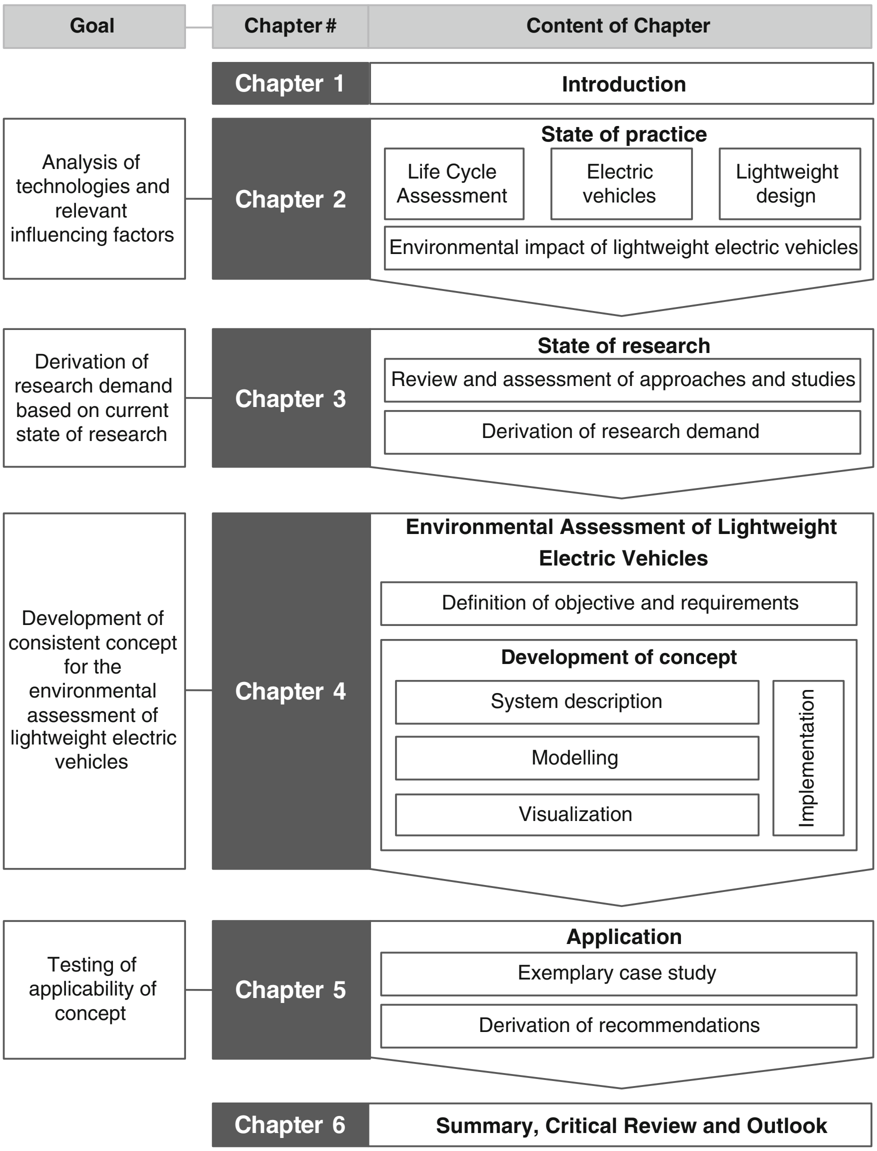

Fig. 1.4 Book structure

elements are presented: (1) the system description, (2) the modelling (3) the visualization and (4) the implementation. The system description enables a holistic view on the influencing factors of the environmental burden of (L)EVs. The modelling describes the terms of use in detail. Furthermore, the necessary calculation methods are developed. The visualization provides a set of charts suited to convey the final results to LCA and particularly non-LCA experts. Finally, an IT-implementation of the concept is presented. Chapter 5 illustrates the application of the concept in a case study which allows the derivation of recommendations. The book concludes with a summary, critical review and outlook in Chap. 6.

References

Buchert M, Jenseit W, Merz C, Schüler D (2011) Ökobilanz zum “Recycling von Lithium-Ionen-Batterien” (LithoRec)

Burgert W, Böhner R, Schiebel D (1996) Tendenzen im Karosserieleichtbau. In: Verein Deutscher Ingenieure (ed) 150 Jahre Wilhelm Maybach. VDI, Düsseldorf, pp 29–50

Cassiani M, Stohl A, Eckhardt S (2013) The dispersion characteristics of air pollution from the world’s megacities. Atmos Chem Phys 13(19):9975–9996. doi:10.5194/acp-13-9975-2013

Creutzig F (2015) Evolving narratives of low-carbon futures in transportation. Transp Rev:1–20. doi:10.1080/01441647.2015.1079277

Das S (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16(3):268–282. doi:10.1007/s11367-011-0264-z

Del Duce A, Egede P, Öhlschläger G, Dettmer T, Althaus H, Bütler T, Szczechowicz E (2013) Guidelines for the LCA of electric vehicles. eLCAr

Ellenrieder G, Gänsicke T, Goede M, Herrmann HG (2013) Die Leichtbaustrategien. In: Friedrich HE (ed) Leichtbau in der Fahrzeugtechnik. Springer Vieweg, Wiesbaden

Gruden D (2008) Umweltschutz in der Automobilindustrie: motor, Kraftstoffe, recycling. Praxis: ATZ/MTZ-Fachbuch. Vieweg+Teubner/GWV Fachverlage GmbH, Wiesbaden, Wiesbaden

Gurjar BR, Butler TM, Lawrence MG, Lelieveld J (2008) Evaluation of emissions and air quality in megacities. Atmos Environ 42(7):1593–1606. doi:10.1016/j.atmosenv.2007.10.048

Hameyer K, De Doncker RW, van Hoek H, Hübner M, Hennen M, Kampker A, Deutskens C, Ivanescu S, Stolze T, Vetter A, Hagedorn J (2013) Elektrischer Antriebsstrang. In: Kampker A, Vallée D, Schnettler A (eds) Elektromobilität: Grundlagen einer Zukunftstechnologie. Springer Vieweg, Berlin, pp 263–295

Hansen F (2013) Mobilität. In: Braess H, Seiffert U (eds) Vieweg-Handbuch Kraftfahrzeugtechnik, 7th edn. Springer Vieweg, Wiesbaden

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi:10.1111/j.1530-9290.2012.00532.x

Henning F, Moeller E (eds) (2011) Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hanser, München

IEA (2012) CO_2 emissions from fuel combustion: highlights, Paris, France

International Transport Forum (2010) Reducing transport greenhouse gas emissions: trends and data 2010

ISO (14044:2006) Environmental management—life cycle assessment—requirements and guidelines (14044:2006)

Kahn Ribeiro S, Kobayashi S, Beuthe M, Gasca J, Greene D, Lee DS, Muromachi P, Newton J, Plotkin S, Sperling D, Wit R, Zhou PJ (2007) Transport and its infrastructure. In: Metz B, Davidson OR, Bosch PR, Dave R, La Meyer (eds) Climate change 2007: mitigation: contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, AlMazroa MA, Amann M, Anderson HR, Andrews KG, Aryee M et al (2012) A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–

2010: a systematic analysis for the global burden of disease study 2010. The Lancet 380 (9859):2224–2260. doi:10.1016/S0140-6736(12)61766-8

Straif K, Cohen A, Samet J (eds) (2013) Air pollution and cancer, vol 161. IARC Scientific Publication

United Nations (2015) World urbanization prospects: the 2014 revision. (ST/ESA/SER.A/366)

World Bank (2004) World development indicators CD-ROM. World Bank, Washington, D.C.

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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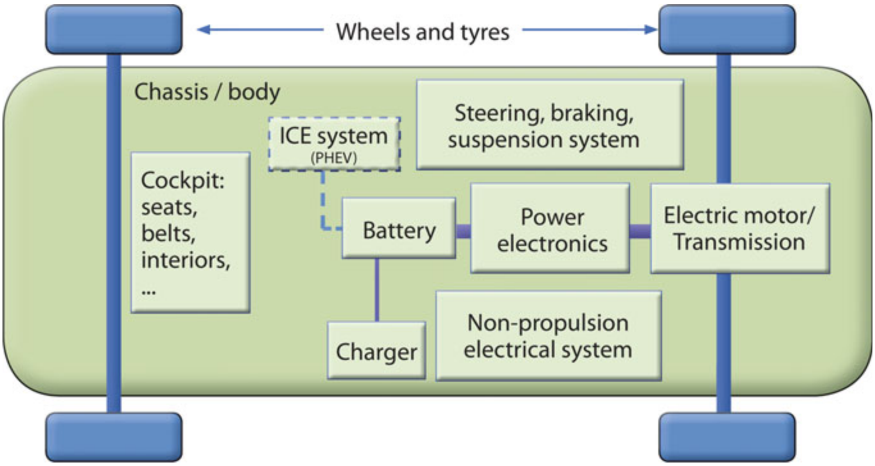

Fig. 2.1 Components of electric vehicle (Del Duce et al. 2013)

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

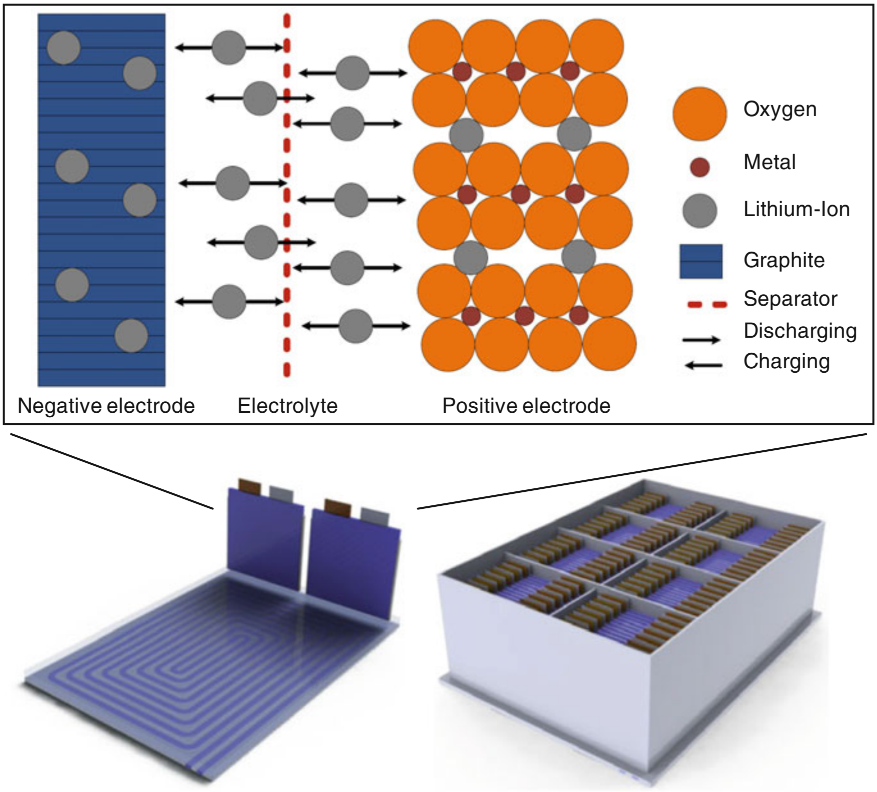

Fig. 2.2 Basic construction of a lithium-ion battery: battery pack with eight modules (*bottom right*), battery pouch cell (*bottom left*) (Schäper 2015), charging and discharging process in battery cell (*top*) (Ecker 2015)

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):

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

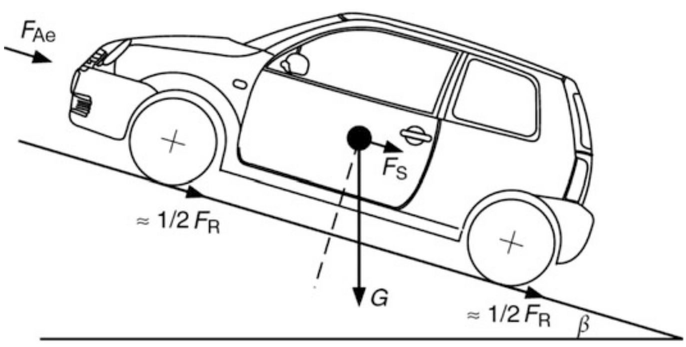

Fig. 2.3 Driving resistances (Ayoubi et al. 2013)

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.

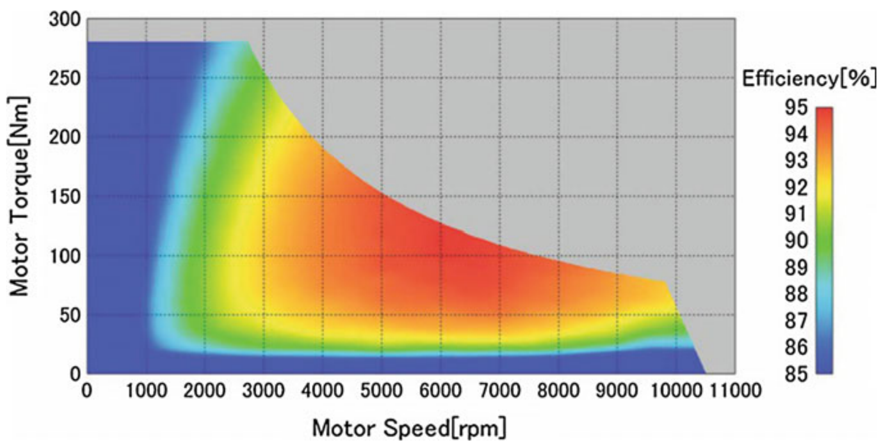

Fig. 2.4 Example of efficiency map for an electric motor (Sato et al. 2011)

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

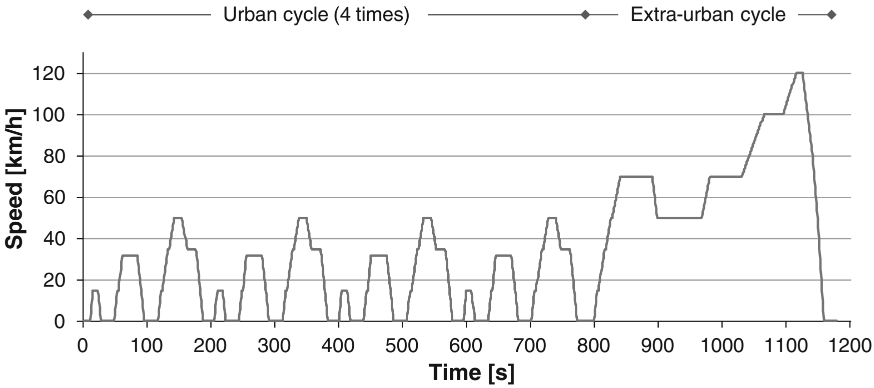

Fig. 2.5 New European driving cycle, own illustration with data from United Nations (2005)

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.

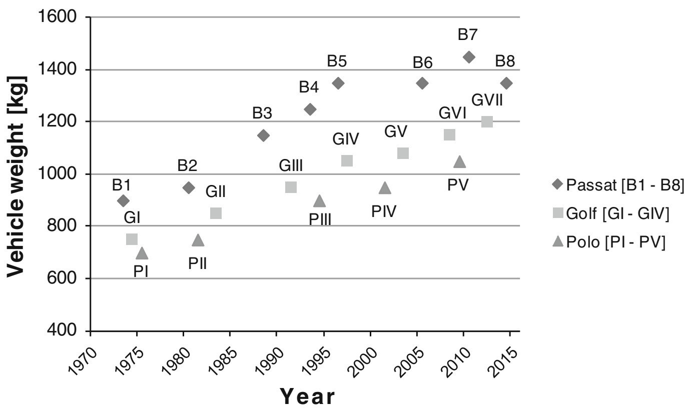

Fig. 2.6 Development of vehicle weight of Volkswagen models Passat, Golf and Polo in the past four decades (based on Eckstein et al. 2010; Volkswagen 2009, 2015a, b)

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

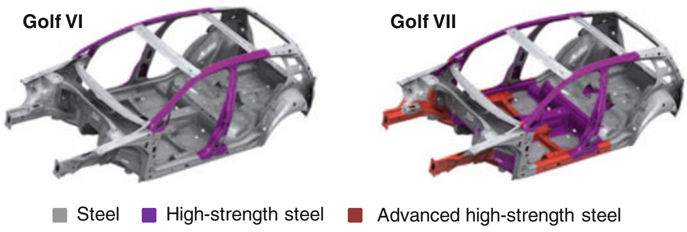

Fig. 2.7 Vehicle body of Golf VI and Golf VII (Ellenrieder et al. 2013)

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

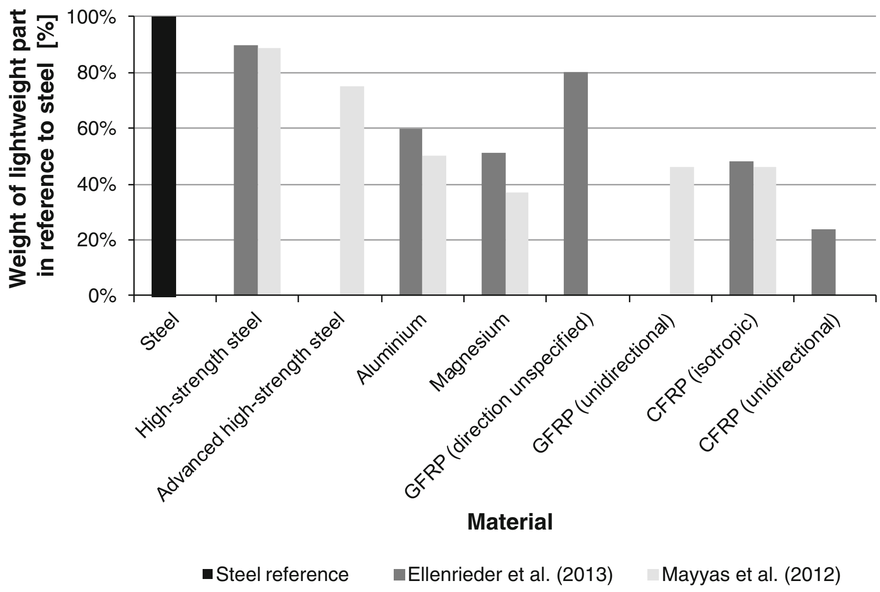

Fig. 2.8 Weight reduction via material substitution (Ellenrieder et al. 2013; Mayyas et al. 2012)

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

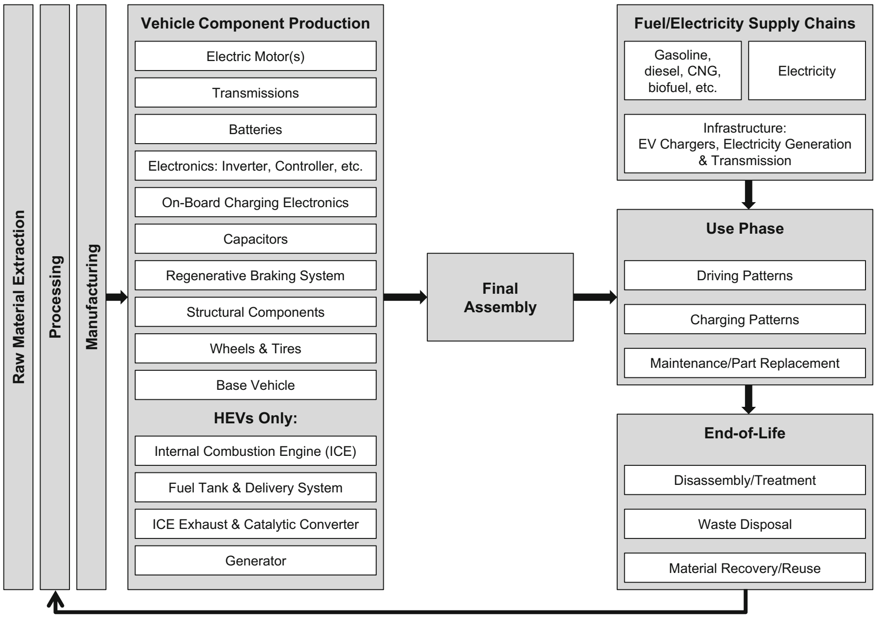

Fig. 2.9 Life cycle of electric vehicle (Hawkins et al. 2012)

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

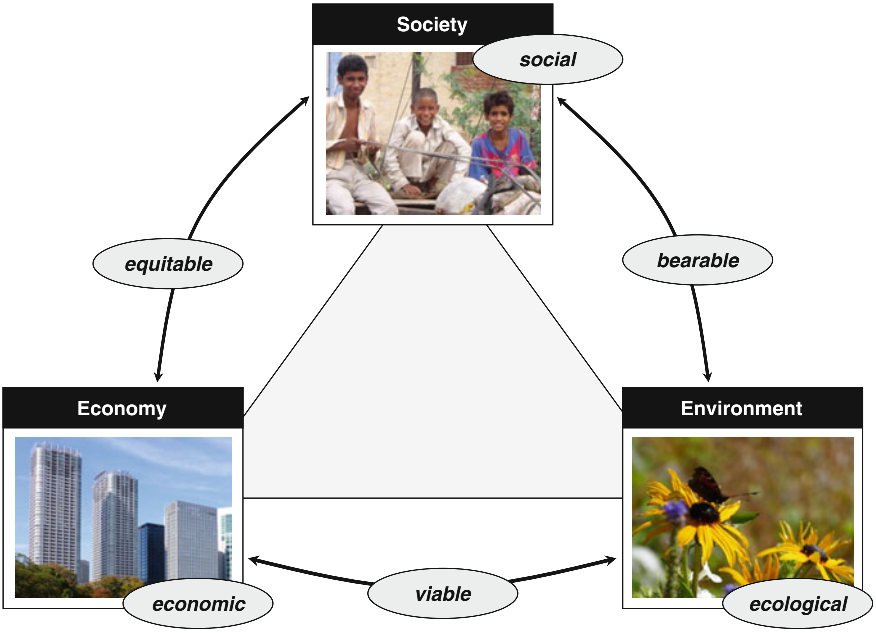

Fig. 2.10 Triangle of sustainability (Ohlendorf 2006, photos replaced)

(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.

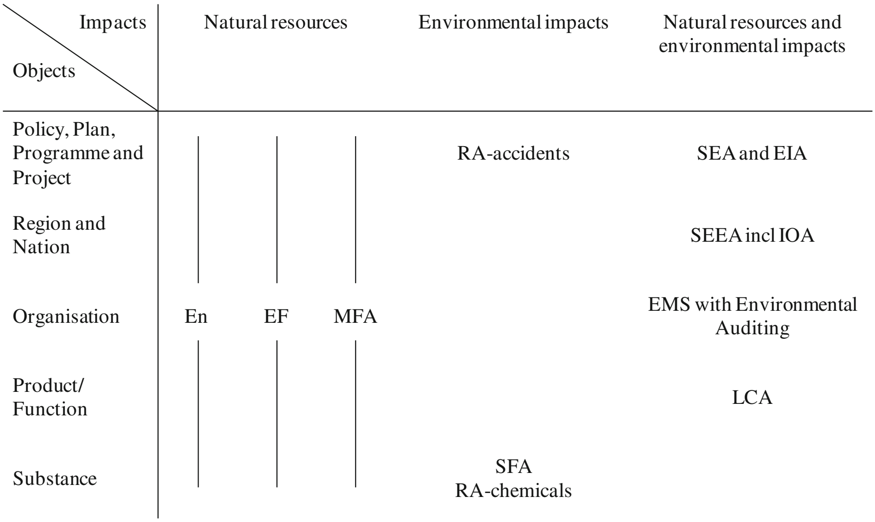

Fig. 2.11 Environmental system analysis tools categorized according to object of interest and impacts studied (Cf. Finnveden and Moberg 2005); energy analysis (*En*), environmental footprint (*EF*), material flow accounting (*MFA*), risk assessment (*RA*), substance flow analysis (*SFA*), environmental 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).

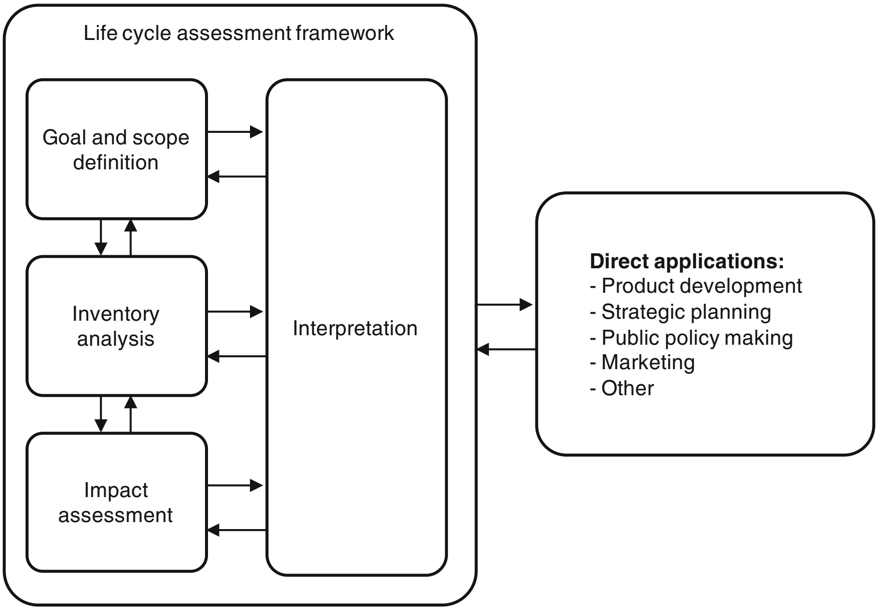

Fig. 2.12 Methodological framework of LCA (ISO 14040:2006). ("Reproduced by permission of DIN Deutsches Institut für Normung e.V. The definitive version for the implementation of this standard is the edition bearing the most recent date of issue, obtainable from Beuth Verlag GmbH, Burggrafenstraße 6,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

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

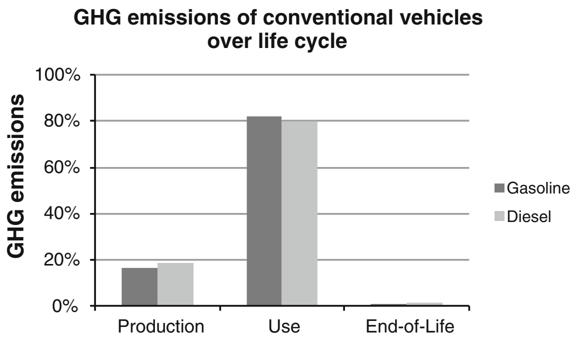

Fig. 2.13 Example of LCIA results from conventional vehicles, own calculation and illustration with data from Hawkins et al. (2013)

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

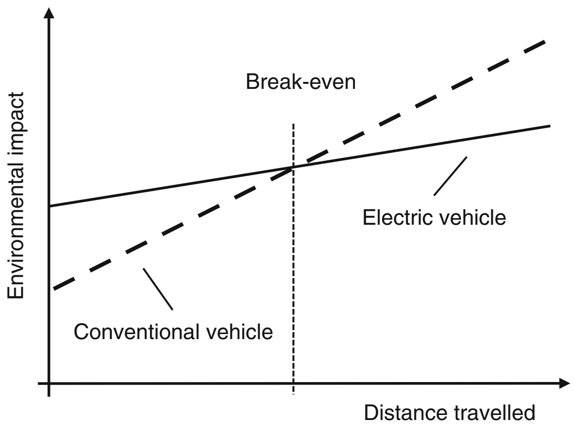

Fig. 2.14 Simple break-even analysis of an electric and a conventional vehicle

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.

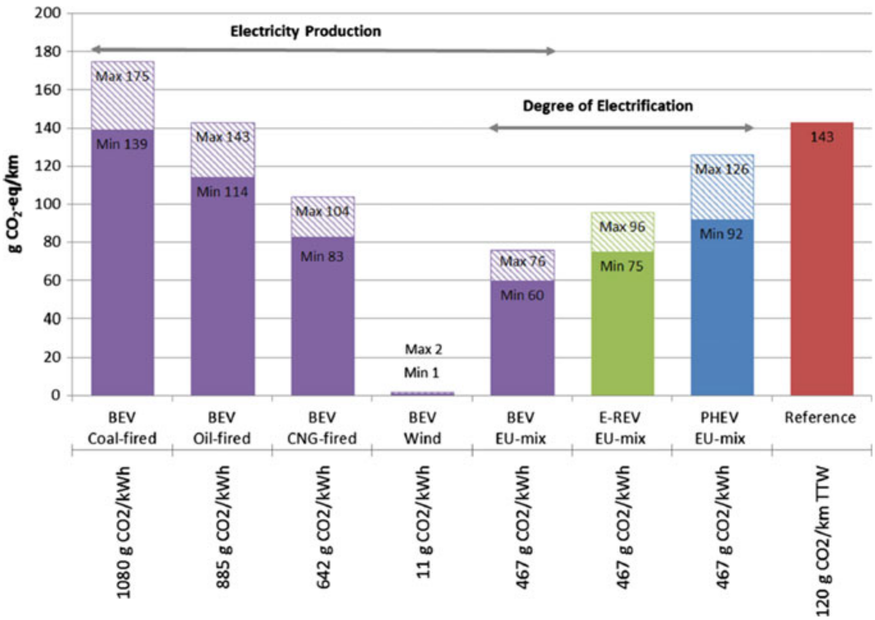

Fig. 2.15 GHG emissions for different types of electricity production and different vehicle types (Nordelöf et al. 2014); battery electric vehicle (*BEV*), extended range electric vehicles (*E-REV*), plug-in hybrid vehicle (*PHEV*)

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

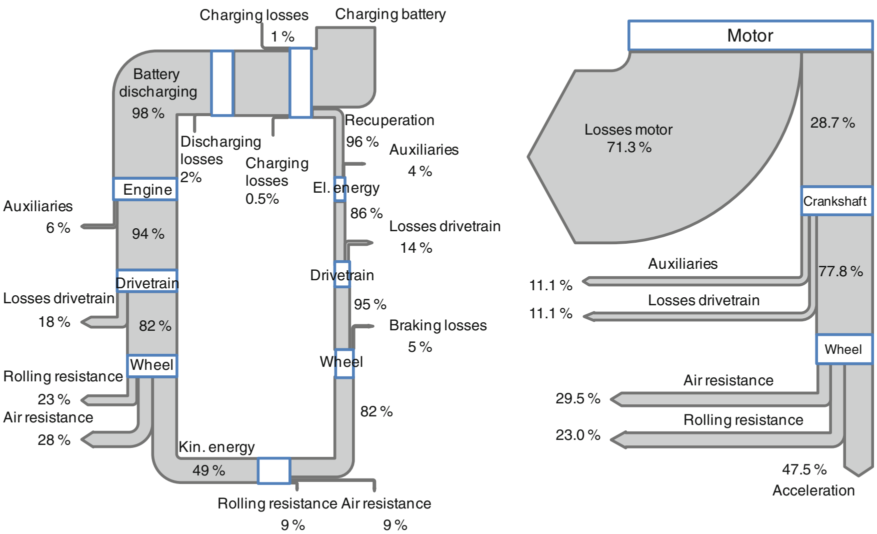

Fig. 2.16 Energy flows of conventional and electric vehicles for new European driving cycle translated from Woll (2013)

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.

