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MÁSTER UNIVERSITARIO EN INGENIERÍA INDUSTRIAL

TRABAJO FIN DE MÁSTER

Lifecycle Assessment of electric vehicles – Development of a model to evaluate End-of-Life strategies

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Madrid

Abril de 2019

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S. Fluchs

Fdo.: Sarah Fluchs Date: 30/04/2019

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[1] The project was carried out in cooperation between the RWTH University of Aachen and the Pontifica Comillas University as part of the Double Degree Master Program T.I.M.E. (Top Industrial Managers for Europe) Association in both universities.

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Lifecycle Assessment of electric vehicles – Development of a model to evaluate End-of-Life strategies

Autor: Maximilian Merklinger

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Madrid

Abril de 2019

EVALUACIÓN DEL CICLO DE VIDA DE LOS VEHÍCULOS ELÉCTRICOS - DESARROLLO DE UN MODELO PARA EVALUAR LAS ESTRATEGIAS DE FIN DE VIDA ÚTIL

Autor: Merklinger, Maximilian
Directora: Fluchs, Sarah
Entidad Colaboradora: ICAI – Universidad Pontificia Comillas

RESUMEN DEL PROYECTO

Introducción

Una de las consecuencias a largo plazo del constante consumo excesivo y la reducción de los recursos de la naturaleza son las altas emisiones de gases de efecto invernadero (GEI) que dañan el clima. Según el informe especial del Grupo Intergubernamental de Expertos sobre el Cambio Climático (IPCC), es imperativo limitar el calentamiento global a 1,5 ºC para finales de este siglo para mantener el control sobre el cambio climático. (IPCC, 2018; Reimer, 2018) . En consecuencia, la reducción de los GEI perjudiciales para el clima es de gran importancia para la sociedad mundial. Los impactos ecológicos deben cuantificarse mediante instrumentos de medición holísticos como la Evaluación del Ciclo de Vida (del inglés: LCA). En este contexto, el sector del transporte y la movilidad es uno de los principales emisores de GEI.

Motivación y objetivos del proyecto

Un posible concepto para reducir los GEI en el sector de la industria del automóvil es la optimización del proceso de fabricación considerando todo el valor añadido como un sistema regenerativo. Este sistema se concentra en la recuperación sostenible de todos los materiales y componentes mediante el establecimiento de circuitos cerrados de energía y materiales (por ejemplo, el reciclaje). En cuanto a la industria del automóvil, esto significa que cuantos más componentes de un vehículo al final de su vida útil (EOL) se puedan recuperar, más sostenible será la evaluación ecológica. Con este objetivo, es inevitable seguir desarrollando e investigando el establecimiento de ciclos de flujo de materiales para conservar y reutilizar cualquier valor añadido durante el mayor tiempo posible. La implementación de los circuitos cerrados se concluye con las denominadas estrategias EOL. Por esta razón, el potencial de ahorro de emisiones de GEI en el sector de la movilidad se describirá en el ámbito de esta tesis mediante la aplicación de estrategias de EOL, utilizando el ejemplo de los vehículos eléctricos. Sin embargo, una evaluación ecológica holística de un vehículo requiere un análisis intensivo de grandes cantidades de datos y, en algunos casos, de flujos de materiales muy complejos. Si no, las emisiones generadas a lo largo de todo el ciclo de vida no pueden determinarse ni publicarse. Sin embargo, la última etapa del ciclo de vida del producto

apenas se considera actualmente en el contexto del LCA de los vehículos (eléctricos). Según el estado actual de la investigación, hay pocos o ningún dato válido sobre la influencia cuantitativa (positiva) del uso de las estrategias de EOL (Hall and Lutsey, 2018, p. 4). Sin embargo, debido a la fuerte promoción (política) y al objetivo de aumentar las cifras de ventas, el establecimiento de vehículos eléctricos es inevitable. Por lo tanto, la pregunta general no es si los vehículos eléctricos deben ser establecidos o en qué medida la tecnología de accionamiento del motor eléctrico es más beneficiosa en términos de cargas de emisiones. Se trata más bien de las medidas que se pueden adoptar para seguir apoyando el establecimiento y el desarrollo de las tecnologías aplicadas. Por lo tanto, esta tesis pretende crear una mejor comprensión del impacto ecológico positivo que las estrategias de EOL pueden tener en el contexto de un proceso de fabricación sostenible.

Metodología

Después de una breve introducción, en el capítulo dos se describe en detalle la necesidad del cambio hacia una Economía Circular (EC). Para ello, se explicará por qué la economía lineal establecida actualmente no puede garantizar una estructura económica sostenible en el futuro. Después de la descripción y análisis de los orígenes teóricos de una EC, se presenta una definición de la EC basada en la investigación científica y sus ventajas. Posteriormente se examina el concepto de estrategias de EOL para poder comprender lo que significa el término y en qué contexto se hacen necesarias. De este modo, se definen las estrategias clave de EOL, incluyendo la consideración de las ventajas y desventajas características. Por último, se señala cómo se aplica actualmente el concepto de CE en la Unión Europea.

El capítulo tres retoma los conocimientos adquiridos y explica cómo puede medirse la sostenibilidad ambiental de los productos o servicios. En este contexto, se describe la metodología de LCA, incluyendo los requisitos de la norma reconocida internacionalmente DIN ISO 14040.

Además, en el capítulo cuatro se analizan y evalúan los resultados de los LCAs actuales, aplicados en la industria del automóvil y en particular para los vehículos eléctricos. El análisis se centra principalmente en la cuestión de si los resultados de los diferentes LCAs de los vehículos eléctricos pueden compararse en términos cuantitativos. La respuesta a esta pregunta es el prerrequisito básico para el modelo de estrategias de EOL. Si los resultados actuales de las LCAs no permiten una evaluación cuantitativa de los beneficios ecológicos utilizando estrategias EOL, el modelo debe llevarse a cabo a nivel teórico y conceptual. Además, los resultados del análisis se utilizarán para describir propuestas con el objetivo de aumentar la comparabilidad de los resultados futuros de los LCAs.

El modelo matematico de estrategias de EOL se desarrolla y describe en el capítulo cinco. A continuación, sobre la base de un cálculo ejemplar, se presentan los porcentajes de ahorro de emisiones para demostrar los posibles beneficios ecológicos. En este contexto, se tomarán varias hipótesis, que son necesarias para simplificar el cálculo. Por último, se aclara qué innovaciones relativas a la fabricación de un vehículo y el nuevo modelo de negocio serían necesarias para permitir una aplicación satisfactoria de las estrategias de EOL..

En el capítulo seis se resumen las conclusiones obtenidas y se ofrece una perspectiva de las posibles ampliaciones y mejoras del enfoque. En este contexto, se describen los desarrollos actuales en el contexto de la protección del clima y se relacionan con los resultados de esta tesis.

Resultados y conclusiones del proyecto

La transformación de una economía lineal a un circular es una necesidad urgente. Esta transformación requiere cambios estructurales fundamentales en la forma en que la sociedad produce, consume y explota los bienes y servicios. Por esta razón, deben analizarse todas las fases del ciclo de vida de un producto. La integración de las estrategias de EOL es esencial, ya que la fabricación caracteriza el elemento principal indispensable de una CE. En este contexto, los LCAs son una herramienta de medición importante. Sin embargo, al analizar la literatura actual queda claro que la norma actual para los LCAs ofrece demasiado margen para suposiciones subjetivas. En consecuencia, los resultados difieren ampliamente y la determinación de un rango adecuado de las emisiones generadas durante la vida útil de los vehículos eléctricos, así como la fabricación de la batería, no es factible.

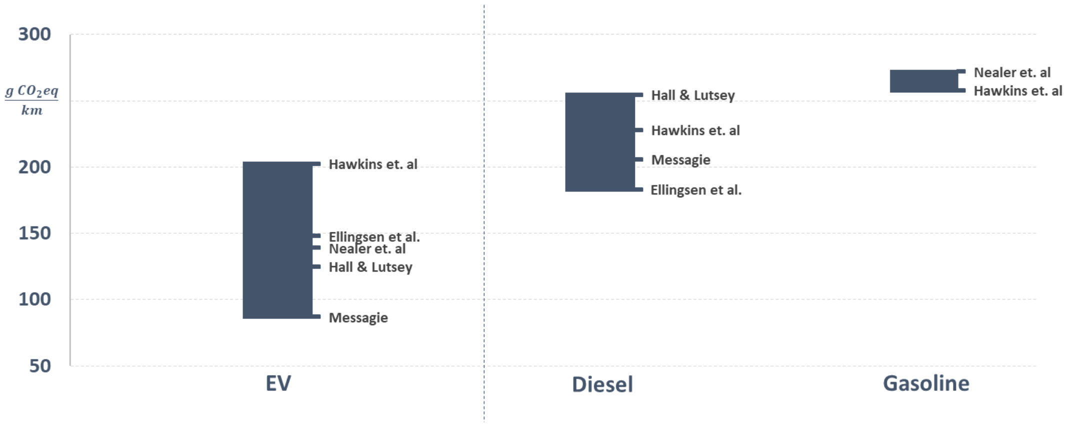
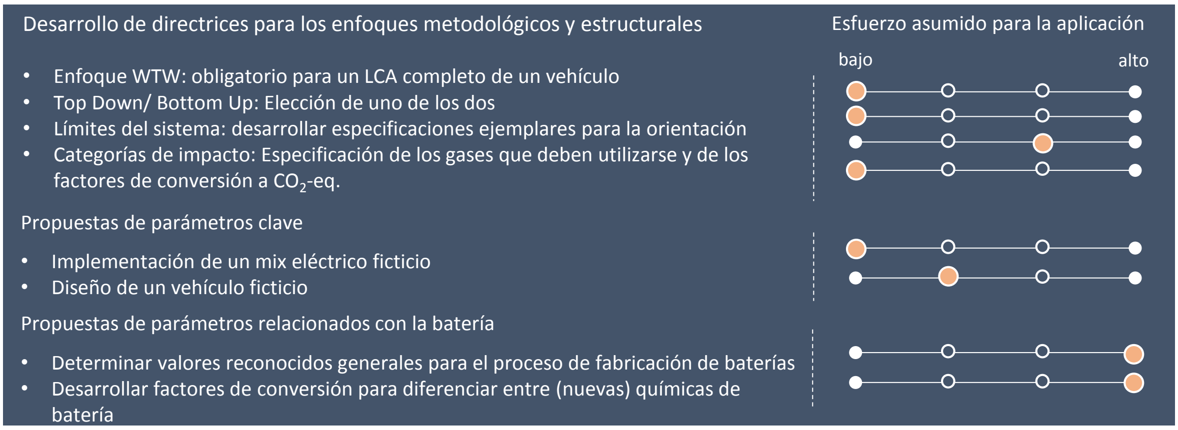


Figura 1: Resumen de los resultados divergentes de los LCAs actuales de los vehículos eléctricos

Para permitir la comparabilidad de los resultados de la LCA en el futuro, se requieren especificaciones más estrictas y uniformes. Por lo tanto, se presentan propuestas para mejorar el valor informativo de los futuros LCAs. Además, se explica que el enfoque actual de evaluación de las tecnologías existentes debería desarrollarse para centrarse en las condiciones marco y los parámetros que deben aplicarse para definir determinados objetivos medioambientales.



Desarrollo de directrices para los enfoques metodológicos y estructurales

- Enfoque WTW: obligatorio para un LCA completo de un vehículo
- Top Down/ Bottom Up: Elección de uno de los dos
- Límites del sistema: desarrollar especificaciones ejemplares para la orientación
- Categorías de impacto: Especificación de los gases que deben utilizarse y de los factores de conversión a CO_2-eq.

Propuestas de parámetros clave

- Implementación de un mix eléctrico ficticio
- Diseño de un vehículo ficticio

Propuestas de parámetros relacionados con la batería

- Determinar valores reconocidos generales para el proceso de fabricación de baterías
- Desarrollar factores de conversión para diferenciar entre (nuevas) químicas de batería

Figura 2: Resumen de las propuestas y esfuerzo asumido para su implementación

Utilizando el modelo desarrollado en el Capítulo 5, es posible demostrar los posibles ahorros de GEIs y sensibilizar sobre la necesidad de las estrategias de EOL. En este contexto, se aclara que la evaluación de las estrategias de EOL como crédito para un vehículo existente puede causar una consideración redundante en los LCAs. Por lo tanto, las mejoras de las estrategias de EOL deben estar siempre relacionadas con la próxima generación de un vehículo..

El cálculo muestra que es posible lograr un gran ahorro de GEI emitidos mediante la aplicación de estrategias de EOL. Sin embargo, el potencial de reducción de emisiones en el proceso de fabricación de baterías no se aprovecha plenamente debido a la novedad de la tecnología. Por lo tanto, los ahorros estimados para el vehículo restante son mucho mayores que para la batería. Por consiguiente, puede suponerse que la mayor parte de la investigación se centrará en la tecnología de las baterías. Además, es necesario introducir cambios estructurales que permitan aplicar y establecer con éxito las estrategias de la EOL. Estos tienen que ser apoyados y acelerados por regulaciones políticas y legales. Al introducir directrices basadas en los conceptos de una EC, surgirán nuevos mercados que podrán ser utilizados por los participantes a través de innovaciones disruptivas en el diseño de productos y modelos de negocio innovadores.

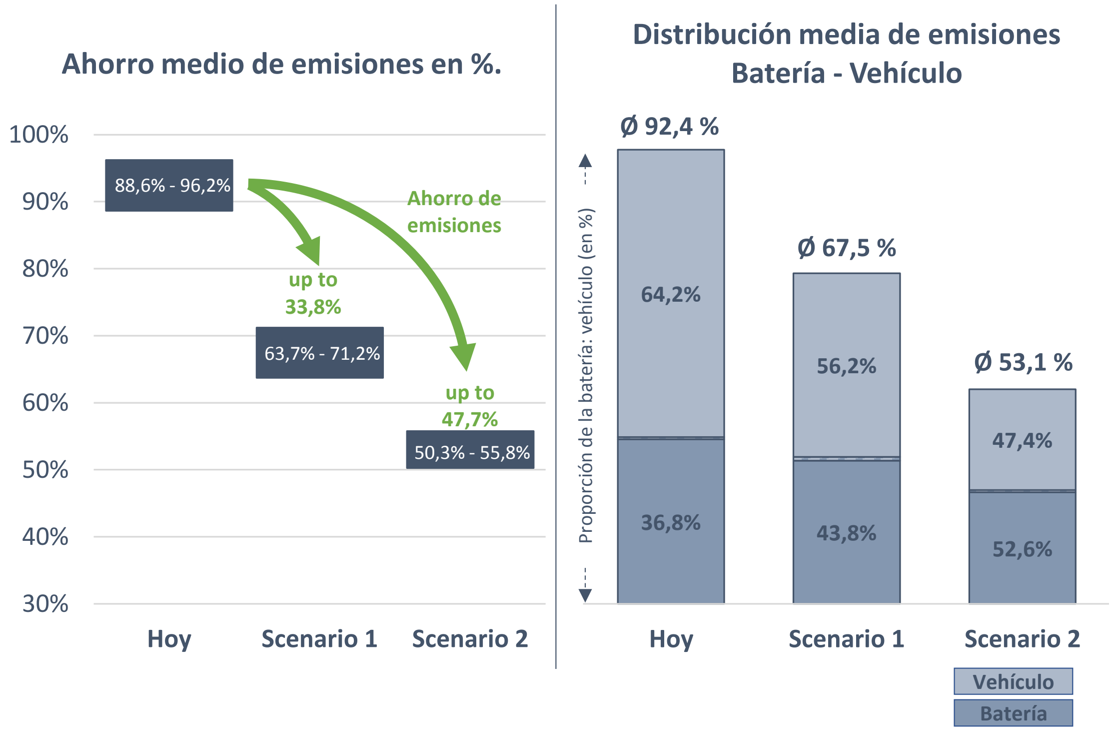


Figura 3: Resultados resumidos del análisis de escenarios

Pronóstico

La sustitución de la combustión interna por un motor eléctrico ofrece un potencial único para introducir cambios estructurales en toda una industria basada en el concepto de CE. Debido a la creciente demanda de transporte en todo el mundo, una implementación exitosa de las estrategias de EOL en la industria del automóvil puede servir como modelo y representar un importante efecto sinérgico para otras industrias. Si se superan los obstáculos del sistema multilateral global y se crean regulaciones nacionales congruentes, se puede revolucionar el sector de la automoción para dar forma al futuro de la electromovilidad.

Referencias

Hall, D. and Lutsey, N. (2018), “Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions. Briefing”, Internatinal Council of Clean Transportation - ICCT.

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LIFECYCLE ASSESSMENT OF ELECTRIC VEHICLES – DEVELOPMENT OF A MODEL TO EVALUATE END-OF-LIFE STRATEGIES

Author: Merklinger, Maximilian

Supervisor: Fluchs, Sarah

Collaborating entity: ICAI - Comillas Pontifical University

PROJECT SUMMARY

Introduction

One of the long-term consequence of the constant overconsumption and reduction of earth resources are high emissions of climate-damaging greenhouse gases (GHGs). According to the special report of the Intergovernmental Panel on Climate Change (IPCC), it is imperative to limit global warming to 1.5 degrees Celsius by the end of this century to remain in control of climate change (IPCC, 2018; Reimer, 2018) . Consequently, the reduction of climate-damaging GHGs is of great importance for the global society. Ecological impacts have to be quantified by holistic measurement instruments such as Lifecycle Assessment (LCA). In this context, the sector of transport and mobility is one of the main emitters of GHGs.

Motivation and aim of the thesis

One possible concept to reduce GHGs in the automotive sector is the optimisation of the manufacturing process by considering the entire added value as a regenerative system. Such a system concentrates on the sustainable recovery of all materials and components through the establishment of closed energy and material loops (e.g. recycling). With regard to the automotive sector, this means that the more components of an end-of-life (EOL) vehicle can be recovered, the more sustainable the ecological assessment becomes. For this purpose it is inevitable to further develop and research the establishment of material flow cycles to preserve and reuse any added value for as long as possible. The implementation of closed loops is concluded by so called EOL-strategies. For this reason, the potential for savings of GHG emissions in the mobility sector shall be described within the scope of this thesis by applying EOL-strategies, using the example of electric vehicles. However, a holistic ecological evaluation of a vehicle requires an intensive analysis of large amounts of data and in some cases very complex material flows. Otherwise, the generated emissions over the entire life cycle cannot be determined and published. However, the last stage of the product life cycle is currently scarcely considered in the context of LCA of (electric) vehicles. According to the current state of research, there are few to no valid data on the (positive) quantitative influence of using EOL-strategies (Hall and Lutsey, 2018, p. 4). However, due to the strong (political) promotion and targeting of expanding sales figures, the establishment

of electric vehicles is inevitable. Hence, the general question is not if electric vehicles should be established or to what extent the drive technology of the electric motor is more beneficial in term of emissions loads. It is rather what measures can be taken to further support the establishment and develop the applied technologies. Hence, this thesis aims to create a better understanding of the positive ecological impact EOL-strategies can have in the context of a sustainable manufacturing process.

Methodology

After a short introduction, in Chapter two the need for the shift towards a Circular Economy (CE) is described in detail. For this purpose, it will be outlined why the currently established linear economy cannot guarantee a sustainable economic structure in the future. After the description and analysis of the theoretical origins of a CE, a scientific research based definition of CE and its advantages are presented. Subsequently the concept of EOL-strategies is examined to be able to understand what the term means and in what context they become necessary. Hereby, the key EOL-strategies are defined, including the consideration of characteristic advantages and disadvantages. Finally, it is pointed out how the concept of CE is currently implemented in the European Union.

Chapter three takes up the insights gained and explains how the environmental sustainability of products or services can be measured. In this context, the methodology of LCA is described, including the requirements of the internationally acknowledged standard DIN ISO 14040.

Further, in chapter four the results of current LCAs, applied in the automotive industry and in particular for electric vehicles, are analysed and evaluated. The analysis is primarily based on the question of whether the findings of different LCAs of electric vehicles can be compared in quantitative terms. The answer to this question is the basic prerequisite for the model of EOL-strategies. If current LCA results do not permit a quantitative assessment of ecological benefits using EOL-strategies, the model must be carried out on a theoretical and conceptual level. In addition, the results of the analysis will be used to describe proposals with the aim to increase the comparability of future LCA results.

The mathematical model of EOL-strategies is developed and described in chapter five. Subsequently, based on an exemplary calculation, percentage savings of emissions are presented to demonstrate the possible ecological benefits. In this context, several assumptions will be taken, which are necessary to simplify the calculation. Finally, it is clarified which innovations regarding the manufacturing of a vehicle and new business model would be necessary to enable a successful implementation of EOL-strategies.

Chapter six summarises the gained findings and gives an outlook on possible extensions and refinements of the approach. In this context, current developments in the context of climate protection are described and linked to the results of this thesis.

Results and Conclusions of this thesis

The transformation from a linear to a CE is an urgent necessity. This transformation requires fundamental structural changes in the way society produces, consumes and exploits goods and services. For this reason, all phases of a product life cycle have to be analysed. The integration of EOL-strategies is essential, since manufacturing characterises the indispensable main element of a CE. In this context, LCAs are an important measurement tool. However, by analysising the current literature it becomes clear that the current norm for LCAs offers too much scope for subjective assumptions. Accordingly, the results diverge widely, and the determination of an adequate range regarding the generated emissions during an electric vehicles lifetime as well as the manufacturing of the battery is not feasible.

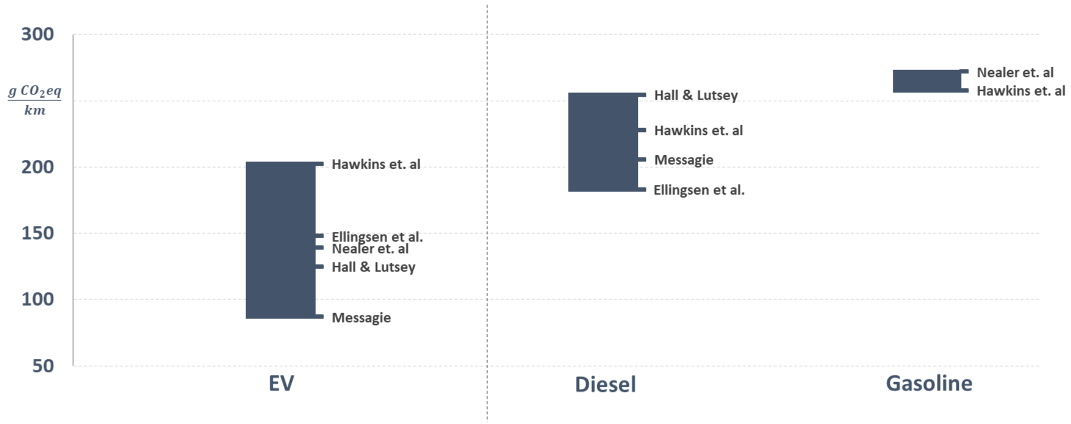
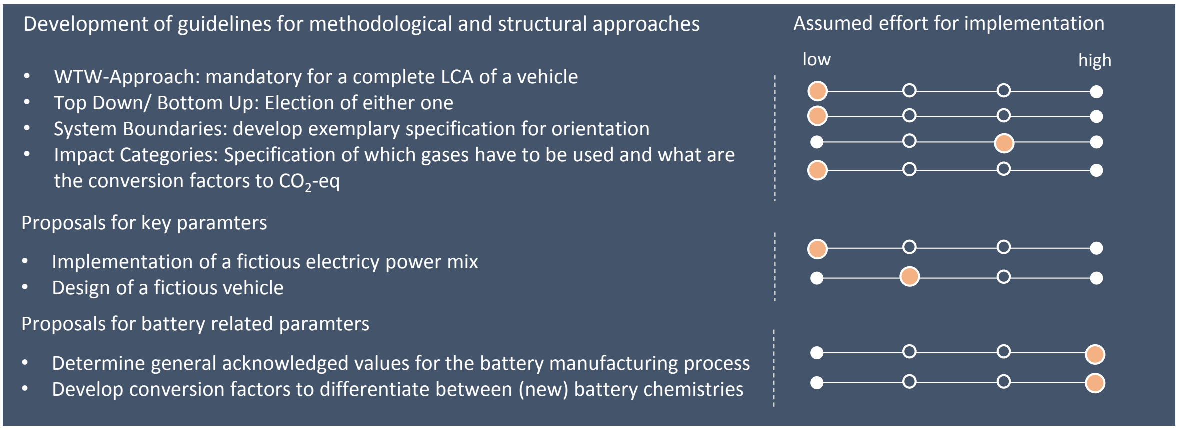


Figure 1: Summary of widely divergy results of current LCAs of electric vehicles

To enable the comparability of LCA results in the future, stricter and uniform specifications are required. Therefore, proposals are presented to enhance the informative value of future LCAs. Furthermore, it is elaborated that the current approach of assessing existing technologies should be developed to focus on what framework conditions and parameters need to be applied to define certain environmental objectives.