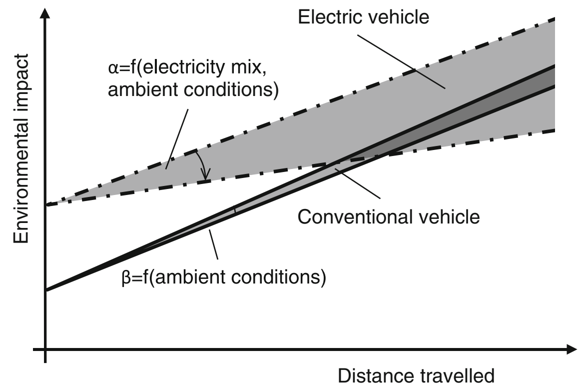

Fig. 2.17 Environmental impact of EVs in comparison to conventional vehicles

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

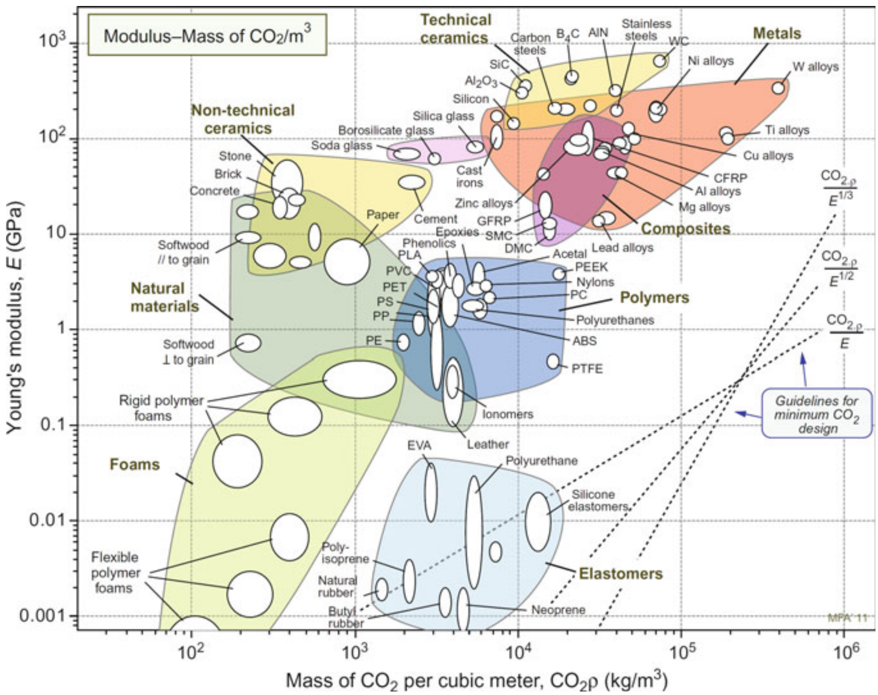

Fig. 2.18 Relation of Young's modulus and mass of CO_2 per cubic meter (Ashby 2012)

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.).

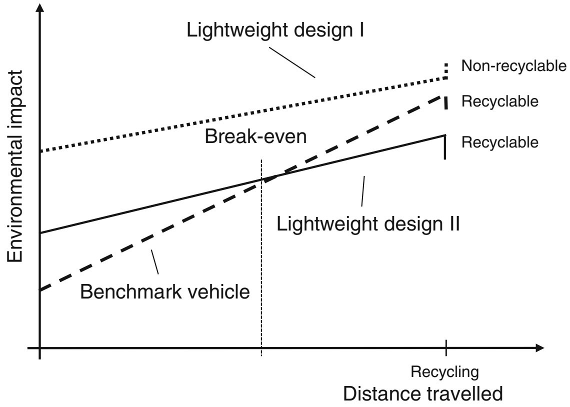

Fig. 2.19 Break-even analysis of reference vehicle and two lightweight vehicles

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

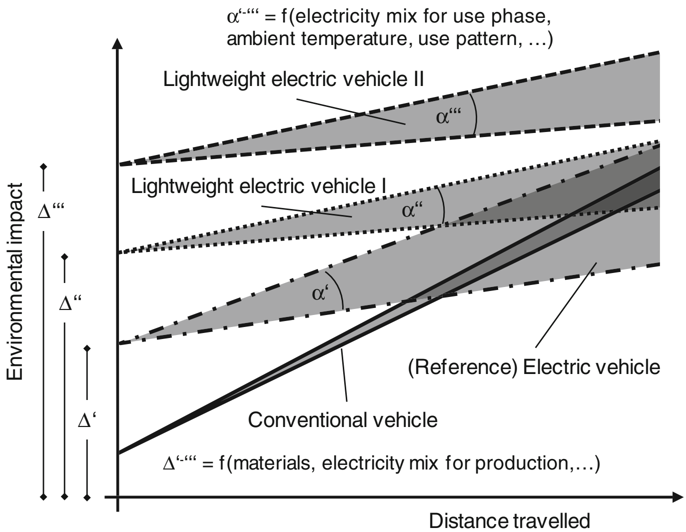

Fig. 2.20 Break-even analysis of conventional, electric and lightweight electric vehicle

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.

References

Achleitner A, Antony P, Ascher F, Berger E, Burgers C, Döllner G, Friedrich JK, Futschik HD, Gruber M, Kiesgen G, Mohrdieck CH, Noreikat KE, Schulze H, Wagner M, Wöhr M (2013) Formen und neue Konzepte. In: Braess H, Seiffert U (eds) Vieweg-Handbuch Kraftfahrzeugtechnik, 7th edn. Springer Vieweg, Wiesbaden, pp 119–219

Ashby MF (2012) Materials and the environment: eco-informed material choice, 2nd edn. Butterworth-Heinemann, Waltham

Ayoubi M, Eilemann A, Mankau H, Pantow E, Repmann C, Seiffert U, Wawzyniak M, Wiebelt A (2013) Fahrzeugphysik. In: Braess H, Seiffert U (eds) Vieweg-Handbuch Kraftfahrzeugtechnik, 7th edn. Springer Vieweg, Wiesbaden, pp 47–118

Barlow TJ, Latham S, McCrae IS, Boulter PG (2009) A reference book of driving cycles for use in the measurement of road vehicle emissions

Baumann H, Tillman A (2009) The hitch hikers's guide to LCA: an orientation in life cycle assessment methodology and application, Ed. 1:3. Studentlitteratur, Lund

Bilitewski B, Bringezu S, Bro-Rasmussen F, Clift R, Frischknecht R, Speck S, Soerup P, Udo de Haes HA (1998) CHAINET definition document. Leiden, Netherlands

Buchert M, Jenseit W, Merz C, Schüler D (2011) Ökobilanz zum "Recycling von Lithium-Ionen-Batterien" (LithoRec)

Calantone RJ, Tamer Cavusgil S, Schmidt JB, Shin G (2004) Internationalization and the dynamics of product adaptation—an empirical investigation. J Prod Innov Manage 21(3):185–198. doi:10.1111/j.0737-6782.2004.00069.x

Consoli F, Allen D, Boustead I, de Oude N, Fava J, Franklin W, Quay B, Parrish R, Perriman R, Postlethwaite D, Seguin J, Vigon B (1993) Guidelines for life-cycle assessment: a code of practice. Brussels, Belgium

Curran MA (2012) Life cycle assessment handbook: a guide for environmentally sustainable products. Wiley, Hoboken

Del Duce A, Egede P, Öhlschläger G, Dettmer T, Althaus H, Bütler T, Szczechowicz E (2013) Guidelines for the LCA of electric vehicles. eLCAr

Directive 2000/53/EC of the European Parliament and the Council of the 18 September 2000 on end-of-life vehicles

Dubreuil A, Young SB, Atherton J, Gloria TP (2010) Metals recycling maps and allocation procedures in life cycle assessment. Int J Life Cycle Assess 15(6):621–634. doi:10.1007/s11367-010-0174-5

Ecker M (2015) Lithium-Ionen-Batterien. In: Tschöke H (ed) Die Elektrifizierung des Antriebsstrangs: Basiswissen. Springer Fachmedien Wiesbaden GmbH, Wiesbaden, pp 60–67

Eckstein L, Schmitt F, Hartmann B (2010) Leichtbau bei Elektrofahrzeugen. ATZ Automobiltech Z 112(11):788–795. doi:10.1007/BF03222207

Ecoinvent (2015) Ecoinvent database. http://ecoinvent.ch/. Accessed 20 Oct 2015

Ekvall T, Tillman A (1997) Open-loop recycling: criteria for allocation procedures. Int J Life Cycle Assess 2(3):155–162. doi:10.1007/BF02978810

Ellenrieder G, Gänsicke T, Goede M, Herrmann HG (2013) Die Leichtbaustrategien. In: Friedrich HE (ed) Leichtbau in der Fahrzeugtechnik. Springer Vieweg, Wiesbaden

Ellingsen LA, Majeau-Bettez G, Singh B, Srivastava AK, Valøen LO, Strømman AH (2014) Life cycle assessment of a lithium-ion battery vehicle pack. J Ind Ecol 18(1):113–124. doi:10.1111/jiec.12072

European Commission (2011) International reference life cycle data system (ILCD) handbook: general guide for life cycle assessment—detailed guidance, 1st edn, Mar 2010. Luxembourg

European Commission—Joint Research Center (2015) ELCD 3.2. http://eplca.jrc.ec.europa.eu/ELCD3/index.xhtml?stock=default. Accessed 22 Nov 2015

European Communities (2001) Economy-wide material flow accounts and derived indicators: a methodological guide, 2000th edn. Office for Official Publications of the European Communities, Luxembourg

Evertz T, Flaxa V, Georgeou Z, Gronebaum R, Kwiaton N, Lesch C, Otto M, Schöttler J, Schulz T, Springub B, Furrer P, Müller A, Dieringa H, Kainer KU, Leyens C, Peters M, Gadow R, Drechsler K, Ziegmann G (2013) Die Leichtbauwerkstoffe für den Fahrzeugbau. In: Friedrich HE (ed) Leichtbau in der Fahrzeugtechnik. Springer Vieweg, Wiesbaden, pp 199–442

Faria R, Moura P, Delgado J, de Almeida Anibal T (2012) A sustainability assessment of electric vehicles as a personal mobility system. Energy Convers Manage 61:19–30. doi:10.1016/j.enconman.2012.02.023

Finnveden G (2000) On the limitations of life cycle assessment and environmental systems analysis tools in general. Int J Life Cycle Assess 5(4):229–238. doi:10.1007/BF02979365

Finnveden G, Moberg Å (2005) Environmental systems analysis tools—an overview. J Clean Prod 13(12):1165–1173. doi:10.1016/j.jclepro.2004.06.004
Fischer F, Große T, Kleemann S, Dröder K, Dilger K, Vietor T (2014) Smart production of hybrid material automotive structures at Forschungs Campus Wolfsburg in the "Open Hybrid Lab Factory". In: ITHEC 2014: 2nd international conference and exhibition on thermoplastic composites, Bremen, Germany, 27–28 Oct 2014, pp 33–36
Frees N (2008) Crediting aluminium recycling in LCA by demand or by disposal. Int J Life Cycle Assess 13(3):212–218. doi:10.1065/lca2007.06.348
Friedrich HE (ed) (2013) Leichtbau in der Fahrzeugtechnik. ATZ/MTZ-Fachbuch. Springer Vieweg, Wiesbaden
Hameyer K, De Doncker RW, van Hoek H, Hübner M, Hennen M, Kampker A, Deutskens C, Ivanescu S, Stolze T, Vetter A, Hagedorn J (2013) Elektrischer Antriebsstrang. In: Kampker A, Vallée D, Schnettler A (eds) Elektromobilität: Grundlagen einer Zukunftstechnologie. Springer Vieweg, Berlin, pp 263–295
Hauschild MZ, Huijbregts MA (2015) Life cycle impact assessment. Springer, Netherlands, Dordrecht
Hawkins TR, Gausen OM, Strømman AH (2012) Environmental impacts of hybrid and electric vehicles—a review. Int J Life Cycle Assess 17(8):997–1014. doi:10.1007/s11367-012-0440-9
Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi:10.1111/j.1530-9290.2012.00532.x
Heijungs R (2014) Ten easy lessons for good communication of LCA. Int J Life Cycle Assess 19(3):473–476. doi:10.1007/s11367-013-0662-5
Henning F, Moeller E (eds) (2011) Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hanser, München
Herrmann C (2010) Ganzheitliches life cycle management. Springer, Berlin
Hornbogen E, Jost N, Thumann M (2008) Werkstoffe, 9th edn. Springer, Berlin [u.a.]
Hunt RG, Franklin WE, Hunt RG (1996) LCA—how it came about. Int J Life Cycle Assess 1(1):4–7. doi:10.1007/BF02978624
Internationales Institut für Nachhaltigkeitsanalysen und -strategien (2015) IINAS. http://www.iinas.org. Accessed 2 Oct 2015
ISO (14040:2006) Environmental management—life cycle assessment—principles and framework (14040:2006)
ISO (14044:2006) Environmental management—life cycle assessment—requirements and guidelines (14044:2006)
Klein B (2013) Leichtbau-Konstruktion: Berechnungsgrundlagen und Gestaltung, 10th edn. Studium. Springer Vieweg, Wiesbaden
Klöpffer W, Grahl B (2009) Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf. Wiley-VCH, Weinheim
Klug F (2010) Logistikmanagement in der Automobilindustrie: Grundlagen der Logistik im Automobilbau. VDI-Buch. Springer, Berlin
Konz M, Lemke N, Försterling S, Eghtessad M (2011) Spezifische Anforderungen an das Heiz-Klimasystem elektromotorisch angetriebener Fahrzeuge. FAT-Schriftenreihe (233)
Kopp G, Burkardt N, Majic N (2011) Leichtbaustrategien und Bauweisen. In: Henning F, Moeller E (eds) Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hanser, München, pp 57–76
Leidhold R (2015) Elektrische Maschinen. In: Tschöke H (ed) Die Elektrifizierung des Antriebsstrangs: Basiswissen. Springer Fachmedien Wiesbaden GmbH, Wiesbaden, pp 25–35
Mayyas AT, Qattawi A, Mayyas AR, Omar MA (2012) Life cycle assessment-based selection for a sustainable lightweight body-in-white design. Energy 39(1):412–425. doi:10.1016/j.energy.2011.12.033
Melnyk S, Sroufe RP, Calantone RJ (2003) Assessing the impact of environmental management systems on corporate and environmental performance. J Oper Manage 21(3):329–351. doi:10.1016/S0272-6963(02)00109-2

Mock P, German J, Bandivadekar A, Riemersma I (2012) Discrepancies between type-approval and “real-world” fuel-consumption and CO_2 values: assessment for 2001–2011 European passenger cars. The International Council on Clean Transportation
Neudorfer H, Binder A, Wicker N (2006) Analyse von unterschiedlichen Fahrzyklen für den Einsatz von Elektrofahrzeugen. Elektrotech Inftech 123(7–8):352–360. doi:10.1007/s00502-006-0363-x
Nicholson AL, Olivetti EA, Gregory JR, Field FR, Kirchain RE (2012) End-of-life LCA allocation methods: open loop recycling impacts on robustness of material selection decisions: 1–6. doi:10.1109/ISSST.2009.5156769
Niemann G, Höhn B, Winter H (2005) Maschinenelemente: Entwerfen, Berechnen und Gestalten im Maschinenbau; ein Lehr- und Arbeitsbuch, 4th edn. Springer, Berlin [u.a.]
Nordelöf A, Messagie M, Tillman A, Ljunggren Söderman M, van Mierlo J (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 19(11):1866–1890. doi:10.1007/s11367-014-0788-0
Ohlendorf M (2006) Simulationsgestützte Planung und Bewertung von Demontagesystemen. Dissertation. Schriftenreihe des Instituts für Werkzeugmaschinen und Fertigungstechnik der TU Braunschweig. Vulkan-Verl., Essen
Otto HE, Mueller KG, Kimura F (2003a) Efficient information visualization in LCA: approach and examples. Int J Life Cycle Assess 8(5):259–265. doi:10.1007/BF02978917
Otto HE, Mueller, Karl, G., Kimura F (2003b) Efficient information visualization in LCA: introduction and overview. Int J Life Cycle Assess 8(4). doi:10.1065/lca2003.06.121
Pischinger F, Adomeit P (2013) Grundlagen der Motorentechnik. In: Braess H, Seiffert U (eds) Vieweg-Handbuch Kraftfahrzeugtechnik, 7th edn. Springer Vieweg, Wiesbaden, pp 222–295
Roesky O, Bodmann M, Mummel J, Kurrat M, Köhler J (2015) Impact of losses on the charging strategy of electric vehicles. In: Hybrid and electric vehicles: 12th symposium, Stadthalle Braunschweig, 24–25 Feb 2015. ITS Niedersachsen, Braunschweig
Samuel S, Austin L, Morrey D (2002) Automotive test drive cycles for emission measurement and real-world emission levels-a review. Proc Inst Mech Eng Part D J Automobile Eng 216 (7):555–564. doi:10.1243/095440702760178587
Sato Y, Ishikawa S, Okubo T, Abe M, Tamai K (2011) Power from within. SAE Int Veh Electrification 2(1)
Sauer DU, Kampker A, Deutskens C, Heimes HH (2013) Batteriesysteme und deren Steuerung. In: Kampker A, Vallée D, Schnettler A (eds) Elektromobilität: Grundlagen einer Zukunftstechnologie. Springer Vieweg, Berlin, pp 295–314
Schäper C, Sauer DU (2015) Batteriesystemtechnik. In: Tschöke H (ed) Die Elektrifizierung des Antriebsstrangs: Basiswissen. Springer Fachmedien Wiesbaden GmbH, Wiesbaden, pp 85–92
Schuh G, Korthals K, Backs M (2013) Environmental impact of body lightweight design in the operating phase of electric vehicles. In: Nee AYC, Song B, Ong S (eds) Re-engineering manufacturing for sustainability: proceedings of the 20th CIRP international conference on life cycle engineering, Singapore, 17–19 Apr 2013. Springer, Singapore, New York
Scrosati B, Garche J (2010) Lithium batteries: status, prospects and future. J Power Sources 195 (9):2419–2430. doi:10.1016/j.jpowsour.2009.11.048
Stan C (2012) Alternative Antriebe für Automobile: Hybridsysteme, Brennstoffzellen, alternative Energieträger, 3. Aufl. 2012. SpringerLink: Bücher. Springer, Berlin
Strupp C, Lemke N (2009) Klimatische Daten und Pkw-Nutzung: Klimadaten und Nutzungsverhalten zu Auslegung, Versuch und Simulation an Kraftfahrzeug-Kälte-/Heizanlagen in Europa, USA, China und Indien. FAT-Schriftenreihe (224)
Thinkstep (2015) Gabi database. www.gabi-software.com. Accessed 2 Oct 2015
Treffer F (2011) Entwicklung eines realisierbaren Recyclingkonzeptes für die Hochleistungsbatterien zukünftiger Elektrofahrzeuge: Lithium-Ionen Batterierecycling Initiative—LiBRi
Umweltbundesamt (2015) Probas database. http://www.probas.umweltbundesamt.de. Accessed 2 Oct 2015

United Nations (2005) Uniform provisions concerning the approval of passenger cars: UNECE R 101. Accessed 25 Oct 2012

United Nations Economic Commission for Europe (2014) UNECE adopts more accurate fuel efficiency and CO_2 test for new cars. Geneva, Switzerland

Volkswagen AG (2009) Der Passat: Umweltprädikat - Hintergrundbericht

Volkswagen AG (2015a) Der Golf. http://www.volkswagen.de/de/models/golf_7.html. Accessed 27 Apr 2015

Volkswagen AG (2015b) Der Passat. http://www.volkswagen.de/de/models/passat.html. Accessed 27 Apr 2015

Wackernagel M, Rees WE (1996) Our ecological footprint: reducing human impact on the earth. New catalyst bioregional series, no. 9. New Society Publishers, Gabriola Island, BC

Wallentowitz H, Freialdenhoven A (2011) Strategien zur Elektrifizierung des Antriebsstranges: Technologien, Märkte und Implikationen, 2., überarbeitete Auflage. Studium. Vieweg +Teubner Verlag/Springer Fachmedien Wiesbaden GmbH, Wiesbaden

Weißbach W (2012) Werkstoffkunde: Strukturen, Eigenschaften, Prüfung; mit 248 Tabellen, 18., überarb. Aufl. Studium. Vieweg+Teubner, Wiesbaden

Weidenmann K, Wanner A (2011) Werkstoffauswahl für den Leichtbau. In: Henning F, Moeller E (eds) Handbuch Leichtbau: Methoden, Werkstoffe, Fertigung. Hanser, München

Woll T (2013) Verbrauch und Fahrleistung. In: Schütz T (ed) Hucho - Aerodynamik des Automobils: Strömungsmechanik, Wärmetechnik, Fahrdynamik, Komfort, 6., vollständig überarbeitete und erweiterte Auflage, pp 137–176

World Commission on Environment and Development (1987) Our Common Future: Report of the World Commission on Environment and Development. Oxford University Press, New York, NY

Zoboli R, Barbiroli G, Leoncini R, Mazzanti M, Montresor S (2000) Regulation and innovation in the area of end-of-life vehicles. European Commission, Institute for Prospective Technology Studies

Chapter 3
State of Research on the Environmental Assessment of Electric and Lightweight Vehicles

The following chapter reviews the state of research on the environmental assessment of LEVs. First, the existing approaches are presented in the categories of LCA guidelines for vehicles and LCA studies on the three topics: (1) EVs, (2) conventional lightweight vehicles and (3) LEVs. Based on this discussion, an evaluation of the current state of research regarding a set of criteria is performed. This evaluation serves as a mean to derive the requirements of research.

3.1 Discussion of Existing Approaches

Four different groups of approaches are considered for the assessment of the state of research: LCA guidelines for vehicles as well as LCA studies on EVs, conventional lightweight vehicles and LEVs. In the following the selected guidelines and studies of each category are presented to provide an overview of the current state of research in each area.

3.1.1 LCA Guidelines for Vehicles

A small number of LCA guidelines addresses the specific topic of vehicles, either in general or with a specific focus. A first set of guidelines was developed by the European Council for Automotive Research and Development (EUCAR) and was published in 1998. These guidelines discuss general aspects of the LCA of vehicles (Ridge 1998). The Guidelines for the LCA of electric vehicles (eLCAr) were developed with a particular focus on full battery electric vehicles (Del Duce et al. 2013). Finally, the Canadian standard SPE-14040-14 Life cycle assessment of auto parts puts a spotlight on conventional lightweight vehicles (Canada Standards Association 2014).

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Sustainable Production, Life Cycle Engineering and Management,
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The EUCAR guidelines were developed by a group of researchers from the automotive industry. The recommendations discuss the use phase, the allocation of the vehicle energy consumption to components, the consideration of the end-of-life phase and the selection of impact assessment methods. The use phase should be modelled with data used for type approval (i.e. the NEDC). Two methods are discussed which can be used to assign the energy consumption of the use phase to a single component or a group of components. Recommendations are given in which situations one method should be preferred over the other. With regard to the end-of-life phase the guidelines are rather vague. The authors refer to the ISO standard and recommend sensitivity analyses. The guidelines do not stipulate to use specific impact assessment methods but weigh up the advantages and disadvantages of methods and practices. A case study of a tailgate exemplifies the given recommendations (Ridge 1998). EVs are not particularly addressed within these guidelines.

The eLCAr guidelines originate from a project funded by the European Commission under the Environment Theme of the 7th Framework Programme for Research and Technological Development. These guidelines were derived from the ILCD Handbook. The build-up of the guidelines follows the steps of an LCA and features a set of common parameters for key values of EVs. Each phase is described in detail and specific guidance is provided how to model these phases in an LCA. Furthermore, an interdependency matrix was developed. This table intends to describe the dependencies of the vehicle components for example to consider secondary effects due to weight changes. The independency matrix is shown in Fig. 3.1. The number one stands for a relation between the components described in

		COMPONENTS										VEHICLE	
	is/are influenced by … / influence(s)…	Charger	Traction-Battery	Power Electronics	E-motor	Transmission	SBSS	Body (Frame)	Aerodynamics	Insulation	Non-p. El. System	Vehicle Weight	Overall Energy Demand (in use phase)
VEHICLE	Vehicle Weight	1	1	1	1	1	1	1	0	1	1		1
	Energy Demand (in use phase, NOT via weight)	1	1	1	1	1	1	0	1	1	1	1	
COMPONENTS	Charger		1	0	0	0	0	0	0	0	0	0	0
	Traction-Battery	0		1	1	0	0	0	0	0	0	0	1
	Power Electronics	0	1		1	0	0	0	0	0	0	0	1
	E-motor	0	0	0		0	0	0	0	0	0	0	1
	Transmission	0	0	0	1		0	0	0	0	0	0	1
	SBSS	0	0	0	0	0		0	0	0	0	1	1
	Body (Frame)	0	1	0	0	0	0		0	0	0	1	0
	Aerodynamics	0	0	0	0	0	0	0		0	0	0	0
	Insulation	0	0	0	0	0	0	0	0		0	0	0
	Non-p. El. System	0	0	0	0	0	0	0	0	1		0	0

Fig. 3.1 Interdependency matrix as published in the eLCAr guidelines (Del Duce et al. 2013)

the rows and columns. The number zero signalizes that there is no correlation. The guidelines also discuss the topics of the incorporation of future developments and multi-functionalities. Although the guidelines do provide information on the consideration of ambient conditions, they do not provide guidance on performing a comprehensive, worldwide assessment. The guidelines also do not address the issue of the resulting energy reduction from lightweight measures (Del Duce et al. 2013).

The guidelines 'SPE-14040-14 Life cycle assessment of auto parts' provide support to assess the environmental impact of weight changes of parts in internal combustion engine vehicles produced by North American automotive manufacturers. Weight changes resulting from exchanged material compositions, manufacturing technologies or part geometries are considered. Hereby, the focus lies on single parts and not the entire vehicle. Nevertheless, secondary effects like secondary weight changes or drive train adaptations are considered in all life cycle phases. The general system boundaries to include in the assessment are shown in Fig. 3.2. Within the system boundary are the production, use and end-of-life phase of the vehicle part of interest. The chart includes possible recycling and end-of-life crediting. Production scrap recycling and crediting is considered as separate processes. The guidelines are applicable to combustion engine vehicles. EVs are therefore not addressed. The guideline was peer reviewed by three independent experts (Canada Standards Association 2014).

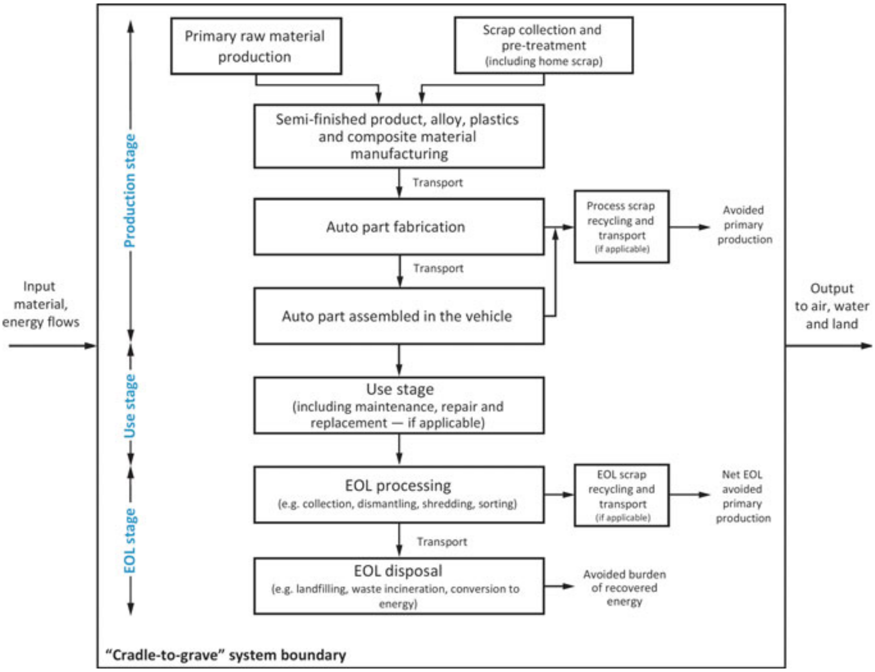

Fig. 3.2 System boundaries defined in guidelines SPE-14040-14 (Canada Standards Association 2014)

3.1.2 LCA Studies on Electric Vehicles

A two-digit number of studies discuss battery EVs (Hawkins et al. 2012; Nordelöf et al. 2014). Even more studies discuss conventional and hybrid vehicles. Considering the need of research this sub-section focuses on studies analysing the differences between electric and conventional vehicles. These studies were selected regarding their completeness of scope and analysed impacts. These criteria are based on the principles of an LCA described in Sect. 2.3.3.

As described above (in Sect. 2.3.3), studies with a limited system boundary, WTW analyses can be conducted. However, an LCA shall include the entire life cycle. Hence, this excludes any type of WTW analysis. Furthermore, LCAs analyse the entire spectrum of the environmental impact of products. Therefore, the minimum requirement is the consideration of at least two impact categories. As said above single score methods are criticized because they do not portray the complexity of a problem (see Sect. 2.3.3). Very often only global warming is analysed in the collected studies. However, the concentration on a single impact category is a major simplification which does not meet the requirements of an LCA. Finally, eight studies were identified which meet the criteria described above: van Mierlo et al. (2009), (Boureima et al. 2009), (Messagie et al. 2010), Notter et al. (2010), Messagie et al. (2011), Szczechowicz et al. (2012), Bartolozzi et al. (2013), Hawkins et al. (2013a) and Girardi et al. (2015).

Four of the studies (van Mierlo et al. 2009; Boureima et al. 2009; Messagie et al. 2010, 2011) originate from the project CLEVER 'Clean Vehicle Research: LCA and Policy measures' which ran from 2007 until 2011. The study of van Mierlo et al. (2009) is the original project report. The publications from Boureima et al. (2009) and Messagie et al. (2010, 2011) are further elaborations of the project. The assessments are based on a range-based approach displayed in Fig. 3.3. The approach contains different vehicle seizes, propulsion systems and emission

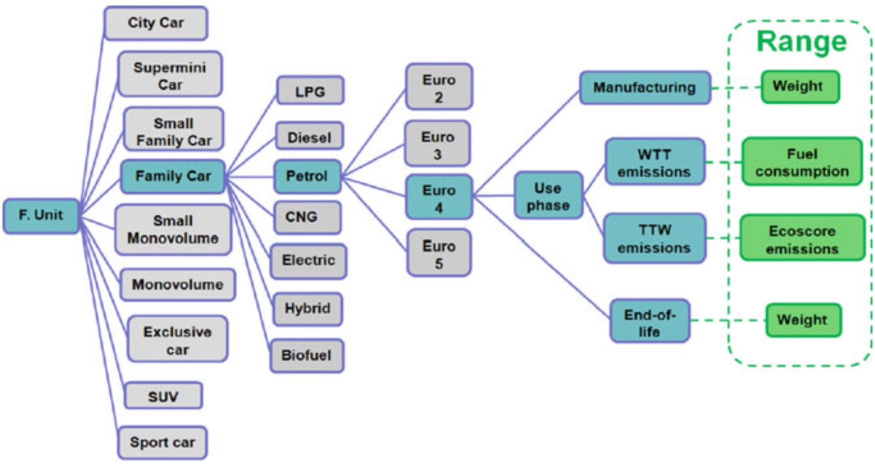

Fig. 3.3 Range-based modelling system applied in the project CLEVER (van Mierlo et al. 2009)

standards. Full LCA studies as well as WTW studies can be performed. It allows the comparison of electric, hybrid, alternative fuel and conventional vehicles in Belgium. The approach avoids the use of average values for the fuel consumption, the weight, direct emissions and lifetime driving distance. An approach was selected in which all parameters (except for the fuel consumption) are described with a function based on the fuel consumption. This enables the calculation of sensitivity analyses with a high number of iterations altering only the fuel consumption. The LCI data for all other processes is taken from data bases (e.g. Ecoinvent v2.0). The reported impact categories are mostly air acidification, eutrophication, human health and greenhouse effect. The results vary depending on the studies. In general, it can be said that in all studies EVs perform better than other solutions. This is even true for EVs driven with electricity based on coal (van Mierlo et al. 2009). It is not clear why EVs show almost no emissions for their production in the graphs presented by Boureima et al. (2009). This contradicts the findings of most other studies (e.g. Hawkins et al. 2013a). In other studies of this series this is not the case (van Mierlo et al. 2009; Messagie et al. 2010).

The analysis of Notter et al. (2010) focuses on the contribution of lithium-ion batteries to the environmental impact of EVs. Consequently, the entire vehicle is analysed roughly. The European electricity mix is applied. The energy consumption is based on the NEDC. However, heating and cooling is accounted for with a static value. The abiotic depletion potential, non-renewable cumulated energy demand, global warming potential and Ecoindicator 99 H/A are assessed. The EV performs better in all categories with the conventional vehicle displaying around 25–65 % higher results. The authors find the results to be sensitive to the electricity mix but not to the energy consumption.

Szczechowicz et al. (2012) perform a full LCA as well as a TTW analysis for a specific region for an electric, hybrid and conventional vehicle. The use case is set in Aachen, Germany. The focus lies on the TTW analysis. The LCIs for the vehicles are taken from other studies. The NEDC is applied to calculate the energy consumption of the vehicles. For the TTW analysis the authors apply a detailed model of the driving behaviour to specific streets with a time resolution of 15 min. The paper contains the most extensive list of impact categories with a total of 22 for the full LCA. EVs perform better in around half of the categories. In the TTW analysis improvements through EVs were also calculated.

Hawkins et al. (2013a) compare electric and conventional vehicles. The authors publish a detailed LCI of an EV based on secondary data and the Ecoinvent database v2.2 for the production and end-of-life phase. The use phase is based on the NEDC. Ten impact categories are presented (Global warming, terrestrial acidification, particulate matter formation, photochemical oxidation formation, human toxicity, freshwater and terrestrial eco-toxicity, freshwater eutrophication, mineral resource and fossil depletion). The authors find the results to depend significantly on the electricity source, use the phase energy consumption, the vehicle lifetime and the battery replacement schedules (in descending order). Also, the environmental impact of the production of EVs is found to have higher environmental impacts than the production of conventional vehicles. The authors introduce the idea that

EVs perform worse in the impact categories of freshwater eutrophication, human toxicity, freshwater eco-toxicity and mineral resource depletion (Hawkins et al. 2013a). The results are presented in Fig. 3.4. Later an update of the inventory and the results was published (Hawkins et al. 2013b).

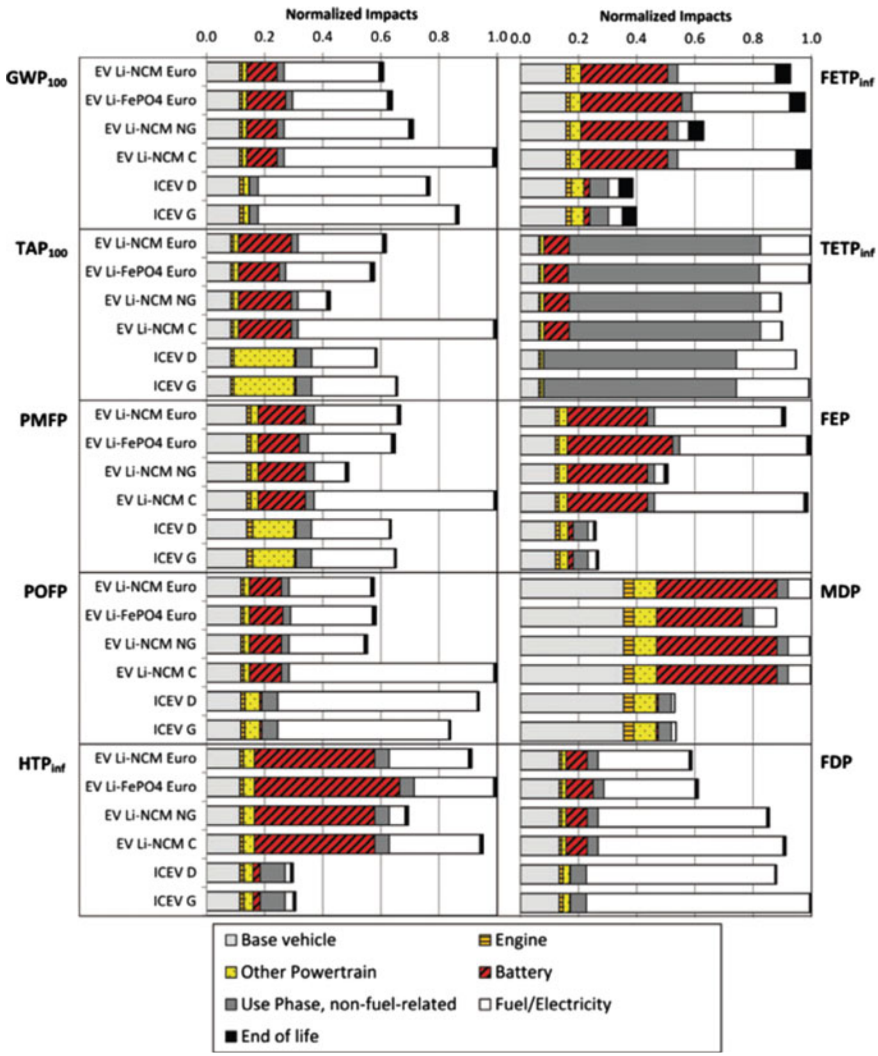

Fig. 3.4 Normalized impacts of EVs and conventional vehicles (Hawkins et al. 2013b); global warming (*GWP*), terrestrial acidification (*TAP*), particulate matter formation (*PMFP*), photochemical oxidation formation (*POFP*), human toxicity (*HTP*), freshwater eco-toxicity (*FETP*), terrestrial eco-toxicity (*TETP*), freshwater eutrophication (*FEP*), mineral resource depletion (*MDP*), fossil depletion potential (*FDP*), internal combustion engine vehicle (*ICEV*), diesel (*D*), gasoline (*G*), electric vehicle (*EV*), lithium iron phosphate (*LiFePO$_4$*), lithium nickel cobalt manganese (*LiNCM*), coal (*C*), natural gas (*NG*), European electricity mix (*Euro*)

The study of Bartolozzi et al. (2013) compares the use of fuel cell vehicles with conventional and EVs in Tuscany, Italy. The focus of the study lies on fuel cell vehicles and different methods of hydrogen production. Three different benchmark scenarios of EVs with different electricity mixes where calculated (wind electricity, electricity from biomass gasification, the Italian electricity mix). For the modelling of the vehicle and the use phase average values from other studies were used (e.g. Notter et al. 2010). Results are presented for ten impact categories: abiotic depletion, acidification, eutrophication, global warming, ozone layer depletion, freshwater aquatic, marine aquatic and terrestrial eco-toxicity, human toxicity, and photochemical oxidation. The authors conclude that in general EVs perform better than fuel cell vehicles. As one reason they remark that the EV scenarios where not modelled as detailed as the fuel cell scenarios. Hence, the authors emphasize that further research is necessary.

Girardi et al. (2015) conduct a comparative assessment of an electric and conventional vehicle under Italian conditions focusing on the electricity mix. The results are reported for the primary energy demand, climate change, photochemical formation, acidification, eutrophication, resource depletion, human toxicity and particulate matter. The assumed energy consumption is static and derived from Italian data. Two scenarios are considered: a low consumption and long battery lifetime and a higher consumption and shorter battery life time. Auxiliaries are not considered separately. The used electricity mix is modelled by mapping the hourly electricity mix with the charging pattern. The electricity mix is set to change over time. The EV performs better in almost all impact categories except human toxicity and eutrophication.

3.1.3 LCA Studies on Conventional Lightweight Vehicles

There exist a number of life cycle assessments studies on conventional lightweight vehicles. Most commonly light metals and carbon fibre reinforced plastics are discussed as viable options for vehicles. As in the previous chapter, studies are considered which (1) compare lightweight to conventional vehicles, (2) cover the entire life cycle and (3) analyse at least two impact categories. Six studies were identified which fulfil these criteria: Das (2011, 2014), Witik et al. (2011), Ehrenberger (2013), Koffler (2014) and Duflou et al. (2014).

Das (2011) compares the environmental impact of two precursor types produced with two different manufacturing processes in reference to a steel part. The part is a floor pan for a large executive car with a conventional gasoline engine. The vehicle is not modelled entirely. Merely the energy consumption for the considered part is taken into account. The carbon fibre parts and their production are presented in great detail. Results are presented for global warming potential, the primary energy demand, human health criteria air pollutants and smog. The components achieve similar results. Improvements in the manufacturing process of the composite materials are necessary to achieve a better performance than steel.

Witik et al. (2011) analyse the environmental impacts and costs of vehicle bulkhead separating vehicle cabin from the trunk. Six alternatives are evaluated: steel, magnesium and four different composite materials. The weight of the component ranges from 1.8 to 5.8 kg. The data source is mainly Ecoinvent 2.1 also for the use phase. The use takes place in Western Europe. Results are presented for four impact categories (climate change, resource depletion, human health and ecosystem quality) calculated with the impact assessment method Impact 2002+. In general the composite materials perform better. In two cases the results steel and magnesium have comparable impacts (climate change and resource depletion). Magnesium has the highest impact on human health. Steel has the highest impact on ecosystem quality.

Ehrenberger (2013) analyses the use of magnesium components in a gasoline vehicle. Different production routes for magnesium are compared as well as aluminium. A fuel reduction value is used to determine the impact of the magnesium component in the use phase. Consequently, not the entire vehicle is considered in the analysis. Results are presented for climate change, acidification, eutrophication and resource depletion. In the first part the life cycles of the materials are analysed in detail. In the second part two different case studies are examined: a steering wheel and an aircraft component. In general magnesium is a viable choice. However, the manufacturing process of the magnesium is decisive for the saving potential.

Koffler (2014) examines the use of GFRP instead of steel for two different components: an assist step and a front end bolster. The weight saving for the assist step is 51 %. For the bolster it is 46 %. Scenarios with secondary weight reductions are also considered. The use phase is set in the United States (US) and employs US driving cycles. The results for global warming potential and acidification potential are shown. A Monte Carlo simulation is used to perform a sensitivity analysis. The GFRP components are found to perform better than their steel alternatives.

Das (2014) assesses three different vehicle designs: a baseline, a high strength steel and an aluminium design with the latter being the best solution. The author states that the study is in accordance with the ISO standard as well as the (at that time unpublished) Canadian standard on the LCA of auto parts. The results are valid for North America. Secondary mass reductions are included in the lightweight design vehicles. For the use phase the mass-induced fuel consumption changes by Koffler et al. (2010) are used. An average fuel consumption is applied. The end-of-life recycling rate is used. No sensitivity analysis is conducted. EVs are not considered in the study.

Duflou et al. (2014) compare the use of flax fibre reinforced composite material and GFRP. The comparison is not done for a specific component but based on achieving the same material properties like equal strength. The study is set in Europe and data from the database Ecoinvent 2.2 was used. The ReCiPe (H) method was chosen to calculate 17 different impact categories. Radar charts are used to present the results. If stiffness is a main target, the authors conclude that due to the material properties of the flax fibre reinforced material, the material cannot perform better than GFRP. However, in other cases the bio-polymer composite can be a viable environmental choice.

3.1.4 LCA Studies on Lightweight Electric Vehicles

A small number of environmental assessment studies has been conducted on LEVs: Ortega and Bras (1998), Schuh et al. (2013) and Schuh et al. (2014), Reuter et al. (2013) and Muttana and Sardar (2013). As opposed to the studies on EVs and conventional lightweight vehicles, a broader scope is used to select the studies on LEVs because this type of studies targets the topic of interest exactly. Therefore, they are considered even if they only cover a limited number of life cycle phases or impact results and if they are not comparative.

Ortega and Bras (1998) focus on the introduction of a decision support tool to consider the life cycle in the product development process. In a small case study, a steel vehicle frame is compared to an aluminium vehicle frame. The alternatives are compared using the impact assessment method Ecoindicator. The results are calculated by adding four values: the Ecoindicator points for the material production, the processing, the use phase and a general credit for the end-of-life phase. A single value is given for the use phase. However, it is not clear what type of electricity mix is used. Due to the origin of the authors it can be assumed that the US–American electricity mix is used for the calculations. Explanations for the energy consumption are not given.

Another approach is presented in two publications Schuh et al. (2013, 2014). The first publication presents findings in the form of a case study. The second publication describes the theoretical background. The approach compares the environmental impact of a conversion design with a purpose design. The conversion design is achieved by replacing the components of a conventional vehicle with the components of an EV and leaving the remaining parts as they are. The purpose design consists of a lightweight car body of different materials and a smaller battery. For the use phase different scenarios are considered. Both the considered electricity mix and the energy consumption depend on the use pattern. Three different use patterns are defined which differ with regard to the share of urban, extra-urban and highway use: homemaker, commuter and businessman. The use of auxiliaries is considered to be constant. The cumulated energy demand, global warming potential and ozone depletion potential are considered. The results are presented for different electricity mixes. The purpose design offers savings in this case study. A comparison to conventional vehicles is not conducted.

Reuter et al. (2013) compare steel, aluminium and CFRP as car body materials for a mid-size EV. The study covers the entire life cycle. The NEDC is used to calculate the energy consumption in the use phase. Efficiencies are provided for the inverter and the motor. A power demand of 1000 W is assumed for auxiliaries. The influence of secondary weight chances is considered. Results are presented for global warming potential, human toxicity, metal and fossil depletion. Different shares of crediting for end-of-life-materials are analysed. The authors conclude that metals, steel and aluminium, are the better choice. Vehicle mileage and crediting of end-of-life-materials are considered important factors for the final results of the study. The topics of the electricity mix as well as the energy consumption are not addressed in this study.

Muttana and Sardar (2013) analyse the impact of replacing a steel car body with an aluminium car body. The raw material extraction, production and use phase are considered. An Indian driving cycle is used to model the energy consumption in the use phase. 250 W are planned for auxiliaries. An Indian electricity mix (820 g CO_2/kWh) is used for the assessment. Two different scenarios are assessed: with and without the secondary effect of reducing the size of the battery. Results are reported for the life cycle energy consumption and CO_2-emissions. Comparing the life cycle energy consumption the authors come to the conclusion that the aluminium vehicle with a battery size reduction leads to savings of around 8.5 % compared to the steel vehicle. Without a battery size reduction the results are very similar. Regardless of the battery size the CO_2-emissions cannot be reduced by the aluminium vehicle in comparison to the steel vehicle. The results are not compared to conventional vehicles.

3.2 Comparative Assessment of Existing Approaches

A comparative assessment of the existing approaches provides an overview of the content covered. A set of criteria is necessary to evaluate the capabilities and scope of the existing approaches. First, this set of criteria is developed. Then a comparative assessment of all presented approaches is completed.

3.2.1 Criteria for Comparative Assessment

For the comparative assessment a set of 17 criteria is derived from the demands of LCA in general and the environmental assessment of electric and lightweight vehicles in particular. These criteria are grouped into the following six categories: goal and scope definition, Life Cycle Inventory, Life Cycle Impact Assessment and Interpretation, electric vehicle and lightweight design. Three different grades of fulfilment can be reached:

- *covered* (●),
- *partially covered* (◐) and
- *not covered* (○).

3.2.1.1 Goal and Scope Definition

The goal and scope definition sets the boundaries of the LCA. A clear and detailed description of the goal is necessary to define the study and make correct choices regarding the methodology and data. The *goal description* should include the purpose for which the study is done, the reasons, the intended audience and whether or not a comparison is done. The *scope* of the study can be limited to the use phase (WTW analysis) or include the vehicle production and end-of-life phase as well. Furthermore, it is important to have deep knowledge of the technical system. Therefore, a detailed *system description* adds to the quality of the study. The *functional unit* should be clear and fit the goal of the study.

3.2.1.2 Life Cycle Inventory

The LCI is the core of the LCA and the foundation for all calculations. It should therefore be transparent and retraceable. Providing the *data* that was used in a study as well as how it was obtained enables others to reproduce the results. Guidelines should provide assistance on where to find suited data. Particularly for long-lasting goods it is important to consider the *future development* of input parameters as these might have an influence on the final results.

3.2.1.3 Life Cycle Impact Assessment and Interpretation

The LCIA transfers the LCI into impact categories which can be interpreted and compared. Considering a large variety of *impact categories* ensures the prevention of problem-shifting and provides the entire picture of the environmental impact of a product. It is therefore preferable to the consideration of a single or few categories. Furthermore, a target-oriented *visualization* of results helps to bring across the message of the LCA and to implement the desired effect among decision makers (who most likely are non-LCA experts).

3.2.1.4 Electric Vehicles

The environmental impact of EVs depends significantly on the parameters of the use phase. Therefore, it is important to ensure that the parameters fit the use case. The most important factors are the *electricity mix* and the *energy consumption*. The electricity mix should fit the geographical area. Using a "better" mix than the average must be well justified. The energy consumption should reflect the surrounding conditions meaning that an appropriate and fitting use of auxiliaries should be included.

3.2.1.5 Lightweight Design

A lightweight design is defined by the achieved *weight reduction* of the vehicle as well as following *energy reduction* of the EV. These parameters should be justified and reflect actual savings. Furthermore, *secondary effects* on EVs should be dealt with, either by changing the vehicle or by arguing for an increased performance of the vehicle. Finally, the *recycling* should be discussed as the end-of-life processes of different lightweight materials can be very different.

3.2.1.6 Comparative Assertion

To make a decision for or against LEVs, the comparison with EVs and conventional vehicles is necessary. Therefore, the guidelines and studies are assessed regarding their coverage of *lightweight electric vehicles* as well as their coverage of comparative assertions with *electric vehicles* and *conventional vehicles*.

3.2.2 Identification of Research Demand

Table 3.1 shows an overview of the comparative assessment of the 18 selected publications: 3 guidelines and 15 LCA studies. The assessment of these publications reveals that the goal and scope in general is well covered. Although the goal description often could be more elaborate and cover all of the required aspects. Two studies (Notter et al. 2010; Hawkins et al. 2013a) provide an extensive description of the LCI used for the calculation and of the obtained results. The studies lack the consideration of the future developments particularly the electricity mix which will change during the life time of the (L)EV. The studies of EVs compare a broad variety of impact categories. Hence, these studies provide a complete view of the environmental performance of EVs in comparison to conventional vehicles. However, for lightweight vehicles (conventional and electric) only few categories are evaluated in the selected studies. The studies focus on the impact category climate change potentially missing out on existing problem-shifting among impact categories. All studies use charts to present their results, solely or in addition to tables. Mostly bar charts are used. However, context-specific visualisation, which considers the audience of the results and the type of results as such, is rarely found. Furthermore, no source provides a complete solution to calculate site-specific energy consumption values which incorporate the use of auxiliaries and use patterns. Some studies do consider ambient conditions but only for singular spots so that the results are non-transferable. A positive example is the eLCAr guideline which shows an approach to calculate the energy consumption considering the ambient temperature. However, the approach does not allow an extensive but only a spot assessment for a selected place. Only four studies have been identified which focus on lightweight materials in EVs. None of these publications completes a comparison of LEVs with both a reference EV and a conventional vehicle.

Table 3.1 Overview of comparative assessment of existing approaches

	Guidelines			LCA studies on EVs					
	EUCAR guidelines	eLCAr guidelines	SPE 14000-14 (Canada)	van Mierlo et al. (2009) etc.	Notter et al. (2010)	Szczechowicz et al. (2012)	Hawkins et al. (2013a)	Bartolozzi et al. (2013)	Girardi et al. (2015)
Goal and scope definition									
Goal description	●	●	●	○	◐	○	◐	◐	●
Scope	●	●	●	●	●	●	●	●	●
System description	●	●	●	○	◐	◐	◐	●	●
Functional unit	●	●	●	●	●	●	●	●	●
Life cycle inventory									
Data presented	◐	●	●	○	●	◐	●	○	◐
Future development	○	◐	○	○	○	○	○	○	●
Life cycle impact assessment and interpretation									
Impact categories	●	●	●	●	◐	●	●	●	●
Visualization	○	○	◐	○	○	○	○	○	○
Electric vehicles									
Electricity mix	○	●	○	●	◐	○	◐	●	●
Consumption	○	◐	○	◐	◐	◐	◐	◐	◐
Lightweight design									
Weight reduction	○	○	○	○	○	○	○	○	○
Energy reduction	○	○	○	○	○	○	○	○	○
Secondary effects	○	○	●	○	○	○	○	○	○
Recycling	◐	◐	●	○	○	○	○	○	○

(continued)

Table 3.1 (continued)

	Guidelines			LCA studies on EVs					
	EUCAR guidelines	eLCAr guidelines	SPE 14000-14 (Canada)	van Mierlo et al. (2009) etc.	Notter et al. (2010)	Szczechowicz et al. (2012)	Hawkins et al. (2013a)	Bartolozzi et al. (2013)	Girardi et al. (2015)
Comparative assertion									
LEV	○	○	○	○	○	○	○	○	○
(Reference) EV	○	●	○	●	●	●	●	●	●
Conventional vehicle	●	○	●	●	●	●	●	●	●

	LCAs on conventional lightweight vehicles						LCAs on LEVs		
	Das (2011)	Witik et al. (2011)	Ehrenberger (2013)	Das (2014)	Koffler (2014)	Duflou et al. (2014)	Ortega and Bras (1998)	Reuter et al. (2013)	Schuh et al. (2013, 2014)
Goal and scope definition									
Goal description	◐	◐	◐	◐	◐	○	○	○	◐
Scope	●	●	●	●	●	●	●	●	●
System description	●	●	●	●	●	◐	◐	●	●
Functional unit	◐	●	●	●	●	●	○	●	●
Life cycle inventory									
Data presented	◐	◐	◐	◐	◐	◐	○	○	◐
Future development	○	○	○	○	○	○	○	○	●

(continued)

Table 3.1 (continued)

	LCAs on conventional lightweight vehicles						LCAs on LEVs		
	Das (2011)	Witik et al. (2011)	Ehrenberger (2013)	Das (2014)	Koffler (2014)	Duflou et al. (2014)	Ortega and Bras (1998)	Reuter et al. (2013)	Schuh et al. (2013, 2014)
Life cycle impact assessment and interpretation									
Impact categories	◐	◐	○	◐	○	●	○	◐	○
Visualization	○	○	◐	○	○	●	○	○	○
Electric vehicles									
Electricity mix	○	○	○	○	○	○	○	○	●
Consumption	○	○	○	○	○	○	○	○	◐
Lightweight design									
Weight reduction	◐	●	○	●	●	◐	●	●	●
Energy reduction	○	○	○	○	○	○	◐	○	◐
Secondary effects	○	○	○	○	○	○	○	●	◐
Recycling	◐	◐	◐	◐	◐	○	○	●	○
Comparative assertion									
LEV	○	○	○	○	○	○	●	●	●
(Reference) EV	○	○	○	○	○	○	●	●	●
Conventional vehicle	●	◐	●	●	●	●	○	○	○

The environmental impact of LEVs depends on a variety of different parameters along the entire life cycle. The environmental impact of the use phase depends on the terms of use. The complexity of this system requires a holistic assessment which incorporates these terms and allows for a regional and use case specific analysis. The focus on one specific set of ambient conditions lacks the freedom to assess the environmental impact at a variety of different locations and for different use cases. The analysis of the state of research reveals that many aspects which are relevant for the assessment of LEVs and have been defined as criterion are covered by different publications. However, none of the considered approaches fulfil all criteria completely. Also no approach was found which fulfils the criteria to a satisfying extend. The existing studies on LEVs do not have a holistic view on the topic and only cover the required criteria in a very limited manner. Thus, an approach for a world-wide environmental assessment of LEVs is not available. Furthermore, the visualization of the results should be focused on. Adapting charts to the message that is to be conveyed helps to implement the results. It ensures that also non-LCA experts gain access to the outcome of the LCA. Emphasis should be put on the evaluation of a multitude of impact categories instead of focusing on single categories. To sum up, it lacks a method which allows an extensive environmental assessment of LEVs and shows whether LEVs are a good environmental choice in comparison to regular electric and conventional vehicles for a specific scenario or not. The method should also support decision making towards future strategies to reduce the environmental impacts of vehicles. Hence, the demand for a concept is derived which covers the environmental assessment of LEVs considering the terms of use and providing guidance on the adequate visualization of results.

References

Bartolozzi I, Rizzi F, Frey M (2013) Comparison between hydrogen and electric vehicles by life cycle assessment: a case study in Tuscany, Italy. Appl Energy 101:103–111. doi:10.1016/j.apenergy.2012.03.021

Boureima F, Messagie M, Matheys J, Wynen V, Sergeant N, Mierlo J, de Vos M, de Caevel B (2009) Comparative LCA of electric, hybrid, LPG and gasoline cars in Belgian context. World Electr Veh J 3(3):469–476

Canada Standards Association (2014) Life cycle assessment of auto parts—guidelines for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry (SPE-14040-14)

Das S (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16(3):268–282. doi:10.1007/s11367-011-0264-z

Das S (2014) Life cycle energy and environmental assessment of aluminum-intensive vehicle design. SAE Int J Mater Manuf 7(3):588–595. doi:10.4271/2014-01-1004

Del Duce A, Egede P, Öhlschläger G, Dettmer T, Althaus H, Bütler T, Szczechowicz E (2013) Guidelines for the LCA of electric vehicles. eLCAr

Duflou JR, Yelin D, van Acker K, Dewulf W (2014) Comparative impact assessment for flax fibre versus conventional glass fibre reinforced composites: Are bio-based reinforcement materials the way to go? CIRP Ann Manuf Technol 63(1):45–48. doi:10.1016/j.cirp.2014.03.061

Ehrenberger S (2013) Life Cycle Assessment of Magnesium Components in Vehicle Construction. Stuttgart

Girardi P, Gargiulo A, Brambilla PC (2015) A comparative LCA of an electric vehicle and an internal combustion engine vehicle using the appropriate power mix: the Italian case study. Int J Life Cycle Assess 20(8):1127–1142. doi:10.1007/s11367-015-0903-x

Hawkins TR, Gausen OM, Strømman AH (2012) Environmental impacts of hybrid and electric vehicles—a review. Int J Life Cycle Assess 17(8):997–1014. doi:10.1007/s11367-012-0440-9

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013a) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi:10.1111/j.1530-9290.2012.00532.x

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013b) Corrigendum to comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):158–160. doi:10.1111/j.1530-9290.2012.00532.x

Koffler C (2014) Life cycle assessment of automotive lightweighting through polymers under US boundary conditions. Int J Life Cycle Assess 19(3):538–545. doi:10.1007/s11367-013-0652-7

Koffler C, Rohde-Brandenburger K (2010) On the calculation of fuel savings through lightweight design in automotive life cycle assessments. Int J Life Cycle Assess 15(1):128–135. doi: 10.1007/s11367-009-0127-z

Messagie M, Boureima F, Matheys J, Sergeant N, Turcksin L, Macharis C, van Mierlo J (2010) Life cycle assessment of conventional and alternative small passenger vehicles in Belgium. In: Vehicle power and propulsion conference 2010

Messagie M, Boureima F, Matheys J, Sergeant N, Timmermans J, Macharis C, van Mierlo J (2011) Environmental performance of a battery electric vehicle: a descriptive life cycle assessment approach. World Electr Veh J 4(4):782–786

Muttana SB, Sardar A (2013) Lightweighting of battery electric cars: an impact analysis using Indian driving cycle. In: 8th SAEINDIA international mobility conference & exposition and commercial vehicle engineering congress

Nordelöf A, Messagie M, Tillman A, Ljunggren Söderman M, van Mierlo J (2014) Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? Int J Life Cycle Assess 19(11):1866–1890. doi:10.1007/s11367-014-0788-0

Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, Althaus H (2010) Contribution of Li-Ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 44 (17):6550–6556. doi:10.1021/es903729a

Ortega RA, Bras B (1998) Including life cycle considerations in the design of an electric vehicle space frame. In: ASME design engineering technical conference

Reuter B, Kulcsár J, Bradshaw AM, Hamacher T, Lienkamp M (2013) Consequences for the environmental impact during the life cycle of an electric vehicle due to different technical and methodological approaches to the treatment of the car body. In: Conference on future automotive technology

Ridge L (1998) EUCAR—automotive LCA guidelines—phase 2. In: Proceedings of the 1998 total life cycle conference, Warrendale, pp 193–204

Schuh G, Korthals K, Backs M (2013) Environmental impact of body lightweight design in the operating phase of electric vehicles. In: Nee AYC, Song B, Ong S (eds) Re-engineering manufacturing for sustainability: Proceedings of the 20th CIRP international conference on life cycle engineering, Singapore, 17–19 April 2013. Springer, New York

Schuh G, Korthals K, Arnoscht J (2014) Contribution of body lightweight design to the environmental impact of electric vehicles. Adv Mater Res 907:329–347. doi:10.4028/www.scientific.net/AMR.907.329

Szczechowicz E, Dederichs T, Schnettler A (2012) Regional assessment of local emissions of electric vehicles using traffic simulations for a use case in Germany. Int J Life Cycle Assess 17 (9):1131–1141. doi:10.1007/s11367-012-0425-8 van Mierlo J, Boureima F, Sergeant N, Wynen V, Messagie M, Govaerts L, Denys T, Vanderschaeghe M, Macharis C, Turcksin L, Hecq W, Englert M, Lecrombs F, Klopfert F, De Caevel B, De Vos M (2009) Clean vehicle research: lca and policy measures "CLEVER". Final Report Phase 1, Brussels

Witik RA, Payet J, Michaud V, Ludwig C, Månson JE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos A Appl Sci Manuf 42(11):1694–1709. doi:10.1016/j.compositesa.2011.07.024

Chapter 4
Concept for the Environmental Assessment of Lightweight Electric Vehicles

This chapter presents a concept for the environmental assessment of LEVs. First, the objective of and the requirements on the concept are described. Then, an overall description of the concept consisting of four main parts is given. These four main parts are then described in detail. They are (1) the system description, (2) the modelling, (3) the visualization and (4) the implementation.

4.1 Objective and Requirements

As a foundation for the development of the concept in this chapter, the objective is defined. Furthermore, requirements on the concept are derived from the findings of Chap. 2 and 3.

4.1.1 Objective

As described in the previous chapter LCA practitioners lack an approach to compare the environmental impacts of LEVs with conventional vehicles and EVs. Therefore, it is the goal to provide a consistent concept for the environmental assessment of LEVs considering the terms of use (i.e. use pattern and regional influences) and providing guidance on the adequate visualization of results.