Development of guidelines for methodological and structural approaches	Assumed effort for implementation low			high
WTW-Approach: mandatory for a complete LCA of a vehicle	●	○	○	○
Top Down/ Bottom Up: Election of either one	●	○	○	○
System Boundaries: develop exemplary specification for orientation	○	○	●	○
Impact Categories: Specification of which gases have to be used and what are the conversion factors to CO_2-eq	●	○	○	○
Proposals for key paramters				
Implementation of a fictious electricy power mix	●	○	○	○
Design of a fictious vehicle	○	●	○	○
Proposals for battery related paramters				
Determine general acknowledged values for the battery manufacturing process	○	○	○	●
Develop conversion factors to differentiate between (new) battery chemistries	○	○	○	●

Figure 2: Summary of proposals and the assumed effort for implementation

By using the developed model in Chapter 5, it is possible to demonstrate possible GHG savings and to sensitise for the need of EOL-strategies. In this context, it is clarified that the assessment of EOL-strategies as a credit for an existing vehicle can cause a redundant consideration in LCAs. Therefore, improvements of EOL-strategies should always be related to the next generation of a vehicle.

The calculation shows that great savings of emitted GHGs are feasible through the application of EOL-strategies. However, the potential for reducing emissions within the battery manufacturing process is not fully exploited due to the novelty of the technology. Hence, the estimated savings for the remaining vehicle are much greater than for the battery. Consequently, it can be assumed that the greater focus of research will remain focused on battery technology. Furthermore, structural changes are necessary to enable a successful implementation and establishment of EOL-strategies. These have to be supported and accelerated by political and legal regulations. By introducing guidelines based on the concepts of a CE, new markets will emerge which can be used by participants through disruptive innovations in product design and innovative business models.

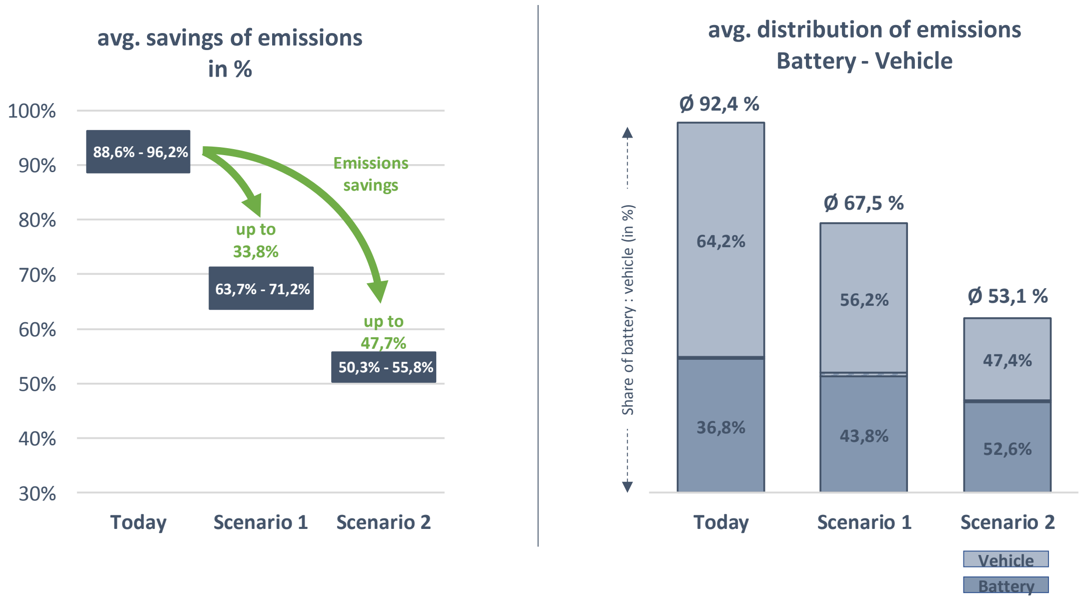


Figure 3: Summarised results of the scenario analysis

Outlook

The replacement of the internal combustion by an electric engine offers unique potential to introduce structural changes within an entire industry based on the concept of CE. Due to the rising demand for transportation worldwide, a successful implementation of EOL-strategies in the automotive industry can serve as a model and represent an important synergy effect for other industries. If the hurdles of the global multilateral system can be overcome and congruent national regulations created, the automotive sector can be revolutionised in order to shape the future of electromobility.

References

Hall, D. and Lutsey, N. (2018), “Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions. Briefing”, Internatinal Council of Clean Transportation - ICCT.

IPCC (2018), Summary for Policymakers: Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, Special report, [Geneva, Switzerland].

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I. Table of Contents

II. List of Abbreviations

abbreviation	description
apra	Automotive Parts Remanufacturer Association Europe
bpb	German Federal Agency for Civic Education
BOM	Bill of Materials
CE	Circular Economy
CEN	European Committee for Standardisation
CO_2-eq	CO_2-equivalent
CRR	Center for Remanufacturing and Reuse
EEA	European Environment Agency
e.g.	exempli gratia
EOL	End-of-Life
EPEA	Environmental Protection Encouragement Agency
EU	European Union
g	gram
GHG	Global Greenhouse Gas
GWP	Global Warming Potential
ICCT	International Council on Clean Transportation
ICEV	Internal Combustion Engine Vehicle
IPCC	Intergovernmental Panel on Climate Change
kg	kilogram
km	kilometer
KrWG	Closed Substance Cycle Waste Management Act (in German: Kreislaufwirtschaftsgesetz)
kWh	Kilo watt hour
LCA	Lifecycle Assessment
P1, P2, P3	Optimisation Potential 1, 2, 3
TTW	Tank-to-Wheel
UNEP	United Nations Environment Programme
VDI	Association of German Engineers (in German: Verband deutscher Ingenieure)
WTT	Well-to-Tank
WTW	Well-to-Wheel

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1 Introduction

1.1 Background

Our world is living beyond its means. Statistically speaking, on the first of August 2018 more resources were already consumed by mankind than can grow back within the same year. The so-called Earth Overshoot Day[1] was never reached so early in the past. This result was even positively influenced by less resource consuming Emerging and Developing countries. Industrialised nations exceeded their national Earth Overshoot Day much earlier[2] (n-tv, 2018; Umweltbundesamt, 2018b).

One of the long-term consequence of this constant overconsumption and reduction of earth resources are high emissions[3] of climate-damaging greenhouse gases (GHGs). According to the special report of the Intergovernmental Panel on Climate Change (IPCC), it is imperative to limit global warming to 1.5 degrees Celsius by the end of this century to remain in control of climate change. Therefore, global GHG emissions have to be halved until 2030. If this does not succeed, large quantities of GHG, e.g. from frozen methane deposits, are released into the atmosphere and an independent and uncontrollable natural process will set in that would cause irreversible natural damages (IPCC, 2018; Reimer, 2018). Consequently, the reduction of climate-damaging GHGs is of great importance for the global society. In this context, multinational political agreements such as the Paris Climate Convention or the Kyoto Protocol have been defined to reduce global GHG emissions. However, these form only the basic prerequisite for legal regulations. The responsibility for their implementation lies with the individual nations due to the global multilateral system. To achieve the feasibility of the set goals, clear (disruptive) concepts are required. Thus, the main GHG emission drivers for the individual industries must be analysed in detail to identify and develop specific optimisation potentials.

The main emitters of GHGs are the sectors transport and mobility, manufacturing industries and construction as well as energy industries (Umweltbundesamt, 2016a). In this context, the transport and mobility sector is particularly important. „Transport is fundamental to our economy and society“ and „enables economic growth and job creation: it must be sustainable

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[1] Earth Overshoot Day: Day of a year at which the global supply of natural resources is exhausted for the entire year. The world population's demand is consequently greater than the supply of natural resources. There is not enough biocapacity and from this day on, the earth's natural stock is consumed and mankind creates ecological debts. The Earth Overshoot Day is calculated and published annually by the Global Footprint Network (Pufé, 2012, p. 21; Global Footprint Network, 2018).

[2] The German population has been living above its means since the beginning of May 2018 (n-tv, 2018).

[3] In the context of this thesis, the term emissions always refers to GHG emissions, even if this is not explicitly stated.

in the light of the new challenges we face“ (European Commission, 2011, p. 3). One of the current key and most debated challenges within this sector is the replacement of the internal combustion engine powered by gasoline and diesel. Accordingly, for several years the automotive industry has been researching and developing alternative drive technologies. In this context, a specific focus is placed on battery-powered electric cars because they represent the only notable technology to enable “a comprehensive integration of renewable energies in the transport sector” in the long-term (Forschungsstelle für Energiewirtschaft (FfE) e.V., 2018, pp. 6–7). Due to the strong (political) promotion and targeting of expanding sales figures, the establishment of electric vehicles is inevitable. Companies like Tesla have drastically increased the international attention to electric mobility. In the meantime, all well-known automobile manufacturers list battery-powered vehicles in their portfolios or are on the way to placing new models on the market soon. Furthermore, new manufacturers are entering the market and exerting additional pressure on the automotive industry. The German government has formulated the ambitious target of one million electric vehicles on Germany's roads by 2020[4] (BMWI, 2018). Hence, the general question is not if electric vehicles should be established or to what extent the drive technology of the electric motor is more beneficial in term of emissions loads. It is rather what measures can be taken to further support the establishment and develop the applied technologies.

Imagining an electrically powered vehicle that generates no emissions while being driven is tempting. However, sustainable assessment also requires consideration of cross-sectoral impacts. In general, the battery of an electrically powered vehicle is charged by connecting it to the national electricity grid. If this electricity is gained by using fossil fuels and not regenerative energies, the vehicle is fed with electricity that has been generated by emitting CO_2. While the automotive industry can promote emission-free mobility by electric vehicles and present its fleet balance more ecologically sustainable, the energy production sector has to justify the additional CO_2 emissions. Consequently, the emissions are not eliminated, but only transferred from one industry to another. In addition, the energy-intensive manufacturing of batteries and the processing of many rare metals generate emissions that do not exist in the manufacturing of a conventional vehicle. Therefore, savings in GHG emissions in the mobility sector can lead to reciprocal increases in the sectors of energy production and manufacturing industries.

Hence, ecological impacts have to be quantified by holistic measurement instruments such as Lifecycle Assessment (LCA). Due to the continuous reduction of emissions in the field of power generation through the defined goals of integrating renewable energy more strongly, the future LCA results of electric vehicles will decrease in absolute values. Since energy generation is the only emission contributor in the use phase of an electric vehicle, savings are easier to generate than in the manufacturing phase. This implies that the percentage of emissions caused by the use phase will decrease, while the percentage of emissions from the manufacturing process will increase at the same time. Therefore, the manufacturing process

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[4] Even though this objective has already been reduced by the current German Chancellor Angela Merkel, the increased interest in electromobility is still evident (BMWI, 2018).

must be focus of optimisation regarding the aim of further improving the results of future LCAs of electric vehicles.

One possible concept for the long-term optimisation of the manufacturing process is based on the objective to consider the entire added value as a regenerative system. Such a system concentrates on the sustainable recovery of all materials and components through the establishment of closed energy and material loops. First approaches, e.g. through recycling, are already in use. With regard to the automotive sector, this means that the more components of an end-of-life (EOL) vehicle can be recovered, the more sustainable the ecological assessment becomes. For this purpose it is inevitable to further develop and research the establishment of material flow cycles to preserve and reuse any added value for as long as possible. The implementation of closed loops is concluded by so called EOL-strategies. For this reason, the potential for savings of GHG emissions in the mobility sector shall be described within the scope of this thesis by applying EOL-strategies, using the example of electric vehicles.

1.2 Research Problem and Aim

A holistic ecological evaluation of a vehicle requires an intensive analysis of large amounts of data and in some cases very complex material flows. Otherwise, the generated emissions over the entire life cycle cannot be determined and published. However, the last stage of the product life cycle is currently scarcely considered in the context of LCA of (electric) vehicles. According to the current state of research, there are few to no valid data on the (positive) quantitative influence of using EOL-strategies (Hall and Lutsey, 2018, p. 4). For this reason, the aim of this thesis is to develop a model to examine how EOL-strategies can be integrated in LCAs of electric vehicles. Furthermore, based on the results and findings of current LCAs, this model is used to show possible reductions in emissions over the life cycle of an electric vehicle.

1.3 Disposition

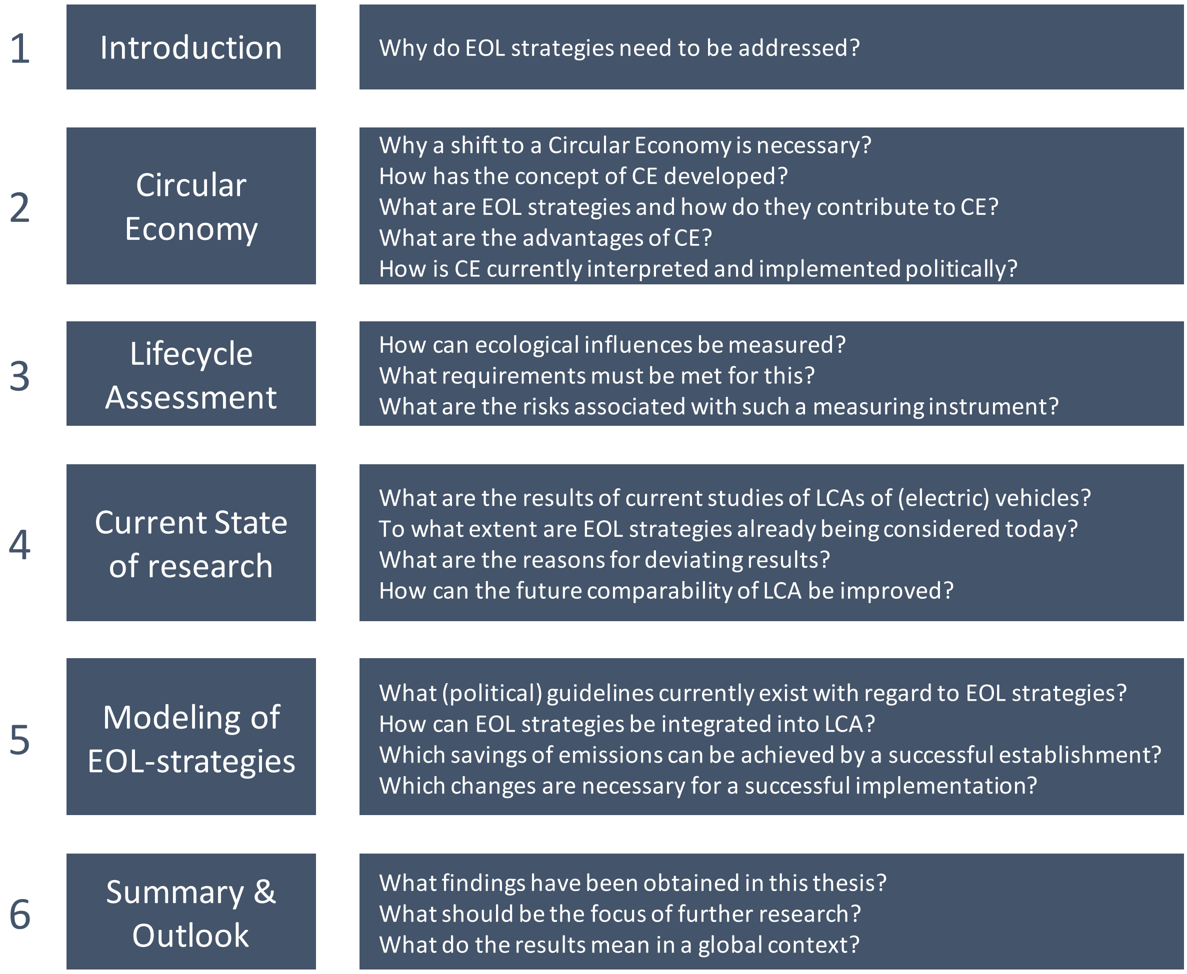
In Chapter two the need for the shift towards a Circular Economy (CE) is described in detail. For this purpose, it will be outlined why the currently established linear economy cannot guarantee a sustainable economic structure in the future. After the description and analysis of the theoretical origins of a CE, a scientific research based definition of CE and its advantages are presented. Subsequently the concept of EOL-strategies is examined to be able to understand what the term means and in what context they become necessary. Hereby, the key EOL-strategies are defined, including the consideration of characteristic advantages and disadvantages. Finally, it is pointed out how the concept of CE is currently implemented in the European Union.

Chapter three takes up the insights gained and explains how the environmental sustainability of products or services can be measured. In this context, the methodology of LCA is described, including the requirements of the internationally acknowledged standard DIN ISO 14040.

Further, in chapter four the results of current LCAs, applied in the automotive industry and in particular for electric vehicles, are analysed and evaluated. The analysis is primarily based on the question of whether the findings of different LCAs of electric vehicles can be compared in quantitative terms. The answer to this question is the basic prerequisite for the model of EOL-strategies. If current LCA results do not permit a quantitative assessment of ecological benefits using EOL-strategies, the model must be carried out on a theoretical and conceptual level. In addition, the results of the analysis will be used to describe proposals with the aim to increase the comparability of future LCA results.

The model of EOL-strategies is developed and described in chapter five. Subsequently, based on an exemplary calculation, percentage savings of emissions are presented to demonstrate the possible ecological benefits. In this context, several assumptions will be taken, which are necessary to simplify the calculation. Finally, it is clarified which innovations regarding the manufacturing of a vehicle and new business model would be necessary to enable a successful implementation of EOL-strategies.

Chapter six summarises the gained findings and gives an outlook on possible extensions and refinements of the approach. In this context, current developments in the context of climate protection are described and linked to the results of this thesis.



1	Introduction	Why do EOL strategies need to be addressed?
2	Circular Economy	Why a shift to a Circular Economy is necessary? How has the concept of CE developed? What are EOL strategies and how do they contribute to CE? What are the advantages of CE? How is CE currently interpreted and implemented politically?
3	Lifecycle Assessment	How can ecological influences be measured? What requirements must be met for this? What are the risks associated with such a measuring instrument?
4	Current State of research	What are the results of current studies of LCAs of (electric) vehicles? To what extent are EOL strategies already being considered today? What are the reasons for deviating results? How can the future comparability of LCA be improved?
5	Modeling of EOL-strategies	What (political) guidelines currently exist with regard to EOL strategies? How can EOL strategies be integrated into LCA? Which savings of emissions can be achieved by a successful establishment? Which changes are necessary for a successful implementation?
6	Summary & Outlook	What findings have been obtained in this thesis? What should be the focus of further research? What do the results mean in a global context?

Figure 1-1: Addressed key questions to answer the research problem of this thesis

2 Concept of the Circular Economy

2.1 Issues of linear economy

CE is the development of the linear economy, which is currently mainly applied in the global economic area. This model was introduced during the Industrial Revolution and is limited to an unidirectional value chain (McKinsey & Company, 2016, pp. 2–3). The Industrial Revolution took place without a clearly defined long-term objective. Its principle was the desire for economic growth. With the transition from manual to mechanical production, it was possible to produce goods in previously impossible productivity and offer them to a broad mass (Braungart and McDonough, 2008, pp. 18–24). A typical linear economic approach describes the structure of a product as follows: “Extract-Make-Use-Dump“ (Korhonen *et al.*, 2018, p. 39). Simplified, the concept implies that resources are extracted (acquired), further processed under the influence of energy and labor and then sold as goods. The value creation is maintained by consumers disposing the used goods in order to purchase new goods afterwards (McKinsey & Company, 2016, pp. 2–3). At the end of the process, the used resources will be returned to nature as waste and emissions and are accepted as collateral damage (Korhonen *et al.*, 2018, pp. 38–39). Newly created possibilities and increasing quality of life have pushed ecological consequences out of the focus (Braungart and McDonough, 2008, pp. 18–24). So far, the general assumption has been that the habitat will permit the constant growth, including the increasing world population, the enormous consumption of resources and the release of emissions. Any obstacles would be overcome by science and technology (Meadows *et al.*, 1972, 17; 170-173).

Until today, the industrial infrastructure is designed to maximise (economic) growth (Frosch and Gallopoulos, 1989, p. 6). Ecological and social factors like enjoyment and delight, but also cultural richness are still of secondary importance (Braungart and McDonough, 2008, p. 42). However, it was already brought into the awareness to a broad global audience for the first time in the 70s by the best seller "Limits to growth" that this approach may obtain major ecological hazards in the long-term (Sachs, 2005, p. 30). Such a “take-make-dispose“ (McKinsey & Company, 2016, p. 5) approach is by nature very wasteful and does not focus on the optimal use of individual resources and raw materials (McKinsey & Company, 2016). Consequently, in 2016 a volume of 2.01 billion tons of solid waste[5] was generated worldwide, of which about one third was treated in an environmentally unsustainable manner. This volume will increase by 70% to 3.40 billion tons by 2050 (World Bank, 2018, p. 3). Due to the constant overconsumption Lester R. Brown[6] describes the Earth's ecosystem as a shrinking system.

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[5] Solid waste refers to residential, commercial, and institutional waste. Industrial, medical, hazardous, electronic, construction and demolition waste are considererd seperately (World Bank, 2018, p. 17).

[6] Lester R. Brown is the founder of the Earth Policy Institute and was named by the Washington Post as „one of the world’s most influential thinkers“, pioneering the concept of environmentally sustainable development. (http://www.earth-policy.org)

His position is justified with simple quantitative assumptions. As a mathematical reference value, he uses the surface of the earth that supports human life. Due to the increasing world population, growing deserts, a higher sea level and the high consumption per capita, the life-supporting area of the earth is constantly reduced (Brown, 2006). Current global growth forecasts confirm this simplified equation by Brown. According to the Finnish innovation fund Sitra[7], the world's population will grow by another 1.5 billion over the next 15 to 20 years. In the same period, an additional 3 billion people will belong to the middle class. 70% of the world's population will live in cities with a population of 10 million or more. The demand for energy will increase by 32% and for water even by 139% (Sitra, 2015, p. 6). As a consequence, the United Nations Environment Programme (UNEP) has published, that if current consumption patterns remain unchanged, the general resource consumption would triple by 2050 (UNEP, 2011, pp. 28–29).

Besides these ecological and social consequences of the linear economy, nowadays there are also increasing economic impairments. One important factor guaranteeing rapid economic growth were the low resource costs in most parts of the 20th century. Since the availability of raw materials is decreasing resource prices have risen sharply in recent years. This high, volatile level is likely to remain for at least the next 20 years (Preston, 2012, pp. 2–3). Hence, a linear economic structure causes negative consequences for all three pillars of sustainability[8]. Consequently, Meadows et al. have shown that the Earth's growth limits will be reached by the year 2070, if the global lifestyle remains the same. The result would be a rapid decline in the global population. (Meadows *et al.*, 1972, 17; 170-173).

To front these challenges, it is necessary to create structural changes and identify in whose responsibilities the required actions lie in. Just focusing the investigations on global corporations and political parties to take them responsible for the negative effects of the linear economy may not meet the complexity of the problem (Braungart and McDonough, 2008, pp. 42–44). Economic success is the basis for long-term existence and ultimately also responsible for the fact that the remuneration of billions of workers enables the high standard of living in many parts of the world (Frosch and Gallopoulos, 1989, p. 1). Waste, emissions or crude products[9] are not only the result of intentional malpractice or pure economic greed by the operating companies. Instead they are more the “consequence of outdating and unintelligent design“ (Braungart and McDonough, 2008, p. 43). Hence, the transformation of the economic structure is a global social responsibility which must be supported above all by uniform political

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[7] Sitra is an “active fund for the future, who studies researches and brings together partners from different sectors in open-minded trials and reforms“. Their future-oriented work is aimed at making Finland suceed as a pioneer of sustainable well-being. https://www.sitra.fi/en/

[8] The three pillars of sustainability are Economy, Ecology and Social Matters and are described as the basis for the definition of sustainability. However, no weightings of the respective pillars are defined within the model (Pufé, 2012, p. 109).

[9] Crude products are not desiged to support ecological and human health. They just fulfill the manufacturers desire and customers expectation (Braungart and McDonough, 2008, p. 37).

incentives and corresponding actions of all value-creating corporations (Braungart and McDonough, 2008, pp. 42–44).

To solve this problem, UNEP has presented a concept for decoupling the use of natural resources and the corresponding environmental damage from economic growth. In this context, decoupling means reducing the processed raw materials respectively the resulting emissions per product unit (UNEP, 2011, p. 4). In today's linear economy recycling already represents a major priority. Nonetheless, the focus is primarily on reducing the extraction of raw materials. Although this is a positive development with the aim of creating a sustainable economic system, the overall system itself remains linear and accordingly wasteful (Preston, 2012, pp. 3–4). To solve a fundamental structural problem, it is not sufficient to just modify individual settings of the existing system. Technical, economic or legal solutions alone are not enough. A completely new system approach is needed to overcome these challenges (Meadows *et al.*, 1972, pp. 170–173). One simple answer to the dilemma of linear flows is the exact opposite: Create a circular economic structure by focusing on the physical flows between nature and men (Brown, 2006; Korhonen *et al.*, 2018, pp. 37–39).

2.2 Roots of the Circular Economy

The roots of the theory of a CE can be traced back to the findings of many authors. Accordingly, several sources need to be mentioned for a well-founded description of the origins of the CE. Basically, the concept gained popularity almost 50 years ago in the course of the 1970s with the first applications to economic and industrial systems and processes (Ellen MacArthur Foundation, 2018). The report by Walter Stahel[10] and Geneviève Reday for the Commission of the European Communities from 1976, in which they described concepts of a circulating economic structure, is one of the bases for the concepts developed over the years regarding a CE[11]. Stahel evaluates the influence of a closed loop economy on the development of jobs, competitiveness and resource consumption as well as the avoidance of waste (Product-Life Institute, 2018).

2.2.1 Industrial Ecology – Frosch and Gallopoulos 1989

One of the first theories which can be related to the CE was the concept of Industrial Ecology (Preston, 2012, p. 3). The theory was introduced to a broad public by Frosch and Gallopoulos in 1989 and further expanded by Thomas Graedel[12]. Industrial Ecology concentrates on the

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[10] As the founder of the Geneva Institute for Product Life Institute, Stahel has intensively researched the effects of a properly operating CE (Product-Life Institute, 2018).

[11] His study was subsequently made available to the public through the book "Jobs for Tomorrow, the Potential for Substituting Manpower for Energy".

[12] Thomas Graedel was elected to the U.S. national Academy of Engineering for “outstanding contributions to the theory and practice of industrial ecology, 2002.” https://environment.yale.edu/profile/graedel/

analysis of material and energy flows in a specific system (Ellen MacArthur Foundation, 2018; Webster, 2017, pp. 51–52). The concept focuses on the development of the established value creation into an industrial ecosystem. Such a system should optimise energy and material usage as well as the reduction of generated waste. Industrial Ecology is based on the principles of biological ecosystems, in which the separated waste of an organism serves as a source of another organism (Frosch and Gallopoulos, 1989). After all, every industrial system is dependent on the resources of the biosphere (Erkman, 1997, p. 1). This is why the terminology "ecology" is used. Resources should be preserved and reused in the best possible way - exactly as it is done in biological systems (Graedel, 1996, pp. 70–75). In this way any unwanted by-products in a system can be eliminated (Webster, 2017, pp. 51–52). The development towards new economy structure is carried out by creating closed loops in which the products can circulate within the system (Ehrenfeld and Gertler, 1997, p. 68; Webster, 2017, pp. 51–52; Ellen MacArthur Foundation, 2018). Individual systems should be considered in harmony with their environment rather than separately from each other (Graedel, 1996; Erkman, 1997, p. 1). Therefore, the recycling of by-products as raw materials is fundamental for this concept (Ehrenfeld and Gertler, 1997, p. 68). The entire cycle from raw materials to further processing of any kind must be continuously optimised (Graedel, 1996, pp. 70–75). To achieve the requirements of Industrial Ecology, energy should be used efficiently through cascading[13]. Accordingly, Industrial countries must be persuaded to adapt their production and consumption patterns and Developing and Newly Industrialised countries must be convinced and financially supported to use new technologies. If this succeeds, a sustainable, environmentally friendly economic system can be created (Frosch and Gallopoulos, 1989, p. 1).

However, Frosch and Gallopoulos are aware that a perfect economic system, supported by circulating materials, requires great efforts. Thus, to ensure successful implementation, it is necessary to create government incentives and sanctions that on the one hand support and encourage companies willing to change their operations and on the other hand leave resistant companies with only a financially unprofitable choice. By increasing landfill storage costs companies can be forced to reduce waste volumes, develop efficient processes and constantly optimise them (Frosch and Gallopoulos, 1989). Due to its interdisciplinary approach, the concept of Industrial Ecology is often referred to as "science of sustainability" (Webster, 2017, p. 51), as it combines economic, ecological and social aspects and seeks to optimise them accordingly (Webster, 2017, pp. 51–52).

2.2.2 Natural Capitalism – Hawken, Lovins and Lovins 1999

The concept of Natural Capitalism contains a different approach in comparison to Industrial Ecology in order to establish a sustainable value creation. Hawken *et al.* (2000) argue that an economy needs four different types of capital, namely Human, Financial, Manufacturing and Natural, to operate properly (see Figure 2-1). The naming of the concept is justified by the fact

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[13] Energy which is generated during a manufacturing process can be stored in liquids and used as a heat source at a lower temperature in another process (Ehrenfeld and Gertler, 1997, p. 68).

that the Natural Capital is by far the greatest in comparison of all four types (Hawken *et al.*, 2000, pp. 2–10).

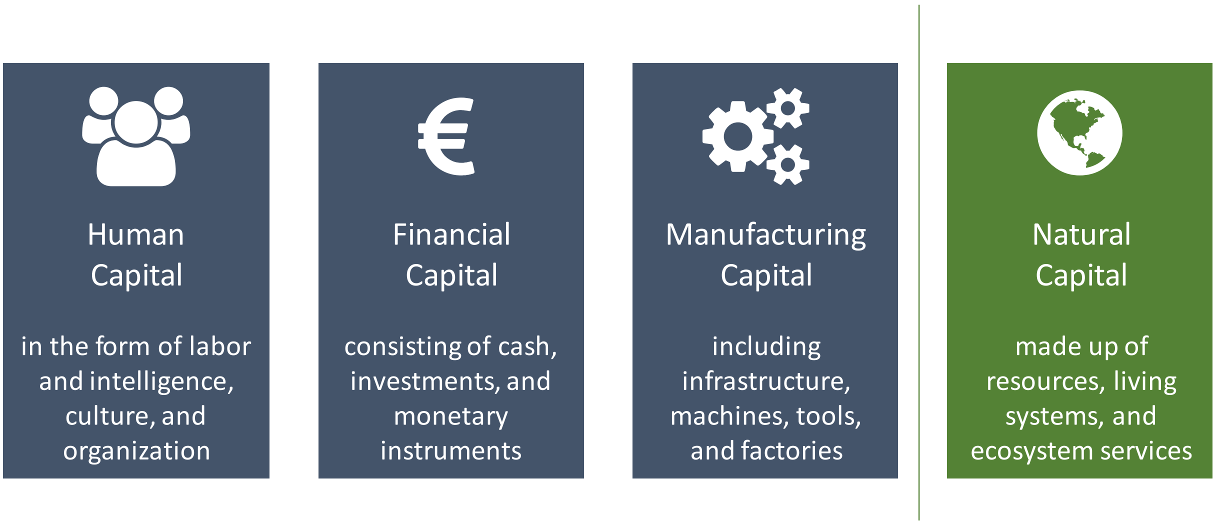

Figure 2-1: Four types of capital for an optimally operating economy[14]

Natural Capital contains all natural resources that our planet provides us with. Roughly summarised it can be described by the categories air, soil, water as well as all forms of living beings (Ellen MacArthur Foundation, 2018). The term living being is interpreted very broadly in this context. From bacteria, fungal structures and amphibians to coral reefs or oceans, all forms of living organisms correspond to this definition (Hawken *et al.*, 2000, pp. 2–10).

However, Natural Capital is only the ingredient for the first three types in order to manufacture any form of product regarding the current economic system. With the concept of Natural Capitalism, humanity should be sensitised that a “critical interdependency between the production and use of human-made capital and the maintenance and supply of natural capital“ (Hawken *et al.*, 2000, pp. 3–4) exists (Hawken *et al.*, 2000, pp. 2–10). Concerning the further development of the economic system, Hawken *et al.* have developed four basic principles, which must be applied to the common practices of the economy:

1. *Dramatically increase the productivity of natural resources*
2. *Shift to biologically inspired production models*
3. *Move to a solutions-based business model*
4. *Reinvest in natural capital*

The radical increase in the productivity of natural resources is the basis for the implementation of the other three principles. Optimal use of natural resources also serves all three pillars of sustainability. By applying those accordingly it is possible to achieve the necessary improvement to support the regenerating and restore processes of Natural Capital. (Ellen MacArthur Foundation, 2018; Hawken *et al.*, 2000, pp. 1–10; Lovins *et al.*, 1999, pp. 146–156).

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[14] Own represenation based on Hawken *et al.* (2000, pp. 2–10).

2.2.3 Cradle-to-Cradle Concept – Braungart & McDonough 2002

The Cradle-to-Cradle (C2C)[15] Concept by Braungart and McDonough can be classified in the field of theories of eco-effectiveness and life cycle analysis. C2C describes the necessary development of the Cradle-to-Grave approach, in which products or any by-products are returned to nature by being "buried" in their grave (respectively the biosphere) once they reach their EOL-stage. Consequently, Cradle-to-Grave can be interpreted as a synonym for the linear economy. By way of contrast, the C2C approach orients itself towards the natural processes. At the end of their life cycle, products are not waste, but the raw material for the next product (Pufé, 2012, p. 193). In this context Braungart & McDonough describe waste as food or nutrients (Braungart and McDonough, 2008, p. 5). Hence, (in accordance with the findings of Industrial Ecology) a completely waste-free economic cycle should be created (Bergius, 2009). Eliminating any form of waste requires that all kind of goods used in the entire global cycle of value creation can be reused infinitely or returned to nature without causing any damages.

From Cradle-to-Grave to Cradle-to-Cradle

In this context Braungart and McDonough explain that the earth can be divided into two elementary metabolisms, namely the biological[16] and the technical[17] metabolism (Braungart and McDonough, 2008, p. 97). Organic consumer goods which can be returned to the biological cycle after their use (e.g. by composting) circulate in the biological metabolism and durable goods in the technical metabolism. The goods of the technical metabolism are manufactured in such a way that all components, materials or raw materials can continuously (or at best infinitely) used after the end of their specific product lifecycle (EPEA, 2018).

Criticism of the notion of eco-efficiency

It is generally recognised that an increased focus on the efficient treatment of resources is essential to maintain future competitiveness and resilience, both for enterprises and for countries (Preston, 2012, pp. 2–3). However, Braungart and McDonough emphasise that for a successful implementation of the C2C concept, the focus should not be solely on increasing efficiency. In their opinion the term (eco-)efficiency creates a purely positive connection that does not correspond to reality. Processing materials with just maximum efficiency is not a feasible solution, if environmentally harmful substances remain being used (Braungart and McDonough, 2008, 4; 68-76). “More control (being „less bad“) is not the same as being good.“ (Braungart and McDonough, 2008, p. 4). If, for example, environmentally harmful chemicals are used in a production process, a reduction in the amount of processed substance is certainly

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[15] The term "Cradle to Cradle" was already used in the later 1970s by Walter R. Stahel to draw attention to the prerequisites as well as the necessity of a CE (Ellen MacArthur Foundation, 2018; Webster, 2017, p. 50).

[16] Biologicial metabolism refers to the so called biosphere, the cycles of nature (Braungart and McDonough, 2008, p. 97).

[17] Tecnological metablosim refers to the so called technosphere, the system of industrial processes (Braungart and McDonough, 2008, p. 97).

a step in the right direction, but by no means a satisfactory overall solution. To make it even more trivial, a starving child is not saved by being given something to eat every second instead of every third day. For this reason, Braungart and McDonough emphasise that it is important to assess what kind of efficiency is helpful in achieving an environmentally sustainable economic structure. Thus, the entire industrial concept of value creation must be fundamentally adapted to modern requirements (Braungart and McDonough, 2008, pp. 45–53).

Conclusion

Consequently, Braungart ad McDonough put the focus on “[r]emaking the way we make thing” (Braungart and McDonough, 2008). The manufacturing processes must be determined based on the valuable contents of the materials and (re-)use of the products after their life cycle should be the focus of attention (Braungart and McDonough, 2008, p. 104). Therefore, all manufacturing concepts require fundamental changes. In anticipation of a well operating CE, new product design and innovative business models are necessary. Hence, C2C is not a universal solution. It sees itself more as a "support strategy" (Braungart and McDonough, 2008, p. 6) to reduce emissions of billions of pounds of polluting material into the air, water and soil. The C2C concept is also not a ready-to-use approach for future product designs. It serves as an incentive to develop new production and sales opportunities (Braungart and McDonough, 2008, p. 6).

2.2.4 Performance Economy – Walter Stahel 2005

The concept of Performance Economy by Walter Stahel[18] represents an action concept which is able to fulfill the necessary requirements for a CE. As part of his research, Walter Stahel first stated in his award-winning article "The product life factor" that selling only the use of goods rather than selling themselves is the optimal strategy for a well operating sustainable economy. By applying this strategy it is possible for companies to increase the productivity of resources and at the same time reduce the externalisation[19] of costs through, e.g. waste (Product-Life Institute, 2018; Webster, 2017, p. 50).

According to Stahel, the economic structure must be developed from an Industrial Economy to a Performance Economy with the help of new strategies and innovative business models. This task concerns Industrial as well as Developing and Emerging countries. Stahel believes that this shift is a necessary step to overcome the shortcomings of the outdated assumptions of the Industrial Revolution (Stahel, 2010, pp. 1–10). In his opinion, "[t]he Performance Economy moves the economy towards sustainability" (Stahel, 2010, p. 5).

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[18] As the founder of the Product-Life-Institute, Geneva, Stahel has intensively researched the effects of a properly operating circular economy (Product-Life Institute, 2018).

[19] Externalisation refers to the transfer of private costs to the general public. Environmental pollution caused, for example, by logistical shipping is not covered by the responsable companies. The (climatical) consequences are shouldered by the general public (Pufé, 2012, p. 106).

The main advantage of a Performance Economy is that both the consumer and the producer have a strong interest in a reasonably priced and long-term viable product. Companies try to maximise the resilience of their products and design any component to be used optimally over a maximum period of time. The linear approach of maintaining value creation by developing and market products with integrated obsolescence is no longer applicable (Bergius, 2009). In the second, revised version of his book on Performance Economy, Stahel recognises that more and more companies are following the trend and focusing on selling services instead of goods. Accordingly, he assumes that the sale of services can be seen as "biggest driver of the transition from an industrial to a performance or functional service economy" (Stahel, 2010, xxii).

2.2.5 Additional concepts: Biomimicry and Blue Economy

Further noteworthy examples of the roots of a CE are Biomimicry by Janine Benyus from 1997 and Blue Economy by Gunther Pauli from 2010.

Benyus emphasises in her book "Biomimicry Innovation Inspired by Nature" that innovations should be based on nature's best ideas. In her opinion, nature gives us a variety of possible solutions to create sustainable approaches within the existing economic structure. As an example, Benyus cites the analysis of leaves to improve solar technologies. Her approach is based on three main principles (Ellen MacArthur Foundation, 2012, p. 27; Biomimicry Institute, 2018):

1. *Nature as model: Study nature’s models and emulate these forms, processes, systems, and strategies to solve human problems.*
2. *Nature as measure: Use an ecological standard to judge the sustainability of our innovations.*
3. *Nature as mentor: View and value nature not based on what we can extract from the natural world, but what we can learn from it.*

Another concept that has gained in popularity especially in the recent past is the Blue Economy by Gunther Pauli. The name is derived from the colour of the ocean, the earth and the dominant colour tone when looking at the earth from orbit. Blue Economy intends to indicate the necessity of a society living in harmony with nature. In accordance with the concepts presented in chapter 2.2.1 to 2.2.4 Pauli appeals for a close adaptation of industrial processes to the Earth's natural cycles. For this purpose, he establishes two main categories: Cascading Nutrients and Energy and Innovations Inspired by Laws of Physics (Pauli, 2011, pp. 1–4). Blue Economy tries to support the innovative thinking of entrepreneurs. Global concerns such as poverty should be combated with global solutions. New macro economical business models should also be implemented at the micro economical level (Iustin-Emanuel and Alexandru, 2014, pp. 201–202). According to Pauli, 100 million jobs could be created in the next 10 years (Pauli, 2011, pp. 1–4). Even though a verified confirmation of the feasibility of independent sources does not exist, the concept supports the sensitisation for a further development of the industrial value creation system.

Although these two concepts correspond the implementation of a CE, they do not represent any disruptive approaches compared to the concepts presented above. For this reason, this thesis refers to their existence, but does not provide a more detailed description.

2.2.6 Summary and comparism of the presented concepts

Industrial Ecology and Natural Capitalism sensitise for a transformation of the economic structure without presenting detailed strategies for a successful implementation. They highlight the need for closed loops to maximise the retention period of any component in the value chain and to minimise or eliminate waste. However, both studies base their argumentation structure on two different pillars. Industrial Ecology focuses very generally on the transformation of current value creation. The consideration of value creation as a holistic ecosystem is placed at the centre of the approach. Thereby, the interactions of different systems in the form of material and energy flows have to be taken into account. This is the only way to understand the overall system and to develop closed loops. On the other hand, Natural Capitalism focuses on the critical dependencies between natural raw materials and the produced goods[20]. The natural raw materials are defined as the source of any value added. Instead of using natural capital as a necessary utensil for the creation of goods, as currently the case, future goods must be developed in such a way that the value creation is based on the maximum sustainable use of natural capital.

Regarding to the aim of this thesis, the holistic approach of Industrial Ecology and the focus on closed loops within both concepts is the theoretical prerequisite for the development of EOL-strategies and accordingly also for the development of the mathematical model. Placing natural resources in the centre of attention should also play an important role in the automotive industry. Accordingly, it is necessary to analyse the components of a vehicle individually to achieve a sustainable manufacturing process. Components which have a high proportion of either low available raw materials, or materials whose related raw material extraction or manufacturing is associated with high environmental impacts, will become the focus of attention and optimisation.

However, both Industrial Ecology and Natural Capitalism only superficially illustrate how the establishment of cycles can be developed and implemented. Due to the complexity the development of closed loops is one of the main barriers regarding the implementation of a CE. The transformation of the entire value creation requires, in addition to the factor time, a high degree of investment as well as research and development expenditure. Disruptive innovations are particularly necessary for product engineering and subsequent manufacturing. Corresponding materials may not be sufficiently researched or not known at all to date. In this context, Industrial Ecology and Natural Capitalism describe the theoretical long-term goal of a value creation that is in complete harmony with nature. However, due to the urgent need of value creation with significantly lower GHG emissions, short-term improvements are required.

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[20] Although Industrial Ecology also focuses on the conservation of natural resources, it does not explicitly place it in the central focus of the work.

C2C addresses exactly this problem and represents a further development of the two previous theories by describing where detailed and innovative approaches for the implementation of closed loops can be applied. With the differentiation of a technical and natural cycle, it is possible to apply the closed loops realistically and to achieve short-term success in accordance with current technological capabilities. The technical cycle accepts the distinction between products, components and materials which can either be completely absorbed by nature or which are to remain in the cycle for a maximum (up to infinity) of time. Thus, all EOL-strategies presented at the end of this chapter and modelled in chapter 5 represent a possible implementation within this technical cycle.

To ensure a maximum retention time of the components, it is necessary to establish innovative business models. Performance Economy provides a basis for such new concepts. It describes a clearly defined approach of how the theoretical concepts Industrial Ecology, Natural Capitalism and C2C can be implemented. Accordingly, at present the concept of Performance Economy is adopted by the Environmental Protection Encouragement Agency (EPEA) founded by Michael Braungart as a strategy to support the C2C concept in a CE (EPEA, 2018).

The relevance of this concept becomes even more apparent by reference to current economic trends. Nowadays more and more manufacturers compete with business models in which they offer their products as a service. Beside the term of Performance Economy, this process is also called Service Economy. The concept of Service Economy breaks the traditional clear separation between a manufacturer and a service provider (Baines and Lightfoot, 2013, pp. 3–4). In this context, the business model power-by-the-hour by Rolls Royce is considered to be one of the most popular case studies for the success of selling a service and not a product[21] (Horton, 2018). The engines remain continuously owned by Rolls-Royce and the airlines pay according to their use. Consequently, both parties show an increased interest in a long-term benefit of the engine (Horton, 2018). In the context of a sustainable economic structure, Rolls-Royce's business model supports the concept of maximum product retention in the overall economic system and can therefore be used as an example of the advantages of a Performance Economy by Stahel. Furthermore, these experiences can be transferred to the automotive industry for the development of new business models based on the concept of Performance Economy[22].

Summarised, all respective studies build on or at least complement one another (see Figure 2-2). While Industrial Ecology and Natural Capitalism form the theoretical basis for a CE, C2C discusses a possible implementation of the concepts. Based on these approaches, Performance Economy provides a detailed proposal of how the CE can be supported by using

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[21] The concept was already developed in 1962 and has been used successfully ever since. In 2002 it was further developed with additional functions under the name Rolls-Royce CorporateCare (Rolls-Royce, 2012). Rolls Royce is the market leader for propulsion technologies in the aviation sector and CorporateCare is considered as the „most comprehensive and cost effective engine maintenance program“ (Worldfinance, 2016).

[22] More detailed approaches, especially regarding the automotive industry, are explained in chapter 5.6.

new business models. Furthermore, all the presented concepts consist that the existence of mankind is at great risk with its current form of value creation. Thus, it is necessary to break existing paradigms and to rethink the modelling of current manufacturing concepts. A new economic structure is necessary, which is oriented towards the natural cycles of the biosphere and in which all materials can be preserved in the cycle for an infinite period through closed loops. Instead of the final product, the possible EOL-strategy options must influence the manufacturing and design processes. These changes are of such magnitude that 200 years after the first, mankind faces the next Industrial Revolution (Hawken *et al.*, 2000, pp. 6–9). In this context it is not expedient to assign activities to the best possible concept. A global consistent definition is necessary. Due to the closed loops and the focus on cycles, one term has established itself in recent years, which combines all concepts: The circular economy.