The output of the assessment is intended for multiple purposes and applications in industry, policy making and research. Original equipment manufacturers can use the assessment outcome to improve the design of a specific vehicle. Also, general recommendations can be derived which can serve as a foundation for decisions of car manufacturers as a first indicator to identify possible target markets for an environmentally meaningful use of lightweight materials in EVs. The question can be answered whether country-specific adaptations pay off and design guidelines can

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be derived. Furthermore, the results can contribute to environmentally sound policy making. The assessment can identify specific materials which should be supported or the definition of a threshold for the share of renewable energy in the electricity mix. Environmental hot spots can be identified which are in need of further investigation. For the research community, the assessment serves to gain further knowledge in the area of environmental impacts of vehicles. The results of the assessment can be used to determine areas that require a further analysis and provides insights on the network of influencing factors in the use phase.

4.1.2 Requirements

The assessment of the environmental impact of LEVs is complex and requires the consideration of multiple aspects. To fulfil the goal of providing a consistent concept, a set of main requirements must be fulfilled which is based on the findings of Chap. 2 as well as the state of research in Chap. 3.

4.1.2.1 Comparison of LEV with Conventional Vehicle and Reference EV

The environmental impact of LEVs should not only be compared to the impacts of a regular EV. The performance of regular EVs in comparison to conventional vehicles should also be known. This ensures that a decision is based on the entire picture which avoids a preference for LEVs even though conventional vehicles would be a better choice (see Sect. 2.4.3).

4.1.2.2 Use Case Specific Energy Consumption

The environmental impact of the use phase of EVs can vary significantly as seen in Sect. 2.4.1. The impact does not only depend on the electricity mix but also on the energy consumption. As described in Sect. 2.1.2 the energy demand for heating and cooling can have a significant influence on the total energy demand. Hence, it is crucial that the energy consumption represents a realistic value which is based on the conditions of use. These conditions of use include both the ambient temperature as well as the time of use which—in combination—influence the energy demand for heating and cooling.

4.1.2.3 Visualization

The calculation of LCAs does not end with the generation of results in the form of numbers. An easily understandable visualization of results makes them more accessible to both LCA and non-LCA experts (see part 'Interpretation' in Sect. 2.3.3). Particularly, the latter benefit from an adequate processing of the results into carefully selected charts. It is important to convey the essential information to the reader of an LCA without diluting the complexity of the system. All results cannot be transported in a single type of chart. Much more it is necessary to choose different types of visualization methods depending on the type of results which the LCA practitioner wants to focus on.

4.1.2.4 Lightweight Design

As a main focus the lightweight design must be studied in detail. The achieved energy reduction can influence the final result (see Sect. 2.2.2). Hence, the value should be determined carefully and the underlying assumptions should be comprehensible and based on technical facts and calculations.

4.2 Concept

The concept on the environmental assessment of LEVs is derived from the requirements described above. It consists of four main parts: (1) the system description, (2) the modelling, (3) the visualization and (4) the implementation as depicted in Fig. 4.1. The evaluation of a LEV requires the comparison with a conventional vehicle and a reference EV (i.e. the same EV without a lightweight design). The comparison with the reference EV investigates whether the use of lightweight design is meaningful or not. The comparison with the conventional vehicle scrutinizes if the use of a conventional vehicle is a better choice. The goal of the study determines the selection of the conventional vehicle. For example, it could be the goal to analyse how the LEV performs in comparison to the conventional vehicle with the best environmental performance available on the market or in comparison to an equivalent lightweight conventional vehicle. Hence, the first two steps are divided into two parts. In the following the build-up of the concept is described. Furthermore, the foundation of the comparison—the equality of the vehicles' functionality—is discussed as a basis to determine the functional unit of the environmental assessment.

The system description outlines the conditions of use of the vehicles and names the influencing factors which should be considered. The description covers essential aspects of the use pattern, regional influencing factors, the lightweight design and the energy consumption. The aspects of the system which require an extensive approach to be described are completed in the part modelling.

The modelling allows the quantification of the influencing factors and their interdependencies. For the comparison of (L)EVs with conventional vehicles the environmental impact of different use cases (i.e. the combination of ambient temperature and use pattern) can be very different. Therefore, it is important to know

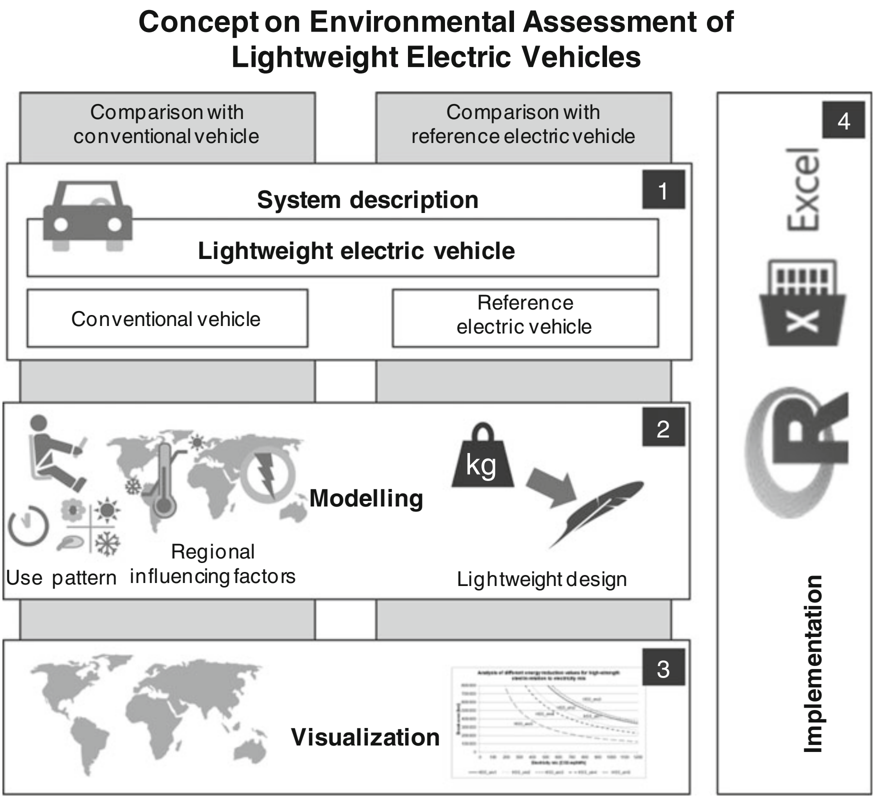


Fig. 4.1 Concept on environmental assessment of lightweight electric vehicles

the conditions of use and conduct a corresponding assessment. In case EVs are considered a viable choice in comparison to conventional vehicles, a comparison of regular EVs and LEVs is useful. The visualization provides different chart options to convey the assessment results in an easy to understand manner particularly for non-LCA experts. The implementation provides guidance on software support to organize the data and create the visualization charts.

The comparison is based on the equality of the vehicles' functionalities: the functional unit. The LEV is compared to a reference EV as well as a conventional vehicle. Only comparing LEVs to EVs neglects the fact that EVs might not perform better than conventional vehicles. The impact of the influencing factors must be considered for all three vehicles to ensure comparable results. Ensuring the equality of their functionalities is essential to achieve a fair comparison.

The basic function of each vehicle is to transport passengers and possibly equipment from a starting to an end-point. However, the quality with which this function can be performed can differ. A conventional vehicle can drive more than 500 km with one tank filling. The speed of the refuelling process is considered to be very comfortable. For (L)EVs the situation is different. With one battery charge a typical range is 150 km. Fully recharging the battery takes several hours. One might therefore argue that the benefits provided by the vehicles are not entirely equivalent which renders their functions unequal. However, the technically possible range only describes the supply side of the function. The demand should also be considered. The average use pattern does not make full use of the maximum range of a conventional vehicle each day. For example, in Germany the average trip length is around 12 km and the average number of kilometres driven per day is around 40 km per person. Furthermore, an analysis has shown that travel time around the globe is stable. The average travel time per day is 1.1 h which includes all modes of transportation (Schafer and Victor 2000). Even considering a 100 % use of a motorized vehicle and an average speed of 100 km/h, the average travelled distance would not be more than 110 km a day. In this case the (L)EV can be recharged fully over night without any restrictions on the transport function provided. Consequently, the additional supplied range of the conventional vehicle provides little additional benefit in a large number of use cases. Therefore, the function provided be a conventional and an (L)EV can be and is considered equivalent in the following. Consequently, the comparison of conventional and EVs based on the function of transportation and the function unit of transportation from A to B within a given time is considered fair.

4.3 System Description

The goal of the system description is to provide the necessary information on the surrounding conditions of use of an LEV. Figure 4.2 shows the influencing factors which impact the life cycle of an LEV. Use patterns, regional conditions and the targeted lightweight design impact the energy consumption (i.e. the use phase) of the vehicle. The use of lightweight materials additionally affects the other life cycle stages raw material extraction and production and end-of-life phase. In the following the single elements and their interactions are described.

4.3.1 Use Pattern

A use pattern describes when and for how long a vehicle is used. A vehicle can be used for private purposes like daily commuting to work or by companies for example to provide delivery or maintenance services. Seasonal and diurnal use patterns can be distinguished. The seasonal use pattern describes the operation of a vehicle during the year. A vehicle can be used evenly each month. But it can also be

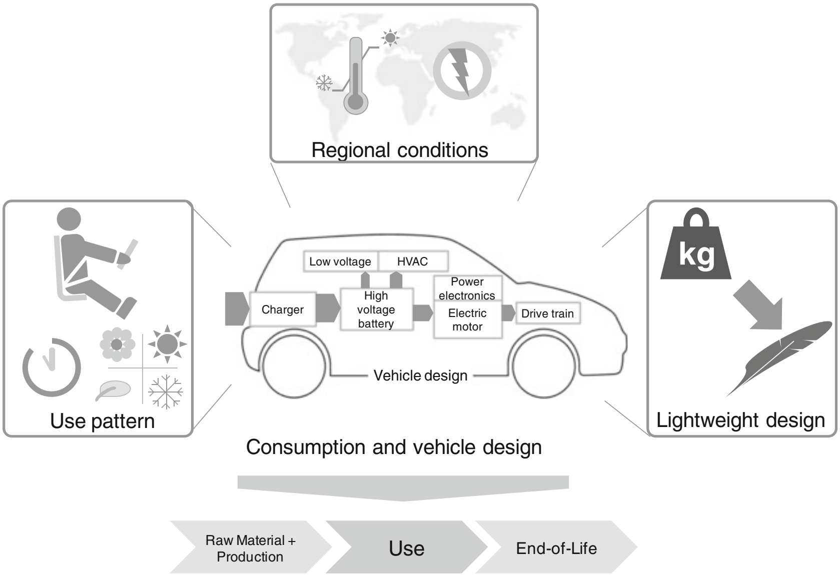


Fig. 4.2 System description of LEVs

preferred by a user during a specific time of year. For example, the vehicle can be used only in winter time while in summer time other modes of transportation like public transportation, biking or walking are preferred. Examples of different seasonal use patterns are shown in Table 4.1. Five different patterns are presented: an even use throughout the entire year and a more frequent or exclusive use from April to September or October to March. The diurnal use pattern describes at what time of day the vehicle is operated for how long. Different use patterns can be categorized

Table 4.1 Examples of seasonal use patterns

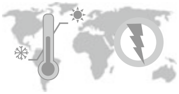
Use month	Even use	Rather Apr–Sep	Rather Oct–Mar	Only Apr–Sep	Only Oct–Mar
Jan	1/12	1/18	1/9	–	1/6
Feb	1/12	1/18	1/9	–	1/6
Mar	1/12	1/18	1/9	–	1/6
Apr	1/12	1/9	1/18	1/6	–
May	1/12	1/9	1/18	1/6	–
Jun	1/12	1/9	1/18	1/6	–
Jul	1/12	1/9	1/18	1/6	–
Aug	1/12	1/9	1/18	1/6	–
Sep	1/12	1/9	1/18	1/6	–
Oct	1/12	1/18	1/9	–	1/6
Nov	1/12	1/18	1/9	–	1/6
Dec	1/12	1/18	1/9	–	1/6

Table 4.2 Examples of diurnal use patterns (SP = Service provider)

Time	Commuter (min)	Day trips (min)	SP day (min)	SP evening (min)	SP night (min)
01:00–02:00					22
02:00–03:00					22
03:00–04:00					22
04:00–05:00					22
05:00–06:00					22
06:00–07:00					22
07:00–08:00					22
08:00–09:00	60				22
09:00–10:00		30	22		
10:00–11:00			22		
11:00–12:00		30	22		
12:00–13:00			22		
13:00–14:00			22		
14:00–15:00			22		
15:00–16:00		30	22		
16:00–17:00			22		
17:00–18:00		30		22	
18:00–19:00	60			22	
19:00–20:00				22	
20:00–21:00				22	
21:00–22:00				22	
22:00–23:00				22	
23:00–00:00				22	
00:00–01:00				22	

based on their frequency and length of use. Table 4.2 shows examples of diurnal use patterns. Five different patterns, two for private and three for commercial use, are presented. The pattern 'commuter' consists of two longer drives to and from a work place, one in the morning and one in the evening. The pattern 'day trips' is made up of four shorter trips during the day. Finally, three different 'service provider' patterns represent the commercial use of a vehicle during the day, evening and night (e.g. a food delivery). The driving style (speed and acceleration) during the operation time can be derived from a driving cycle or real-world data.

4.3.2 Regional Influencing Factors



The conditions of use which prevail are specific to a region. The ambient temperature and the electricity mix are regional influencing factors which impact the environmental performance of (L)EVs. The ambient temperature varies throughout the day and the year and influences the demand for cooling and heating of the vehicle cabin. Hence, this is relevant for the comparison of conventional vehicles and EVs. While the cooling air must be generated separately in the case of both vehicle types, the provision of heated air differs significantly. In conventional vehicles the excess heat from the combustion engine is used to heat the vehicle cabin. This is not possible in EVs. The electric motor is much more efficient and does not generate heat in the same order of magnitude. Consequently, heat is generated separately in EVs using electric energy as described in Sect. 2.1.2. Hence, knowledge of the climate conditions is relevant to calculate the energy consumption and determine the environmental impact.

The electricity mix is a very decisive factor for the calculation of the environmental impact of EVs. All values used in the LCA of vehicles can be expected to have a certain range. However, the electricity mix can render the use phase to be of outmost relevance or to be almost irrelevant depending on the energy source (see Fig. 2.15). Like the climate the composition of energy sources of the electricity mix in many countries undergoes seasonal and diurnal changes.[1] Therefore, it is possible to connect the use pattern to the time-specific electricity mix. This means that the electricity mix available at the time of charging is assigned to the LCI. Hence, depending on the time of charging electricity mixes with different compositions of energy sources are used for the LCA calculation. However, this can only be justified when a charging management system is used which favours specific charging times due to their environmental characteristics (or economic characteristics if there is a direct relation to the environmental impact). If a user relies on the option to charge at all times, the average electricity mix should be assigned. A user should neither be rewarded nor punished because of coincidental charging at convenient or inconvenient times.

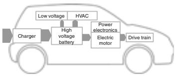
Regional differences lead to differences within a country. Hence, conveying these results is a particular challenge. Guidance on how to visualize these regional differences is provided in Sect. 4.5.1.

[1]Some countries rely on very few or only a single energy source for their electricity. Therefore, the environmental impact of their electricity is very stable. Examples are Norway which is powered mainly with hydropower or Poland which mainly uses coal (The World Bank 2012).

4.3.3 Lightweight Design

The target of a lightweight design is to reduce the vehicle weight and thereby the energy consumption during the use phase. However, not all elements of the energy consumption of a vehicle depend on the weight of the vehicle. Hence, determining the actual energy reduction which is achieved by the vehicle mass reduction requires the consideration of this fact. The use of lightweight materials also has an influence on the other phases of the life cycle. The raw material extraction and production can differ significantly from material to material due to different deposits, extraction methods and material properties (Ashby 2012). A visualization chart is developed to convey the impact of the lightweight design on the life cycle (see Sect. 4.5.2).

4.3.4 Energy Consumption



The energy consumption during the use phase is an important input parameter to calculate the environmental impact of the use phase. Use pattern, regional factors and the lightweight design influence the environmental impact of the use phase. The daily and seasonal use patterns as well as the ambient temperature influence the energy consumption of the heating and cooling auxiliaries. Because the impact on the heating and cooling auxiliaries differs for EVs and conventional vehicles, this is particularly relevant for the comparison of these two types of vehicles. A method to determine the energy consumption considering use pattern and ambient temperature is presented in Sect. 4.4.1. The lightweight design has an impact on the weight related summands of the energy consumption. This aspect is relevant for the comparison of EVs with LEVs. A detailed modelling of the energy reduction value is presented in the modelling part in Sect. 4.4.2.

4.4 Modelling

As described above two aspects of the environmental assessment of LEVs require a detailed modelling: (1) the influence of the use pattern and the ambient temperature on the energy consumption for the comparison of conventional vehicles and (L)EVs as well as the (2) energy reduction value achieved by lightweight measures for the comparison of EVs and LEVs.

4.4.1 Energy Consumption of Electric Vehicles Depending on Terms of Use

To achieve the goal of a regional comparison of EVs and conventional vehicles, it is necessary to consider the energy consumption of heating and cooling as described above. The energy required for heating and cooling depends on the ambient conditions. In the following an approach is developed which considers the ambient temperature.

The relation of energy demand and ambient temperature is described in the eLCAr guidelines and shown in Table 4.3. Five different stages are differentiated. The vehicle requires medium heating (2.5 kW) from 10 to 15 °C and maximum heating (5 kW) below 10 °C. Medium cooling (0.5 kW) is needed between 20 and 25 °C, maximum cooling (1 kW) above 25 °C. Between 15 and 20 °C neither cooling nor heating is turned on. However, the temperature varies throughout the day and the year. Likewise different use patterns are possible which indicate driving at different times of day and year. Hence, it is necessary to link this information. For a single place or a small number of places the course of temperature can be analysed on a daily basis to determine the energy consumption throughout the seasons. However, for a larger area (e.g. a continent or the entire world) with different courses of temperature the required data increases drastically. Consequently, a method is needed which fulfils two requirements. Firstly, it should describe the course of temperature throughout the day and year and secondly, it must allow a categorisation of temperature groups for the entire world to reduce the amount of required data. The solutions to both issues are described in the following resulting in an approach to determine the energy consumption for heating and cooling depending on the use pattern and the ambient temperature.

The energy consumption for heating and cooling is estimated with the help of climate categories and thermo-isopleth diagrams. Thereby, the need for weather data for each grid point of a map is avoided because areas of the same climate category are summarized.

The course of temperature throughout the day and year is described by thermo-isopleth diagrams as introduced by Troll (1965). These diagrams show the average daily course of temperature for each month of the year. Different groups of these thermo-isopleth diagrams can be created using climate classifications. The most common classification of climate zones goes back to Köppen (1900). The classification contains five different climate groups with a total of 29 climate types.

Table 4.3 Power demand for heating and cooling according to Del Duce et al. (2013)

Temperature [°C]	Heating power [kW]	Cooling power [kW]
Below 10	5	–
10–15	2.5	–
15–20	–	–
20–25	–	0.5
Above 25	–	1

Table 4.4 Main climate groups of Köppen classification with subcategories (first and second letter) and description of criteria (Kottek et al. 2006), temperature (T), precipitation (P), accumulated annual value (ann), winter (w), summer (s), dryness threshold depending on temperature (th)

Type	Description	Criterion
A	**Equatorial climates**	$\mathbf{T_{min} \geq +18\ °C}$
Af	Equatorial rainforest, fully humid	$P_{min} \geq 60$ mm
Am	Equatorial monsoon	$P_{ann} \geq 25\ (100 - P_{min})$
As	Equatorial savannah with dry summer	$P_{min} < 60$ mm in summer
Aw	Equatorial savannah with dry winter	$P_{min} < 60$ mm in winter
B	**Arid climates**	$\mathbf{P_{ann} < 10\ P_{th}}$
BS	Steppe climate	$P_{ann} > 5\ P_{th}$
BW	Desert climate	$P_{ann} \leq 5\ P_{th}$
C	**Warm temperate climates**	$\mathbf{-3\ °C < T_{min} < +18\ °C}$
Cs	Warm temperate climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Cw	Warm temperate climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Cf	Warm temperate climate, fully humid	Neither Cs nor Cw
D	**Snow climates**	$\mathbf{T_{min} \leq -3\ °C}$
Ds	Snow climate with dry summer	$P_{smin} < P_{wmin}$, $P_{wmax} > 3\ P_{smin}$ and $P_{smin} < 40$ mm
Dw	Snow climate with dry winter	$P_{wmin} < P_{smin}$ and $P_{smax} > 10\ P_{wmin}$
Df	Snow climate, fully humid	Neiter Ds nor Dw
E	**Polar climates**	$\mathbf{T_{max} < +10\ °C}$
ET	Tundra climate	$0°C \leq T_{max} < +10$ °C
EF	Frost climate	$T_{max} < 0$ °C

Each type is labelled with a two or three letter code. The five groups are based on the vegetation groups and describe the vegetation of the equatorial zone (A), the arid zone (B), the warm temperate zone (C), the snow zone (D) and the polar zone (E) (Kottek et al. 2006). Each of these climate categories possesses individual characteristics which distinguish the classes from each other. These characteristics are described in Tables 4.4 and 4.5. The first table describes the main climate

Table 4.5 Sub-categories of Köppen climate classification and criteria description (Kottek et al. 2006)

Type	Description	Criterion
h	Hot steppe/desert	$T_{ann} \geq +18$ °C
k	Cold steppe/desert	$T_{ann} < +18$ °C
a	Hot summer	$T_{max} \geq +22$ °C
b	Warm summer	Not (a) and at least 4 $T_{mon} \geq +10$ °C
c	Cool summer and cold winter	Not (b) and $T_{min} > -38$ °C
d	Extremely continental	Like (c) but $T_{min} \leq -38$ °C

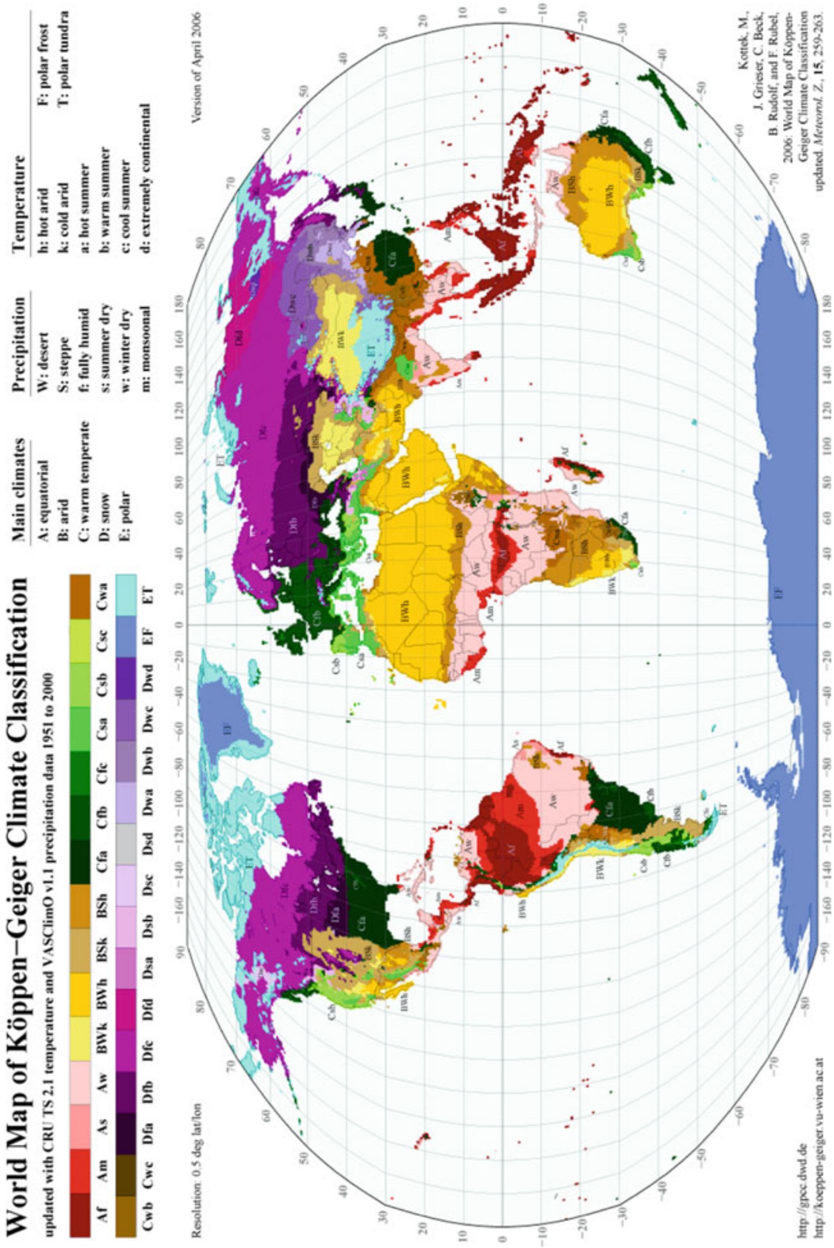


Fig. 4.3 World map of Köppen climate classification (Kottek et al. 2006)

categories (first and second letter). The second table shows the possible sub-category (third letter). The climate groups are delineated by temperature and precipitation. For example, the group Af 'equatorial rainforest' is described by a minimum temperature of 18 °C and a minimum precipitation of 60 mm per month. Figure 4.3 shows the world map with the corresponding climate classifications.

To create the thermo-isopleth diagrams the average minimum temperature T_{min} and maximum temperature T_{max} for each month of the year are used as well as the average time of sunrise S_{rise} and solar noon S_{noon}. The warmest time of day occurs around 2–3 h after solar noon. The temperature continues to rise after solar noon because the earth does not lose as much radiation as it absorbs. The coldest time of day is just after sunrise. There is a short delay until the solar radiation starts to heat up the earth. Until then heat is lost (Zielinski and Keim 2005). An example of such a data set is shown in Table 4.6 for the city of Braunschweig, Germany.[2] The resulting thermo-isopleth diagram is shown in Fig. 4.4. Furthermore, the thermo-isopleth diagrams of Sydney, Australia and Pilani, India are shown in Figs. 4.5 and 4.6. The different temperatures become visible and the average values increase from Braunschweig, over Sydney to Pilani. The climate in Pilani is of the category Bsh. It is characterized by arid conditions and a hot steppe like terrain. Both climate types of Braunschweig and Sydney are of the category Cf. This

Table 4.6 Average minimum and maximum temperature and average time of sunrise and solar noon in Braunschweig, Germany

Month	T_{min} [°C]	T_{max} [°C]	S_{rise} [hh:mm]	S_{noon} [hh:mm]
1	−2.3	2.8	8:20	12:27
2	−2.3	3.7	7:34	12:32
3	0	8.1	6:33	12:27
4	3.3	13.1	5:21	12:18
5	7.2	18	4:23	12:14
6	10.3	21	3:56	12:18
7	12.4	22.6	4:14	12:24
8	12	22.3	5:01	12:22
9	9.2	18.9	5:52	12:13
10	5.5	13.2	6:43	12:04
11	2.4	7.5	7:38	12:02
12	−0.7	4.1	8:21	12:13

Temperature data taken from AmbiWeb GmbH (2015), solar data taken from Time and Date AS (2015)

[2]Daylight saving time was levelled out.

Month

Time of day	1	2	3	4	5	6	7	8	9	10	11	12
01:00	0	0	3	6	10	13	15	15	12	8	5	1
02:00	0	0	3	5	9	12	14	14	12	8	4	1
03:00	-1	0	2	5	8	11	13	13	11	7	4	1
04:00	-1	-1	2	4	7	10	12	13	10	7	4	0
05:00	-1	-1	1	3	8	11	13	12	10	6	3	0
06:00	-1	-2	1	4	9	12	14	13	9	6	3	0
07:00	-2	-2	0	5	10	13	15	14	9	6	3	0
08:00	-2	-2	1	6	11	14	16	15	10	6	2	-1
09:00	-2	-2	2	7	12	15	17	16	11	7	3	0
10:00	-1	-1	3	8	13	16	18	17	12	8	4	1
11:00	0	0	4	9	14	17	19	18	13	9	5	1
12:00	1	1	5	10	15	18	20	19	14	10	5	2
13:00	1	1	6	11	16	19	21	20	15	11	6	3
14:00	2	2	7	12	17	20	22	21	16	12	7	3
15:00	3	3	8	13	18	21	23	22	19	13	8	4
16:00	2	4	8	12	17	20	22	22	18	13	7	4
17:00	3	3	7	12	16	19	21	21	18	12	7	4
18:00	2	3	7	11	16	19	20	20	17	12	7	3
19:00	2	3	6	10	15	18	19	19	16	11	6	3
20:00	2	2	6	10	14	17	19	19	16	11	6	3
21:00	1	2	5	9	13	16	18	18	15	10	6	2
22:00	1	1	5	8	12	15	17	17	14	10	5	2
23:00	1	1	4	8	11	14	16	16	14	9	5	2
00:00	0	1	4	7	11	14	16	16	13	9	5	2

Braunschweig,Germany

Fig. 4.4 Thermo-isopleth diagram with temperatures in °C for Braunschweig, Germany

Month

Time of day	1	2	3	4	5	6	7	8	9	10	11	12
01:00	21	21	20	17	14	12	11	12	13	16	18	20
02:00	21	21	20	16	13	11	10	11	13	16	18	20
03:00	20	20	19	16	13	11	10	11	12	15	17	19
04:00	19	20	19	15	12	10	9	10	11	14	16	18
05:00	19	19	18	14	12	9	8	9	11	14	16	18
06:00	18	18	17	14	11	9	8	9	10	13	15	17
07:00	19	19	17	15	11	8	7	8	11	14	16	18
08:00	20	20	18	16	12	9	8	9	12	15	17	19
09:00	21	21	19	17	13	11	10	11	13	16	18	20
10:00	21	22	20	18	14	12	11	12	15	17	19	21
11:00	22	22	21	19	15	13	12	13	16	18	20	22
12:00	23	23	22	20	16	14	13	14	17	19	20	22
13:00	24	24	23	21	18	15	14	16	18	20	21	23
14:00	25	25	24	22	19	16	16	17	19	21	22	24
15:00	25	26	24	23	20	18	17	18	20	22	23	25
16:00	26	26	25	23	19	17	16	18	20	23	24	26
17:00	26	26	25	22	19	16	16	17	19	22	23	25
18:00	25	25	24	21	18	16	15	16	18	21	23	25
19:00	25	25	24	21	18	15	14	16	18	21	22	24
20:00	24	24	23	20	17	15	14	15	17	20	22	23
21:00	23	23	23	19	16	14	13	14	16	19	21	23
22:00	23	23	22	19	16	13	13	14	16	18	20	22
23:00	22	22	21	18	15	13	12	13	15	18	20	22
00:00	22	22	21	18	15	12	11	12	14	17	19	21

Sydney, Australia

Fig. 4.5 Thermo-isopleth diagram with temperatures in °C for Sydney, Australia

Month

Time of day	1	2	3	4	5	6	7	8	9	10	11	12
01:00	12	15	20	26	30	31	30	28	27	23	18	14
02:00	11	14	19	24	29	30	29	28	27	22	17	12
03:00	10	13	18	23	28	30	29	27	26	21	15	11
04:00	9	12	17	22	27	29	28	27	25	20	14	10
05:00	8	11	16	21	26	28	27	26	24	19	13	9
06:00	7	10	15	20	25	29	27	25	24	17	12	8
07:00	6	9	14	22	26	30	28	26	25	19	11	7
08:00	8	11	16	24	28	32	29	27	26	21	13	9
09:00	10	12	18	26	30	33	30	28	27	23	15	11
10:00	11	14	20	28	32	34	31	29	29	25	18	14
11:00	13	16	23	29	34	35	32	30	30	27	20	16
12:00	15	18	25	31	36	37	33	31	31	29	23	18
13:00	17	20	27	33	37	38	34	32	32	30	25	20
14:00	19	22	29	35	39	39	35	33	34	32	27	22
15:00	20	24	31	37	41	41	36	34	35	34	30	25
16:00	22	26	30	36	40	40	35	34	34	33	29	24
17:00	21	25	29	35	39	39	35	33	33	32	27	22
18:00	20	24	28	34	38	38	34	33	33	31	26	21
19:00	19	22	27	33	37	37	34	32	32	30	25	20
20:00	18	21	26	31	36	36	33	31	31	29	24	19
21:00	17	20	25	30	34	35	32	31	30	27	23	18
22:00	16	19	24	29	33	34	32	30	30	26	21	17
23:00	15	18	23	28	32	33	31	30	29	25	20	16
00:00	14	17	22	27	31	32	30	29	28	24	19	15

Pilani, India

Fig. 4.6 Thermo-isopleth diagram with temperatures in °C for Pilani, India category is a warm temperate climate that is rather humid throughout the year. The summers are slightly different with warm summers in Braunschweig (sub-category b) and hot summers in Sydney (sub-category a).