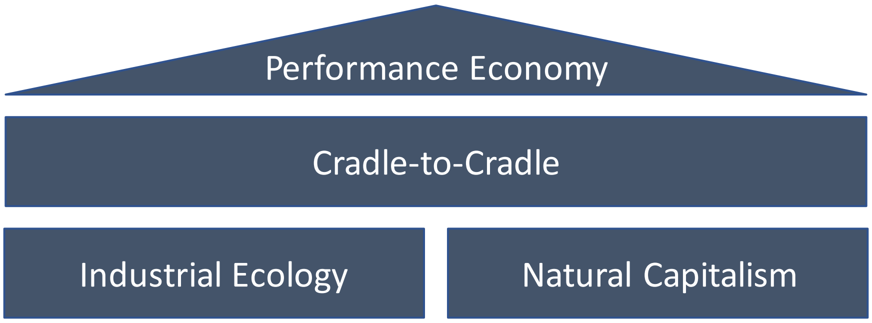

Figure 2-2: Correlation of the roots of CE

2.3 Scientific definition of Circular Economy

The aim of a CE is to „[d]esign out waste“ (Ellen MacArthur Foundation, 2012, p. 22) in order to „reduce virgin inputs to the system and waste emission outputs from the system“ (Korhonen *et al.*, 2018, p. 40) while using renewable energy sources. §3 (19) of the Closed Substance Cycle Waste Management Act[23] (KrWG) of the Federal Republic of Germany defines CE as the prevention and recycling of waste (Bundesministerium der Justiz und für Verbraucher, 2017). According to the German Federal Agency for Civic Education (bpb), CE refers to "the organisation of the economic production process in the form of closed loops wherever possible. The objectives of the CE are to use scarce raw materials as sparingly and effectively as possible“ (bpb, 2018).

Despite this mutual understanding of CE, there is no uniform norm of definition. Hence the Ellen MacArthur Foundation describes the concept as “eclectic“ (Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015, p. 23) and lacking a clear scientific definition. To support the

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[23] The introduction of the Closed Substance Cycle and Waste Management Act (Kreislaufwirtschafts- und Abfallgesetz) in 1996 aims to ensure that manufacturers apply manufacturing processes which generate as less waste as possible and support the re-use of a large proportion of the products (Bundesministerium der Justiz und für Verbraucher, 2017).

development of the CE, Korhonen *et al.* (2018)[24] defined the concept[25] of a CE for the first time as follows:

“Circular economy is an economy constructed from societal production-consumption systems that maximizes the service produced from the linear nature-society-nature material and energy throughput flow. This is done by using cyclical material flows, renewable energy source and cascading-type energy flows. Successful circular economy contributes to all the three dimensions of sustainable development. Circular economy limits the throughput flow to a level that nature tolerates and utilises ecosystem cycles in economic cycles by respecting their natural reproduction rates“ (Korhonen et al., 2018, p. 39).

2.4 Advantages of a circular economy compared of a linear economy

As it has no beginning and no end, the characteristic of a loop or a circle already stands in complete contrast to the principles of the linear economy. Thus, the advantages of a CE represent the positive counter-movement to the negative consequences of the linear economy. (Webster, 2017, pp. 81–84) As large quantities of finite raw materials (e.g. metals or minerals) remain in the system and can be (re-)used in different ways the value is conserved inside the system (Preston, 2012, pp. 2–3). If this succeeds, it can be seen as an ecological gain in comparison to linear economic processes (Korhonen *et al.*, 2018, pp. 38–39).

In summary, a CE offers the opportunity to establish a value creation that generates economic opportunities and potentials and at the same time ecologically and socially sustainable benefits. „The CE does not just reduce the systemic harm produced by a linear economy; it creates a positive reinforcing development cycle.“ (Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015, p. 46). With the aid of a CE, the endangerment of the resource scarcity as well as the world-wide emission and waste load can be combated. From an economic point of view, general procurement costs for new raw materials are minimised or eliminated. At the same time, charges or taxes for waste, energy consumption or emissions can be reduced. A further advantage is achieved by the decreasing dependence of some countries on the procurement of raw materials. The reliability of supply of raw materials is promoted. Thus, possible geographical competitive disadvantages can be compensated. Likewise, new potential for the development of business models such as shared economy concepts are emerging. The repeated use of goods creates new markets and, at the same time, new business models, which in turn create space for work. In addition, the positive image of green marketing for products and services can be used as a side effect (McKinsey & Company, 2016,

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[24] In this context, Korhonen et. al also critise that the „scientific research content of CE is largely unexplored“ (Korhonen *et al.*, 2018, p. 37). Based on the presented studies in chapter 2.2, a well-founded research content certainly is available and this critisim cannot be confirmed.

[25] Their definition is based inter alia on the findings of (Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015; McKinsey & Company, 2016; Sitra, 2015).

pp. 4–10; European Parliament, 2015; European Commission, 2017; Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015, pp. 46–52; Korhonen *et al.*, 2018, pp. 37–39).

The European Parliament estimates that by 2030 "through waste prevention, eco-design, reuse and similar measures [...] net savings of €600 billion per year or 8 percent of the annual turnover of EU businesses could be achieved while reducing GHG emissions by 2 to 4 percent". Through "innovation, growth and employment (creating 580,000 jobs in the EU) [...] consumers will benefit from longer lasting and more innovative products, leading to cost savings and a higher quality of life" (European Parliament, 2015) [26]. The estimated global market value of a CE obtains at least 1000 billion Euros (Sitra, 2015, p. 72). Hence, the transition from a linear to a CE opens great opportunities for Europe and its citizens. Successful implementation offers the potential to modernise the European economic area and create a basis for a long-term sustainable development (European Commission, 2017).

2.5 End-of-Life Strategies are necessary to close the loops

For a successfully operating CE, it is necessary to achieve a maximum degree of energy and material recovery[27] at the end of a product's life (Kampker *et al.*, 2016, pp. 1–2). This is why the application of different EOL-strategies is a major requirement to create closed loops. The following concepts can be distinguished as the key EOL-strategies:

- Reuse
- Repair
- Reconditioning/ Refurbishing
- Repurposing
- Remanufacturing
- Recycling
- Composting
- Incineration
- Landfill

Recycling and landfill represent the two most common and applied concepts of EOL-strategies. Especially landfill does not contribute to a well operating CE but is the current final stage of many linear economic processes. In contrast, recycling supports the concept of a CE. However, recycled products are also usually re-added to the life cycle at a very early stage and therefore have to go through the (energy-intensive) manufacturing process again. Thus, recycling can be described as a short-term solution. In general, resource-efficiency and profitability of the system can be increased congruently the closer the loops are (Webster, 2017, p. 83). The later the components are re-introduced into the production process, the lower the additional emission burden will be (see Figure 2-3). Therefore, the focus should be on maximising all long-term potential benefits within the framework of CE.

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[26] According to the Ellen MacArthur Foundation, these values represent a best case scenario (Ellen MacArthur Foundation, 2012, p. 66).

[27] Within this thesis the terms “recover” or “recovery” will be used to describe all kind of EOL-strategies.

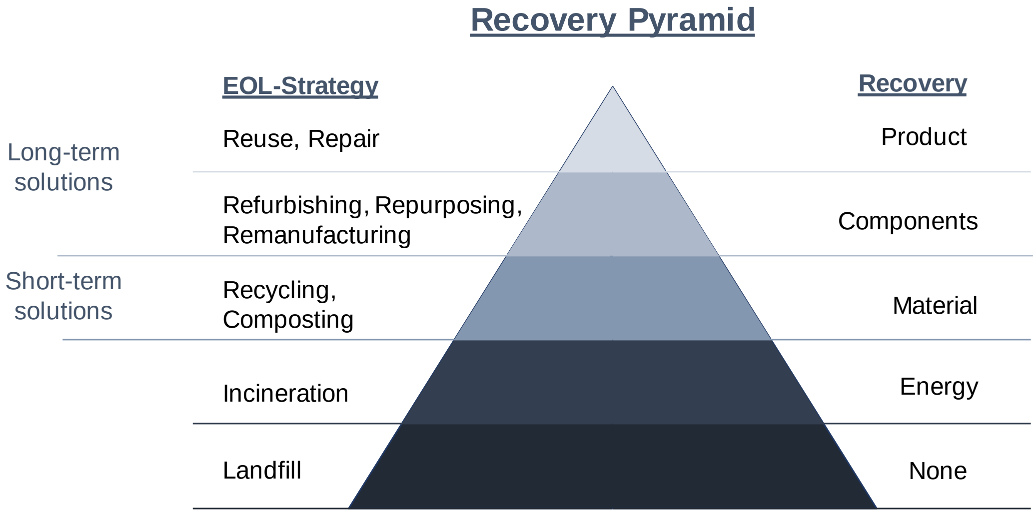

Figure 2-3: Recovery Pyramid[28]

To create closed loops, so-called reverse logistics[29] have to be established. The establishment and operation of reverse logistics respectively EOL-processes should be supported by financial incentives, e.g. by omitting taxation, since the processes are of great importance for a properly operating CE (apra, 2018). As long as these processes cause less emissions than the original manufacturing, the LCA of the respective product can be improved (European Parliament, 2015).

To ensure a uniform description of the various EOL-strategies, this thesis refers mainly to the definitions of the Centre for Remanufacturing and Reuse[30] (CRR) and the Automotive Parts Remanufacturer Association Europe (apra). Both parties are classified as trustworthy sources by the Ellen MacArthur Foundation and refer in their definitions indirectly and partly directly to the contents of the British standard BS8887-2:2009 "Design for manufacture, assembly, disassembly and end-of-life processing (MDA). Terms and definitions".

2.5.1 Reuse

In the KrWG of the Federal Republic of Germany, reuse is mentioned as the first measure to be taken in case that the generation of waste of any kind cannot be avoided (Bundesministerium der Justiz und für Verbraucher, 2017). Reuse describes the process in which products, their individual components or by-products can be directly reused or returned unchanged to the manufacturing process at EOL, normally without physical or chemical modification and accordingly also without additional (emitting) expenditure. The reused products must, by definition, be used for their original purpose (Business Dictionary, 2018;

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[28] Own presentation based on Kampker *et al.* (2016, p. 2) - Extended by EOL strategies

[29] Reverse logistics describes the logistical process through which products or other goods are returned from their original final stage to the value creation process (Hawks, 2006).

[30] The CRR was established in 2007 to support the remanufacturing and reuse industry in the UK. Today the CRR disseminates its content through the channels of the European Remanufacturing Council. http://www.remancouncil.eu/

CRR, 2018, pp. 8–9; Bundesministerium der Justiz und für Verbraucher, 2017; Ellen MacArthur Foundation, 2012, p. 25).

2.5.2 Repair

In opposition to reuse, the process of repairing a product involves physical changes to the product or component in case it is damaged or broken. By repairing the product, it is put into a state where it can be reused (CRR, 2018, pp. 10–11; Diez *et al.*, 2016, p. 51). In the repair process, remanufactured or reconditioned parts can be used (apra, 2012, p. 8). This process is particularly useful for highly valuable products. Individual damaged components can be repaired and there is no need to purchase a completely new product. However, repaired products usually show a high loss in value. In addition, securities and guarantees for the repaired components are rare. Furthermore, economies of scale are necessary for a profitable system. Hence, it is very complex to create a profitable market since a product should not be limited in its functionality (CRR, 2018, pp. 10–11; apra, 2012, p. 8).

2.5.3 Reconditioning/ Refurbishing

Refurbishing or reconditioning describes the process in which a used product or individual components are returned to a satisfactory condition. For this purpose, individual components are partially repaired or replaced including optical improvements. Components do not necessarily have to be damaged but may also be about to be defective due to general wear and tear (CRR, 2018, pp. 6–7; Business Dictionary, 2018; Ellen MacArthur Foundation, 2012, p. 25). The overall performance of the product is partly below compared to the original product (apra, 2012, pp. 6–7).

Compared to refurbishing, the input variables of reconditioning are usually in a better condition and the desired result can be achieved with less effort (Business Dictionary, 2018). Warranty claims are also valid for refurbished or reconditioned goods, although to a lesser extent than for new goods. In contrast to warranty claims for repaired goods, the warranty usually applies to the entire product (Ellen MacArthur Foundation, 2012, p. 25; apra, 2012, pp. 6–7).

Differences between a refurbished and a reconditioned good are not clearly defined. CRR interprets both terms as equivalent. However, Apra describes refurbishment as a purely aesthetic improvement in which no repair or rebuild work is carried out (apra, 2012, pp. 6–7). Other sources describe the difference exactly the other way around.

2.5.4 Repurposing

The aim of repurposing is to enable the use of products or components in a different way than originally intended. Modifications can be made to meet the new usage requirements (apra, 2012, p. 8; CRR, 2018, pp. 9–10; Investopedia, 2018). A simple example would be the use of batteries from electric vehicles as energy storage devices in private households with photovoltaic systems. Therefore, repurposing can also be regarded as a form of recycling in a broader sense (Investopedia, 2018).

2.5.5 Remanufacturing

Remanufacturing corresponds in particular to the objectives of a CE, because direct reuse is only possible in rare cases (Kampker *et al.*, 2016, p. 1). Hence, according to the VDI[31] it is seen as a central component regarding the processes of the CE (Dr.-Ing. Lange and VDI Zentrum Ressourceneffizienz, 2017, p. 9).

Definitions for remanufacturing are available in a large number. In each case, the basic idea constantly overlaps. The focus is above all on resetting used products at least to a condition equivalent to the original condition (CRR, 2018, pp. 4–6; Business Dictionary, 2018; apra, 2012, p. 7). Quality and guarantee of the remanufactured product must be identical or better compared to the original product (CRR, 2018, pp. 4–6; Business Dictionary, 2018; apra, 2012, p. 7; Dr.-Ing. Lange and VDI Zentrum Ressourceneffizienz, 2017, pp. 9–12). With standardised processes, the respective products are disassembled, subjected to cleaning and testing, and reassembled after eventual refurbishment of individual components. Quality assurance ensures that the product can be sold as a product with the quality level of a new product. An example of a typical remanufacturing process is shown in Figure 2-4 (Dr.-Ing. Lange and VDI Zentrum Ressourceneffizienz, 2017, pp. 9–12; Sundin, 2004, pp. 28–29; Ellen MacArthur Foundation, 2012, p. 25). Furthermore, the remanufactured product has to be labelled accordingly (apra, 2018; Dr.-Ing. Lange and VDI Zentrum Ressourceneffizienz, 2017, pp. 9–12). The higher the value or complexity of a product or the lower its availability, the more a remanufacturing process is useful (Kampker *et al.*, 2016, p. 3).

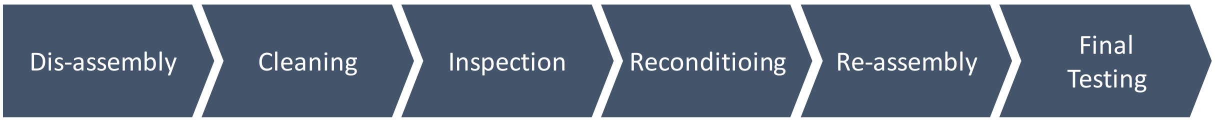

Figure 2-4: Example of a remanufacturing process[32]

By remanufacturing the individual materials, the dependence on resource imports is additionally reduced and exposed to a lesser extent to volatile world market prices (Dr.-Ing. Lange and VDI Zentrum Ressourceneffizienz, 2017, p. 9). However, not every product is suitable for remanufacturing, as the products have to be disassembled into their individual components. Furthermore, it is either not known in which quality the components are transferred to the remanufacturing process or which components have to be remanufactured at all. In addition, the demand for re-fabricated instead of new products is difficult to determine. The implementation of a properly operating economic system with firmly integrated remanufacturing processes is time-consuming and cost-intensive. Thus, the development of new business models must be supported financially (CRR, 2018, pp. 4–6). A further conflict may be that the remanufacturing process inevitably requires the disclosure of technical

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[31] The Association of German Engineers (in German: Verband deutscher Ingenieure (VDI)) is with over 150.000 personal members the largest engineering association in West Europe. Its purpose is to represent the interests of engineers. In this context, the VDI participates in political discussions and actively contributes to the definition of standards (VDI, 2018).

[32] Own presentation based on Sundin (2004, p. 28).

information (Kampker *et al.*, 2016, p. 3). To ensure that service and repair services cannot only be performed by the actual manufacturer, the possibilities and rights for repair services (also by third parties) should be extended (apra, 2018).

2.5.6 Recycling

Recycling applies to materials, end- or by-products or secondary materials that are classified as waste. The respective products, (organic) materials or substances are processed to such an extent that they can be used as raw materials either for their original use or for a new use. Regarding the processing of waste into combustibles for energy recovery, the definitions of apra and the CRR differ. Apra's understanding includes the treatment for energy recovery. In contrast to this, CRR recycling is clearly distinguished from energy recovery processes. This differentiation is also carried out in the KrWG and in the studies of the Ellen MacArthur Foundation. Even if the processing of organic materials is counted as a recycling process, § 3 (25) KrWG clearly excludes further processing for energy recovery, e.g. in the form of combustibles, from the definition. For this reason, the processing of waste for energy recovery is considered separately from recycling processes in this thesis (Buxmann, 1998, p. 5; CRR, 2018, p. 12; apra, 2012, p. 6; Bundesministerium der Justiz und für Verbraucher, 2017; Ellen MacArthur Foundation, 2012, p. 25).

Recycling can be divided into two categories as it is unlikely that recycled products fulfil exactly the same quality requirements as originally intended. If the recycled product is of lower or higher quality than the original product, it is called down- respectively upcycling (Ellen MacArthur Foundation, 2012, p. 25). In practice, most recycling processes are in the area of downcycling (Braungart and McDonough, 2008, p. 56). As the quality of the final product is lower within the scope of downcycling, the overall quality of ores is continuously reduced the more frequently individual components are reprocessed. Accordingly, sometimes ecological benefits have to be ignored if the recycled product does not meet certain quality requirements.

From an economic perspective, recycled products have only a low market-value. In addition, the quantity of recycled goods is often higher than the actual demand. During the recycling process, various wastes may also be mixed (CRR, 2018, p. 12). William McDonough[33] has criticised recycling as a process that only preserves existing harmful materials in the cycle. From his perspective, recycling processes and bio-labelling giving mankind a false sense of security, that they sufficiently support the environment. Negative impacts would remain hidden under the guise of ecologically valuable recycling processes. This is why McDonough recommends recycling projects only in the case that all molecules and materials can be recycled or absorbed by nature in the long term (Goleman, 2009, pp. 42–43).

2.5.7 Composting

Composting is a special form of recovery of solid organic materials by using the natural process of rotting (Fischer and Jauch, pp. 27–29). The organic substances are processed into compost

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[33] William McDonough and Michael Braungart developed the presented in chapter 2.2.3 concept of C2C

under so-called aerobic conditions by microorganisms (e.g. bacteria or fungi). Afterwards, the compost can be returned to the natural cycle as an organic substance, e.g. a nutrient or fertilizer for plants (Umweltdatenbank, 2018; CRR, 2018, p. 14; Ellen MacArthur Foundation, 2012, p. 25). For this reason, composting is partly also described as a form of recycling (Ellen MacArthur Foundation, 2012, p. 25).

In the context of composting, a distinction can be made between domestic and industrial composting. As domestic composting is used primarily for the recycling of private organic waste such as fruit and vegetable residues and all types of garden waste, industrial composting offers the possibility to generate biogases as fuel for energy generation (CRR, 2018, p. 14). Through industrial composting, biogas can be obtained by anaerobic digestion[34], which can be used in its application as an energy source similar to natural gas (Ellen MacArthur Foundation, 2012, p. 25). For a successful composting process, no synthetic or other inputs are permitted that pose an environmental threat. Consequently, organic waste used for composting relieves landfills and reduces the financial costs of waste storage (CRR, 2018, p. 14).

However, composting can only be used for organic or explicitly labelled products. In addition, a composting process can take up to three years (CRR, 2018, p. 14). Compost should only be used as a nutrient in reasonably calculated doses. Excessive use can cause the opposite effect by overloading the soil with nutrients (Fischer and Jauch, pp. 43–47).

2.5.8 Incineration (with energy recovery)

Incineration involves the combustion of both organic and inorganic products (CRR, 2018, p. 15). The aim is either to drastically reduce the volume of waste through the incineration process or to achieve an additional sustainable effect by using the resulting heat. These so-called waste-to-energy concepts include "combustion, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery" (Ellen MacArthur Foundation, 2012, p. 25).

Despite energy generation, waste incineration is more an existing stopgap rather than a sustainable concept for handling waste products. All kind of combustion generates emissions. In general, products that have not been designed for an environmentally friendly combustion process are nonetheless incinerated. Accordingly, the combustion causes emissions that cannot be filtered by the installed technology. Even if the waste is sorted before incineration, there is always uncertainty about the exact content of the products that are combusted in the blast furnace. If the waste had been properly reprocessed, their value could have been maintained in the life cycle by the EOL-strategies reuse, remanufacturing, reconditioning, refurbishing, repair, repurpose or recycling (Braungart and McDonough, 2008, p. 54).

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[34] “A process in which microorganisms break down organic materials, such as food scraps, manure, and sewage sludge, in the absence of oxygen. Anaerobic digestion produces biogas and a solid residual. Biogas, made primarily of methane and carbon dioxide, can be used as a source of energy similar to natural gas. The solid residual can be applied on the land or composted and used as a soil amendment“ (Ellen Macarthur Foundation, 2012, p. 25).

2.5.9 Landfill

Landfill describes the last possible EOL-strategy of a product life cycle. Solid waste is finally disposed under controlled conditions either above or below ground in landfills (Ellen MacArthur Foundation, 2012, p. 25; CRR, 2018, p. 15; Bundesministerium der Justiz und für Verbraucher, 2017). Landfills contaminates the soil and groundwater so that far-reaching ecological damage can occur. Furthermore, from a socio-political point of view, landfills are an obstacle to the development of the local population in many developing countries. The search for valuable materials on the landfills may be more profitable than seeking a school or academic education to get a corresponding professional career (Salm-Reifferscheidt, 2017).

2.6 Current reception of the Circular Economy

As a result of the increasing focus and the endeavour to integrate a sustainable economy in Europe and globally, the concept of CE is prominently placed in political, business and economic dialogues (Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015). For this purpose, the Ellen MacArthur Foundation has developed a model which has been established through the use by the European Union in the so called Circular Economy Package.

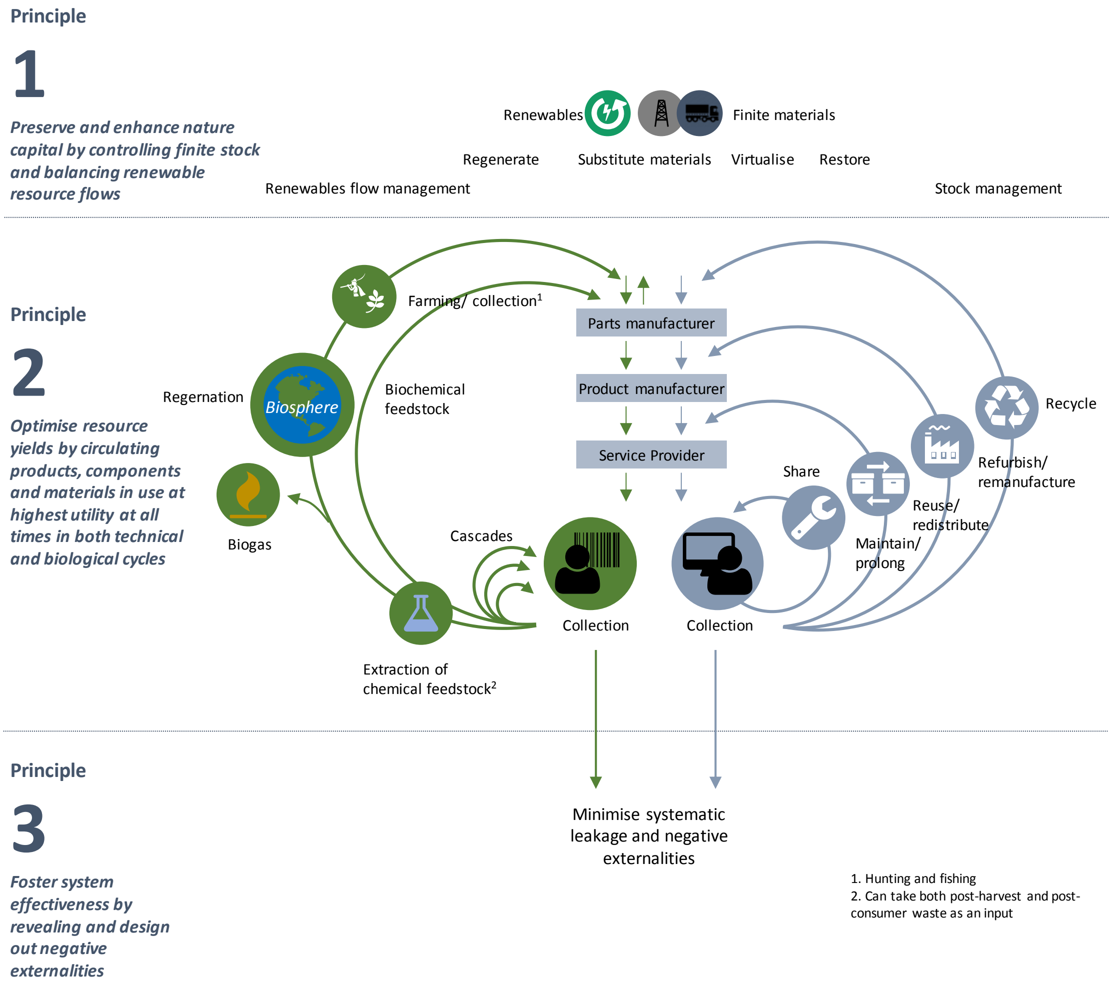

Figure 2-5: Model of the Circular Economy based on the Ellen MacArthur Foundation (2018)

In the context of the Ellen MacArthur study, CE is a „economy that provides multiple value-creation mechanism which are decoupled from the consumption of finite resource.“ (Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015, p. 46) This description is based on three main principles. (McKinsey & Company, 2016, p. 25; Ellen MacArthur Foundation, SUN, McKinsey & Co., 2015, p. 5). In the following, these principles are analysed to determine to what extent they are related to the four above presented concepts:

1. „Preserve and enhance nature capital by controlling finite stock and balancing renewable resource flows“

This principle is defined by all four concepts as one of the basic requirements to achieve sustainability inside the CE.

2. „Optimise resource yields by circulating products, components and materials in use at highest utility at all times in both technical and biological cycles“

The focus on biological cycles and the associated protection of natural capital is directly related to the contents of Industrial Ecology and Natural Capitalism. In addition, a consideration of two separate cycles reflects the model of C2C.

3. „Foster system effectiveness by revealing and design out negative externalities“

This principle is basically the result of all the presented theories. A holistic analysis of the system to recognise all negative effects was already defined as a necessity in the concept of Industrial Ecology. The resulting effectiveness, which distinguishes between positive and negative effects, implements the critical notes of Braungart & McDonough regarding the general understanding of the term "Eco-Effectiveness".

A content-related connection with the concept of the Performance Economy is not directly evident in the presented model in Figure 2-5. However, the illustration developed by the Ellen MacArthur Foundation only describes the model of CE. Since the Performance Economy is already a possible solution for the implementation of the concept, its integration into the model would be misplaced. Nevertheless, in the context of the Ellen MacArthur Foundation's studies, the idea of Service Economy is promoted as the first business model which supports the development to a CE.

2.7 Current actions taken by the European Union

Every theoretical concept only gains relevance when it is implemented in practice. A conceptual development by EOL of the LCA of an automobile is only effective if it can be assumed that these measures will also be implemented. Through clear guidelines and incentives, the industry, including the automotive sector, must be promoted or forced to actively address the issue and identify solutions.

In January 2016, the European Commission published the Circular Economy Package to support the transformation towards a circulating economic structure with the aim of closing the loop of product life cycles. Therefore, the package includes legislative proposals on waste management to reduce landfill in the long term and increase recycling and reuse operations. The Circular Economy Package also refers to the contents of the Circular Economy Action

Plan which was drawn up by the Commission in December 2015. This Action Plan is designed to support CE at every stage of the value chain, from production and consumption to EOL strategies like waste management (European Commission, 2017). Within the Circular Economy Action Plan, five priority areas have been defined which face specific challenges due to product characteristics, the environmental footprint or dependence on materials from countries outside Europe. These focus areas encompass plastics, food waste, critical raw materials, construction and demolition waste as well as biomass and bio-based products. It is necessary to develop specific measures for these five sectors to consider comprehensively the interactions between the different phases of the lifecycle along the entire value chain (European Commission, 2015, pp. 15–21). In order to support the implementation of the planned objectives, the EU has allocated more than 650 million Euro for demonstration projects within the framework of the initiative "Industry 2020 in the Circular Economy" (European Commission, 2015, p. 22). Furthermore, the European Commission has defined numerous key initiatives to support recycling management. The implementation report of the European Commission published in 2017 states that some of these have already been implemented (see Figure 2-6) (European Commission, 2017, pp. 3–7).

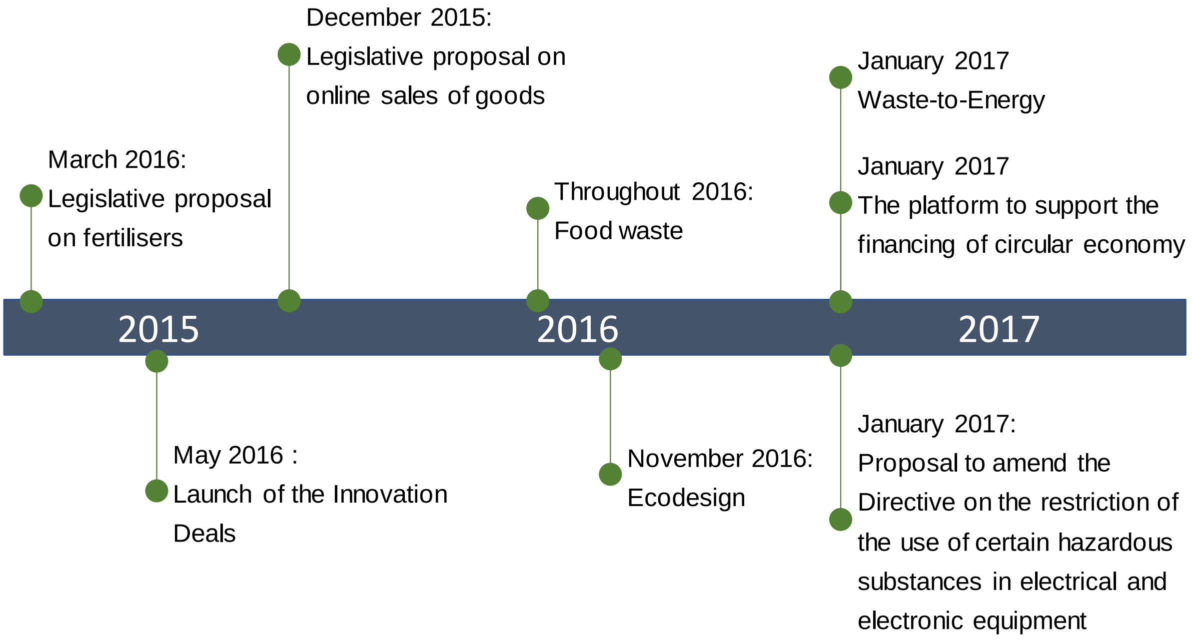

Figure 2-6: Approved key initiatives in adoption of the circular economy action plan

The presentation of the results serves as an exemplary illustration that the European Union has recognised the need for transition to a CE and actively supports it. Since the last publication of the European Commission, further legislative proposals[35] have been prepared and in some cases have already been implemented. However a detailed description of these would go beyond the scope of this work. Regulations which explicitly concern the automotive

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[35] Further information on the current implementation status of the Circular Economy Package are distributed by the European Commission through its own channels. http://ec.europa.eu/environment/circular-economy/

industry are mentioned again in detail in chapter 5.1 and are directly related to the developed model.

2.8 Conclusion

The fact that a shift to CE is politically supported represents an important movement in the right direction and constitutes the prerequisite for a successful establishment of EOL-strategies. Nevertheless, the model of the CE by the Ellen MacArthur Foundation, which in this form is also explicitly adopted and disseminated by the European Union, is by no means a new concept or an innovative solution for the presented negative prospects of the linear economy. Considering the concepts of Industrial Ecology, Natural Capitalism, C2C and Performance Economy, the established concept of CE is rather a summary of findings that have been published in detail and substantiated for more than 30 years. Even if the origin of the problematic can be found in the structure of the linear economy it has to be critically questioned why this problem is still so relevant today. The threats have been known and published accordingly for almost 50 years. Consequently, the statement by Braungart and McDonough (2008) that the present problem is above all of structural nature takes political parties and large corporations too much out of responsibility. Those parties certainly have to contribute to the further development of the current system and to ensure that ecological and social factors are at least equally balanced with economic factors. It is necessary to create government incentives and sanctions that on the one hand support and encourage companies willing to change their operations and on the other hand leave resistant companies with only a financially unprofitable choice. Increased landfill storage costs can e.g. force companies to reduce waste volumes, develop efficient processes and constantly optimise them (Frosch and Gallopoulos, 1989, pp. 5–6).

3 Concept of Lifecycle Assessment

The mere fact that measures correspond to the theoretical concepts of the CE is not a solid indication that they are also preferable from a sustainable point of view. For this reason, appropriate measuring instruments are required to assess the success and ecological impact of actions regarding the CE.

3.1 Historical development of Lifecycle Assessment

Within the framework of quantitative analyses of environmental impacts, there is a multitude of generally accepted technical terms (Schmidt, 1995, pp. 3–9). Sustainability analyses and assessments are normally divided into the three categories social, economic or environmental (Finnveden *et al.*, 2009, p. 2). However, a clear reference to the environmental analysis of products and services has established itself for the term life cycle assessment (LCA). Economic and social aspects are usually not considered within the LCA. (Schmidt, 1995, pp. 3–9). The concept of an LCA has evolved out of an effort to identify a holistic approach to analyse the environmental impacts of a product over its entire life cycle. As a result, the European Committee for Nomination (CEN) published an international standardisation for the first time in 1997. This standard was established as ISO 14040 "Environmental management - Life cycle assessment - Principles and framework" (Renner and Klöpffer, 2005, pp. 35–36). According to the ISO standard, an LCA includes the definition of the goal and the scope of the investigation, the setting-up of an inventory analysis, an impact assessment as well as the interpretation of the results (ift-Rosenheim, 2018, pp. 2–3; DIN, 2009, pp. 4–5).

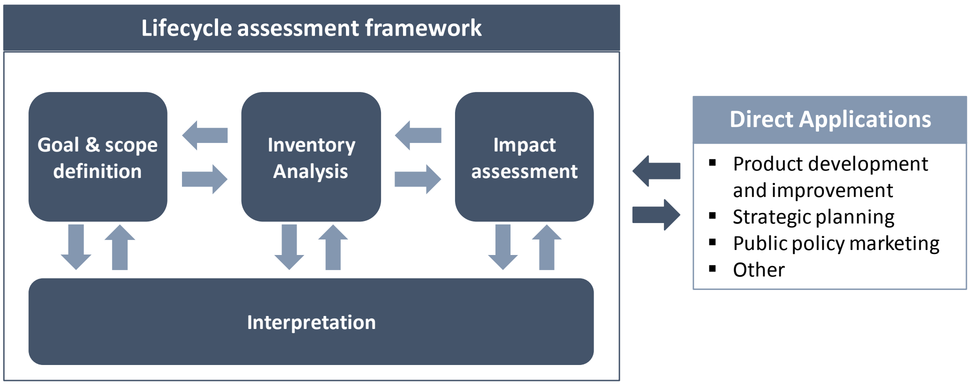

Figure 3-1: Stages of an LCA according to DIN ISO 14004[36]

3.2 DIN ISO 14040

This subchapter only provides a brief overview of the general structure of an LCA. For further information on the procedure and structure of an LCA, please refer to the DIN ISO 14040 standard and the literature listed in this chapter.

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[36] Own presentation based on DIN (2009, pp. 16–17).

3.2.1 Goal and Scope Definition

Regarding the definition of goals, it has to be specified for which application the LCA is intended, what the reasons for the implementation are and what the estimated quality of the used data is. In case of data gaps, generic data may be used (ift-Rosenheim, 2018, p. 2). A clear definition of the goal ensures that the right questions are asked from the start in order to support a goal-oriented implementation of the LCA (Giegrich *et al.*, 1995, p. 123). ISO 14040 offers scope for manoeuvre, since measures are supported by principal requirements, but are not specified in concrete terms. This was deliberately chosen because the standard was defined with a development-related character. However, the standard has not been extended or corrected since 2009 (Renner and Klöpffer, 2005, p. 37).

The scope of the LCA is defined in accordance with the specific goal. Due to the dependence on the analysed subject, the scope of the different LCA frameworks can diverge considerably. In order to limit the assessment it is necessary to establish explicit system boundaries (DIN, 2009). Without these system boundaries, the analysed model would be infinite (Giegrich *et al.*, 1995, pp. 123–125). The complexity of defining system boundaries increases with the number of interconnections to one or more other systems (Powell, 1996, pp. 99–100). By applying cut-off criteria, the LCA can be limited to a feasible setting. Sub-processes or input and output variables may only be excluded from the assessment if the general evaluation and the associated conclusion of the LCA are not significantly changed. Sensitivity analysis can be used to estimate the impact on the overall results and further to justify the application of the cut-off criteria in the final assessment of the LCA (ift-Rosenheim, 2018, p. 3).

3.2.2 Life Cycle Inventory (LCI) Analyses

The LCI analysis is the quantitative centre of an LCA. In this step, all data are collected[37] that are generated over the entire life cycle of a product within the respective system boundaries (Giegrich *et al.*, 1995, pp. 125–126). Due to the individually definable system boundaries and cross-process flows, the inventory analysis offers a certain amount of freedom (Renner and Klöpffer, 2005, pp. 37–38). Within the inventory analysis, all material and energy flows, including emissions, must be recorded and named as input and output variables of the overall system, which are taken from and finally returned to the biosphere (DIN, 2009; Schmidt, 1995). However, the finished product does not belong to the input and output quantities (Renner and Klöpffer, 2005, pp. 37–38).

All material and energy flows are always related to a declared or functional unit (ift-Rosenheim, 2018, pp. 2–3). This unit describes a mathematical reference quantity which is used to normalise the input and output quantities. Therefore, it is imperative that the functional unit is

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[37] In general, the necessary data are either directly available or must be collected generically. In-house data for production or disposal processes are often directly available. Energy supply or transport costs are often described generically by adapting mean values from known economic areas (Renner and Klöpffer, 2005, pp. 37–38).

clearly defined and measurable. It is the central and decisive parameter in an LCA and the reference value for all data used within the analysis (Giegrich *et al.*, 1995, pp. 124–125) .

Allocation

The complexity of an LCA is significantly increased as soon as cross-process flows have to be included. If, e.g., energy is generated from purely natural resources or if waste is completely stored, there are no methodological problems. The overall system consists only on so called elementary flows and such flows that serve either as input or output of the system. However, practice demonstrates other circumstances. If waste is used to generate energy or if individual components of waste are recycled, flows are created that interact with other (product) systems. It is necessary to assess the proportion of ecological data that can be attributed to the respective (subsidiary) flows between several systems. Thus, an allocation needs to be applied. In general, the recycling of individual components or even entire products is widespread today, so that it is inevitable that one has to deal with the issue of allocation within the scope of an LCA. For a proper allocation it is necessary to combine generally obligatory allocation procedures in order to be able to guarantee a valid distribution of ecological data or burdens to the individual product systems (Buxmann, 1998, pp. 3–10).

3.2.3 Lifecycle Impact Assessment (LCIA)

LCIA is used to evaluate the environmental impact of a specific process. Its general aim is to determine the extent of the environmental impact for the individual life cycle phases. Hence, it is possible to compare the ecological impact of single life cycle phases or relate them with the overall process (ift-Rosenheim, 2018, pp. 6–8). For this purpose, the quantitative results of the LCI will be assigned to corresponding impact categories. An impact category is a “class representing environmental issues of concern to which life cycle inventory analysis results may be assigned” (DIN, 2009, p. 13). Each impact category contains an impact category indicator in order to quantify the result[38]. (DIN, 2009; Renner and Klöpffer, 2005, pp. 38–41).

3.2.4 Interpretation

Within the last step of an LCA, the results of the LCI and LCIA are summarised and evaluated to derive possible conclusions, recommendations, decision making and further explanations. The respective results are linked with an (individual) evaluation system defined by the evaluator. Thus, the interpretation also contains a certain degree of subjectivity although it is influenced by factual information and depends on fixed criteria (Giegrich, 1995, pp. 259–261; DIN, 2009). In order to publish the results in a comprehensive and transparent manner, a common approach is to categorise the findings according to impact-oriented[39] (e.g.

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[38] Example: Impact Category: Climate Change; Impact Category Indicator: Global Warming Potential; Functional Unit: CO_2-equivalents. For more information please refer to chapter 3.5.

[39] The results of LCA regarding (electric) vehicles are mainly assigned to impact-oriented impacts.

greenhouse effect), problem-oriented (e.g. transport volume, energy demand) and media-oriented (e.g. atmospheric or groundwater protection) impacts (Giegrich, 1995, pp. 267–269).

3.3 Advantages of an LCA

Traditional environmental assessment focuses its analysis on individual, sectoral and medial areas (Schmidt, 1995, pp. 7–8). Thus, only direct environmental impacts of e.g. manufacturing facilities are analysed. However, there are also many indirect environmental impacts, especially in manufacturing. An LCA proceeds in an overarching manner and analyses areas that would otherwise only be considered individually (Example: Effects of road traffic and waste storage by a car and subsequent demolition are connected). In addition, the effects on several environmental mediums (air, water, soil) are investigated (Schmidt, 1995, pp. 7–9). Therefore, LCA can be used to optimise the life cycle as in its entirety (Mampel, 1995, p. 133). This holistic approach is a unique attribute of an LCA and its most important property (Finnveden *et al.*, 2009, p. 1; Giegrich *et al.*, 1995, p. 121). Improvement potentials can be identified and addressed at every point in the entire system. Vulnerabilities of the existing value chain can be reduced with appropriate optimisations. Thus, it is possible to selectively enhance the amount of used materials for individual components of a product. The identified potentials can be used to minimise raw material and energy consumption, which in long-term planning not only decreases the environmental impact, but also creates cost saving potentials at the same time (Mampel, 1995, pp. 133–136; Schmidt, 1995, pp. 9–11). Furthermore, due to the overarching focus on all life cycle phases it is possible to show that measures in one sector can cause negative consequences in another (Schmidt, 1995, pp. 9–11). Environmental impacts could possibly only be shifted from one industry to another. By analysing the problem across sectors, it is possible to avoid problem-shifting without any environmental improvement.

3.4 Limits of LCA

Nonetheless, the holistic approach also causes methodological problems in an LCA, because the analysed systems may become increasingly complex. For this reason the selection of relevant system boundaries and the use of cut-off criteria and allocations are highly significant for a successful LCA (Schmidt, 1995, pp. 8–9). Due to the single focus on a specific product within an LCA, local (negative) environmental impacts caused by or in parallel product systems may not be considered. Therefore, an LCA is no equivalent to a general environmental risk analysis (Finnveden *et al.*, 2009) and has due to the certain degree of subjectivity and the dependence on the selected functional unit only a relative significance. Comparative statements can only be made if the system to be compared has been evaluated with the same functional unit (DIN, 2009; Schmidt, 1995, pp. 8–9; Renner and Klöpffer, 2005, pp. 15–16). The difficult comparability is additionally hindered by the fact that many companies do not release internal data to the public. Hence, only generally valid data and assumptions can be used for public studies, which limit the significance of the study. For this reason LCAs are often used for internal purposes such as product and process optimisation and remain unpublished (Schmidt, 1995, pp. 9–10). Moreover, the results of an LCA can vary greatly due to the geographical location. Depending on where components of a product are manufactured, supplied or used, there may be widely diverging environmental impacts, e.g. due to different energy sources (Giegrich *et al.*, 1995). Accordingly, LCAs do not provide a platform for political decisions. However, they can create a large data spectrum with which decisions, optimisations and investments can be substantiated (Schmidt, 1995, pp. 8–9).

3.5 CO_2-Equivalents – Definition and calculation

This thesis analyses in particular LCAs of electric vehicles. In this context climate change represents the impact category and the greenhouse effect is the corresponding impact category indicator. To determine and compare the environmental impacts of the various GHGs a standardised functional unit is necessary. Thus, the IPCC has proposed the Global Warming Potential (GWP) as an appropriate aggregation method. The GWP is expressed in CO_2-equivalents, which consequently corresponds also to the functional unit of the LCA (Renner and Klöpffer, 2005, pp. 38–41).

Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs) and Sulphur Hexafluoride (SF_6) are defined as the six global GHGs within the Kyoto Protocol. In 2015, the list of GHGs was extended by Nitrogen Trifluoride (NF_3) (French, 1998, p. 19; Umweltbundesamt, 2016b). To calculate the environmental impact in CO_2 equivalents, it is necessary to determine how much a given mass of the respective GHG contributes to global warming compared to the corresponding amount of CO_2. Table 3-1 shows the currently applicable conversion factors according to the IPCC for a period of 100 years[40]. Accordingly, one ton of CH_4 corresponds to a global warming potential of 28 tons of CO_2-equivalents. In other words: The environmental impact of one ton CH_4 is 28 times higher than the same amount of CO_2 (Umweltbundesamt, 2016b).

CO_2	CH_4	N_2O	HFCs (CHF_3)	PFCs ($CClF_3$)	SF_6	NF_3
1	28	265	12.400	13.900	23.500	16.100

Table 3-1: GWPs of selected Greenhouse Gases[41]

3.6 Conclusion

Eventually, LCA is an established and widely recognised way of assessing the holistic environmental impact of a product. However, the allowed degree of subjectivity can cause conflicts regarding the comparability of different LCA. Therefore, as a next step, it is necessary to analyse to what extent the LCA methodology is applied in today's ecological assessment of passenger cars, what results are achieved and whether the results are comparable.

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[40] The IPCC also publishes GWP values for a period of 20 years to demonstrate short-term impacts. Furthermore, the data are updated as part of the IPCC's ongoing publications.

[41] In accordance with IPCC (2013, Table 8.A.1, pp. 8-88 - 8-91).

4 Analysis of current LCA studies of electric vehicles

At each stage of a product's life cycle GHG emissions are expelled. Depending on the analysed product, these are distributed with different weightings over the respective life cycle stages. For a well-founded statement regarding the LCA of an electric vehicle, it is necessary to carry out an extensive literature review of the current published studies. The literature review is done in Science Direct, Google Scholar and Springer Link and the focus is mainly on studies carried out between 2016 and 2018. The key words "LCA", "EV", "Electric vehicle", "Electric car", "Life Cycle Assessment" and "Life Cycle Analysis" are used and combined as search strings. Studies from previous years are also considered if they are assessed as relevant for the presentation of the results. Within all identified studies, only studies publishing a holistic LCA of an electrically powered passenger car are taken into account for the detailed analysis.

The analysis of the relevant studies has two main objectives: First, it will be evaluated how EOL-strategies have been applied in the field of LCA and if they can serve as a basis for the development of the model. Secondly, it will be analysed whether the quality of the existing data allows a quantitative extension of existing LCAs by the application of EOL-strategies. If the quality of these data is insufficient, the model should focus more on theoretical concepts than on quantitative evaluations.