Furthermore, the difference of seasons on the hemispheres can be seen. Whereas summer in the Northern hemisphere (where Braunschweig and Pilani are located) is from June until August, summer in the Southern hemisphere (where Sydney is located) is rather from December until February. This means that separate data for the Northern and Southern hemisphere have to be obtained in order to match the temperature data with the seasonal use pattern.

The thermo-isopleth diagrams allow the connection of the ambient temperature with the use pattern. Due to the similarities of the climate among the Köppen categories, a summarizing diagram for each category can be created. Hence, the approach fulfils the requirements described above. A description on the implementation of the required database of thermo-isopleth diagrams is presented in Sect. 4.6.

4.4.2 Energy Reduction Value of Electric Vehicles

To compare an LEV with a reference EV the reduction of the energy consumption of the vehicle due to the mass reduction has to be considered. In the following this energy reduction value is derived by adapting existing approaches used for conventional vehicles.

When the total vehicle weight decreases, the energy consumption of the vehicle in the use phase also decreases. Two different approaches are presented in the EUCAR guidelines to calculate the energy saving of a lightweight component: the proportional and the incremental method (Ridge 1998). The proportional method is based on the assumption that the entire energy consumption is related to the weight of the vehicle. However, this is not the case. The driving resistances which define the basic energy consumption can be divided into a weight dependent and non-weight dependent part (see Sect. 2.1.2). The rolling, the acceleration and the slope resistance depend on the vehicle mass but the aerodynamic resistance does not. The incremental method addresses this issue and introduces a fuel reduction value.[3] This value brings into account that the energy consumption is not entirely proportional to the weight of the vehicle. Hence, the incremental method can be considered the state-of-the-art method. Koffler and Rohde-Brandenburger (2010) as well as the guidelines on Life Cycle Assessment of auto parts by the Canada Standards Association (Canada Standards Association 2014) also favour the incremental method.

[3]For conventional vehicles the value is referred to as fuel reduction value. Transferred to (L)EVs the term energy reduction value is appropriate and therefore substituted in the following.

The energy reduction value c_{erv} expresses the reduced energy demand in the use phase due to mass savings in kWh/km/kg. The energy reduction [kWh] per kilometre c_{ER} of a specific vehicle results from the multiplication of the c_{erv} with the actual mass saving Δm [kg] of that vehicle.

$$c_{ER} = c_{erv} * \Delta m \tag{4.1}$$

Consequently, the vehicle energy consumption of the LEV c_{lw} can be described in relation to the energy consumption of the reference EV c_{ref}:

$$c_{lw} = c_{ref} - c_{ER} \tag{4.2}$$

This relation leads to a simplification of the break-even calculation of EVs and LEVs. The environmental impact of each vehicle I is made up by the sum of impacts of each life cycle phase: production P, use U and end-of-life E. The environmental impact of the use phase is made up by the environmental impact of the electricity mix by kWh i.e. for each impact category i, the number of kilometres driven x and the energy consumption c_{veh}. For the reference vehicle the equations look as follows:

$$\begin{aligned} I_{ref} &= P_{ref} + U_{ref} + E_{ref} \\ I_{ref} &= P_{ref} + c_{ref} * i_e * x + E_{ref} \end{aligned} \tag{4.3}$$

The equivalent function I_{lw} for the LEVs is described by:

$$\mathrm{I}_{lw} = \mathrm{P}_{lw} + \left(c_{ref} - c_{ER}\right) * i_e * x + E_{lw} \tag{4.4}$$

Furthermore, the reference and the lightweight vehicle can be seen as assemblies of the replaced and replacing part(s) and the rest of the vehicle. Hence, the production of the reference vehicle is composed of the production of the part(s) of the reference material (e.g. steel) with a specific environmental impact $i_{p,ref}$ and the mass of the replaced part m_{ref} as well as the environmental impact of the production of the rest of the vehicle P_{rest}:

$$P_{ref} = P_{rest} + i_{p,ref} * m_{ref} \tag{4.5}$$

In the same manner the values E_{ref}, P_{lw} and E_{lw} can be calculated. Furthermore, the weight of the lightweight part(s) is a defined fraction of the reference part(s) depending on the lightweight factor a_{lw} of the material used. Therefore, the weight of the lightweight part(s) can be expressed in relation to the weight of the reference part(s):

$$m_{lw} = a_{lw} * m_{ref} \tag{4.6}$$

To determine the possible break-even point after which the LEV achieves a lower environmental impact than the reference EV, the sum of the environmental impacts of both vehicles I_{lw} and I_{ref} must be equal. Solving the break-even of an LEV and a reference EV with the equations above leads to:

$$x = \frac{a_{lw}(i_{P,lw} + i_{E,lw}) - (i_{P,ref} + i_{E,ref})}{c_{erv} * i_e(1 - a_{lw})} \quad (4.7)$$

Equation 4.7 shows that the total energy consumption of the vehicle as well as the weight of the replaced part(s) are not relevant to determine the break-even point of the LEV and the reference EV. Therefore, the considerations on the energy demand for cooling and heating is not of interest for this calculation. However, the energy reduction value is relevant for the calculation.

To the best of the author's knowledge only one publication was found to provide explicit information on the energy reduction value of EVs. Redelbach et al. (2012) briefly compare different vehicle types (conventional, hybrids and electric) regarding their fuel and energy reduction values in two graphs. They use simulation to determine these values. Explicit numbers are not provided. In the following a theoretical approach is used to verify these simulation results of Redelbach and colleagues.

Koffler and Rohde-Brandenburger (2010) describe an approach[4] to derive the fuel reduction value of conventional vehicles using the equation of driving resistances, the NEDC and the Willans line. The Willans line describes the linear correlation between the power output and the fuel consumption (Koffler and Rohde-Brandenburger 2010). In the following this approach is applied to EVs.

The following function describes the Willans line for an EV. $P_{el.bat.out}$ stands for the power leaving the battery. P_D describes the necessary power to propel the vehicle (Del Duce et al. 2013):

$$P_{el.bat.out} = 1.118 * P_D + 0.436. \quad (4.8)$$

Figure 4.7 shows the graphical visualization of the Willans line. The results of seven different driving cycles mark a straight line. The different characteristics of the driving cycles (their speeds and accelerations) cause the different positions of the points.

The mass-related part of the energy consumption of a conventional vehicle is approximate 0.54 kWh/100 km/100 kg when using the NEDC (Koffler and Rohde-Brandenburger 2010). It depends on the underlying drive cycle and is independent from the specific vehicle. For EVs, the energy demand is lower because energy is recovered and restored in the battery. The share of recovered energy is calculated as presented in the eLCAr guidelines (Del Duce et al. 2013).

[4]The approach is based on Rohde-Brandenburger and Obernolte (2002) and Rohde-Brandenburger and Obernolte (2008).

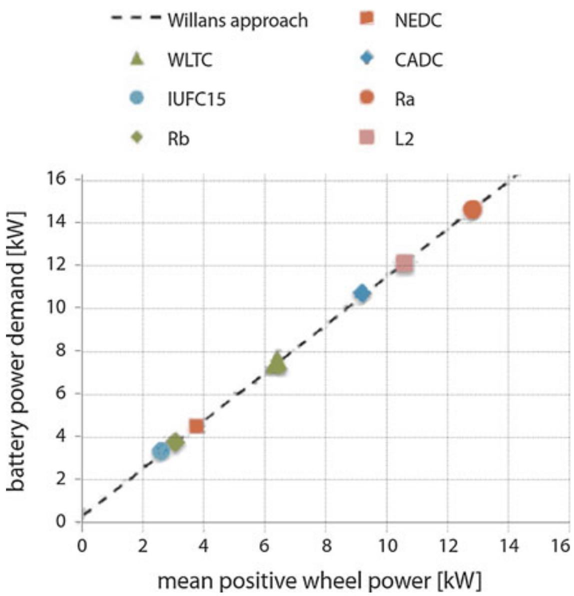


Fig. 4.7 Willans approach (Del Duce et al. 2013), New European driving cycle (*NEDC*), Worldwide harmonized light vehicles test procedure (*WLTP*), common artemis driving cycle (*CADC*), 15 Inrets urbain fluide cour (*IUFC15*), Swiss cycle Ra (*Ra*), Swiss cycle Rb (*Rb*), NEDC + Highway cycle BAB (german: Bundesautobahn) (*L2*)

The recovered energy is described by a cycle value $P_{recu,cycle}$ (the theoretically possible recoverable energy) and a maximum recuperation value $P_{recu,max}$ (a value limiting the actual recoverable energy). In case the cycle value is smaller than the maximum value, the cycle value is recovered. Otherwise, the maximum value is recovered.

The amount of energy which can possibly be recovered in a cycle is derived by inverting the Willans line (Del Duce et al. 2013):

$$P_{recu,cycle} = \frac{1}{1.118} * P_D + 0.436. \quad (4.9)$$

The highest amount to be recovered is defined by the control software of the vehicle. It limits the recovered energy depending on the velocity v as follows (Del Duce et al. 2013):

$$P_{recu,\max} = -0.3 * v + 1.8. \quad (4.10)$$

Using the NEDC cycle and calculating the recovered energy for every second, a number of around 0.211 kWh/100 km/100 kg is identified. Consequently, the energy needed to propel an EV is around 0.33 kWh/100 km/100 kg. However, due to inefficiencies of the drive train the actual required energy to move the vehicle mass is higher. To account for these inefficiencies the Willans line can be used.

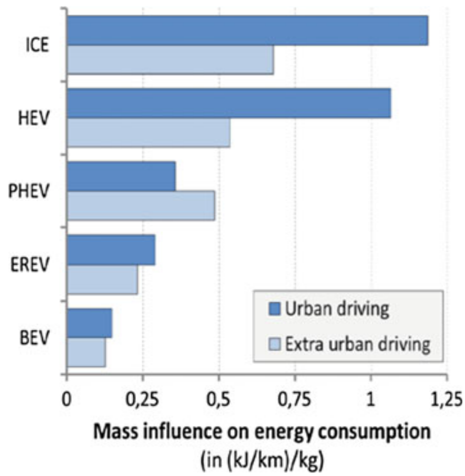


Fig. 4.8 Energy reduction of LEV for NEDC (Redelbach et al. 2012)

$$
\begin{aligned}
c_{erv,NEDC} &= 0.33\ \text{kWh}/100\ \text{km}/100\ \text{kg} * 1.118 \\
c_{erv,NEDC} &= 0.369\ \text{kWh}/100\ \text{km}/100\ \text{kg}.
\end{aligned}
\tag{4.11}
$$

This theoretically calculated value corresponds well with the simulation results of Redelbach et al. (2012). As stated above the publication provides graphs and does not state explicit numbers on the fuel and energy reduction values. Hence, the numbers are read of the graph. Figure 4.8 shows the more detailed graph of the two graphs in the publication on the energy reduction value of an LEV in relation to a reference EV. The graph shows a change in energy consumption of about 0.125 kJ/km/kg. This equals around 0.347 kWh/100 km/100 kg. This value is in the same order of magnitude as the theoretical value $c_{erv,NEDC}$ of 0.369 kWh/100 km/100 kg calculated above. Considering the scale of the graph and the resulting accuracy of reading the values represent a good match.

A comparison with fuel reduction values also confirms the theoretically calculated value. In general, the mass-induced energy reduction is lower for EVs than for conventional vehicles. The reason is found in the lower efficiency rates of conventional vehicles as well as the ability of EVs to recover energy (Redelbach et al. 2012). Koffler and Rohde-Brandenburger (2010) calculate a fuel reduction value of 0.15 l/100 km/100 kg for a gasoline vehicle. This equals around 1.36 kWh/100 km/100 kg. The value is around 3.7 times higher than for EVs and confirms the statement that the energy savings due to lightweight design is higher for conventional vehicles than for EVs.

The described approach can also be used for other driving cycles. Standardized driving cycles as well as driving cycles based on real driving data can be used as a foundation. The only requirement is that the speed profile over time is available.

4.5 Visualization

As described in Sect. 2.3.3, a visualization that considers the audience and the intended impact of the result is important for any LCA. Currently, bar charts are typically used in LCA publications on vehicles for any type of result (see Sect. 3.2.2). This type of chart is for example adequate to show how each process contributes to a single impact category. However, it is less suited when the reader wants to compare impact categories. This requires the eye to have to go back and forth from each bar to compare their length. Therefore, the type of chart to chose depends on the results which the LCA practitioner wants to convey. Focusing on processes requires a different kind of chart than putting emphasis on different impact categories. Therefore, different visualization aids are collected and presented in the following to portray and discuss results on relevant aspects of the environmental assessment of LEVs. In this context, these are regional differences, the influence of the lightweight design and differences across impact categories.

4.5.1 Regional Differences

Due to differing electricity mixes and different climate conditions the environmental impacts of (L)EVs vary greatly across the world. Therefore, the outcome of comparative assertions of conventional vehicles and (L)EVs varies significantly across regions as well. This combination of cartographical information and impact category results requires a special type of visualization. A choropleth map (also called heat map) is a type of thematic map which visualizes a parameter with its different intensities or categories for a selected region. This region can be a small area like a city or the entire world. An example of a choropleth map is the visualization of the Köppen climate classification (see page 87). In the following the choropleth maps showing LCA results are referred to as LCA maps.

Their ability to focus on ranges of values for a parameter instead of single values is a great advantage of choropleth maps in comparison to bar charts. This provides the advantage of incorporating the uncertainty of the results in the visualization. By not showing exact values the reader of the LCA is not induced to assume that the results are certain. Showing ranges conveys a degree of freedom and uncertainty. Therefore, choropleth maps are well suited to visualize LCA results which always incorporate uncertainty and variability.

Different types of colour progressions exist to depict the range of values for a scale displayed on the map: single-hue, bi-polar, complementary hue, partial spectral hue, blended hue, value and full-spectral progressions (Robinson et al. 1995). Examples of the colour progressions are shown in Fig. 4.9. Furthermore, different categories can be displayed as it is done in the Köppen climate classification map. The most suited colour progression should be selected according to the type of

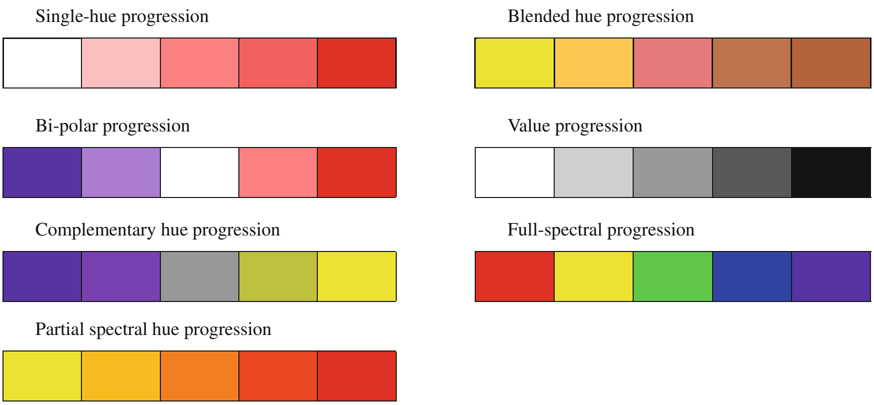


Fig. 4.9 Depiction of different types of colour progression for choropleth maps (based on Robinson et al. 1995)

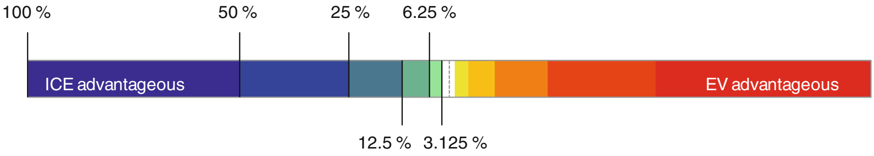


Fig. 4.10 Colour scale for comparison of conventional vehicles and (L)EVs

results which is being conveyed to the reader. The reader should be able to distinguish the colours from one another easily and assign them to one group of results.

When the impact of one vehicle is displayed for different regions, the single-hue or value progression is most suited to convey the results. When conventional vehicles and (L)EVs are compared, the bi-colour progression is well suited. This colour progression allows one side to show that (L)EVs perform better and the other side of the scale to show that conventional vehicles perform better as shown in Fig. 4.10. An odd number of colour steps allows for a neutral value group when using a bi-polar progression. Two aspects can enhance the meaning of the scale: standardization and an uneven distribution of the colour steps. First, standardization allows using the same scale for impact categories. The absolute values for the impact categories are very different. Introducing a standardization means that the same colour scale can be used for all impact categories. This can be realized by setting the highest value of each impact category to 100 %. Second, an uneven distribution of the colour steps allows for a detailed analysis of the areas close to zero. A very detailed classification for the entire scale would mean a very large number of categories which become indistinguishable for the human eye. Hence, a rough classification at the outer ends and a detailed classification close to zero are chosen. The distribution is achieved with a 50 % reduction from each category to the next (e.g. 100 % → 50 % → 25 %, etc.).

4.5.1.1 Population Density

In some cases it can be of interest to aggregate the information on the environmental impact for a larger region like a country or continent. This can be useful if the LCA practitioner wants to give a recommendation for the strategy of a country. To account for the fact that there is more travelling in some areas than others, the population density can considered when data is aggregated over large areas to form a mean value. This will lead to a fairer result because favourable as well as unfavourable areas are only considered to the extent to which they are relevant. This becomes particularly clear for vast countries with a very concentrated population density like Australia or Canada. The population of these countries is mainly found at the coast (Australia) and in the south (Canada). However, as seen in the Köppen map (page 87) the countries feature different climate categories. This imbalance should be accounted for to avoid false deductions.

4.5.2 Impact of Lightweight Design

When comparing an LEV with a reference EV, the focus lies on the lightweight design and the influence it has on the environmental impact. Therefore, visualization tools should be selected which highlight this aspect. In the following two different charts are presented. One focuses on the different life cycle phases while the other connects the abstract impact assessment results with the regional electricity mix.

The comparison of different lightweight design options is often conducted as a delta analysis with a reference vehicle as a benchmark. Therefore, the break-even analysis can be presented with the reference vehicle as a horizontal line. An example by Ehrenberger (2013) is seen in Fig. 4.11. This chart puts a focus on the different life cycle phases. Also, the distance at which a break-even point is achieved can be identified easily. For example, the break-even point for the magnesium produced via the (average) pidgeon process allowing crediting is achieved after around 50,000 km (green line). The additional environmental impact of a solution in the raw material and manufacturing phase become visible on the left side of the chart. The use phase and break-even point is shown in the middle of the diagram. Finally, on the right the end-of-life impact is illustrated.

The break-even point depends on different parameters as described in Sect. 4.4.2. The following function was derived:

$$x = \frac{a_{lw}(i_{P,lw} + i_{E,lw}) - (i_{P,ref} + i_{E,ref})}{c_{erv} * i_e(1 - a_{lw})}. \qquad (4.7)$$

To show the span of results, a break-even analysis is presented in relation to the electricity mix in Fig. 4.12. In this example two lightweight materials are presented with a minimum and a maximum value for the environmental impact of their

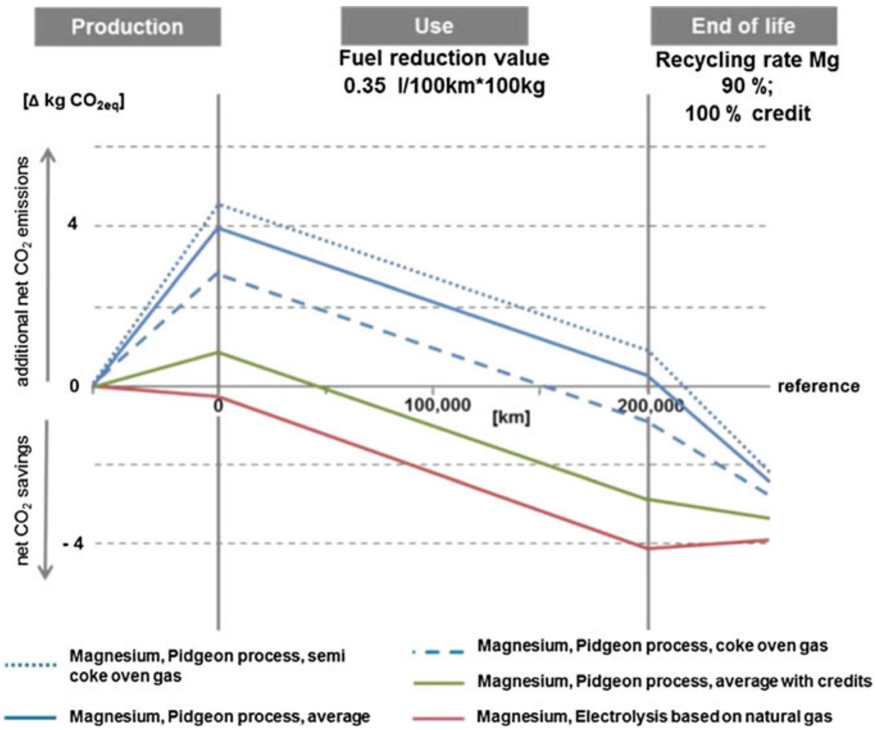
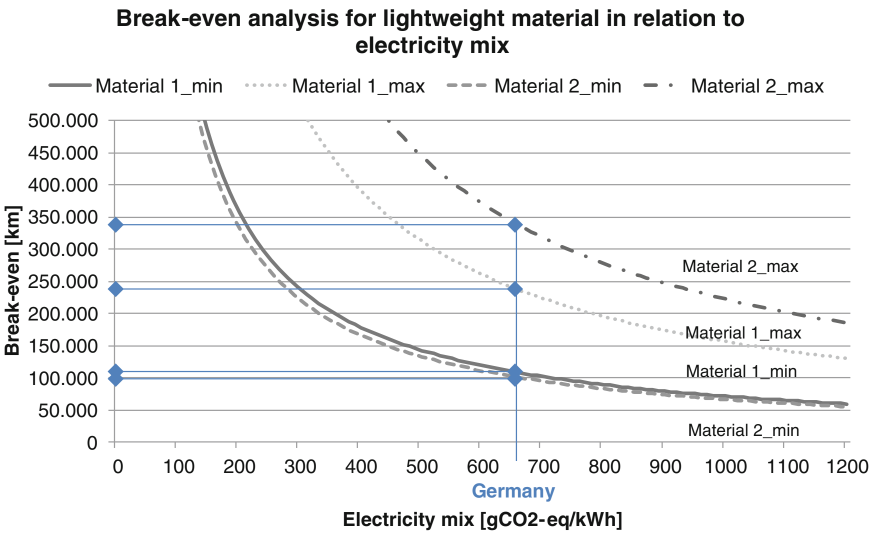


Fig. 4.11 Delta-analysis chart visualizing the savings of different lightweight options (Ehrenberger 2013)

production and end-of-life. The spans of the environmental impact of the materials i_P and i_E (i.e. their minimum and maximum values) as well as their lightweight factors a_{lw} lead to the range of results of each material. The graph allows case specific types of deductions. For a given country (with a given electricity mix), the range of the break-even can be identified. In Fig. 4.12, the results for the German electricity mix are shown. The diagram reveals that the break-even point ranges from around 100,000 km to around 340,000 km depending on the lightweight material. Also, an electricity mix can be identified for which the operation of a LEV is of interest. This can be useful in policy making to identify thresholds when LEVs become meaningful or to set targets for the share of renewable energy sources to achieve a specific value of greenhouse gas emissions of an electricity mix.

When choosing a target break-even point (in the unit km), it is important to consider that only kilometres driven past this break-even point achieve a reduction of environmental impacts. Hence, to achieve significant savings it is preferable to define the break-even at an early point of the vehicle's life cycle. Furthermore, a low break-even point helps securing the robustness of results. A break-even close to the end-of-life might not be reached because of data uncertainty and assumptions which were made that are not met in real life.



	Reference	Material 1_min	Material 1_max	Material 2_min	Material 2_max
$i_P + i_E$ (kgCO2-eq/kg)	2.38	2.7	2.9	2.8	3.3
α_{lw} (-)	-	0.94	0.94	0.92	0.92
erv (Wh/km/kg)	0.0369				

Fig. 4.12 Break-even analysis for lightweight material in relation to electricity mix

4.5.3 Impact Categories

Considering a variety of impact categories is very important as environmental burdens might shift from one impact category to another. Limiting the scope to only a few or even a single impact category eliminates the opportunity to discover and avoid this type of problem-shifting (as described in Sect. 2.3.3). However, many studies limit the reporting of results to greenhouse gas emissions (see Chap. 3). In the few cases in which more than one impact category is reported, they are usually displayed in separate bar charts. This type of chart is well suited to show the differences of each scenario for each single impact category. However, it is less suited to compare the changes of the different impact categories at one glance.

A visualization chart that is well suited to show differences among impact categories is the radar chart (or spider diagram). Particularly because many studies show so limited impact categories, there is an urging need to assess and present results on this issue and to discuss the problem-shifting across impact categories related to the use of (L)EVs. Figure 4.13 shows selected results from Hawkins et al. (2013) in a radar chart. The differences of the three alternatives (i.e. a gasoline

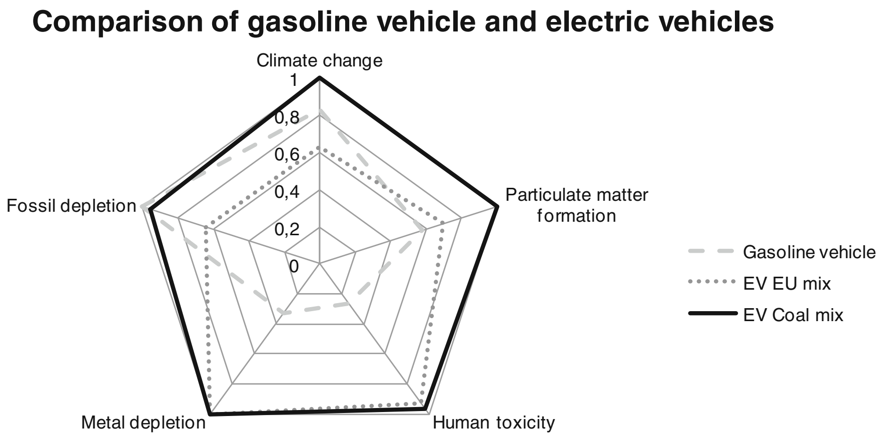


Fig. 4.13 Radar chart for the comparison of vehicles in five different impact categories; values taken from Hawkins et al. (2013)

vehicle and an EV powered with the European electricity mix and electricity based on coal) can easily be identified at first glance.

Problem-shifting among impact categories can occur between conventional vehicles and EVs as well as between different EVs. Hence, this type of chart is suited for both types of comparative assertions.

4.6 Implementation

The implementation of the concept on the environmental assessment of LEVs requires the processing of a variety of data and the visualization of maps. The following section presents the selected software solutions, the data processing, country-specific electricity mixes, vehicle data and the creation of thermo-isopleth diagrams to implement the developed concept.

4.6.1 Software Solutions

The implementation of the concept into a software solution requires the selection of a suited programme which meets the visualization requirements. Most elements can be implemented using a spreadsheet program. However, the preparation of LCA maps requires special treatment. To select a suited programme for the preparation of these maps two aspects must be considered. The data processing of the concept should be completed using software which is easily accessible to LCA practitioners (i.e. which does not required specific knowledge in programming and which is free of charge or frequently available). This is particularly true for the LCA maps. The concept serves as a mean to make knowledge from LCA experts available to people from other disciplines such as other researchers, vehicle designers or policy makers. It is rather unlikely that these groups use maps on a regular basis. Therefore, it is unlikely that professional mapping software is at their disposal or that they are knowledgeable about it. The information should be easily exchangeable and should be able to be changed by different people. Another important aspect for the software selection is that the tool should allow displaying results not only for countries but also for the grid created by latitude and longitude (e.g. with a resolution of 1°). The results depend on climate groups which vary across a country.

Options for open source spreadsheet programs are Apache OpenOffice Calc (2015), LibreOffice Calc (2015) or Gnumeric (2015). Microsoft Excel is a licensed spreadsheet program; yet, a standard program which most researchers have access to. Commercial as well as open source mapping solutions are available. Microsoft offers an add-in solution for Excel Business 5 2013 as well as standalone solutions. Further examples of payware as well as freeware are the professional mapping software ArcGIS (Esri Deutschland GmbH 2015), Polymaps (SimpleGeo and Stamen 2015) or jVectorMap (Lebedev 2015). Another solution is the program R (R Foundation 2015). R is a software for statistical computing and graphics. The package rworld was designed specifically to create choropleth maps (South 2011).

Microsoft Excel was selected as spreadsheet program because it is accessible and widely known. For the mapping R in combination with the package rworldmap was selected to complete the LCA maps. It provides the best solution regarding access and the option to display gridded maps.

4.6.2 Data and Data Processing

The presented concept on the environmental assessment of LEVs requires the processing of a variety of different data. The required data and their processing are presented in Fig. 4.14. The figure is divided in three parts: (1) data sources, (2) data processing and (3) visualization.

Background data as well as case specific data is processed to generate the results and create the different visualization charts. Data on sun rise and solar noon are combined with the monthly minimum and maximum temperatures to create the thermo-isopleth diagrams. These diagrams are combined with the daily and seasonal use pattern to determine the specific energy consumption for the auxiliaries. To display the differences for heating and cooling on a map, it is necessary to use a world map with gridded data. For each grid point, the climate zone and the country name must be available. Only then the information on heating and cooling can be brought together with the correct electricity mix. Such a data table is available within the package rworldmap in R. Along with the vehicle data and electricity mix data, the grip-specific LCIA values can be calculated. Likewise the data is prepared for the other types of visualization.

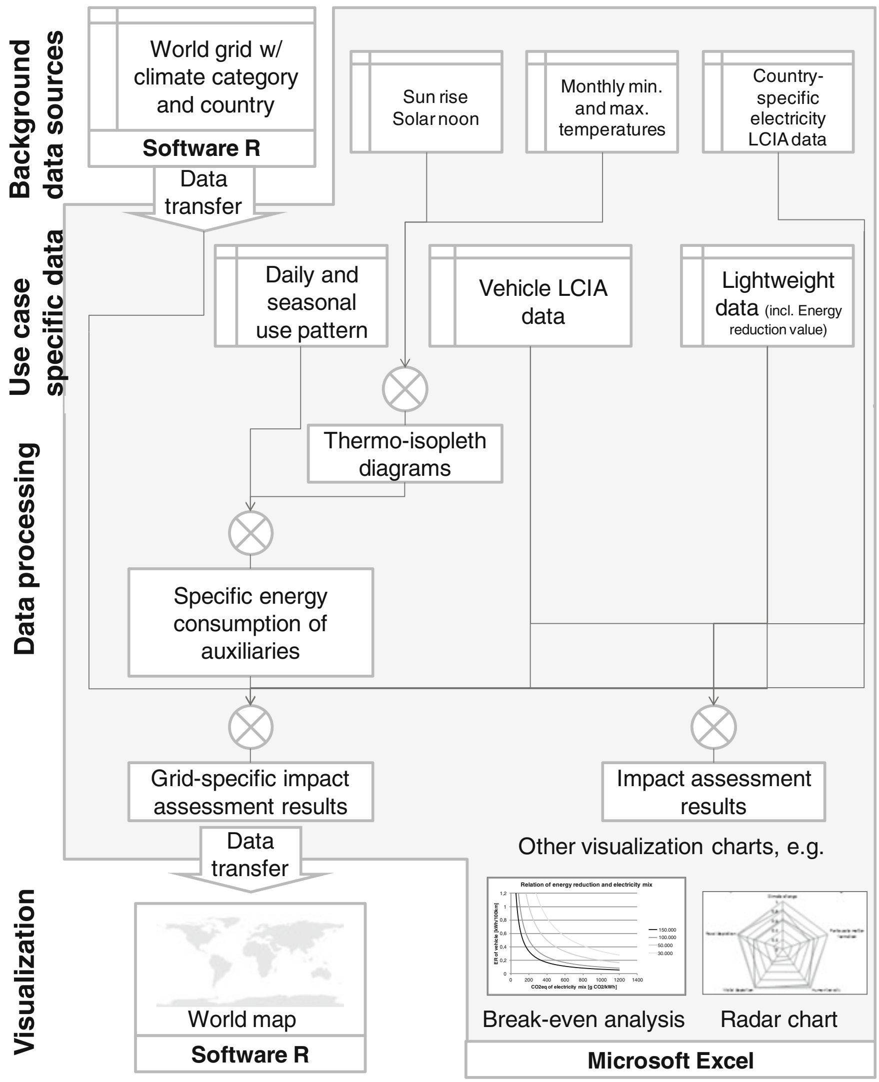


Fig. 4.14 Data and data processing

4.6.3 Country-Specific Electricity Mixes

Country-specific electricity LCIA data is available in Ecoinvent mainly for Europe and larger non-European countries (e.g. the United States, Canada, China). To fill the remaining data gap World Bank Data on the electricity production was used. The World Bank provides data on the share of coal, oil, gas, hydroelectric and renewable energy sources for the production of electricity in a larger number of countries (The World Bank 2012). The Ecoinvent database provides information on the environmental impact of each category of electricity production. Hence, the LCIA data for the electricity mixes can be calculated. In case that more than one process is available in Ecoinvent (e.g. wind < 1 MW, 1–3 MW and > 3 MW turbine) an average is calculated. In case that still no data is available on the electricity mix of a country, the global average is applied.

4.6.4 Vehicle Data

The environmental impact of the production and end-of-life processes of the analysed vehicles must be available (vehicle LCIA data and lightweight data). In case primary data (i.e. case-specific data) is available it should be preferred. Otherwise secondary data from the most current literature should be used. In the case of secondary data it is most likely that datasets are not available. In this case usually only the LCI results are available. Possible secondary data sources are the LCI databases Ecoinvent (2015) or Gabi (Thinkstep 2015) as well as publications on LCAs of EVs with extensive supporting data (e.g. Hawkins et al. 2013; Notter et al. 2010).

4.6.5 Thermo-isopleth Diagrams

As described in Sect. 4.4.1 thermo-isopleth diagrams are needed for the Northern and Southern hemisphere for each climate category. For each category and hemisphere two locations from (if possible) distant places were selected to form an average and achieve a more representative diagram than with only one location. The selected cities are shown in Table 4.7. The temperature data was taken from AmbiWeb GmbH (2015), the solar data (sun rise and solar noon) from Time and Date AS (2015). In total a number of 92 data sets were used to create a worldwide mapping of the diurnal and seasonal temperature course. Not all climate groups exist on each hemisphere. The groups of category D do not exist on the southern hemisphere as the land is closer to the equator than the land on the northern hemisphere. In a one case no data was found in the data sources for the desired climate category (Dwd). As only a small area (100 grid points of a total of around 60,000 displayed grid points) in the north-eastern part of Russia belongs to this group, it was assumed that the surrounding climate group Dfd provides a good estimate for the ambient conditions. Data in the case of a frost climate (EF) which prevails on Greenland's ice sheet and in the Antarctic is not considered as the areas are not relevant for private motorized transportation.

Table 4.7 Selected cities for the preparation of representative thermo-isopleth diagrams

Climate	North 1	North 2
Af	Bandar Seri Begawan, Brunei	Singapur
Am	Monrovia, Liberia	Tabuk, Philippines
As	Puerto Vallarta, Mexico	Jaffna, Sri Lanka
Aw	Kabo, Central Africa	Nagpur, India
BWk	Wuzhong, China	Leh, India
BWh	La Paz, Mexico	Sabha, Libya
BSk	Forsyth, Montana, USA	Matad, Mongolia
BSh	Pilani, India	Monterrey, Mexico
Cfa	New Orleans, USA	Hangzhou, China
Cfb	Braunschweig, Germany	Cumberland, Canada
Cfc	Adak, USA	Thorshaven, Faroer
Csa	Lucknow, India	Athens, Greece
Csb	La Coruna, Spain	Seattle, USA
Csc	–	–
Cwa	Kishanganj, India	Las Limas, Honduras
Cwb	Jacaltenango, Guatemala	Fichte, Ethiopia
Cwc	Arquaziye, Ethiopia	Gich, Ethiopia
Dfa	Des Moines, USA	Wogogra, Russia
Dfb	Karlshamn, Sweden	Gilleleje, Denmark
Dfc	Östersund, Sweden	Moosonee, Canada
Dfd	Tiksi, Russia	Jakutsk, Russia
Dsa	Cashmere, USA	Ankara, Turkey
Dsb	Spokane, USA	Sarab, Iran
Dsc	Anchorage, USA	Sussuman, Russia
Dsd	–	–
Dwa	Chengde, China	Machuanzi, China
Dwb	Cukanovo, Russia	Beigou, China
Dwc	Bangda, Tibet	Huacaopo, China
Dwd	–	–
EF	–	–
ET	Resolute, Canada	Nuuk, Greenland
Climate	**South 1**	**South 2**
Af	Iquitos, Peru	Alotau, Papua New Guinea
Am	Manaus, Brazil	Jakarta, Indonesia
As	Mossoro, Brazil	Mombasa, Kenya
Aw	Palmas, Brazil	Port Moresby, Papua New Guinea
BWk	Walvis Bay, Namibia	Beaufort West, South Africa

(continued)

Table 4.7 (continued)

Climate	South 1	South 2
BWh	Koes, Namibia	Lima, Peru
BSk	Mildura, Australia	Puerto Deseado, Argentina
BSh	Luana, Angola	Derby, Australia
Cfa	Sydney, Australia	Buernos Aires, Argentina
Cfb	Charleston, New Zealand	Puerto Montt, Chile
Cfc	Iwikau, New Zealand	Belejao, Ethiopia
Csa	Santa Emilia, Chile	Perth, Australia
Csb	Cape Town, South Africa	Los Angelos, Chile
Csc	El Colorado, Chile	La Placilla, Chile
Cwa	Lusaka, Sambia	S. Ramon de la N. Oran, Argentina
Cwb	Nairobi, Kenya	Sucre, Bolivia
Cwc	Chupa, Peru	Villa Exaltacion, Bolivia
Dfa	–	–
Dfb	–	–
Dfc	–	–
Dfd	–	–
Dsa	–	–
Dsb	–	–
Dsc	–	–
Dsd	–	–
Dwa	–	–
Dwb	–	–
Dwc	–	–
Dwd	–	–
EF	–	–
ET	Puerto Williams, Chile	Atcas, Peru

References

AmbiWeb GmbH (2015) Climate Data. http://de.climate-data.org/. Accessed 24 Nov 2015

Apache Open Office (2015) Apache OpenOffice Calc. https://www.openoffice.org/de/. Accessed 31 Oct 2015

Ashby MF (2012) Materials and the environment: eco-informed material choice, 2nd edn. Butterworth-Heinemann, Waltham

Canada Standards Association (2014) Life cycle assessment of auto parts—guidelines for conducting LCA of auto parts incorporating weight changes due to material composition, manufacturing technology, or part geometry (SPE-14040-14)

Del Duce A, Egede P, Öhlschläger G, Dettmer T, Althaus H, Bütler T, Szczechowicz E (2013) Guidelines for the LCA of electric vehicles. eLCAr
Ecoinvent (2015) Ecoinvent database. http://ecoinvent.ch/. Accessed 20 Oct 2015
Ehrenberger S (2013) Life cycle assessment of magnesium components in vehicle construction, Stuttgart, Germany
Esri Deutschland GmbH (2015) Esri. http://www.esri.de. Accessed 2 Nov 2015
Gnumeric (2015) Gnumeric spreadsheet. http://www.gnumeric.org. Accessed 31 Oct 2015
Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi:10.1111/j.1530-9290.2012.00532.x
Koffler C, Rohde-Brandenburger K (2010) On the calculation of fuel savings through lightweight design in automotive life cycle assessments. Int J Life Cycle Assess 15(1):128–135. doi:10.1007/s11367-009-0127-z
Köppen W (1900) Versuch einer Klassifikation der Klimate vorzugsweise nach ihren Beziehungen zur Pflanzenwelt. Geographische Zeitschrift(6):593–611, 657–679
Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15(3):259–263. doi:10.1127/0941-2948/2006/0130
Lebedev K (2015) jVectorMap. http://jvectormap.com. Accessed 2 Nov 2015
LibreOffice (2015) LibreOffice Calc. https://de.libreoffice.org/. Accessed 31 Oct 2015
Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, Althaus H (2010) Contribution of Li-Ion batteries to the environmental impact of electric vehicles. Environ Sci Technol 44 (17):6550–6556. doi:10.1021/es903729a
R Foundation (2015) R: project for statistical computing. https://www.r-project.org/. Accessed 30 Oct 2015
Redelbach M, Klötze M, Friedrich HE (2012) Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts. In: European electric vehicle congress
Ridge L (1998) EUCAR—automotive LCA guidelines—phase 2. In: Proceedings of the 1998 Total life cycle conference Warrendale, pp 193–204
Robinson AH, Morrison JL, Muehrcke PC, Kimerling AJ, Guptill SC (1995) Elements of cartography, 6th edn. Wiley, New York
Rohde-Brandenburger K, Obernolte J (2002) Wieviel Kraftstoff kosten 100 kg Mehrgewicht—Theoretische und experimentelle Untersuchungen: Interne Studie, Wolfsburg
Rohde-Brandenburger K, Obernolte J (2008) CO2-Potential durch Leichtbau im Pkw. In: Deutscher Verband für Materialforschung und -prüfung e.V. (ed) Leichtbaustrategien
Schafer A, Victor DG (2000) The future mobility of the world population. Transp Res Part A Policy Pract 34(3):171–205. doi:10.1016/S0965-8564(98)00071-8
SimpleGeo and Stamen (2015) Polymaps. http://polymaps.org/. Accessed 2 Nov 2015
South A (2011) rworldmap: a New R package for mapping global data. R J 3(1):35–43
The World Bank (2012) Electricity production. http://data.worldbank.org. Accessed 19 Oct 2015
Thinkstep (2015) Gabi database. www.gabi-software.com. Accessed 2 Oct 2015
Time and Date AS (2015) Time and date. http://www.timeanddate.com/. Accessed 24 Nov 2015
Troll C (1965) Jahreszeitenklimate der Erde: Der jahreszeitliche Ablauf des Naturgeschehens in den verschiedenen Klimagürteln der Erde. In: Jusatz HJ, Rodenwaldt E (eds) Weltkarten zur Klimakunde, Dritte edn. Springer, Berlin
Zielinski GA, Keim BD (2005) New England weather, New England climate. University Press, New England

Chapter 5
Case Studies on the Comparison of (Lightweight) Electric Vehicles with Conventional and Reference Electric Vehicles

This chapter shows the application of the concept developed in Chap. 4. It is divided into two parts. First, the comparative assertion of conventional vehicles and EVs is conducted. Second, the comparison of a LEV with a reference EV is presented. Following the collection of data and presentation of results, findings are presented of each part. The aim of the case studies is to show how the developed concept can be used for the environmental analysis of (L)EVs under different terms of use (i.e. regional ambient conditions and use patterns) and how this enables to identify hotspots and derive recommendations for future research and development of LEVs for manufacturers and political decision makers.

5.1 Comparison of Electric Vehicles and Conventional Vehicles

In their study Hawkins et al. (2013a, b) compare conventional vehicles (diesel and gasoline) and EVs (one with a lithium nickel cobalt manganese and one with a lithium iron phosphate battery) and provide comprehensive supporting information on their LCI and results. These results are provided for a large number of impact categories.[1] To the author's best knowledge this study presents the most detailed LCI of EVs (see Sect. 3.2.2). The use phase is described by an average value. Hence, it is well suited to conduct an extended analysis of the use phase. Therefore, it is selected as a foundation to test the concept described in Chap. 4. This case study uses the supporting information provided by Hawkins et al. (2013b) for the production and end-of-life phase as well as the non-fuel or energy related part of the use phase. The use phase is then modelled based on the procedure presented in Sect. 4.4.1.

[1]See Sect. 3.1.2 for a more detailed description of the study.

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Sustainable Production, Life Cycle Engineering and Management,
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5.1.1 Data Collection and Results

To conduct the comparison of EVs and conventional vehicles, it is necessary to calculate the environmental impact for each life cycle phase. The required data for the production and end-of-life phase is taken from Hawkins et al. (2013b) as described in Table 5.1. The production processes include the production of the base vehicle, the engine/motor, the remaining power train and the battery. The non-fuel/energy related part of the use phase covers emissions like the abrasion of the rubber tires. The end-of-life covers recycling and disposal processes. For the fuel/energy-related use phase the following information is necessary: the basic energy consumption, the energy consumption for heating and cooling, the total driving distance and the environmental impact of the energy/fuel. The modelling from Sect. 4.4.1 is used to determine the energy consumption for heating and cooling. For the total driving distance a value of 150,000 km is assumed. The environmental impact of the electricity mix is used as described in the implementation part of the concept (see Sect. 4.6). For the basic energy consumption an adequate value must be determined.

The basic energy consumption should cover all aspects of the energy consumption as presented in Sect. 2.1.2 except for the energy demand for heating and cooling as this is added separately. Furthermore, the value should be easily

Table 5.1 Environmental impacts of different vehicle types assuming and a lifetime of 200,000 km

Impact category	Life cycle phase	EV_FePO4	Gasoline
GWP (kg CO2-eq)	Prod.	12,023.4	6348.8
	Use (non-fuel/energy related)	890.6	1360.5
	EoL	890.6	453.5
TAP (kg SO2-eq)	Prod.	51.3	62.7
	Use (non-fuel/energy related)	4.11	10.11
	EoL	2.05	2.02
PMFP (kg PM10-eq)	Prod.	21.4	20.4
	Use (non-fuel/energy related)	2.01	3.30
	EoL	0.67	0.66
POFP (kg NMVOC-eq)	Prod.	28.9	20.7
	Use (non-fuel/energy related)	3.34	5.45
	EoL	1.11	1.09
FDP (kg oil-eq)	Prod.	3381.1	2181.8
	Use (non-fuel/energy related)	541.0	681.8
	EoL	135.2	136.4

Data derived from Hawkins et al. (2013b), electric vehicle with iron phosphate battery (EV_FePO4) global warming potential (GWP), terrestrial acidification potential (TAP), fossil depletion potential (FDP), particulate matter formation potential (PMFP), photochemical formation potential (POFP) available. These criteria are fulfilled by the NEDC. The value is readily accessible for all vehicles available on the European market. It does not cover the use of auxiliaries as these are shut off during the measuring procedure. (United Nations 2005) Therefore, the NEDC is very suited as a value for the basic energy consumption. The energy demand for low voltage auxiliaries is very small in comparison to the high voltage auxiliaries. The mean electric power of the low voltage auxiliaries ranges from 20 to 150 W for radio/navigation and lighting and are therefore neglected.

After having collected the required data for the calculation, it is necessary to develop scenarios for the description of the terms of use. A scenario is defined by the daily use pattern, the seasonal use pattern and the impact category. The characteristics of the daily and seasonal use can be found in Tables 4.1 and 4.2. To analyse the differences, variations of the three parameters are shown in comparison to a basic scenario. The basic scenario A is defined as the comparison of a gasoline vehicle with an EV containing a lithium iron phosphate battery for the impact category climate change. It is assumed that the vehicles are used for commutes from and to a work place with an even use during the year. A number of daily trips (e.g. as a second family car) and the use of a service provider in the evening (e.g. a food delivery) are chosen as variations of the daily use (scenario B and C). The variations of the seasonal use are defined as a use 'rather from October to March' (scenario D) and exclusively from 'April to September' (scenario E). Finally, different impact categories are analysed of the basic scenario. In this case study the use phase is analysed in detail. Therefore, it is of interest to take a closer look at those impact categories where the use phase has the most significant influence on the comparative assertion of conventional vehicles and EVs. The results of Hawkins et al. (2013b) are presented in Fig. 3.4. Apart from the impact category climate change, the use phase is important for the categories terrestrial acidification, fossil depletion, particulate matter formation potential and photochemical oxidation formation. Therefore, these impact categories are analysed in detail (scenario F, G, H and I). The analyzed scenarios are described in Table 5.2. The LCA maps of the nine scenarios are presented in Figs. 5.1, 5.2, 5.3, 5.4, 5.5, 5.6, 5.7, 5.8 and 5.9. The legend is designed as described in Sect. 4.5.1. The yellowish and reddish colours indicate that the gasoline vehicle is a better environmental choice. The bluish and greenish colours show that the EV has a lower environmental impact.

5.1.2 Findings

Different findings can be derived from the LCA maps shown. In the following these are presented for the basic scenario A, the variations of the daily use pattern (scenarios B and C), the variations of the seasonal use pattern (scenarios D and E) and the analysis of the different impact categories (scenarios F, G, H and I).

Table 5.2 Definition of analyzed scenarios for the comparison of a gasoline vehicle with an EV with a lithium iron phosphate battery

Scenario	Daily use	Seasonal use	Impact category
Basic scenario			
A	Commuter	Even use	Climate change
Variation of daily use			
B	Daily trips	Even use	Climate change
C	Service provider evening	Even use	Climate change
Variation of seasonal use			
D	Commuter	Rather Oct–Mar	Climate change
E	Commuter	Apr–Sep	Climate change
Variation of impact category			
F	Commuter	Even use	Terrestrial acidification
G	Commuter	Even use	Fossil depletion
H	Commuter	Even use	Particulate matter formation potential
I	Commuter	Even use	Photochemical oxidation formation

5.1.2.1 Basic Scenario (Scenario A)

The LCA Map of scenario A shows a divers distribution of the global warming results. In general three different cases can be identified: the results are (1) clearly in favour of one vehicle type (red or blue), (2) the results are slightly in favour of one vehicle type (yellow/orange or green) or (3) indifferent or range around zero (white) and can be in favour of both vehicles in different places of the country. In the first case, an overall recommendation for one of the two vehicles can easily be given. In the other two cases, particularly the last case, a further analysis is necessary to make a decision.

On an areawide basis, the conventional vehicle is favourable in more places than the EV. The map also reveals that the extent to which one vehicle can be favourable in comparison to the other is stronger for the conventional vehicles. This means that the savings of the conventional vehicle can be much higher than the savings of the EV. Examples for a very good comparative performance of the conventional vehicle (dark blue) are the south-western part of China or the northern part of Mongolia. Examples for a good comparative performance (medium blue colour) are India as well as large parts of the United States and Russia. In this scenario a very good comparative performance of EVs does not exist (dark red). Yet, EVs perform well (light red or dark orange) in for example in the northern parts of South America and Europe as well as the southern part of Africa. Examples for countries in which both vehicles can be favourable are Argentina and Mexico.

Both the climate and the electricity mix influence the final results. These aspects are analysed in the following. The fact that the countries are mostly not of one colour shows that the climate has a significant influence on the results. For comparison the LCA Map is shown without the consideration of heating and cooling in

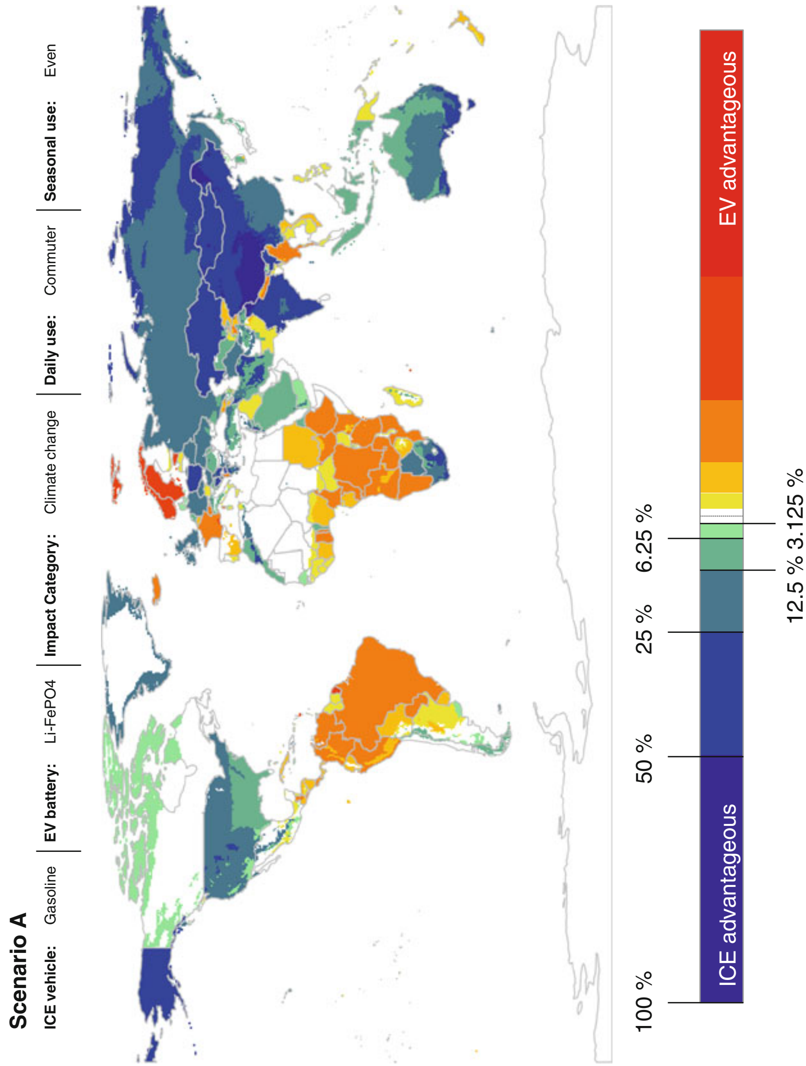


Fig. 5.1 LCA map of scenario A (created with R-package rworldmap)

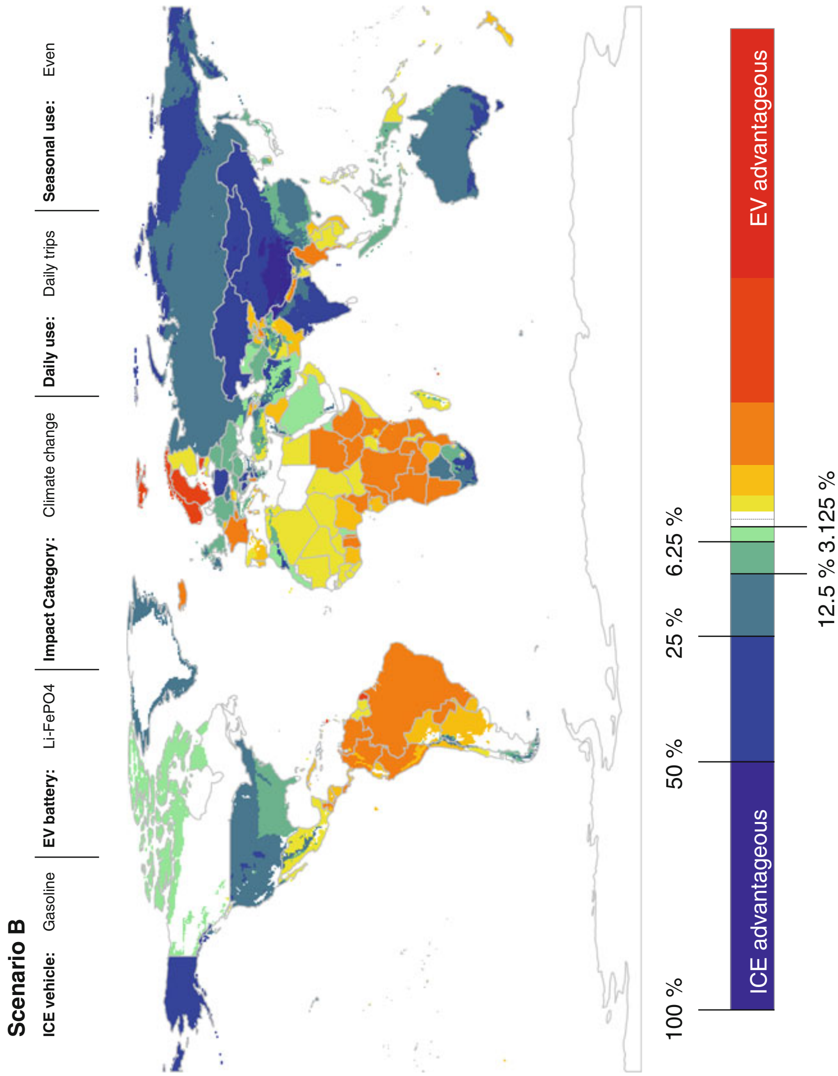


Fig. 5.2 LCA map of scenario B (created with R-package rworldmap)

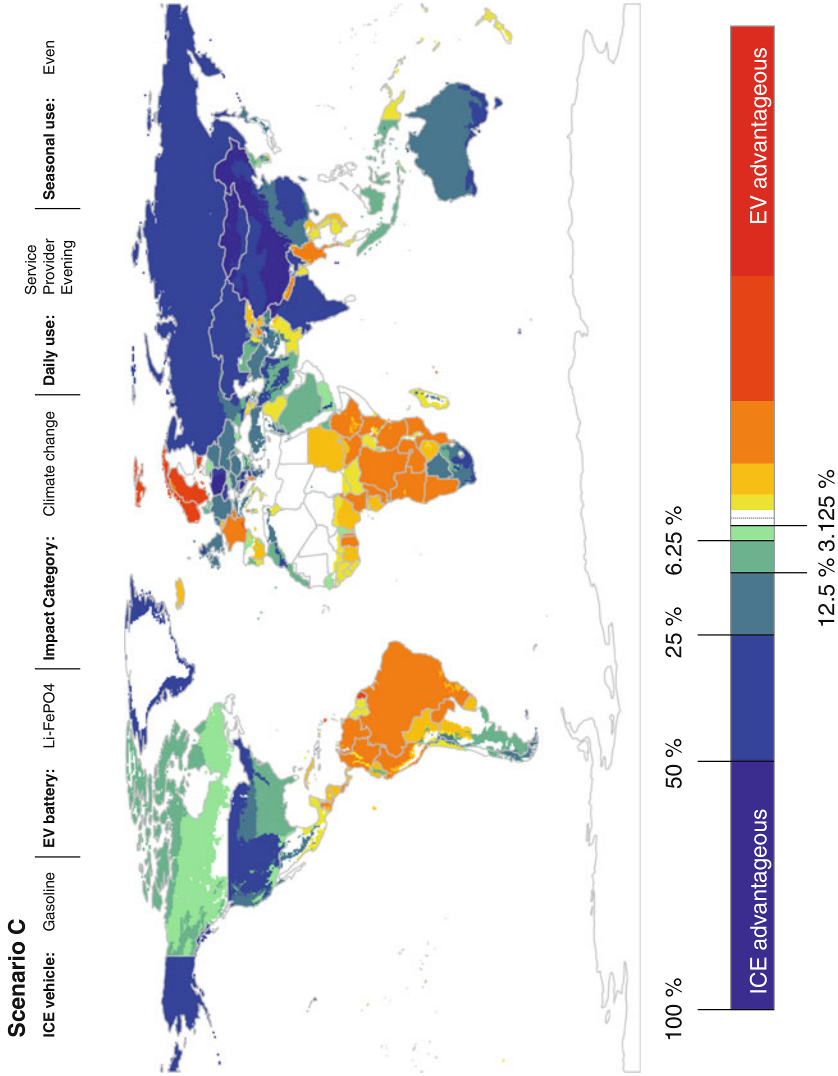


Fig. 5.3 LCA map of scenario C (created with R-package rworldmap)