In the context of the literature review, a total of 15 relevant studies related to LCAs are identified of which six fulfilled the selection criteria of assessing an electrically powered passenger car (see Table 4-1). A seventh study is not directly included in the comparative analysis but is nevertheless integrated into the evaluation based on its innovative approach. The most important findings are summarised in Table 4-2. In each study the results are presented either in an absolute value of emissions in tons CO_2-eq over the entire life cycle or in grams CO_2-eq per km. To enable comparability, the unit of emission of grams of CO_2-eq per kilometre is chosen. Absolute values are correspondingly divided by the total kilometres of the considered vehicle. Even if this provides a uniform unit, the pure results cannot be used to make any statements about the calculation that led to the result of the respective LCA. The uniform presentation of the results serves solely to be able to relate the results to one another.

#	Author	Y/N?	Reason, if not considered in the analysis:
1	Hall and Lutsey (2018)	Y	
2	Burchart-Korol *et al.* (2018)	N	Results are not verified & officially published
3	Cerdas *et al.* (2018)	N	Only repetitions of results by Hawkins *et al.* (2013).
4	La Souza *et al.* (2018)	N	Focus on Transit Busses
5	Karaaslan *et al.* (2018)	N	Focus only on sport vehicles
6	Messagie (2017)	Y	
7	Wolfram and Wiedmann (2017)	Y	
8	Lombardi *et al.* (2017)	(Y)	considered only because of new approach
9	Moro and Lonza (2017)	N	Focus only on WTW-Emissions
10	Ellingsen *et al.* (2016)	Y	
11	Bicer and Dincer (2017)	N	Focus only on WTW-Emissions
12	Canals Casals *et al.* (2016)	N	Focus only on WTW-Emissions
13	Lajunen and Lipman (2016)	N	Focus only on transit busses
14	Nealer *et al.* (2015)	Y	
15	Hawkins *et al.* (2013)	Y	

Table 4-1: Results and classification of the relevant studies of the literature review

Many authors do not provide values of several parameter which they used to carry out their calculations. To reconstruct the missing values, the sources of the respective studies had to be additionally examined. Therefore all data in Table 4-2 are labelled regarding their origins of the data.

x	Value and source named within the respective study.
x	Value is specified, but source is not named.
x	Value was not specified and had to be reconstructed by analysing the referred literature.
x	Value and source were not specified. Value had to be reconstructed by using generic data.

Figure 4-1: Legend to explain the origins of the data

	Hall and Lutsey	Messagie	Wolfram and Wiedmann	Ellingsen *et al.*	Nealer *et al.*		Hawkins *et al.*		Lombardi *et al.*
Battery in kWh	*30*	30	*38,2*	17,7 | 24,4 42,1 | 59,9	24	85	24		33
Chemistry	n/a	LMO	n/a	Li-NMC	n/a		LiFePO4	Li-NCM	LiFePO4
Bat. manufacturing in kg CO_2-eq/ kWh	175	55	237,8	292-487,2	90,6	85,1	259	199	166
Consumption in kWh/100km	15,2	20	*23*	14,6 | 17 18,5 | 20,7	18,6	23,6	17,3		*22,3*
Emission ICEV in g CO_2-eq/ 100km	120	165	208	124 | 149 166 | 205	8,9l gas	11,24 l gas	6,9l gas	5,4l diesel	6,74 gas
Distance in '000 km	150	*200*	230	180	217	288	*150*		200
Battery exchange	1	1,5	*1,5*	n/a	1		1		2
Electric vehicle in kg	1580-1640	*1200*	*1650*	1100 | 1500	1650	2350	1521		1550-1700
ICEV in kg	1050-1161	n/a	*1140-1460*	1750 | 2100	1500	2150	1255-1365		
E-Mix (Country) in g CO_2-eq/ kWh	275,9 (EU)	300 (EU)	1048 (AUS)	521 (EU)	*480 (U.S.)*		n/a (EU)		644,9 (IT)
Impact Category	GHG	GHG	GHG	GHG	GHG	GHG	GHG		GHG
System boundaries	n/a	n/a	n/a	n/a	n/a		n/a		n/a
Electric Vehicle	100-150	87	351	120 | 147 167 | 197	139	166	206	197	225
ICEV (diesel)	250-260	206	303	147 |183 211 | 261	n/a	n/a	228		n/a
ICEV (gasoline)	n/a	n/a	331	n/a	273	354	258		266

Table 4-2: Summary of the key parameters of all analysed studies

4.1 Presentation and critical evaluation of the results

4.1.1 Summary of the main findings in the literature analysis

Within the literature review two things are particularly apparent. First, many studies do not deal with a holistic LCA of an electric vehicle, but instead focus primarily only on the energy-intensive manufacturing process of the battery. Secondly, the holistic LCA studies cannot be directly compared with each other and therefore do not allow a general statement in which quantitative extent an electric vehicle exceeds a conventionally operated vehicle in terms of emissions.

However, with the exception of Wolfram and Wiedmann (2017), all scientists agree that an electric vehicle emits less climate-warming GHGs than an Internal Combustion Engine Vehicle (ICEV) (See Figure 4-2). The assessment by Wolfram and Wiedmann (2017) is justified by the high proportion of coal in the Australian energy production. If the future decarbonisation of energy production is successful, they also agree with the results of the other studies. Further, it is congruently shown that the manufacturing process of an electric vehicle produces more emissions than that of an ICEV, mainly due to the energy-intensive manufacturing of the battery. Nonetheless, this disadvantage is compensated by lower emissions during the use phase. The more kilometres an electric vehicle covers, the more positive its LCA becomes. Furthermore, a diesel-powered is more efficient than a gasoline-powered vehicle. Nevertheless, there are large differences in the absolute values of the emitted grams of CO_2-eq per km both for electric vehicles and for ICEVs. Due to the deviation between the results of Hawkins *et al.* (2013) and Messagie (2017) with 202[42] and 89 grams CO_2-eq per km, it is not possible to determine a specific or close range of emissions generated by electric vehicles. The differing results are caused by a large number of uncertainties regarding the quality of the results, which become apparent after a detailed analysis of the studies and are examined in chapter 4.2 to 4.3.

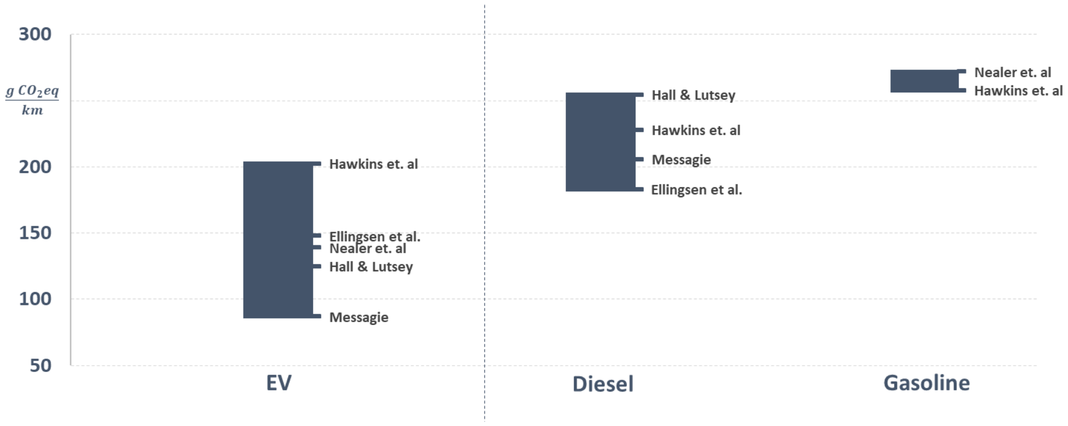

Figure 4-2: Summary of the key results (excluding findings of Wolfram and Wiedmann)

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[42] If Wolfram and Wiedmann (2017) are considered in the comparism the upper limit extends to 351 g CO_2-eq per km.

4.1.2 Application of EOL-Strategies

Studies which consider the application of EOL-Strategies	
Ellingsen *et al.* (2016)	Based on pyrometallurgical treatment
Nealer *et al.* (2015)	Consideration of recycling process for the vehicle; battery recycling is not assessed to due scarce data
Hawkins *et al.* (2013)	Material recovery und disposal are allocated to the vehicle life cycle
Lombardi *et al.* (2017)	Battery: Disposal because recycling technology is not commercially available; Remaining vehicle: the consumptions for the dismantling phase were accounted for on the basis of the total weight
Studies which exclude EOL-Strategies	
Hall and Lutsey (2018)	Because of uncertainty regarding the quality of existing data
Studies which do not mention the treatment of EOL-Strategies	
Messagie (2017); Wolfram and Wiedmann (2017)	

Table 4-3: Application of EOL-Strategies

EOL-Strategies are only applied to a limited extent in the analysed studies (see Table 4-3). Transparent numerical values as well as a detailed processing of the results are not provided by any study. Messagie (2017) and Wolfram and Wiedmann (2017) neither explicitly mention nor list EOL-Strategies in their assessments or graphical evaluation. Due to uncertainty, Hall and Lutsey (2018) deliberately exclude EOL-processes from their analysis. Ellingsen *et al.* (2016), Nealer *et al.* (2015), Hawkins *et al.* (2013) and Lombardi *et al.* (2017) integrate EOL-processes into the results of their LCAs. However, if at all, only recycling is mentioned. In this context, EOL-strategies are partially assessed as additional emission loads which have to be proportionately added to the life cycle emissions of a vehicle.

Ellingsen *et al.* (2016) consider the EOL treatment for the battery and the vehicle itself separately. The data of the treatment of the vehicle without the battery are based on the findings of Hawkins *et al.* (2013). Regarding battery EOL-treatment, Ellingsen *et al.* (2016) rely on pyrometallurgical processes and EOL treatment of conventional vehicles is based on published data from the automobile manufacturers Daimler and Volkswagen. Vehicle as well as the battery are "not attributed any benefits from the EOL processes" (Ellingsen *et al.*, 2016, p. 3). Hawkins *et al.* (2013) base their analysis of data established by ecoinvent[43]. EOL treatment of the battery is described with dismantling and cryogenic[44] shattering processes. All other processes of material recovery and disposal by landfill are considered and added as

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[43] The used data are published in 2006 and are also used by Ellingsen *et al.* (2016).

[44] Cryogenics: production and application of low-temperature phenomena (Encyclopaedia Britanica, 2018).

further emissions. The used data basis and effects of battery recycling as well as further EOL-processes for electric vehicles and ICEVs are not specified in detail. Nealer *et al.* (2015) only consider recycling and disposal (through landfill) processes and exclude the recycling of lithium-ion batteries in their analysis due to limited data availability. They estimate the decrease of emissions of already applied recycling processes within the manufacturing process up to “15 to 20 percent” (Nealer *et al.*, 2015, p. 41). However, it is not published, which components of a vehicle are explicitly considered. Nealer *et al.* (2015) point out that emissions from landfill storage (excluding batteries) are considered low and similar in the literature for battery electric vehicles and ICEVs. They estimate landfill emissions to be 5% of total vehicle manufacturing emissions without mentioning any respective source. Due to the fact that the novelty of electric vehicles does not yet result in a well-founded data situation regarding EOL potentials, the authors make the conservative assumption that neither savings of emissions through recycling or reuse of the battery nor through the use of recycled batteries in other industries can be allocated to the LCA (Nealer *et al.*, 2015, pp. 19–22). Lombardi *et al.* (2017) describe how ecological benefits may be determined in the context of LCAs. However, they also only focus on recycling processes for the metals of the vehicle without considering the battery. Depending on the weights, it is assumed which proportion of the respective metal can be separated for recovery. The corresponding impact is offset against the saved primary resources and counted as a positive effect of the LCA. In this context Lombardi *et al.* (2017) assume that the entire vehicle is manufactured with primary raw materials. However, the authors make no statements regarding the absolute ecological impacts (Lombardi *et al.*, 2017, p. 1996).

4.1.3 Intermediate conclusion of current research

EOL-strategies find little or no consideration within current LCAs of electric vehicles. The analysed studies do not provide any valuable data regarding EOL-strategies and cannot serve as a basis for the development of the model. Furthermore, Lombardi *et al.* (2017) explicitly mention that they only used selected data for primary materials from the used database. It is not transparently published whether this has been done in the same way in the other studies. Therefore, it must be assumed that the current LCA results may evaluate the ecological impact of a manufacturing from scratch. Currently established EOL-processes such as recycling are not congruently taken into account and further EOL-strategies like remanufacturing are not mentioned at all.

However, all researchers agree regarding the positive future potential. Due to the growing industry for electromobility and the increasing number of registered electric vehicles, EOL-strategies will become more feasible in the future inter alia through economies of scale. The (further) development of current battery recycling processes offers the possibility to reduce the use of valuable metals and to avoid emissions caused by the energy-intensive manufacturing processes. Additionally, the market potential for reuse or remanufacturing of key components of electric vehicles will increase (Messagie, 2017, p. 13; Hall and Lutsey, 2018, pp. 7–10; Nealer *et al.*, 2015, p. 41; Romare and Dahlöf, 2017, p. 38). Hence, the focus on EOL-strategies is a key element to optimise the LCA of future electric vehicles. Neither a partial consideration of solely the additional emissions caused by EOL-strategies nor focus only on recycling processes is sufficient. This is why it is necessary to include the possible benefits of EOL-strategies in the model of LCAs of electric vehicles in a detailed and transparent way.

In this context, it has to be determined what causes the currently widely diverging results of LCAs. If it is possible to identify the reasons, it may be feasible to make corrections or set the results in relative proportions. Thus, it can be evaluated whether the transmitted data are sufficient to be able to represent the advantage of EOL-strategies in absolute values within the framework of the modelling in chapter 5. The subsequent analysis is divided into two parts. On the one hand, it is examined whether there are different methodological approaches to calculate the LCA and on the other hand, to what extent the choice of parameters differ in the respective studies.

4.2 Different methodological approaches

Long-term comparable LCA results can only be achieved if the individual studies adhere to an identical structure and clearly defined methodological approaches. Before the detailed analysis of the key parameters is presented, the most prominent structural and methodological approaches for assessing the use and the manufacturing phase of the vehicle have to be clarified.

4.2.1 Use Phase: Well-to-wheel (WTW) approach

When considering the use phase, the WTW approach becomes relevant[45]. An ecological WTW analysis describes all emissions expelled to power a vehicle, from the production of fuels for vehicles, the extraction of raw materials through processing into a usable energy carrier and subsequent transport of the energy carrier to the actual engine of the automobile. Emissions are produced whether it is a conventional vehicle or an electrically powered vehicle (Moro and Lonza, 2017, p. 6).

This process can be divided into two parts: Well-to-tank (WTT) and Tank-to-Wheel (TTW). WTT considers the pure provision of energy. The result is strongly dependent on the energy carrier, which is used to generate the required energy (in the form of electricity for an electric vehicle). Regarding an LCA, this value is subject to large fluctuations, especially in the field of electromobility. TTW encompasses the efficiency of the vehicle or in other words: How much of the energy used in the form of fuel actually contributed to the drive of the vehicle. Since automotive manufacturers cannot influence the energy supply, they may only improve the results of the TTW analysis within the scope of emission-optimising actions. Considering a conventional vehicle, a significant amount of emissions is generated during this phase. In the case of an electrically powered vehicle, there are no direct emissions in the TTW analysis. Nonetheless, TTW may not be omitted in the context of an LCA of an electric vehicle. The efficiency influences the actual energy consumption and has an influence on the overall result of the evaluation of the WTW approach. Hence, WTT and TTW must be both considered in an

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[45] Emissions generated during the production of hardware components are not considered.

LCA (Edwards *et al.*, 2011, pp. 13–21; Nordelöf *et al.*, 2014, p. 1871; Moro and Lonza, 2017, pp. 6–7). To highlight the "weakness" (Lombardi *et al.*, 2017, p. 1994) of a simple TTW consideration, Lombardi *et al.* (2017) provide an example of the deviating results of a TTW or WTW approach. As part of their studies, they investigate the environmental impact of a conventional, purely electric, fuel cell battery-powered and hybrid electric vehicle. In a pure TTW analysis, the electric vehicle performs best due to its efficient energy conversion. However, if one considers the entire use phase, a hybrid vehicle achieves the best results due to its smaller battery unit[46] (Lombardi *et al.*, 2017, pp. 2000–2001).

Hence, within the scope of an LCA, the WTW lifecycle must always be considered for the use phase (see Figure 4-3). The holistic approach of assessing both manufacturing and use phase, is also referred as a complete LCA (Nordelöf *et al.*, 2014, p. 1871; Edwards *et al.*, 2011, pp. 13–21). For a meaningful result, the focus on a complete LCA is imperative. Consequently, all studies listed in Table 4-1 have been excluded from the comparative analysis, which focus either only on the WTW or on one of the two sub-processes.

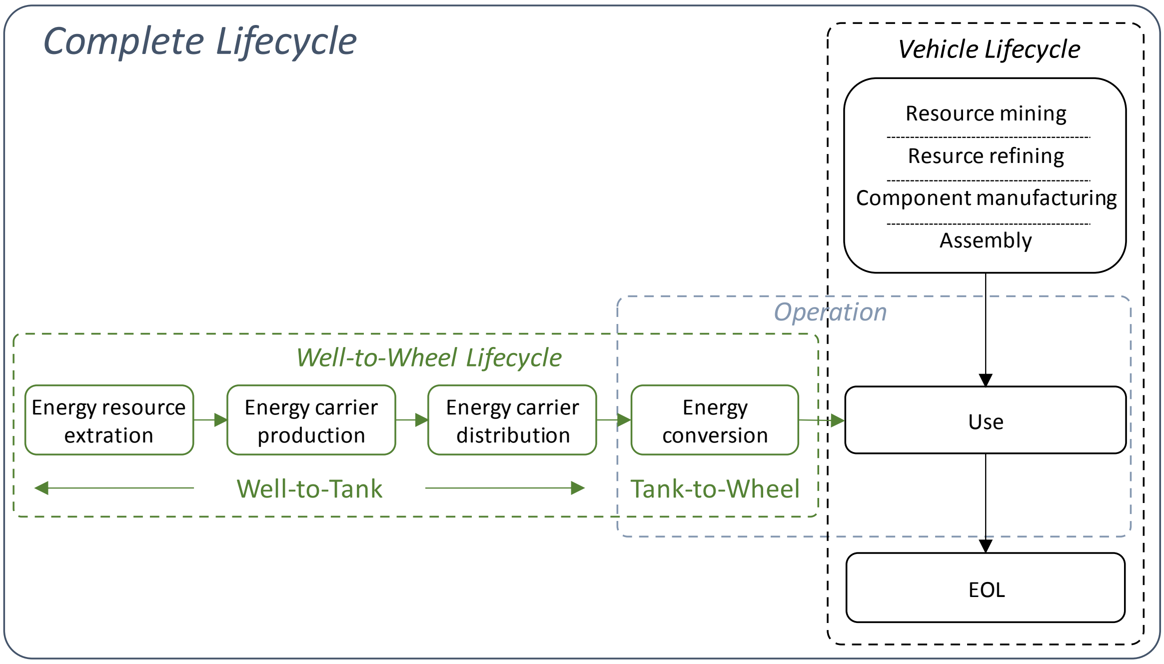

Figure 4-3: Integration of the WTW Approach in the complete product life cycle[47]

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[46] This is confirmed by the studies of Moro and Lonza (2017), who have obtained a correspondingly positive result through a pure WTW analysis in their work. The GHG emissions of an electric vehicle with a 14.5 kWh battery with 65 g CO_2 eq per km only amount to 36% of the emissions of a petrol-driven vehicle or 45% of the emissions of a diesel-driven vehicle. Futhermore, the absolute value is signficicantly lower than the emissions published in the studies in this chapter. (Note: Emissions of the electricity mix were given as an EU-wide average of 447 g CO_2-eq per kWh generated in 2013.)

[47] Own presentation based on Nordelöf *et al.* (2014).

4.2.2 Manufacturing Processes: Bottom-Up- or Top-Down approach

To achieve an accurate assessment of the amount of emitted GHGs (converted into CO_2-equivalents) during the manufacturing process, the correct values need to be allocated to each component of a vehicle. For this purpose, either the Bottom-Up or the Top-Down approach can be applied. The Bottom-Up approach attempts to consider the emission of each manufacturing step. Consequently, the values of all components are collected and summed up after the final manufacturing of the vehicle. Within a Top-Down approach, the entire emission data of a manufacturing facility is distributed to the individual manufacturing steps. The risk of this procedure is that individual process steps and emissions may be counted several times. However, the Top-Down approach is also described as more complete, as it integrates for example the energy use of auxiliary processes into the calculation. Therefore, Top-Down approaches achieve results that are often more than two times higher than the results of a Bottom-Up approach (Hall and Lutsey, 2018, p. 2; Romare and Dahlöf, 2017, pp. 12–13). However, it is not congruently specified which approach was used for the respective calculations. Regarding the analysed studies, it is not possible to evaluate if different approaches led to the wide range of results. The possible impact of a diverse use of both approaches to assess an identical object are further examined in detail in chapter 4.5.3.

4.2.3 System boundaries

An LCA that is carried out in accordance with DIN ISO 14004 must clearly define the system boundaries. This unambiguous definition is not provided in any of the relevant studies. However, this does not mean that the authors did not set limits for their scope. They may just have not published it. Hawkins *et al.* (2013), for example, limit their analysis to "vehicle manufacturing, use, and end of life together with all relevant supply chains" (Hawkins *et al.*, 2013, p. 55). Hence, a lack of transparency regarding the publication and documentation of these system boundaries is apparent. Potential deviations in the definition of system boundaries may cause significant differences regarding the results.

4.2.4 Impact categories

All studies refer in their assessment to the impact category of Global Greenhouse Emissions or Global Greenhouse Gas Potential, which is expressed in (kilo-)grams of CO_2-eq. However, it is not clear whether individual GHGs are excluded from the analysis or what length of stay of the GHGs within the atmosphere is used as a reference. Hence, it is not possible to determine if a differing consideration of GHGs led to the wide range of LCA results.

4.3 Analysis of key parameters

4.3.1 Applied electricity mix

All phases of an LCA are influenced by the considered electricity mix. Accordingly, it has a significant influence on the result. Hence, the applied electricity mix can be seen as one or the key parameter in the context of LCAs. However, none of the presented studies uses identical values for the power mix in its LCA. The reasons are on the one hand the different publication years and on the other hand different power mixes depending on the geographical location[48]. All used values vary from about 300 to over 1000 g CO_2-eq per generated kWh. Comparability exists, if at all, only in the studies that focus on the European electricity mix.

On first analysis, it seems that contrary to the causality between global or at least European efforts to successively decarbonise energy production, the respective values do not decrease the more current the respective year is. Ellingsen *et al.* (2016) reports the average value of European electricity generation at 521 g CO_2-eq per kWh in 2014. On the contrary, Hall and Lutsey (2018) refer to the European Environment Agency (EEA)[49] as saying that the value for the same year is only 276 g CO_2-eq per kWh. Consequently, it is necessary to analyse the respective data sources. Ellingsen *et al.* (2016) refer to the results of Itten *et al.* (2014). The first major difference consists in the fact that Itten *et al.* (2014) refer to the European and EEA only to the electricity mix of the European Union. Furthermore, a detailed analysis of the results of Itten *et al.* (2014) shows that the data refer to the year 2008 and not to the year 2014 as assumed on basis of the mentioned source by Ellingsen *et al.* (2016). Thus, the quantitative difference can be explained. The result of the source analysis examines the importance of a transparent presentation of the used data to simplify the understanding of the obtained result for the reader. Nevertheless, different sources do not quantify the same emission values for an identical year. Messagie (2017) reports a value of 300 g CO_2-eq per kWh for the EU electricity mix in 2015 according to data from the European Commission[50]. This value is higher than the reported value by Hall and Lutsey (2018) for the previous year. By analysing the respective sources, it is not possible to determine the basis on which the European Commission and the EEA calculated their differing emissions levels. Either way, both sources are considered reliable.

Therefore, depending on the chosen source, different emission levels may arise from energy production. Even after a detailed analysis, no uniform values can be defined. Hence, the non-

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[48] Wolfram and Wiedmann (2017) refer to the Australian, Nealer *et al.* (2015) to the U.S.-American, Lombardi *et al.* (2017) to the Italian and all other studies to the average European electrcity mix. Hawkins *et al.* (2013) also refer to the European electricity mix, but specify neither a concrete value nor a source.

[49] Used data is based on European Environment Agency (2016).

[50] Used data is based on Vita *et al.* (2016).

congruent use of emissions by energy production is identified as one cause for the different results of the analysed studies.

4.3.2 General and vehicle related parameters

Although all studies refer to light duty vehicles[51], there is no uniform definition of this term. Cars, SUVs, mini vans but also personal light trucks can be described as such types (Hawkins *et al.*, 2013, p. 62). Consequently, significant differences in the dimensioning of the vehicle appear within the analyses of the relevant studies. In order to be able to carry out the analysis on the basis of industry-related values, the studies partly use data from real vehicles[52]. The advantage of using real vehicles is that it is possible to rely on verified data from manufacturers. On the downside, basically two different vehicles of the same category are compared. Accordingly, the values of important parameters vary.

Car weight and size of the battery

The weight of the considered electric vehicles differ between 1051 kg (Hall and Lutsey, 2018) and 1650 kg (Nealer *et al.*, 2015). Car weight and battery size correlate positively. A heavier vehicle requires more energy, and therefore needs a larger (and heavier) battery. Including all considered battery capacities per study, a total of 10 different battery sizes is used in the respective studies. In this context the electric vehicle is always heavier than the ICEV. If it is assumed that both vehicles have identical efficiencies in terms of energy use, the lighter vehicle is generally advantageous. Nevertheless, the approach that an electric and a conventionally powered vehicle have different total weights is not fundamentally wrong. The different drive technology in the form of an electric or an internal combustion engine always leads to different weights.

Battery consumption and efficiency

Internal battery efficiency determines the amount of energy loss during charging and discharging processes. Losses are mainly caused by internal resistances within the battery. The lower these resistances are, the lower the losses are (Peters *et al.*, 2017, p. 502). The consumption values range between 14,6 kWh/ 100km (Ellingsen *et al.*, 2016) and 23 kWh/ 100km (Wolfram and Wiedmann, 2017). These differences clearly correlate with the different dimensions of the vehicles and should therefore not be regarded as arbitrary, because they have a significant influence on the overall result. During the use phase, minimal deviations in the efficiency of the electric motor can sometimes have major long-term effects. The

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[51] This assumption is in line with current perceptions, since in the field of electromobility small vehicles with a short range have been identified as the optimal target group (Ellingsen *et al.*, 2016).

[52] Hall and Lutsey (2018), Nealer *et al.* (2015) und Hawkins *et al.* (2013), for example, use the Nissan Lead EF as reference for an electric car in different motorisations (due to the publication dates of the studies) and in the case of Hall and Lutsey (2018) a Peugeot 208 for an ICEV.

consumption of only 1 kWh[53] more energy per 100 kilometres results in an additional 1500 kWh over an observation period of 150,000 km. Assuming 489[54] g CO_2-eq per generated kWh, this additional consumption of a single vehicle during the use phase generates additional emissions of 733.5 kg CO_2-eq or approx. 5 g CO_2-eq per km during the use phase. Hence, already small differences between values for the energy consumption can cause a significant influence on the overall result.

Number of kilometres and lifetime of the battery

Based on the total number of driven kilometres during the lifetime of the vehicle, the overall conditions of the use phase are established. By orienting the analysis on the total kilometres it is possible to carry out a time-independent analysis. Thus, the analysis is based solely on the resilience of the battery. In this context, all studies use widely diverging assumptions. The maximum number of kilometres of 288.000 km by Nealer *et al.* (2015) for a full-sized[55] electric vehicle is almost twice as high as the 150.000 km considered by Hall and Lutsey (2018) and Hawkins *et al.* (2013).

The total number of kilometres is closely linked to the calendar and cyclic expiration time[56] of a battery. With the exception of Ellingsen *et al.* (2016) all studies publish their assumptions regarding the calendar and cyclic life time of the battery[57]. Hall and Lutsey (2018), Lombardi *et al.* (2017), Nealer *et al.* (2015) and Hawkins *et al.* (2013) assume that the battery will survive the total service life of the vehicle and does not need to be replaced. Messagie (2017) as well as Wolfram and Wiedmann (2017) assume, that on average 1,5 batteries are required per vehicle life cycle. According to the current state of the art, a battery cannot be replaced partially. In case of a defective battery it has to be completely replaced (Peters *et al.*, 2017). With regard to the presented studies, the final results of Messagie (2017) and Wolfram and Wiedmann (2017) must be corrected upwards, as the estimation of 1,5 batteries should be rounded up to two batteries within the respective observation period as it is considered by Lombardi *et al.*

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[53] With an average consumption value of 15 kWh per 100 km, this corresponds to a deviation of just 6.7%. In relation to an internal combustion engine with an average consumption of 8 litre per 100km, this would be a corresponding additional consumption of only 0.5l per 100km.

[54] Forecasted value for the year 2017 by the German Federal Environment Agency (Icha and Kuhs, 2018, p. 9).

[55] The full-sized electric vehicle is based on the dimension of the Tesla Model S

[56] This expiration time is described by the so-called process of degratation. The decay depends on the depth of discharge (DOD), the chaging rate and the operation temperature. In principle, a LIB is considered to have reached its EOL as soon as it can only use 80% of its original capacity. However, only scarce data and information exist for the influence of degredation of a battery. In general, a calendar life of at least 10 years is assumed (Peters *et al.*, 2017, p. 501).

[57] Nevertheless it can be interpreted out oft he context that Ellingsen *et al.* (2016) assume that the battery does not need to be exchanged during the lifetime of the vehicle.

(2017). Therefore, the cycle or calendar life of a battery can limit[58] the estimated total number of kilometres of an entire electric vehicle within an LCA. However, it is currently not possible to determine a well-founded estimation, which range of total kilometres is feasible for an electric vehicle and its battery, due to one simple reason. Because of the novelty of electric mobility, there are currently no measured data available (Romare and Dahlöf, 2017).

4.3.3 Battery related parameters

Emissions during battery manufacturing

The assessment of battery manufacturing mainly focuses on the emissions generated by the production of one (kilo-)watt-hour of storage capacity[59]. In relation to the ecological analysis of an electric vehicle, this data is a key parameter. No direct description of the used data leads to a great lack of transparency for the evaluation of the main different component regarding the manufacturing process of an electric vehicle and an ICEV. However, only Hall and Lutsey (2018) and Messagie (2017) directly quantify a value for the occurring kg CO_2-eq per generated kWh of storage capacity. In all other studies, this value either had to be researched in the stated literature or calculated retrospectively using the given data and battery size or weight. The values differ from 55 to 259 kg CO_{2}-eq per kWh. Although even Hall and Lutsey (2018) and Messagie (2017) choose an identical battery size, the values of emissions generated during the manufacturing process are more than twice as high in the analysis of Hall and Lutsey (2018) since both refer to different battery chemistries. Hence, no congruent data exists for one or the most important parameter regarding LCAs of electric vehicles. Consequently, the uncertainty regarding the emissions during battery remanufacturing is identified as another main reason for the differing results of LCAs of electric vehicles.

Battery chemistry

Every battery chemistry generates a different amount of emissions during its manufacturing. Solely for lithium-ion batteries a multitude of different chemical possibilities exists to manufacture the battery. All these battery types have their individual advantages and disadvantages, which influence the LCA of the battery and therefore the overall result (Peters *et al.*, 2017, pp. 492–495; Romare and Dahlöf, 2017, pp. 11–12). Messagie (2017), Ellingsen *et al.* (2016), Lombardi *et al.* (2017) and Hawkins *et al.* (2013) rely their findings on three

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[58] Batteries can also be damaged if they are used too infrequently. The process of degratation can be accelerated by the rare loading and unloading of batteries (Peters *et al.*, 2017, pp. 499–500). This restriction is limited to the sporadic use of automobiles. In the context of an LCA, it is questionable to what extent such a consideration is purposeful. Neither a conventional nor an electrically powered vehicle should be purchased from an ecological perspective if they are not subsequently used. In the case of sporadic use, switching to other mobility solutions is advantageous. For this reason, it is legitimate that in the analysed studies the potential damage to batteries caused by non-use has not be taken into account.

[59] Further, the respective result is multiplied by the power value of the battery to obtain the total emissions from battery production.

different chemistries[60]. The remaining studies do not provide which chemistry is used during the LCA[61]. Thus, due the continuous development of battery technology no congruent chemistry can be selected, which represents another reason for differing LCA results.

4.4 Consequences for the assessment of the Use and Manufacturing phase

The structural framework conditions and parameters, presented in Chapter 4.2 and 4.3, form the basis for the ecological assessment of the use and manufacturing phase. Due to the presented reasons, differing results per study are the logical consequence. The strongly diverging results of the different LCAs are caused by a multitude of methodological approaches and assumptions of key parameters that are interpreted and applied individually. Varying parameters such as vehicle weight, energy consumption or electricity mix have a significant influence on the evaluation of the use and manufacturing phase. Therefore, a comparability of the LCA results is not given.

Furthermore, it becomes clear that within the assessment of the manufacturing process, a large number of studies refer to the optimisation of the manufacturing process and especially to the energy-intensive processes of battery manufacturing. Only Lombardi *et al.* (2017) and Hawkins *et al.* (2013) provide a detailed description of emissions from the manufacturing of battery-independent components. All other studies also divide the emissions in the manufacturing process between the battery and the remaining components of the vehicle, but do not provide a detailed derivation of the emissions of the battery-independent components. None of the studies mentions if a Top-Down or a Bottom-Up approach was used to calculated the respective emission load. Messagie (2017) states identical emission values for the manufacturing of battery-independent components of an electric and a conventional vehicle. The authors do not clarify, whether it is assumed that the remaining components other than the battery of an electric vehicle are identical to those of a conventional vehicle or whether it is a coincidental result within their analysis. However, there are significant differences, especially in the design of the powertrain. Regenerative brakes, the electric motor itself and power control electronics, for example, are not installed or necessary in a conventional vehicle (Nealer *et al.*, 2015, p. 17). Thus, beside the differing values for key parameters, the focus on battery manufacturing alone is not sufficient and should be carried out in detail for all parts of the vehicle to ensure a transparent end-result.

4.5 Proposals of necessary changes for future LCAs

Based on these findings, the following changes, which could guarantee future comparability, are proposed and evaluated according to their feasibility. The overall result of the analysis is

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[60] LMO; Li NCM and LiFePO4

[61] Even after a detailed analysis of the used bibliography (if provided) no further information regarding the used chemistry within the studies could be found.

the statement that the currently applicable standard is too general and offers too much space for subjective assumptions. To enable comparable results in future LCA, more strongly regulations and a stricter definition of the standard is needed. In this context, one possible approach is to develop product-dependent instead of on general standards for LCAs.

4.5.1 Guidelines for methodological and structural approaches

WTW and Top-Down or Bottom-Up Approach

Within such a (electric) vehicle focused standard for LCA, a clear agreement must be reached whether the analyses should be carried out with a Top-Down or Bottom-Up approach. Furthermore, it has to be clearly pointed out in advance that the WTW approach is applied. If these measures are not identical for the assessment of the use and the manufacturing phase, the comparability of different LCAs is rejected even before the detailed analysis has been started.

System boundaries and impact categories

In addition, clear guidelines are necessary regarding the general conditions of the LCA. System boundaries and the functional unit have to be defined. A comparability of LCA results is only feasible if a uniform definition of the system boundaries is standardised. If these limits are not clearly defined, there will continue to be uncertainty regarding the results in the future. However, it is questionable if the definition of concrete limits is feasible due to the high complexity. An exemplary description of the system boundaries of an LCA of an electric vehicle (see Figure 4-4) is outlined by Lombardi *et al.* (2017). Although the authors do not outline concrete quantifying limits, their description can be used to create a basis for orientation to enhance the comparability of future LCAs.

Regarding the functional unit, it has to be determined which GHGs are considered and which conversion factors are valid. In this context, the generally accepted conversion values, resented in chapter 3.5 can serve as a reference.

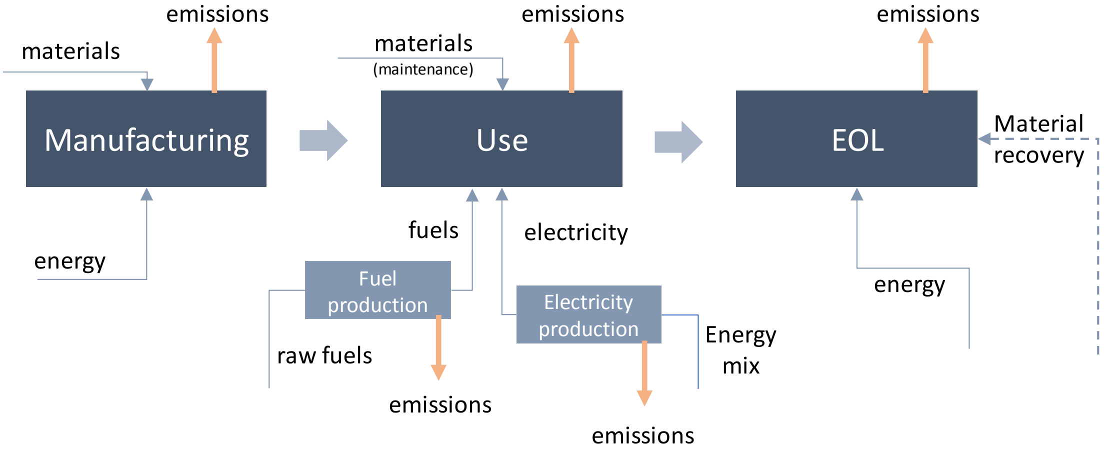

Figure 4-4: System boundaries of an LCA[62]

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[62] Own presentation based on Lombardi *et al.* (2017).

4.5.2 Proposals for key parameters

Applied electricity mix within the LCA

Due to strong geographical differences, it is questionable whether the orientation towards real emission values caused by energy generation is appropriate with the aim of obtaining a reliable benchmark for the LCA of (electric) vehicles. In general, improvements due to technological progress and increased efficiency in the manufacturing process, are mixed with the effect of the parallel decarbonisation of the electricity mix and do not become apparent in the results. As an alternative, fixed emission levels in grams CO_2-eq per kWh could be used to improve comparability. By considering a fictious power mix with x-hundred grams of CO_2-eq per kWh instead of real emission values, several studies can fall back on these values and calculate their total LCA based on an identical electricity mix. Afterwards the selected fictious electricity mix must be compared with real values. If the fictious scenario represents already established circumstances, realistic results are nonetheless contained. In case they do not display realistic values, which can be achieved in the near future, the estimated maximum of allowed emissions define concrete requirements that have to be met in the future to guarantee sustainability.

Dimensions of the vehicle

To generate comparable data, it would be necessary to compare up to what point an identical vehicle would be better equipped with an electric motor or a combustion engine. Similar to the power mix, the comparison could be made with an identical fictious vehicle, which differs only in the form of the drive technology. Within a scenario analysis, the effect of beforehand defined battery size categories and efficiency can be taken into account. Thus, when evaluating the different vehicles, a direct dependency on the respective components of each vehicle is created. Furthermore, improvements due to technological innovations of individual components can be assessed precisely. However, to estimate the lifetime of an electric vehicle or battery, it is necessary to wait until sufficient data has been collected. As long as partial replacement of the battery is not feasible, only integers may be used for calculations.

4.5.3 Proposals for battery related parameters

Emissions caused by battery manufacturing

To achieve comparable LCA results and avoid the current lack of transparency, standardised or widely acknowledged values regarding the generated emissions within the manufacturing of one kWh storage capacity have to be determined. Therefore, it must be clarified if such a value already exists or can be determined according to the current state of research. In general, the determination of this parameter is based on the results of an additional and independent LCA. Since this value represents the largest difference within the substitution of internal combustion by electric engines, the analysis of current data regarding battery manufacturing is subsequently carried out in detail.

Status quo of research regarding the generated emissions within battery manufacturing

The International Council of Clean Transportation (ICCT) has published a meta-study in February 2018 which assesses the current state of research. According to ICCT, the battery manufacturing of an electric vehicle generates emissions between 56 and 494 kg CO_2-eq per kilowatt hour (kWh) of storage capacity. To determine this range, the ICCT has analysed 11 studies and summarised the results (Hall and Lutsey, 2018, p. 2). Due to the enormous difference, it is not possible to draw informative conclusions from these data. For this reason, the current results of LCAs with regarding battery manufacturing need to be analysed in detail.

Analysis of current literature regarding the generated emissions within battery manufacturing

This task remains very complex. Comparing the results and the sources of the ICCT meta-study, it becomes clear that all 11 studies refer to a large grid of previous studies. This grid has been analysed within a meta-analysis by Peters *et al.* (2017). According to their data, an average energy requirement of 328 Wh is required for the manufacturing of 1 Wh of storage capacity which emits GHG emissions of 110 g CO_2-eq. This average value is based on the analysis of, according to their own statement[63], all published LCAs of batteries or battery manufacturing between the years 2000 and 2016 (Peters *et al.*, 2017, pp. 497–499). However, Peters *et al.* (2017) discovered that only seven of the analysed studies developed and calculated their own data set. Another eight studies have partly extended existing data. The remaining studies used existing data and applied them in their analysis (Peters *et al.*, 2017, pp. 497–499). This finding raises the question, how the results of many studies can be that different, as they are almost all based on the same data set. Accordingly, two consequences can be assumed for the assessment of the emissions generated during battery manufacturing.

1. *Researches only modify existing data*

Based on the already existing data, several studies apply their individual impact assessment methodology, scope and system boundaries. For this reason, and due to the various assumptions regarding the interpretation of the data basis and key parameters such as battery cycle life or efficiency, the results of the studies differ (Peters *et al.*, 2017, pp. 492–497; Romare and Dahlöf, 2017, pp. 11–12).

2. *The frequent use of already existing data may create mathematical conflicts*

Even the few studies mentioned by the ICCT refer to their mutual results (see Figure 4-5). This mutuality can cause methodological and mathematical issues. Due to the use of the same data base, many authors calculate average values using existing literature. In general, calculating an average value is a reliable approach. Nevertheless, there is a potential risk behind this procedure. Among the studies published by the ICCT are the results of Peters *et al.* (2017) and Ellingsen *et al.* (2016). The average value determined by Peters *et al.* (2017) also considers the results of Ellingsen *et al.* (2016). Any future analysis that determines an average value using the values presented by the ICCT would consider the results of Ellingsen *et al.* (2016) twice. From a mathematical perspective this is not valid. Due to the complexity of the data structure, it has to be challenged if the current data sets are completely independent. The

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[63] The authors identified 79 LCA studies on batteries and 34 on electric vehicles. Of these, 36 LCA were selected that met the selection criteria. All results were standardised to the generation of 1Wh storage capacity. If studies indicated ranges of emissions, average values have been determined.

probability is highly given that in the multitude of scientific work (including the average value established by Peters *et al.* (2017)) a lot of studies are considered more than once.

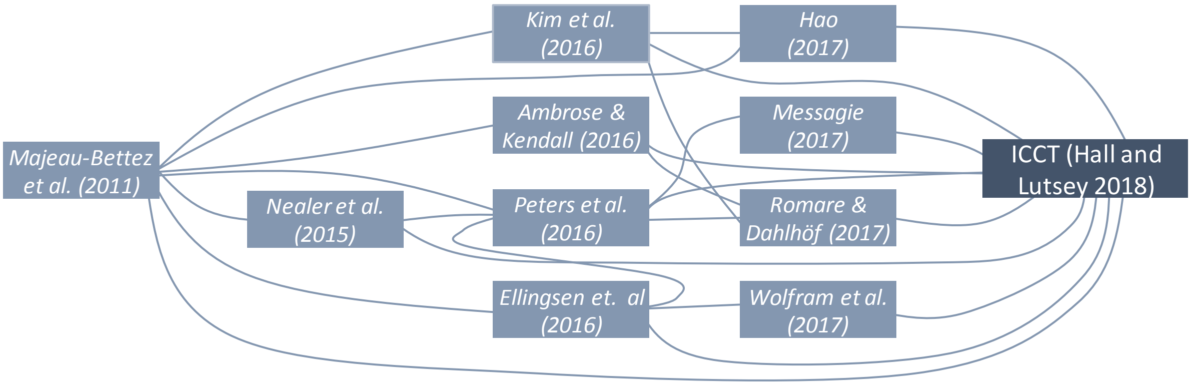

Figure 4-5: Exemplary presentation of the grid of recent studies of battery manufacturing[64]

Summary of the analysis of emissions in the context of the battery manufacturing process

The analysis of the results of studies focusing on the ecological evaluation of the manufacturing process of lithium-ion batteries shows that the current state of research is based on a complex network of past data and findings. There are large differences in the assessment of the ecological consequences within the manufacturing process of lithium-ion batteries. Hence, Peters *et al.* (2017) concluded that there is currently “no recent review about LCAs of [Lithium-Ion batteries]“ (Peters *et al.*, 2017, p. 492). The available data does not obtain the necessary transparency to be able to make detailed and well-founded conclusions regarding the GHG emissions caused by the manufacturing of lithium-ion batteries (Romare and Dahlöf, 2017, p. 43). For these reasons, it is currently not possible to quantify valid data for the manufacturing of batteries of electric vehicles which would be necessary to overcome the existing lack of transparency to create comparable results of LCAs.

Conclusion

The fact that no congruent data exist for the most important components of electric vehicles prevents any comparable ecological analysis. In consideration of the already proposed norms, the battery manufacturing process has to be evaluated transparently again to create a valid data basis. Only in this way it is possible to integrate the continuous further development of battery technology into new research. However, compared to the other proposed changes, this process is associated with a significantly higher and more complex effort.

Chemistry

A simple solution to achieve uniform results could be the definition of one battery chemistry, which is used to power the drive of an electric vehicle. However, due to the constant development of battery technologies and existing uncertainties, which chemistry composition will prevail in the future, this approach would not be expedient (Romare and Dahlöf, 2017, p. 10). An alternative could be the determination of conversion factors between the individual battery chemistries. Therefore, the respective chemistries need to be analysed individually.

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[64] To determine the dependencies, all sources of the studies were analysed and compared accordingly.

In this context, Peters *et al.* (2017) have identified that no uniform modelling is used regarding the assessment of battery manufacturing processes. Some studies have been carried out with a Top-Down approach and others with a Bottom-Up approach. Accordingly, the results already vary within the respective chemistry. Chemistries which have been predominantly evaluated with a Top-Down approach show higher emission values than studies which were carried out with a Bottom-Up approach[65] (Peters *et al.*, 2017, pp. 497–499). This complicates the comparison of the results of the individual chemical compositions. Within the scope of an LCA, it is not sufficient to distinguish between the different battery technologies. In case it is possible to calculate a satisfactory average value, it is necessary to analyse proportionately whether the Top-Down or Bottom-Up approaches predominate in the evaluation of this chemistry.

For these reasons, the determination of conversion factors for the individual battery chemistries is not considered feasible in accordance with the current state of research. Based on the proposed structural changes for future LCAs, it will only be possible to relate individual battery chemistries mutually if a uniform manufacturing process and methodological approach for the evaluation is established. This would require a re-evaluation of every battery chemistries. Although this new evaluation involves a great effort for the analysis of complex data, it enables the possibility to establish conversion factors between the individual chemistries for future LCA in accordance with the continuous research and development of new technologies.