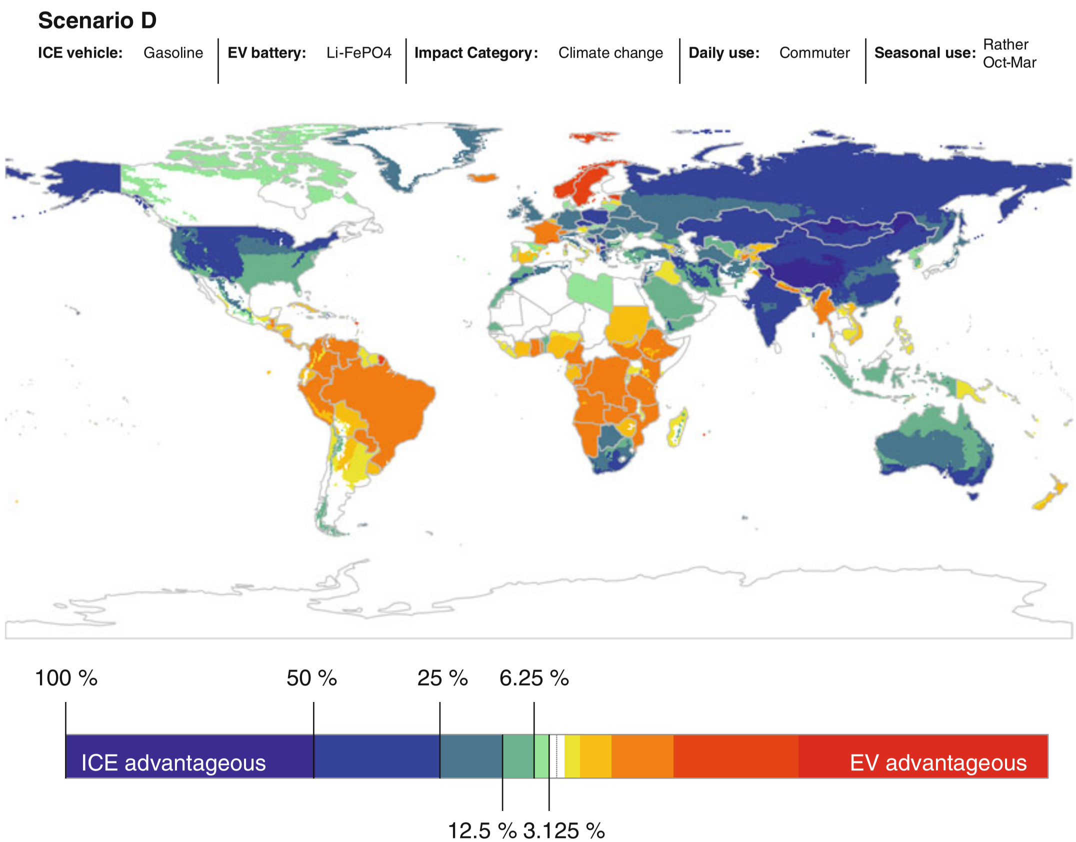


Fig. 5.4 LCA map of scenario D (created with R-package rworldmap)

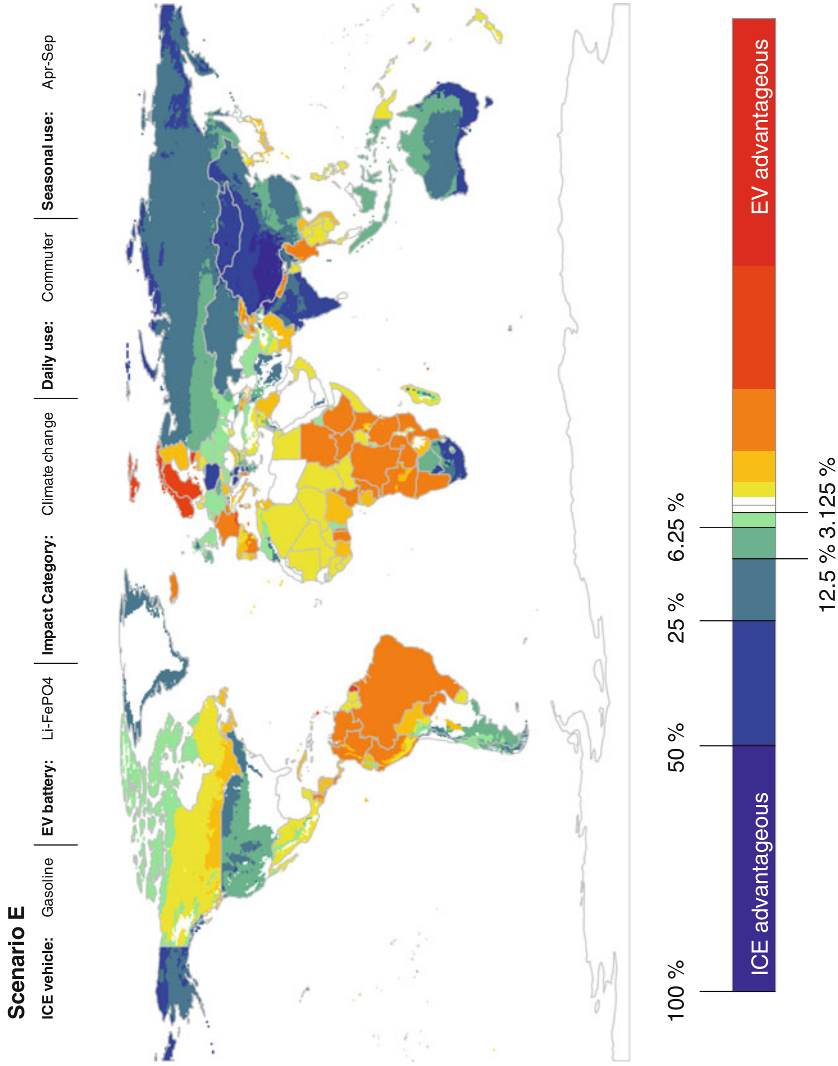


Fig. 5.5 LCA map of scenario E (created with R-package rworldmap)

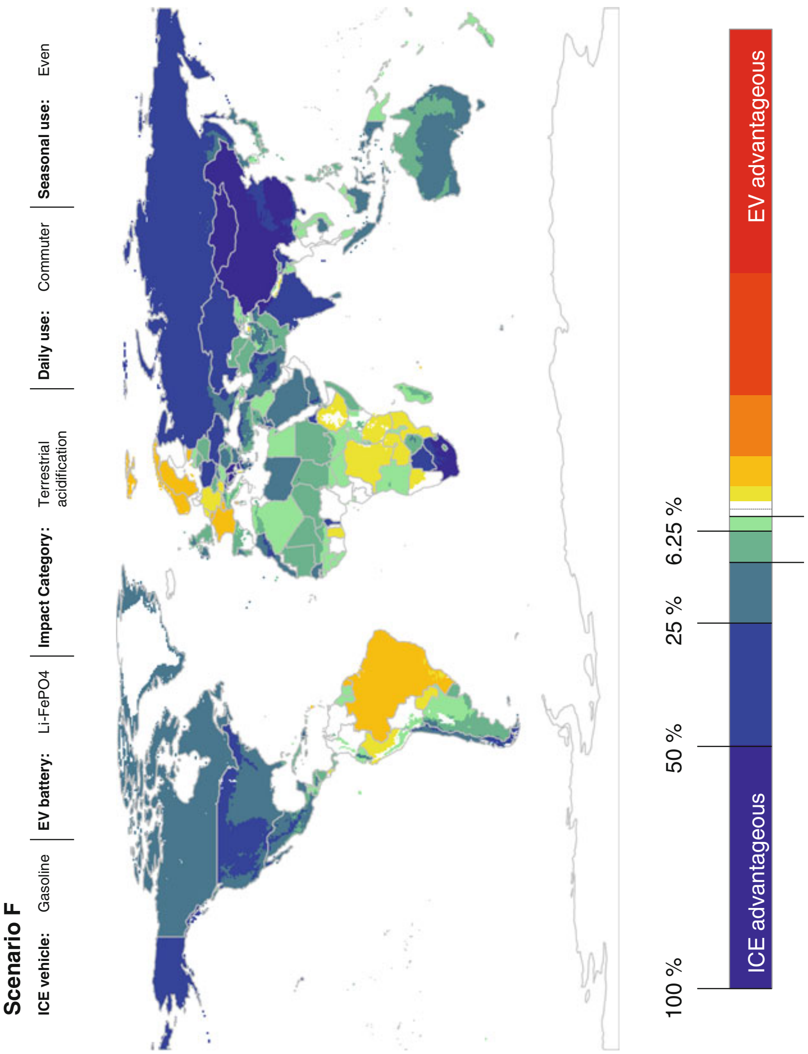


Fig. 5.6 LCA map of scenario F (created with R-package rworldmap)

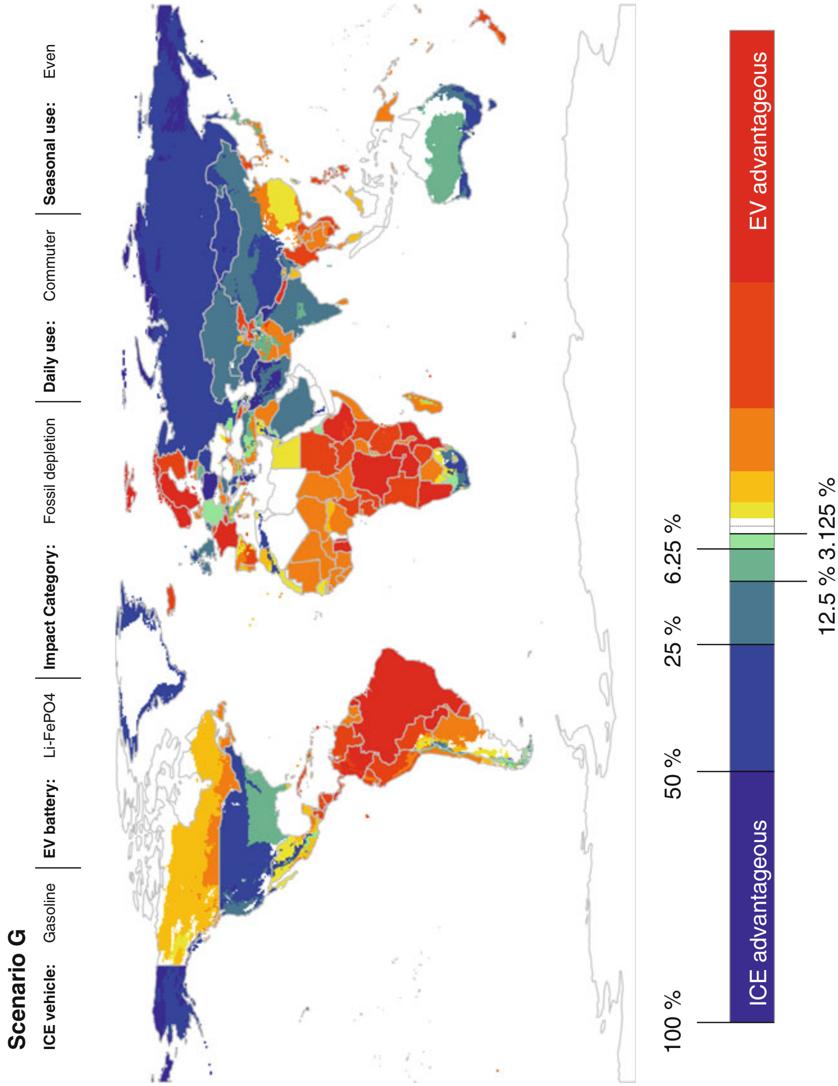


Fig. 5.7 LCA map of scenario G (created with R-package rworldmap)

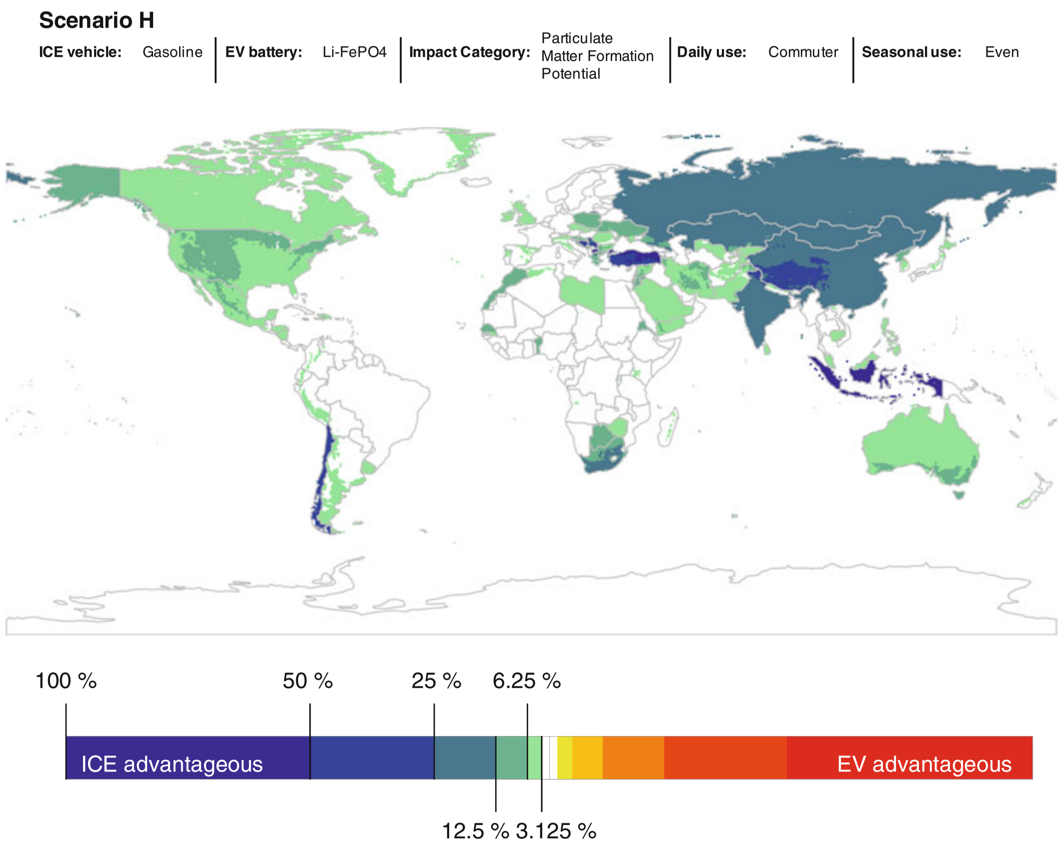


Fig. 5.8 LCA map of scenario H (created with R-package rworldmap)

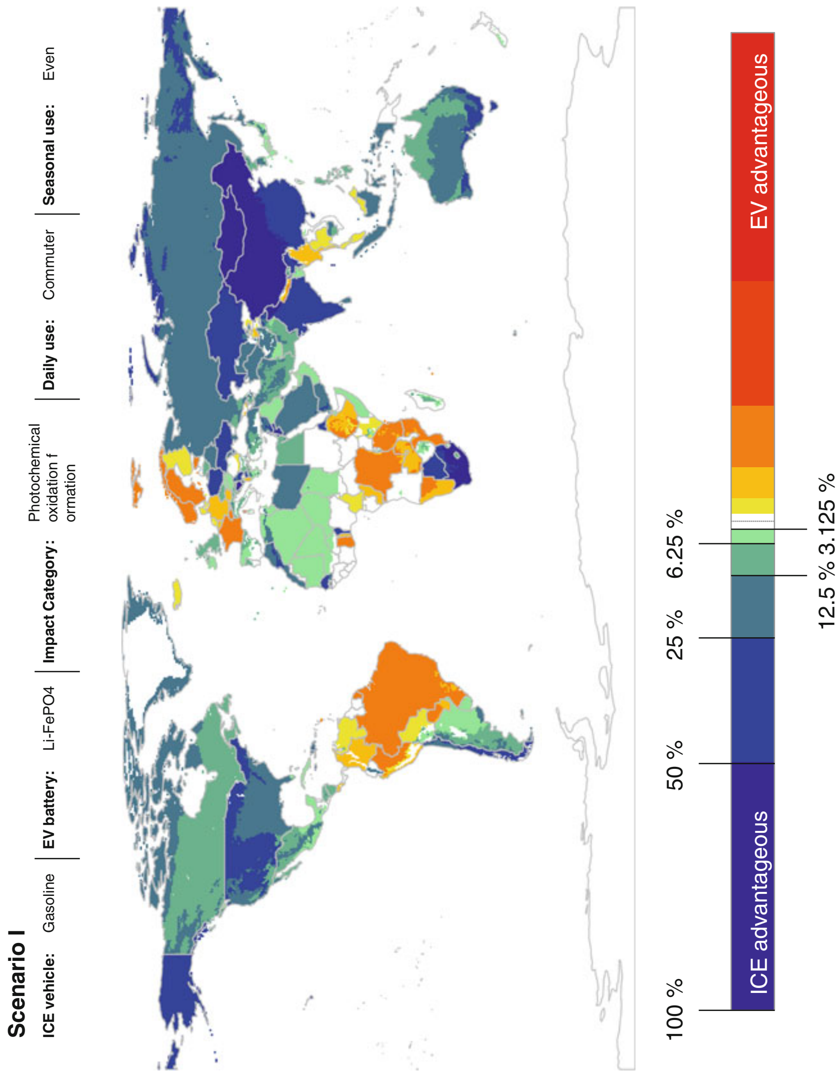


Fig. 5.9 LCA map of scenario I (created with R-package rworldmap)

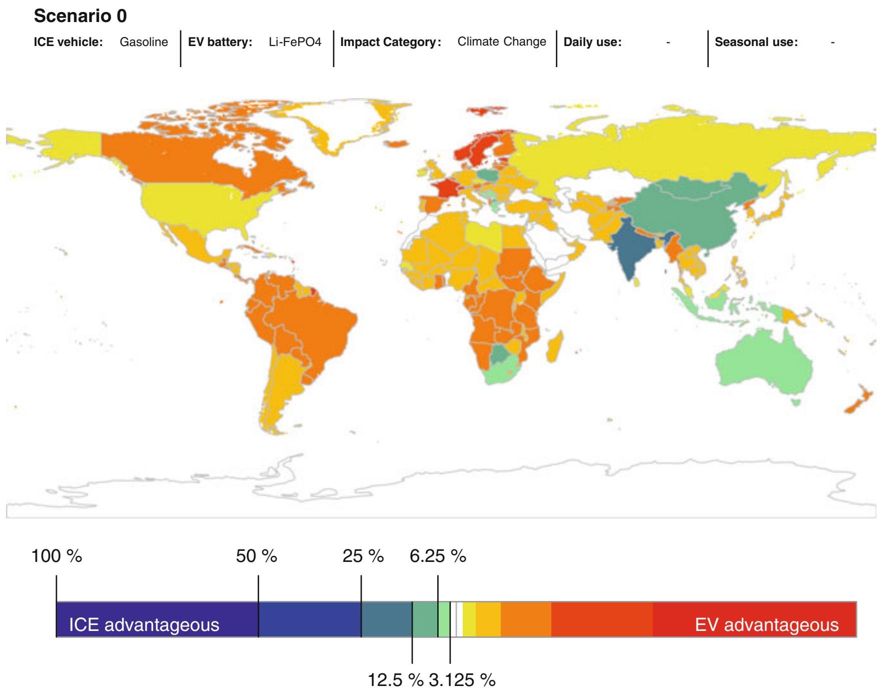


Fig. 5.10 LCA map of scenario 0 (created with R-package rworldmap)

Fig. 5.10 (scenario 0; i.e. that the use pattern become irrelevant). This map suggests that the consideration of heating and cooling changes the overall outcome of the comparison of conventional vehicles with EVs significantly. In this case EVs would perform much better than conventional vehicles. For future LCA studies, it is therefore strongly recommended to consider if the goal and scope of the LCA requires the consideration of heating and cooling or if it allows neglecting it.

Figure 5.11 shows the GWP values for the electricity mixes of each country in CO2-eq kg/kWh. Comparing the results of scenario A shows a correlation between the GWP of the electricity mix and outcome of the comparison. A high GWP of the electricity mix makes the EVs unfavourable. In addition, scenario A shows that the climate also influences the result. A warmer climate favours the EV. This is visible for example in Canada. In the south of Canada, the result is indifferent. Further in the north the gasoline vehicle becomes favourable as the climate becomes colder. This effect can be stronger than the electricity mix. This becomes evident when the results for India are compared with the results of southwest China. India has the highest GWP value for its electricity mix. The comparative assertion of scenario A reveals a good comparative performance of the gasoline vehicle (medium blue). Even though the electricity mix of China is better, the colder climate leads to a very good comparative performance of the gasoline vehicle in the south-western part of China.

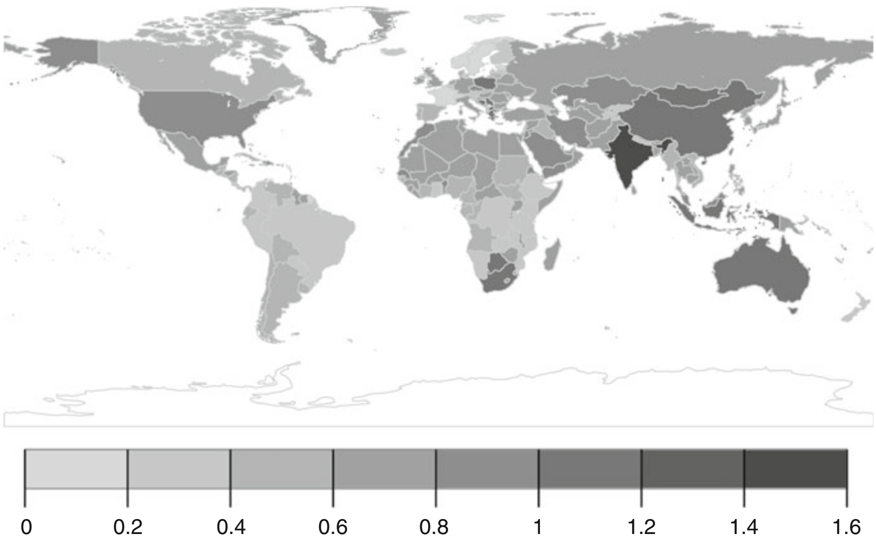


Fig. 5.11 Visualization of GWP of electricity mix in CO2-eq kg/kWh (created with R-package rworldmap)

To sum up, it can be said that while the electricity mix defines the ranking of results, the consideration of heating and cooling has a strong influence on the vertex of the comparative assertion of conventional vehicles and EVs favouring the conventional vehicle in most parts of the world today. This means that the ranking of countries remains similar even when heating and cooling is considered. However, the consideration of heating and cooling shifts the overall results in favour of the conventional vehicle because the additional energy consumption is higher for the EV than it is for the conventional vehicle.

5.1.2.2 Variations of Daily Use (Scenarios B and C)

The variation of the daily use is shown in Figs. 5.2 and 5.3 displaying scenario B and C. While the shift of the daily use pattern does not alter the results from favouring one vehicle to favouring the other, it can push the results from being indifferent to indicating the preference for one vehicle type. The daily trips lead to a slight change of results in favour of the EV. This is particularly the case in northern Africa and the Middle East. The use by a service provider in the evening shifts the results in favour of the conventional vehicle. This is visible in Asia as well as North America. During the daily trips it will most likely be warmer than for commuting, for the evening use it will rather be colder. This result is comprehensible as heating is more energy intensive than cooling. This means that a shift to warmer ambient temperatures favours the EV, a shift to colder ambient temperatures favours the conventional vehicle.

5.1.2.3 Variations of Seasonal Use (Scenarios D and E)

The variation of the seasonal use is shown in Figs. 5.4 and 5.5 displaying scenario D and E. Similar to the variation of the daily use pattern, the variation of the seasonal use pattern shifts the preference in relation to the ambient conditions. In contrast to the daily use pattern, the difference between the northern and southern hemisphere becomes evident in this variation. Scenario D (i.e. use rather from October to March) leads to stronger results of the gasoline vehicle on the northern hemisphere and stronger results of the EV on the southern hemisphere. In the same manner scenario E (i.e. use from April to September) leads to the opposite change. Again these shifts occur due to the fact that warmer weather favours the EV. It is visible that the exclusive use from April to September leads to stronger changes than a slightly heavier use from October to March.

These shifts can move a result from being indifferent to being in favour for a specific vehicle. In the case of Canada in scenario E it becomes evident that it can be useful to consider the population distribution of a country. Figure 5.12 shows the population distribution in Canada. The majority of results seem to indicate that the conventional vehicles perform better. However, when the population distribution is considered as well, it becomes clear that the populated areas are located in a zone that favours EVs.

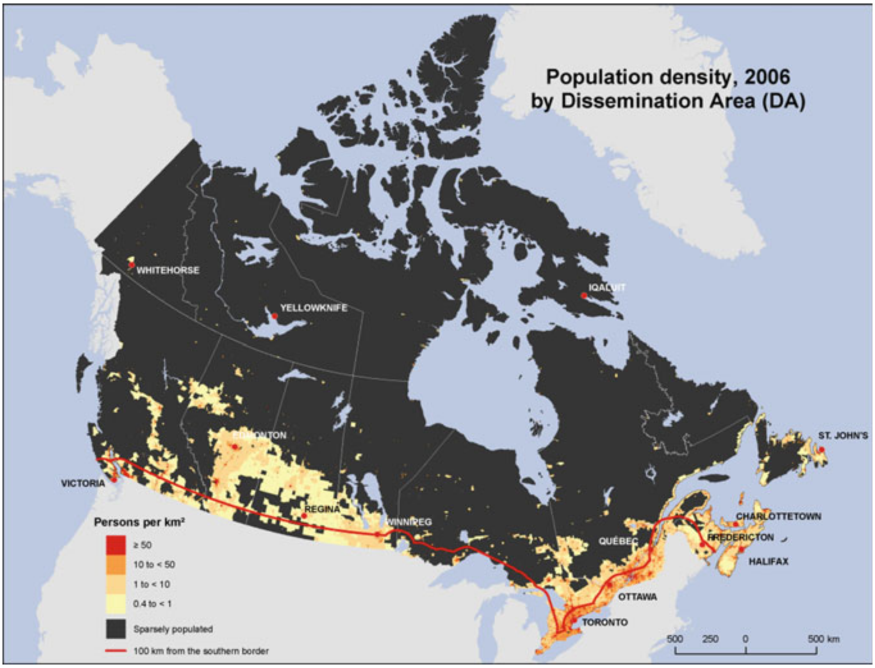


Fig. 5.12 Population density of Canada in 2006 (Government of Canada 2006)

5.1.2.4 Analysis of Impact Categories (Scenarios F, G, H and I)

The four different impact categories have been analyzed for which the use phase is decisive for the comparative assertion of conventional vehicles and EVs: terrestrial acidification, fossil depletion, particulate matter formation and photochemical oxidation formation potential.

Terrestrial acidification describes the process of a descending pH-value due to acids. (Baumann and Tillman 2009) The terrestrial acidification is in general better for the gasoline vehicle. Exceptions are Brazil and the northern and north-western part of Continental Europe as well as a number of countries in the southern part of Africa. The determination of the fossil depletion potential is based on the scarcity of fossil fuels. (Baumann and Tillman 2009) The fossil depletion shows very extreme results at both ends of the scale. This means that in some countries EVs have a very good comparative performance (dark red) and in other the gasoline vehicle (dark blue). The overall result is mixed. EVs perform better in most parts of Africa and South America, the south-eastern part of Asia, the northern and western part of Continental Europe as well as Canada. The particulate matter formation potential describes the emission of very fine matter smaller than 10 µm (PM10) (Goedkoop et al. 2013). The particulate matter formation potential shows one-sided results in favour of the conventional vehicle. This is mainly due to the fact, that there exist few very high results in favour of conventional vehicles and the scale is defined by the highest value that is achieved. One single grid out of around 60,000 grid points, has a very large value. It is located in Indonesia, where one single grid point has the climate category Cfa. This point was deleted from the results to even out the scale and achieve more useful results of the LCA Map. The photochemical oxidation formation describes the creation of photo-oxidants as a second pollutant from nitrogen oxides (NOx) and hydrocarbons. (Baumann and Tillman 2009) It is mostly better for the gasoline vehicle. Only in northern South America, southern Africa, parts of South-East Asia as well as northern and north-western Continental Europe EVs perform better.

The intensity of the results (i.e. the exploitation of the scale) is related to the sensitivity of the fuel and electricity values in the use phase. For example, the impact category fossil depletion is very sensitive to the choice of energy type which leads to dark red as well as dark blue results.

As opposed to global warming, terrestrial acidification, particulate matter formation and photochemical oxidation formation are environmental impacts that are limited to the location where they occur. When the impact categories are weighed up against each other it should be kept in mind that densely populated areas are particularly vulnerable to these local emissions and would benefit significantly from vehicles which do not cause such emissions.

The findings of the regional assessment allow a classification of nine regions: North America, southern and northern South America, southern and northern Africa, northern and western Continental Europe, the remaining part of Europe, Asia and parts of South-East Asia. The results for the impact categories global warming, terrestrial acidification, fossil depletion and the photochemical oxidants

Table 5.3 Summary of regional comparison of gasoline vehicle and EV with lithium iron phosphate battery

Continent	Specification	GWP	TAP	FDP	PMFP	POFP
North America		○	○	○/●	○	○
South America	North	●	●	●	○	●
South America	South	○	○	●	○	○
Africa	North	○	○	●	○	○
Africa	South	●	●	●	○	●
Asia		○	○	○	○	○
Asia	Parts of south-east	●	○	●	○	●
Europe	Northern and Western continental	●	●	●	○	●
Europe	Rest	○	○	○	○	○

○ indicates preference for gasoline vehicle, ● indicates preference for EV, global warming potential (GWP), terrestrial acidification potential (TAP), fossil depletion potential (FDP), particulate matter formation potential (PMFP), photochemical formation potential (POFP)

formation are summarized in Table 5.3. The circle indicates that the gasoline vehicle is preferable and the dot indicates that the EV is preferable. In general, the northern part of South America, the southern Africa as well as the northern and western part of Continental Europe are identified as suited locations for the use of EVs in comparison to conventional vehicles from an environmental point of view. For parts of South-East Asia, the results are mixed.

5.2 Comparison of Lightweight Electric Vehicles with Reference Electric Vehicles

The following case study aims at analysing the parameters of the break-even calculation of lightweight materials using the break-even analysis chart presented in Fig. 4.12. For this, data is collected for the different values and analyses are conducted for the impact category climate change and the reference material steel and the lightweight materials high-strength steel, aluminium, magnesium and CFRP.

5.2.1 Data Collection and Results

The required data for the analysis can be derived from Eq. (4.7). The necessary parameters are the environmental impact of the lightweight material per kg i, the energy reduction value c_{erv}, the lightweight factor a_{lw} and the environmental impact of the electricity mix i_e.

The lightweight factors for the different materials are derived from Fig. 2.8 and presented in Table 5.4. High-strength steel achieves a reduction of around 90 %,

Table 5.4 Lightweight factors of different materials derived from Fig. 2.8

Lightweight materials	a_{lw} (%)
High-strength steel	90
Aluminium	55
Magnesium	44
CFRP	47

Table 5.5 Different energy reduction values *erv*

erv #	Source	c_{erv} (Wh/km/kg)
1	NEDC (own calculation)	0.0369
2	WLTP (own calculation)	0.048
3	Redelbach et al. (2012)	0.0347
4	Schuh et al. (2013)	0.055
5	Muttana and Sardar (2013)	0.11145

aluminium of 55 %, magnesium of 44 % and CFRP of 47 %. However, it must be noted that the presented values only serve as guidance and that the actual value depends on the design.

Energy reduction values are presented in Table 5.5. The energy reduction value for the NEDC was calculated in Sect. 4.4.2 and adds up to 0.0369 Wh/km/kg. Likewise, the value was calculated for the WLTP (0.048 Wh/km/kg). Furthermore, energy reduction values were taken from Redelbach et al. (2012) directly and taken indirectly from Schuh et al. (2013) and Muttana and Sardar (2013) by deduction from the presented results. These values are 0.0347, 0.055 and 0.11145 Wh/km/kg. While the first four values are similar, the last one is more than double their value and represents a high assumption. As the publications 5 (and 4) do not provide further information on how their values were obtained, the reason for the difference is not known.

The environmental impacts of different materials depend on different parameters like the electricity mix that was used for the production or whether it was produced from ore (primary material) or from scrap (secondary material). Therefore, the span of value for one material can be large depending on its origin. In the case of steel, two different production types represent primary and secondary production. These are the basic oxygen furnace (BOF) and electric arc furnace (EAF). Table 5.6 shows a collection of different GWP values for primary and secondary steel. For this selection the average world value for BOF steel is 2.38 kg CO2-eq/kg. The average world value for EAF steel is 0.7 kg CO2-eq/kg.

A selection of values for high-strength steel is presented in Table 5.7. Chromium steel from the Ecoinvent database is used to approximate high-strength steel because it accounts for a higher share of alloys. Based on this selection, there is no difference between the average values for the primary and the secondary production routes. The value is around 4.7 kg CO2-eq/kg.

The production of aluminium is very energy intensive. Hence, the environmental impact of aluminium is defined significantly by the environmental impact of the electricity mix used for the production. This is reflected by the highly differing

Table 5.6 Collection of GWP values of steel

Source	Region	Material	kg CO2-eq/kg
Ecoinvent (2015)	Europe	BOF steel, low-alloyed	2.33
Ecoinvent (2015)	World	BOF steel, low-alloyed	2.35
Ecoinvent (2015)	Europe	EAF steel, low alloyed	0.42
Ecoinvent (2015)	World	EAF steel, low alloyed	0.78
World Steel Association (2011)	World	BOF steel and EAF steel (40:60)	1.6
Burchart-Korol (2013)	Poland	BOF steel	2.46
Burchart-Korol (2013)	Poland	EAF steel	0.91
		Average BOF	2.38
		Average EAF	0.7

Table 5.7 Collection of GWP values of high-strength steel

Source	Region	Material	kg CO2-eq/kg
Ecoinvent (2015)	Europe	BOF steel, chromium	4.68
Ecoinvent (2015)	World	BOF steel, chromium	4.71
Ecoinvent (2015)	Europe	EAF steel, chromium	3.95
Ecoinvent (2015)	World	EAF steel, chromium	5.5
Kim et al. (2010)[a]	–	High-strength steel	2.8
		Average BOF	4.7
		Average EAF	4.73
		Average total	4.33

[a]Original source KNCPC (2005) not accessible anymore

values for a selection of regions in Table 5.8. Whereas the lowest values for primary aluminium range around 7–9 kg CO2-eq/kg for Europe, North America and for the world mix, the highest values can reach almost 26 kg CO2-eq/kg in China. The comparable values for secondary material are much lower with an average of around 0.9 kg CO2-eq/kg. These results show a relation with the electricity used for the material production. The GWP values for the electricity in Europe, the United States, Canada and China are around 520, 830, 460 and 1140 kg CO2-eq/kWh respectively (Ecoinvent 2015).

The two main production processes for magnesium are the pidgeon process, a thermal reduction, and electrolysis. 80 % of the world's primary magnesium process is conducted in China using the pidgeon process. The environmental impact of magnesium depends significantly on the parameters of the production process: the electricity mix and the use of sulphur hexafluoride (Ehrenberger 2013). It is used as a protection gas and has a very strong greenhouse gas effect (Ko et al. Ko et al. 1993; Ehrenberger 2013). A selection of values for the GWP of magnesium produced via both process types is provided in Table 5.9. The pidgeon process leads to

Table 5.8 Collection of GWP values of aluminium

Source	Region	Material	kg CO2-eq/kg
Ecoinvent (2015)	Europe	Primary aluminium, ingot	9.43
Ecoinvent (2015)	China	Primary aluminium, ingot	25.93
Ecoinvent (2015)	Oceania	Primary aluminium, ingot	23.7
Ecoinvent (2015)	World	Primary aluminium, ingot	7.07
The Aluminium Association (2013)	North America	Primary aluminium, ingot	8.94
The Aluminium Association (2013)	North America	Secondary aluminium, ingot	1.23
European Aluminium Association (2013)	Europe	Primary aluminium, ingot	8.48
European Aluminium Association (2013)	Europe	Secondary aluminium, ingot	0.51
		Average primary	13.93
		Average secondary	0.87
		Average total	10.66

Table 5.9 Collection of GWP values of magnesium

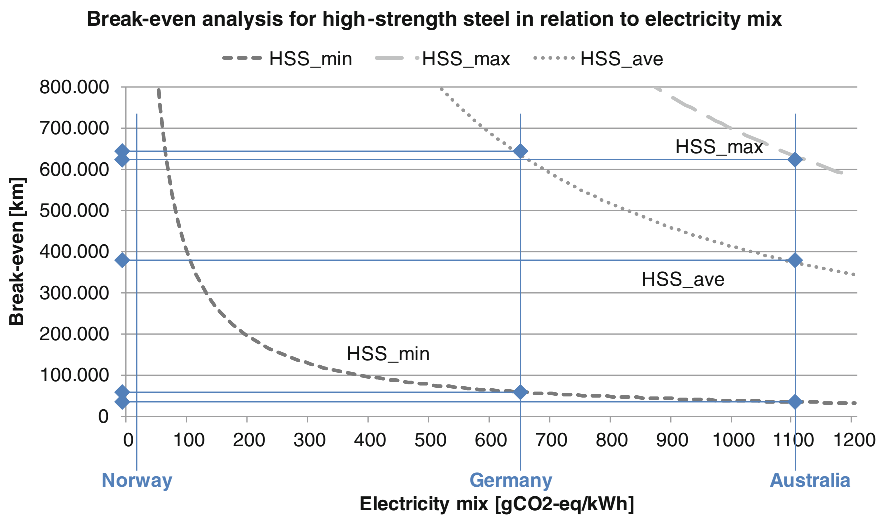
Source	Comment	Material	kg CO2-eq/kg
Ecoinvent (2015)	World	Magnesium, electrolysis	19.38
Ecoinvent (2015)	World	Magnesium, pidgeon	31.77
Ecoinvent (2015)	China	Magnesium, pidgeon	33.47
Ehrenberger (2013)		Magnesium, electrolysis	17.8
Ehrenberger (2013)	China	Magnesium, pidgeon	25.8
Ehrenberger et al. (2008)	Natural gas	Magnesium, pidgeon	47.0
Ehrenberger et al. (2008)	Coal	Magnesium, pidgeon	25.0
Cherubini et al. (2008)	China	Magnesium, pidgeon	42.0
Cherubini et al. (2008)	Australia	Magnesium, electrolysis	24.5
Cherubini et al. (2008)	World mix	Magnesium, divers	36.0
		Average pidgeon	34.17
		Average China	33.76
		Average electrolysis	20.56
		Average total	30.27

higher environmental impacts than the electrolysis production with around 34 and 21 kg CO2-eq/kg respectively.

As opposed to steel and the light metals—more established lightweight materials—environmental impacts on CFRP are not well documented. Das (2011) has published a paper on a polymer and an organic polymer CRFP produced with two production methods. Their results range between 12 and 17 kg CO2-eq/kg. Witik et al. (2011) have a published a very high value of 50 CO2-eq/kg. The value of

Table 5.10 Collection of GWP values of carbon fibre reinforced fibre

Source	Material	kg CO2-eq/kg
Das (2011)	Polymer w/PT1	16.9
Das (2011)	Polymer w/PT2	14.6
Das (2011)	Organic polymer w/PT2	14.9
Das (2011)	Organic polymer w/PT2	12.5
Witik et al. (2011)	CFRP	50.0
Mayyas et al. (2012)	CFRP, isotropic	17.25
	Average total	21.03

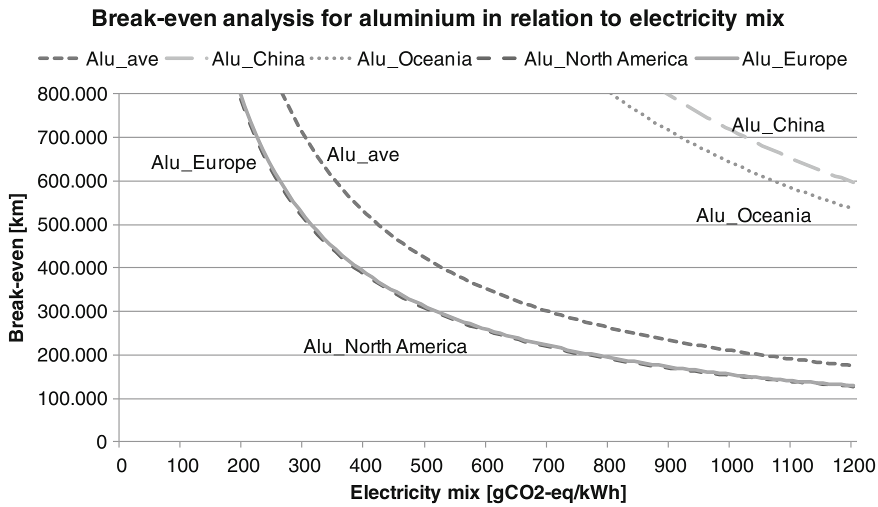


	Reference steel	HSS_min	HSS_ave	HSS_max
$i_{P,lw} + i_{E,lw}$ (gCO2-eq/kg)	2.38	2.8	4.33	5.5
α_{lw} (-)	-	0.9	0.9	0.9
erv (Wh/km/kg)	0.0369			

Fig. 5.13 Break-even analysis of high-strength steel

Mayyas et al. (2012) is similar to the value of Das (2011) ranging around 17 CO2-eq/kg (see Table 5.10).

In the following, break-even analyses are conducted for all five lightweight materials (Figs. 5.13, 5.14, 5.15 and 5.16). The NEDC energy reduction value is used for these analyses. Due to the small range of the steel values, the average value is used for all analyses. Furthermore, the impact of the energy reduction value is analysed in Fig. 5.17 using the example of average high-strength steel (Table 5.7).



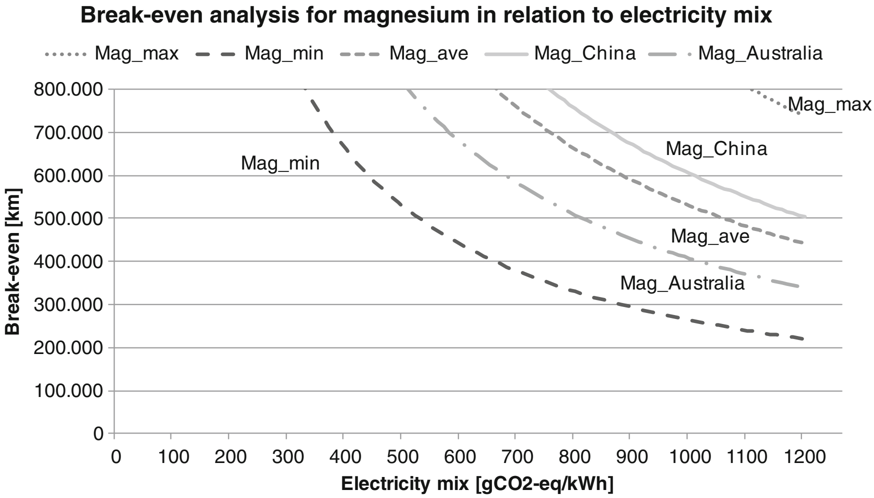
	Alu_North America	**Alu_Europe**	**Alu_ave**	**Alu_Oceania**	**Alu_China**
$i_{P,lw} + i_{E,lw}$ *(gCO2-eq/kg)*	8.94	9	10.66	23.7	25.93
α_{lw} *(-)*	0.55	0.55	0.55	0.55	0.55
$i_{P,ref} + i_{E,ref}$ *(gCO2-eq/kg)*	2.38	*erv (Wh/km/kg)*	0.0369		

Fig. 5.14 Break-even analysis of aluminium

5.2.2 *Findings*

The charts show that a high environmental impact per kWh of an electricity mix results in the break-even being achieved earlier. This means that an increasing share of renewable energy is disadvantageous for the use of today's lightweight materials which have higher environmental impacts for production and end-of-life processes than the reference material steel. A lightweight material should have a high lightweight factor a_{lw} and a low environmental impact i to pay off as early as possible. Thus, measures can be useful which reduce the environmental impact of lightweight materials. For example, the use of renewable energy for the material production can have a very positive impact on the total environmental impact.

Overall, the results show that LEVs can be a viable option to reduce the environmental impact of EVs. In this case study only high-strength steel with the smallest GWP value (HSS_min) would be able to achieve a wide-spread energy reduction for almost any electricity mix. The German, Norwegian and Australian electricity mix are marked on the chart. For the Norwegian mix, a break-even is never achieved. For the German and Australian electricity mix a useful break-even



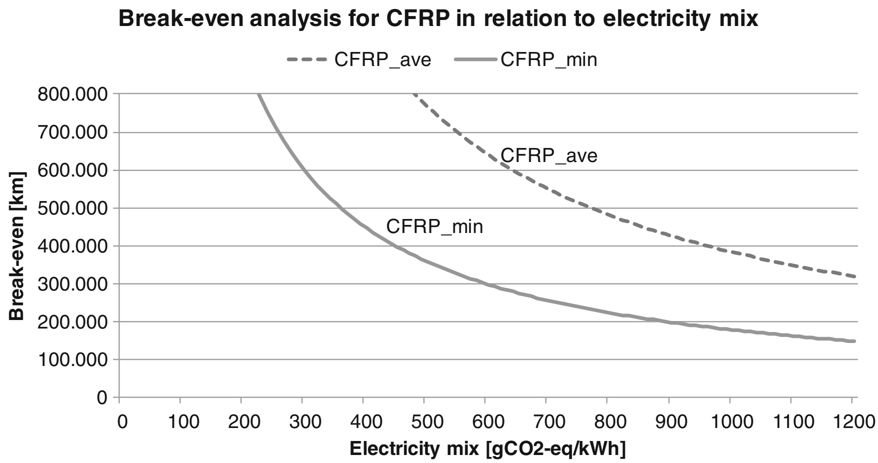
	Reference steel	Mag_min	Mag_ Australia	Mag_ave	Mag_China	Mag_max
$i_{P,lw} + i_{E,lw}$ *(gCO2-eq/kg)*	2.38	17.8	24.5	30.27	33.76	47
α_{lw} *(-)*		0.44	0.44	0.44	0.44	0.44
erv (Wh/km/kg)	0.0369					

Fig. 5.15 Break-even analysis of magnesium

is reached for the minimum assumption of high-strength steel. The break-even points for the other assumptions (average and maximum values) are achieved above 350,000 km. This is unlikely to be achieved. It is important to note that this only means that the LEV performs better or worse than the reference EV. In many parts of the world the conventional vehicle can still be the better choice (see previous sub-section).

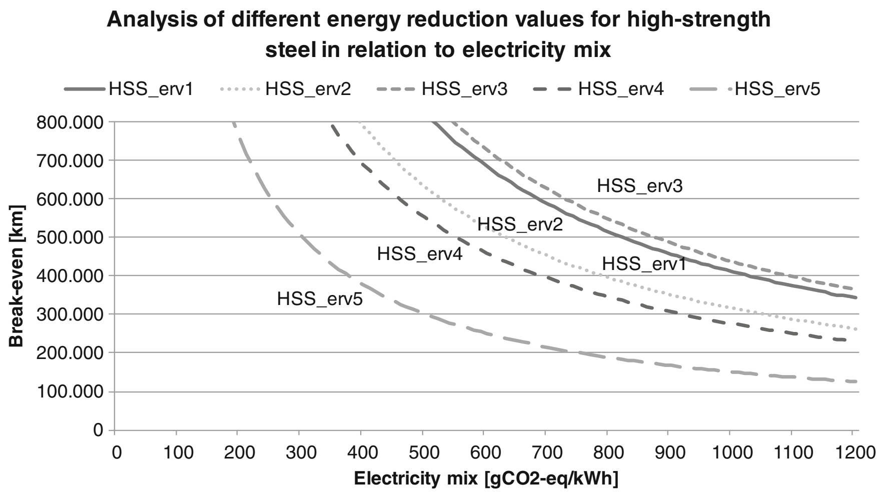
In this case study achieving a break-even with the other materials is doubtful. The assessment shows that for aluminium, magnesium and CFRP a break-even is barely achieved before 200,000 or 300,000 km. This will most likely be around or already past the end-of-life of the vehicle. However, the specific parameters of a vehicle design can be different and alter the final outcome. Very favourable conditions (e.g. an electricity mix with very low environmental impacts for the material production, a high energy reduction value and lightweight factor of the material) could lead to an earlier break-even.

The results from the previous chapter show that the different parameters lead to a wide range of results. It is therefore very important to determine the values of the parameters carefully. It is crucial to know the origin and production process of the material. As seen particularly for aluminium or magnesium the origin of the material makes a difference for the break-even analysis. Here, it is necessary to



	Reference steel	CFRP_min	CFRP_ave
$i_{P,lw} + i_{E,lw}$ (gCO2-eq/kg)	2.38	8.94	9
α_{lw} (-)		0.55	0.55
erv (Wh/km/kg)	0.0369		

Fig. 5.16 Break-even analysis of CFRP



	erv_1	erv_2	erv_3	erv_4	erv_5
erv (Wh/km/kg)	0.0369	0.048	0.0347	0.055	0.11145
$i_{P,ref} + i_{E,ref}$ (gCO2-eq/kg)	2.38	$i_{P,lw} + i_{E,lw}$ (gCO2-eq/kg)	4.33	α_{lw} (-)	0.9

Fig. 5.17 Analysis of different energy reduction values for average high-strength steel in relation to electricity mix

stress that the regional specification of the materials concerns their place of production and not the place of use of the vehicle. This means that a vehicle driven in Europe was not necessarily build with a material from Europe. The place of use of the vehicle must also be known to determine the electricity mix used for its propulsion. Likewise, the lightweight factor a_{lw} must be selected carefully and in accordance with the actual design.

It can be concluded that due to the sensitivity of the results, general recommendations for or against a material cannot be made. Much more, the results show that a detailed analysis is necessary to ensure the robustness of any recommendation. This work provides the required concept to do so.

References

Baumann H, Tillman A (2009) The hitch hikers's guide to LCA: An orientation in life cycle assessment methodology and application, 1:3 edn. Studentlitteratur, Lund

Burchart-Korol D (2013) Life cycle assessment of steel production in Poland: a case study. J Clean Prod 54:235–243. doi:10.1016/j.jclepro.2013.04.031

Cherubini F, Raugei M, Ulgiati S (2008) LCA of magnesium production. Resour Conserv Recycl 52(8–9):1093–1100. doi:10.1016/j.resconrec.2008.05.001

Das S (2011) Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 16(3):268–282. doi:10.1007/s11367-011-0264-z

Ecoinvent (2015) Ecoinvent database. http://ecoinvent.ch/. Accessed 20 Oct 2015

Ehrenberger S (2013) Life cycle assessment of magnesium components in vehicle construction, Stuttgart, Germany

Ehrenberger S, Schmid SA, Song S, Friedrich HE (2008) Status and potentials of magnesium production in China: life cycle analysis focussing on CO2 eq emissions. In: 65th annual world magnesium conference

European Aluminium Association (2013) Environmental profile report for the European aluminium industry

Goedkoop M, Heijungs R, Huijbregts MAJ, Schryver AD, Struijs J, van Zelm R (2013) ReCiPe 2008: a life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level

Government of Canada (2006) Statistics Canada. http://www12.statcan.gc.ca. Accessed 30 Oct 2015

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013a) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):53–64. doi:10.1111/j.1530-9290.2012.00532.x

Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013b) Corrigendum to comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17(1):158–160. doi:10.1111/j.1530-9290.2012.00532.x

Kim H, McMillan C, Keoleian GA, Skerlos SJ (2010) Greenhouse gas emissions payback for lightweighted vehicles using aluminum and high-strength steel. J Ind Ecol 14(6):929–946. doi:10.1111/j.1530-9290.2010.00283.x

KNCPC (2005) Korean national life cycle inventory database. www.kncpc.re.kr/lci/. Accessed Aug 2008

Ko MKW, Sze ND, Wang W, Shia G, Goldman A, Murcray FJ, Murcray DG, Rinsland CP (1993) Atmospheric sulfur hexafluoride: sources, sinks and greenhouse warming. J Geophys Res 98 (D6):10499. doi:10.1029/93JD00228

Mayyas A, Qattawi A, Omar M, Shan D (2012) Design for sustainability in automotive industry: a comprehensive review. Renew Sustain Energy Rev 16(4):1845–1862. doi:10.1016/j.rser.2012.01.012

Muttana SB, Sardar A (2013) Lightweighting of battery electric cars: an impact analysis using indian driving cycle. In: 8th SAEINDIA international mobility conference and exposition and commercial vehicle engineering congress

Redelbach M, Klötze M, Friedrich HE (2012) Impact of lightweight design on energy consumption and cost effectiveness of alternative powertrain concepts. In: European electric vehicle congress

Schuh G, Korthals K, Backs M (2013) Environmental impact of body lightweight design in the operating phase of electric vehicles. In: Nee AYC, Song B, Ong S (eds) Re-engineering manufacturing for sustainability: proceedings of the 20th CIRP international conference on life cycle engineering, Singapore 17–19 Apr 2013. Springer, Singapore

The Aluminium Association (2013) The Environmental footprint of semi-finished aluminum products in North America: a life cycle assessment report

United Nations (2005) Uniform provisions concerning the approval of passenger cars: UNECE R 101. Accessed 25 Oct 2012

Witik RA, Payet J, Michaud V, Ludwig C, Månson JE (2011) Assessing the life cycle costs and environmental performance of lightweight materials in automobile applications. Compos A Appl Sci Manuf 42(11):1694–1709. doi:10.1016/j.compositesa.2011.07.024

World Steel Association (2011) Methodology report: life cycle inventory study for steel products

Chapter 6
Summary, Critical Review and Outlook

This chapter serves as a conclusion of this work. First a summary gives a brief overview of each chapter—its main purpose and outcome. Second, a critical review provides an evaluation of this work, highlights, the innovative elements and existing restrictive aspects. Finally, an outlook on future research activities to expand this topic is given.

6.1 Summary

Current environmental challenges of motorized vehicles—the emission of GHGs, local air pollution and the use of fossil resources—has lead to the development of technologies which aim at the reduction of these environmental impacts. The implementation of LEVs is one of these options. However, whether LEVs actually perform better than regular electric and conventional vehicles or not depends on the terms of use (e.g. the electricity mix, the ambient temperature and the use pattern). Hence, a globally valid answer to the question cannot be given as these parameters vary for each use case and the site of use. Therefore, the goal was to develop a concept that allows the environmental assessment of LEVs considering the terms of use in comparison to conventional vehicles and regular EVs.

Chapter 1 introduces the motivation of assessing LEVs and derives a research structure. This part points out the relevance of private vehicle transportation and the environmental impacts related to it. LEVs are introduced as one solution to ease these impacts. Following, the complexity of assessing the environmental impact of LEVs are highlighted and the structure of this book is introduced.

In Chap. 2 the necessary theoretical background is introduced in four parts to explain the complexity of assessing the environmental impact of LEVs. First, the main components and functioning of EVs as well as the composition of their energy consumption are introduced. Second, lightweight design and particularly

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lightweight materials are discussed. Third, the issue of environmental impacts are discussed by describing the life cycle of EVs as well as the background and principle of the method LCA—the environmental assessment tool for products. Based on this information, the most important aspects of assessing the environmental impacts of EVs and lightweight materials and consequently LEVs are derived and summarized in five main key findings.

The state of research on the topic is conducted in Chap. 3. LCA guidelines of vehicles as well as LCA studies on EVs, conventional lightweight vehicles and LEVs are assessed based on a set of 17 criteria. None of the 18 selected publications fulfil the criteria to a satisfying extend. Consequently, the need for a consistent concept is derived which allows the environmental assessment of LEVs considering the terms of use and providing guidance on the adequate visualization of results.

Chapter 4 consists of the developed concept for the environmental assessment of LEVs. The concept is made up of four parts: (1) a detailed system description, (2) the modelling of (a) the energy consumption of EVs depending on the terms of use and (b) the energy reduction value of EVs, (3) the visualization and (4) the implementation. The system description contains the definition of the goal, functional unit as well as the different elements of the system (use pattern, climate, lightweight design etc.). The modelling provides an approach to determine the energy consumption of an EV depending on the ambient temperature and the use pattern. A second approach describes the derivation of the energy reduction value of EVs from a driving cycle. The visualization suggests different charts for the display of regional differences, the impact of the lightweight design and the differences among impact categories. The implementation part provides guidance on how to collect and process the data and particularly on how to create LCA maps.

A case study is conducted in Chap. 5 to present the use and to test the concept. The chapter is divided into two parts: (1) the comparison of EVs with conventional vehicles and (2) the comparison of LEVs with reference EVs. For the first part eight different scenarios are created and compared to a reference scenario. These nine LCA maps allow deductions on the influence of the daily and seasonal use as well as the impact of the electricity mix and the climate on the final results. In total five different impact categories (global warming, terrestrial acidification, fossil depletion, particulate matter formation potential and photochemical oxidation formation) are assessed. The second case study shows the impact of different parameters on the environmental advantage of LEVs. The results reveal that LEVs can be a viable environmental choice in comparison to EVs. But this outcome is not a given. The results are very sensitive to the variation of the parameters (e.g. electricity mix, environmental impact of material production and end-of-life, lightweight factor of material). Therefore, a careful analysis of any actual design is necessary to answer the question whether LEVs are good environmental choice in comparison to EVs or not.

6.2 Critical Review

The presented concept allows an environmental assessment of LEVs considering the terms of use. Although no general recommendations for or against a material can be provided, this work provides the necessary concept to answer the question. Thereby, it fills the research gap identified in Chap. 3. Prior assessments were completed for single places. For the first time a solution is provided which allows a site-specific assessment for a global map and different use patterns. The concept considers the regional energy consumption for heating and cooling and allows the definition of different daily and seasonal use patterns. Furthermore, LEVs are not only compared to regular EVs but also to conventional vehicles avoiding to opt for LEVs in case EVs are not a good environmental choice in the first place. A method for the calculation of the energy reduction value of an EV was presented. It was derived from an approach for conventional vehicles and it allows the deduction of energy reduction values from any driving cycle. Furthermore, different types of charts are provided to allow for a visualization which is adapted to the core message of the results. Choropleth maps are useful to highlight regional differences and to easily identify regions and countries where (L)EVs have environmental advantages in comparison to other vehicles. This can be a helpful tool for decision makers in politics and industry on topics like law making and the identification of new markets. Radar charts put emphasis on problem-shifting among impact categories and promote the consideration of multiple impact categories. This is important because most studies focus on GHG emissions only. The break-even chart is useful for the design of vehicles. It allows the analysis of the different parameters which influence the results in an easier to understand manner. This makes the consequences of design changes and their following energy savings more clear. In total, these visualization recommendations ensure a good understanding of the results and make the implementation among LCA and non-LCA experts easier and therefore more likely.

However, some limitations are present regarding the use of the concept. These are elaborated in the following:

- **Necessity of data**—The concept provides the frame to assess LEVs. This can be useful in politics and industry alike. However, in any case it is necessary to have detailed knowledge on the vehicles which are to be analysed as well as its alternatives. As for any LCA, data availability is a crucial element also for this type of comparison. Increasing the data availability and the reduction of uncertainty is beneficial to the outcome of the LCA. Therefore, putting effort into the investigation of the analyzed vehicles types and the surrounding system continues to be necessary. In case different vehicle designs are evaluated at the beginning of the design process other methods and tools might need to be consulted to make estimates on the final vehicle LCI.
- **Energy consumption**—So far the calculation of the energy consumption does not portray the possible level of detail. For example, simulation models of EVs

would be able to provide more detailed data on the actual energy consumption. This would also allow the consideration of other ambient conditions like the solar radiation. Downsides of this increased level of detail are that the calculation of these simulation models are very time consuming and will most likely exceed the knowledge of the average LCA practitioner.

- **Sunrise and solar noon**—Currently, two locations where used to create the choropleth maps for each climate group of each hemisphere. The times for sunrise and solar noon were also derived from the average of these two locations for each month. This is a simplification of the actual conditions because the times depend on factors like the latitude and longitude. Considering the actual values for each point of the grid is possible but requires an enormous data volume. In case this is included in the analysis the use of a database management system is recommended.
- **Electricity mix**—The electricity mix is considered equal within a country. In fact, an electricity network is not necessarily limited by political borders. Particularly for large countries, several independent electricity networks exist. Consequently, these networks have different energy sources and differing environmental impacts. While the consideration of the country-mix provides an average and good assumption of the conditions, the consideration of these networks would increase the quality of results.

6.3 Outlook

In addition to the added value of this concept, further activities are possible to increase the knowledge of the system of LEVs and the consequences of their implementation. In the following, five fields of further development are presented.

- **Consequential LCA**—Implementing a new technology with a big volume of products can have environmental repercussions on other, neighbouring systems. When such large-scale implementations are planned, the considerations of these changes should be included in an environmental assessment. Such assessments are called consequential LCAs. The attributional LCA used in this concept gives answers to the question whether LEVs have a better environmental performance than conventional vehicles and regular EVs. A consequential LCA would provide information on actual savings that could be achieved considering the success of the product LEV on the market and the actual replacements with other vehicles that take place.
- **Extension of parameters**—The presented concept provides a basic framework to conduct the environmental assessment of LEVs. Extending the concept with further parameters (e.g. topography, the humidity, daily and seasonal electricity mixes or available recycling technologies) would improve the assessment and provide a more detailed picture of the environmental impact of (L)EVs. The

concept can also be taken a step further be adding other assessment dimensions like costs and technical requirements. This would highlight the aspect of the feasibility of introducing LEVs.

- **Consideration of all modes of transportation**—Motorized vehicles are a part of a much larger transportation system which includes other modes of transportation like walking, biking, flying and public transportation. Extending the comparison of LEVs to all modes of transportation would provide insights in the savings or cause which result from the question further up the line. In the same manner that the question is asked whether EVs are better than conventional vehicles before comparing EVs and LEVs, the question should be asked whether other available modes of transportation are better or not.
- **Ecological scarcity**—The method of ecological scarcity belongs to the impact assessment phase of the LCA. It was first published in 1990 (Ahbe et al. 1990) and has since been developed further (Brand et al. 1998; Frischknecht et al. 2006; Ahbe et al. 2014). The method considers the existing burden of specific substances in a region (e.g. a country). Hence, it allows assessing the severity of additional contributions of the considered substances. This would account for the fact the environmental impacts that have a strong local influence like acidification or eutrophication are seen in relation to the environment in which they occur. As the presented concept is already based on a regional concept, the method of ecological scarcity provides a matching addition.
- **Further development of IT-implementation**—Currently, the concept is not available as a single tool. Implementing the concept in one tool with touch and zoom functions for the map visualization would be a great opportunity to gain easy, visual access to the data. Other types of visualization could be called up for specific locations to provide the needed data for decision makers in politics and industry and new alternatives could easily be compared. The use of database programs can decrease the calculation time and improve the handling of the background data.

References

Ahbe S, Braunschweig A, Müller-Wenk R (1990) Methodik für Ökobilanzen auf der Basis ökologischer Optimierung. Schriftenreihe Umwelt, vol 133. Bundesamt für Umwelt, Wald und Landschaft, Bern

Ahbe S, Schebek L, Jansky N, Wellge S, Weihofen S (2014) Methode der ökologischen Knappheit für Deutschland: Eine Initiative der Volkswagen AG. AutoUni—Schriftenreihe, vol 68. Logos Verlag, Berlin

Brand G, Scheidegger A, Schwank O (1998) Bewertung in Ökobilanzen mit der Methode der ökologischen Knappheit: Ökofaktoren 1997, vol 297. Bundesamt für Umwelt, Wald und Landschaft (BUWAL)

Frischknecht R, Steiner R, Braunschweig A, Egli N, Hildesheimer G (2006) Swiss ecological scarcity method: the new version 2006