4.5.4 Consequences for the analysis of the Use and Manufacturing phase

Assuming that the previously described proposals for modification are implemented, the calculation of the use and manufacturing phase can be carried out under new conditions. Due to the identical parameters, especially when considering a fictitious electricity mix, differences in the use phase are no longer probable. The use of a fictitious vehicle also offers the possibility of a transparent assessment of the manufacturing process. When analysing the vehicle, only actual differences caused by the drive technology are relevant. It is further still valid, that the battery and the emissions resulting from the manufacturing process are the most important factor and key to enable comparability of LCA results of electric vehicles. If all other proposed modifications can be established, a transparent assessment of the battery manufacturing process is conceivable. Thus, best practices can be created to define the framework conditions for the future manufacturing and use of electric vehicles. However, a simple evaluation of current technologies remains serving as a benchmark of the current status quo. Eventually, the implementation of such a new standard requires nonetheless a high effort, time and the analysis of large amount of data.

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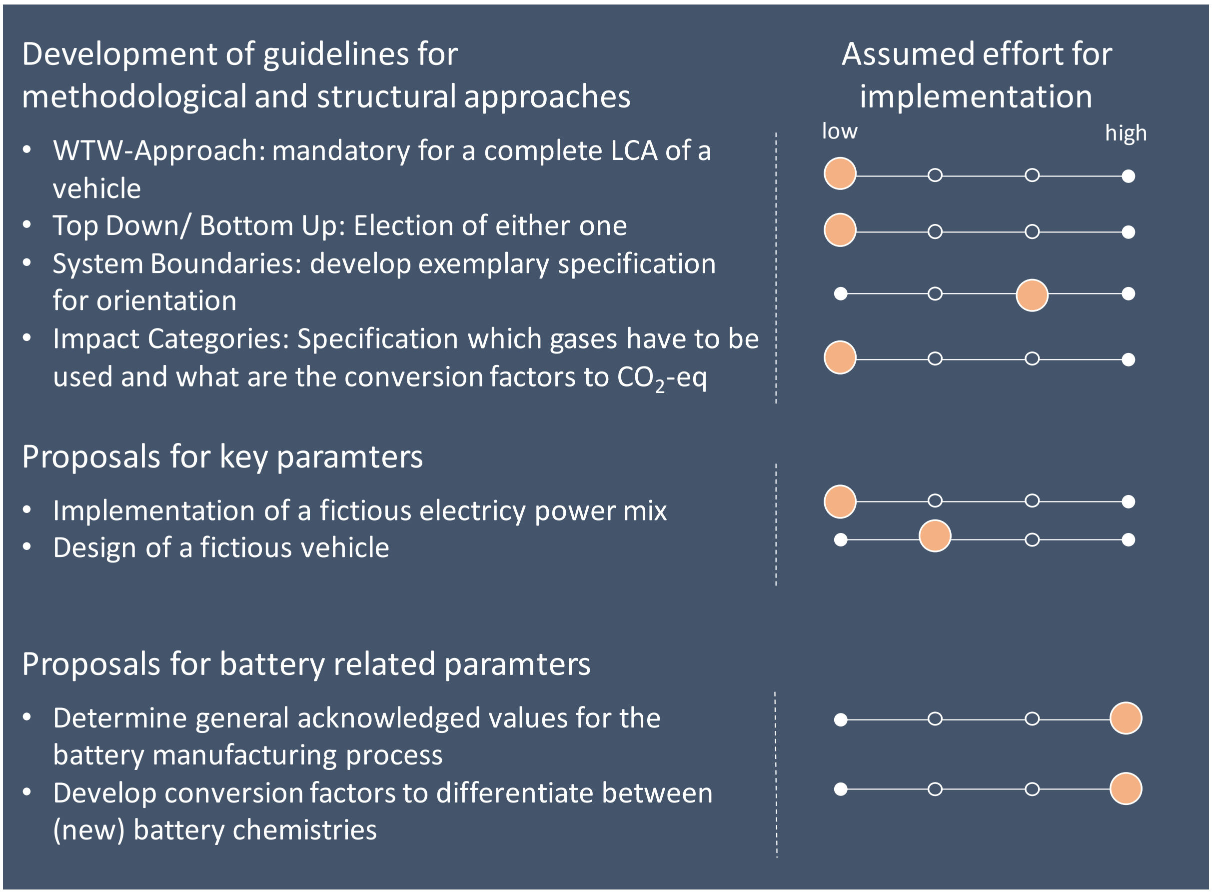
[65] According to Peters *et al.* (2017) e.g. LFP batteries showed high GHG emissions. However, seven out of nine studies were conducted with a Top-Down approach, which mostly determines higher values.



Development of guidelines for methodological and structural approaches

- WTW-Approach: mandatory for a complete LCA of a vehicle
- Top Down/ Bottom Up: Election of either one
- System Boundaries: develop exemplary specification for orientation
- Impact Categories: Specification which gases have to be used and what are the conversion factors to CO_2-eq

Proposals for key paramters

- Implementation of a fictious electricy power mix
- Design of a fictious vehicle

Proposals for battery related paramters

- Determine general acknowledged values for the battery manufacturing process
- Develop conversion factors to differentiate between (new) battery chemistries

Figure 4-6: Summary of proposals and the assumed effort for implementation

4.6 Conclusion

It is proven that current studies do not allow comparability due to the multitude of possible variables. This also applies to individual LCAs of single components such as the battery. The reasons for differing results and lack of comparability are congruent. Thus, these findings represent an example for the potential conflict due to subjective implementations of LCAs, which is already described in chapter 3.4. Hence, the quality of the existing data does not allow a quantitative extension of existing LCAs. For this reason, the modelling of EOL-strategies will be carried out conceptually. Thus, it is possible to incorporate future trends and technological developments into the model and to further develop it accordingly.

Furthermore, it is elaborated that many parameters have to be re-evaluated or standardised to enable comparable results in the future. The proposals of possible modifications demonstrate that with the help of stricter standards, the comparability of future LCAs may be increased, even though this step requires a great effort and time. In this context the approach of Lombardi *et al.* (2017) can serve as an orientation. Within their analysis, Lombardi *et al.* (2017) try to reduce the complexity and uncertainty in the context of an LCA of electric vehicles. The authors focus on the comparison of different drive technologies and a GM Chevrolet Malibu is taken as a reference vehicle. Based on this body four vehicles are modelled, which differ only regarding the technology of the powertrain. The weight of the vehicle varies between 1500 and 1700 kg depending on the drive technology. This approach greatly simplifies the dimensioning of the vehicle. It is possible to concentrate on the significant differences between the vehicles and reduces the complexity of the LCA. Nevertheless, this approach does not provide data for an LCA of the entire life cycle of an electric vehicle and uncertainties in battery manufacturing or due to the use of different electricity mixes are still remaining.

5 Development of the mathematical model

5.1 Status quo and implementation of EOL-strategies

The recovery of EOL vehicles is regulated in the European Union by Directive 2000/53/EC (See Figure 5-1). It claims that „no later than 1 January 2015, for all end-of life vehicles, the reuse[66] and recovery[67] shall be increased to a minimum of 95% by an average weight per vehicle and year. Within the same time limit, the reuse and recycling[68] shall be increased to a minimum of 85% by an average weight per vehicle and year“ (European Parliament and the Council, 2000, L 269/38).

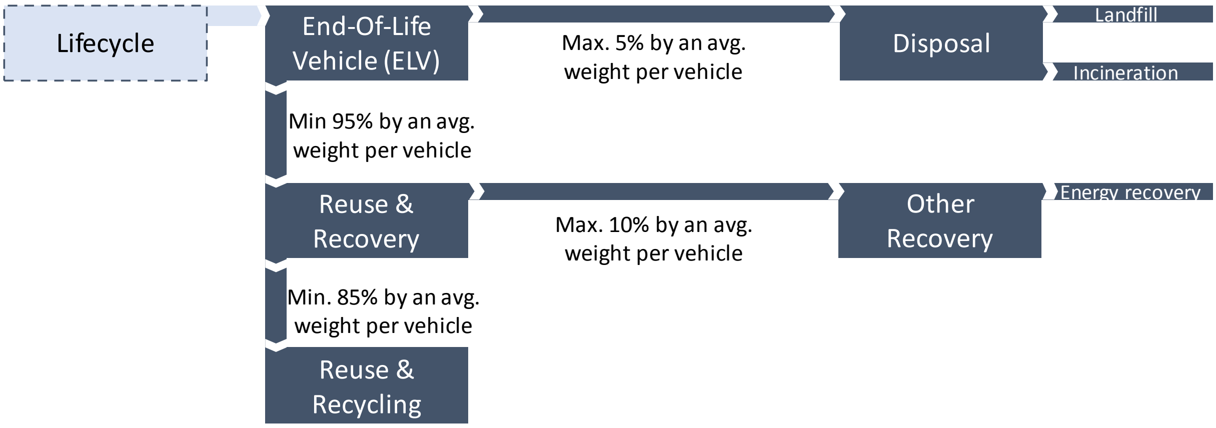


Figure 5-1: Own graphic illustration of the minimum requirements for the recovery of end-of-life vehicles according to 2000/53/EC

Thus, today almost all components of an automobile have to be recovered by using EOL-strategies. Similar regulative requirements also apply to battery technology[69]. Hence, the assumption that all components of a vehicle have to be completely reproduced does not correspond to reality, neither for electric vehicles nor for conventional vehicles. This knowledge is decisive for the modelling and implementation of EOL-strategies. Consequently, potential savings of emissions always have to be related to current recovery values and not to a vehicle that is manufactured from scratch. Nevertheless, the regulations only refer to the vehicle

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[66] In the directive ‘reuse’ means any operation by which components of end-of life vehicles are used for the same purpose for which they were conceived (Bundesministerium der Justiz und für Verbraucher, 2017).

[67] In the directive ‘recovery’ means any of the applicable operations provided for in Annex IIB to Directive 75/442/EEC (Bundesministerium der Justiz und für Verbraucher, 2017).

[68] In the directive ‘recycling’ means reprocessing in a production process of the waste materials for the original purpose or for other purposes but excluding energy recovery. Energy recovery means the use of combustible waste as a means to generate energy through direct incineration with or without other waste but with recovery of the heat (Bundesministerium der Justiz und für Verbraucher, 2017).

[69] The directive regarding batteries is explained in detail in chapter 5.3.3.

weight. Thus, it is theoretically possible that light components, whose manufacturing generates a high amount of emissions, are not included in the recovery process.

5.2 Modelling

5.2.1 General requirements

All emissions of the manufacturing process can be subdivided into the four individual stages of resource mining, resource refining, component manufacturing and assembly. By applying EOL-strategies, individual raw materials or used components can be returned between two of those stages. Within this thesis only EOL-strategies are considered that serve as a recovery process for the manufacturing of a (similar) new vehicle. Thus, other applications like further ecological advantages resulting from the provision of spare parts, which could at the same time prolong the service life of the vehicle, are not included in the model.

In total, there are three optimisation potentials at which components and materials can be recovered for the manufacturing process of a new vehicle (see Figure 5-2). Optimisation potential 1 (P1) covers all EOL-processes from which raw materials emerge, optimisation potential (P2) covers all EOL-processes from which further processed raw materials are derived and optimisation potential (P3) comprises all EOL-processes, from which already manufactured components emerge, which afterwards only have to be assembled. Depending on the used optimisation potential, all precedent manufacturing phases can be omitted in chronological order[70].

Even if the assembly of the individual components is part of the manufacturing process, the share of emissions is estimated to be very low, as the processes of resource mining and refining as well as component manufacturing are more energy-intensive. In addition, it is no longer possible to differentiate between the individual components at this stage of manufacturing. Regarding the model this causes a mathematical conflict. Before reaching the assembly phase all emissions can be allocated to the respective components. This individual distribution is not possible once all components are assembled. In addition, every component that can theoretically be reused directly without additional treatment must still be de- and reassembled. Therefore, the assembly process of a vehicle cannot be optimised by EOL-strategies and is not considered in the context of the model.

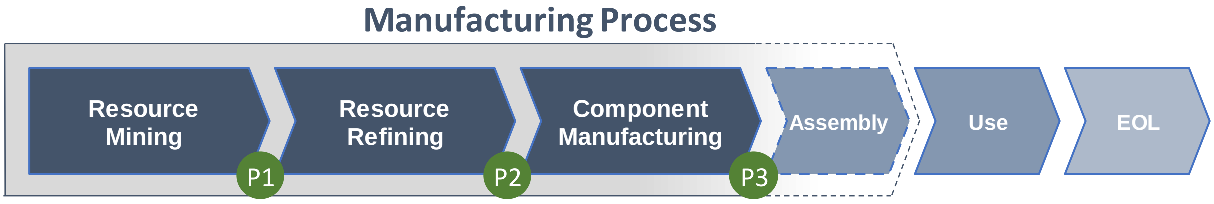

Figure 5-2: Illustration of the optimisation potentials P1, P2 and P3 in the manufacturing process

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[70] e.g., resource mining does not have to be carried out for all components refered to P1

5.2.2 Determining the relevant EOL-strategies

To evaluate the ecological benefits of EOL-strategies it has to be assessed which of the EOL-strategies defined in Chapter 2.5 are relevant for the model. Within this thesis, it is assumed that the EOL-strategies recycling can be used for P1, remanufacturing and reuse for P2 and reuse, refurbishing and remanufacturing for P3. Nevertheless, the allocation of components to one of the optimisation potentials is the main task. Once it is evaluated which components and materials of a vehicle can be used for P1, P2 or P3, it is of secondary importance[71] which specific EOL-strategies is finally used.

Repurposing, repair, incineration and landfill are not considered within the model. Repurposing contradicts the condition of the model that recycled components are only used for the manufacturing of a new automobile. In general, repair will continue serving as an important EOL-strategy to improve the maintenance and lifetime of a vehicle. However, this strategy only becomes relevant if a malfunction occurs. Considering repair processes in the model presupposes that failures in the vehicle are known and planned in advance. Such a procedure contradicts the goal of the CE to preserve vehicles or components and materials for as long as possible in the product life cycle and to minimise the number of defects accordingly. Eventually, repair is not considered for the model.

Landfill and energy recovery from incineration have no direct influence on the modeling and evaluation of the manufacturing process. However, energy recovery could be considered as ecological credit. Either way, the generated electricity through incineration and its resulting emissions are already taken into account in the ecological assessment of the energy production. An additional integration into the LCA model of a vehicle would cause redundancy and falsify mathematical calculations. Nevertheless, all components of a vehicle that are processed through landfill and incineration represent the proportion of a new vehicle that must in any case pass through the entire manufacturing process.

5.2.3 Description of the model

The model should be able to represent the possible benefits regarding emissions of the manufacturing process through the planned application of EOL-strategies. An improvement occurs when the emissions of a new vehicle is lower than that of the previous generation. Before developing the model is has to be determined how ecological benefits through EOL-strategies can be integrated in LCAs. One option is to count them as credits to the LCA of an existing vehicle. However, this raises the question of how to assess the manufacturing process of the next vehicle for which the recycled components are used. Due to added credits to the previous vehicle, a reduced emission level during the manufacturing of the new vehicle with recycled materials leads to a mathematical redundancy. For this reason, ecological potentials

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[71] In case two components with differing complexity may be both remanufactured, one component could be assigned to P2 and the other to P3.

for improvement should always refer to the second-generation vehicle or mathematically expressed for the generation t+1[72].

Ecological benefits through the application of EOL-strategies are calculated by subtracting the sum of emissions saved by applying EOL-strategies of the sum of all emissions during the original manufacturing process (see formula (1)). Furthermore, all calculations have to be performed in CO_2-eq.

Mathematical Model

$$LCA_{t+1} = \sum_{i=0}^{i=2} E_i - \sum_{k=1}^{k=3} S_k \tag{1}$$

with

$$\sum_{i=0}^{i=2} E_i = \sum_{i=0}^{i=2}\sum_{j=1}^{j=n} e_{i,j} \tag{2}$$

$$\sum_{k=1}^{k=3} S_k = \sum_{k=1}^{k=3}\sum_{l=1}^{l=m} s_{k,l} = \sum_{l=1}^{l=m}\left[\left(\sum_{i=0}^{i=2} e_{i,l}\right)-\left(\sum_{k=1}^{k=3} r_{k,l}\right)\right] \tag{3}$$

and the constraints

$$l \in j;\; m \le n \tag{4}$$

$$\left(\sum_{i=0}^{i=2} e_{i,l}\right)-\left(\sum_{k=1}^{k=3} r_{j,l}\right) \ge 0\; for\ each\ component\ l\ used\ for\ \mathrm{EOL-Strategies} \tag{5}$$

Variables:

$E_i = emissions\ generated\ in\ manufaturing\ stage\ i$

$e_{i,j} = emissions\ generated\ by\ compoenent\ j\ in\ manufacturing\ stage\ i$

$S_k = emissions\ savings\ due\ to\ Pk$

$s_{k,l} = emissions\ savings\ of\ component\ l\ due\ to\ Pk$

$r_{k,l} = emissions\ generated\ by\ EOL\ strategies\ in\ Pk$

$i = manufacuring\ stages; i\ \in \{0,1,2\} \triangleq \{Resource\ mining, Resource\ refining, Component\ manufacturing\}$

$j = component\ of\ BOM;\ j \in\ \{1, \dots, n\} \triangleq \{all\ BOM\ components\}$

$k = optimisation\ potential; k \in \{1,2,3\} \triangleq \{P1, P2, P3\}$

$l = component\ applicable\ with\ EOL\ strategies; l \in \{1, \dots, m\} \triangleq \{all\ EOL - applicable\ BOM\ components\}$

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[72] With t equal to the time of the previous manufacturing of an automobile.

Explanation of the calculation of emissions: Formula (2)

Variable E_i describes the emissions that are expelled during manufacturing stage i. Summarised over the three manufacturing stages, the total emissions of the manufacturing process are calculated without taking EOL-strategies into account. Hereby the emissions E_i of a manufacturing stage i are composed of the sum of the emissions $e_{i,j}$ of all j components of the Bill of Materials (BOM) within this manufacturing stage.

Explanation of the calculation of savings through the application of EOL-strategies: Formula (3)

The variable S_k describes the emission savings achieved by replacing a manufacturing phase l with EOL-strategies through optimisation potential k. Index k represents the three optimisation potential P1 to P3. In total, the sum of all savings of emissions S_k result in the total saving of emissions within the manufacturing process. The saved emission quantity S_k is the sum of the saved emissions $s_{k,l}$ of all l components of the BOM, which do not have to go through the previous manufacturing phases ($i=0$ to $i=k-1$) due to the application of EOL-strategies. However, emissions are also produced during the various EOL-processes. Thus, the variable $s_{k,l}$ describes the difference between the sum of the emissions $e_{i,l}$ of the original manufacturing process and the emissions $r_{k,l}$ caused by EOL-strategies. The sum of the emissions $e_{i,l}$ pictures the emissions of all components l which do not have to pass through the manufacturing phases $i=0$ to $i=k-1$. Accordingly, variable $r_{k,l}$ describes the emissions of the EOL-strategies of all components l, which can be returned to the life cycle through the application of EOL-strategies.

Explanation of the constraints

The first constraint (see formula (4)) ensures that all l components that are applicable for EOL-strategies are taken of the set of all j BOM components. Hence, the total number m of EOL-applicable components can never obtain a higher value than the total number n of all BOM-components. Furthermore, EOL-strategies may only be applied if they create an actual decrease in emissions. If the EOL-process of a component l produces more emissions than the original manufacturing process, the EOL-strategy should not be applied (see formula (5)). In case this constraint is constantly met, the variables $s_{k,l}$ and S_k automatically represent a positive value. For this reason, it is necessary to perform this test for each individual component l individually.

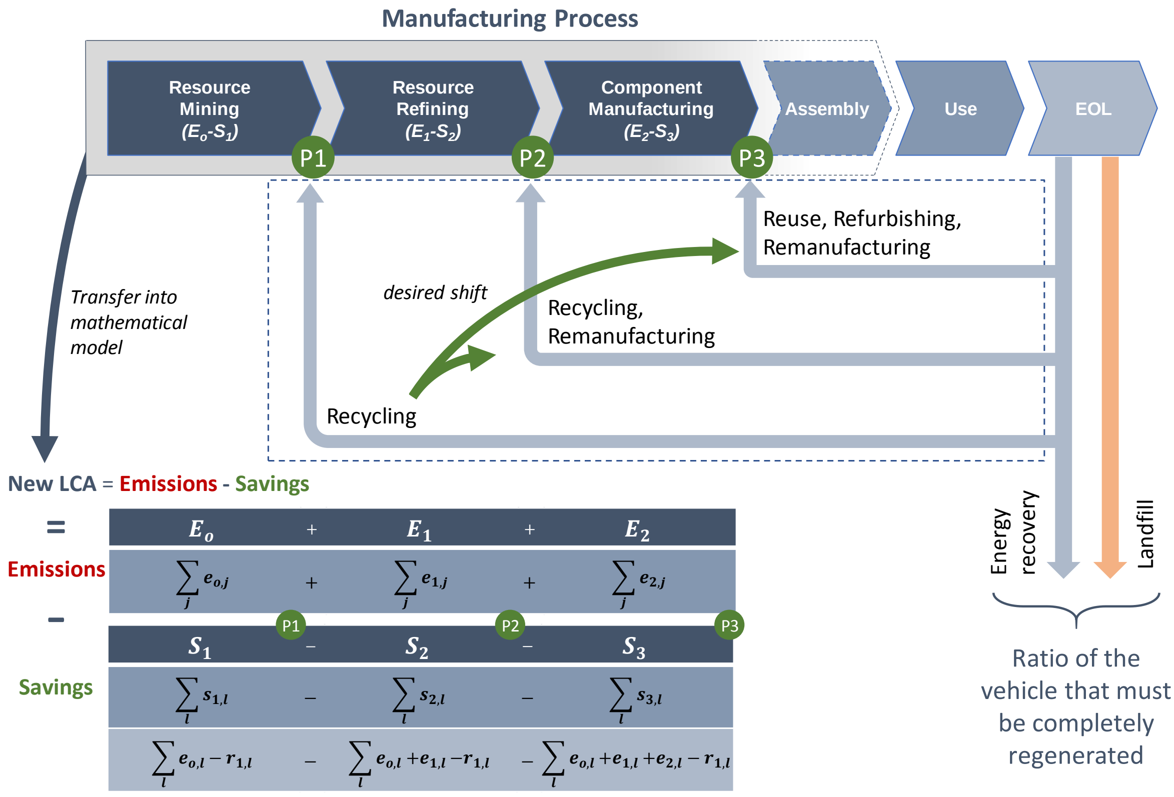

Figure 5-3: Visualisation of P1 to P3 including the corresponding EOL-strategy and the transfer into a mathematical model

However, the modelling using formulas (1) to (5) is only necessary to show how EOL-strategies can be considered in LCAs of a vehicle in order to illustrate the positive effect of their application. As soon as EOL-processes are successfully established and sufficiently integrated into the manufacturing process of vehicles, the mathematical modelling can be simplified (see formula (6)). To calculate the LCA results, it is sufficient to sum up the emissions per manufacturing stage. For all components that do not have to be completely manufactured from scratch, the emission value in the saved production phases is correspondingly zero. To present the achieved successes through the improved application of EOL-strategies, it is then sufficient to compare past and current values. As soon as one wants to evaluate an improvement in the application of EOL-strategies, the calculation must be calculated once for the initial and once for the optimised application of EOL-strategies. The difference describes the absolute improvement.

$$LCA = \sum_{i=0}^{i=2} E_i = \sum_{i=0}^{i=2} \sum_{j=1}^{j=n} e_{i,j} \tag{6}$$

5.3 Numerical evaluation of ecological impact of EOL-strategies

In order to illustrate the ecological advantages that can be achieved through the application of EOL-strategies, a calculation is carried out. Due to the uncertainty regarding data of current LCA's of electric vehicles, no absolute values are used. The aim of the calculation is to show as a percentage which ecological improvements might be possible, independent of the actual emission values. Thus, it is possible to apply the results for many vehicles. For this purpose, several assumptions and simplifications are necessary for reasons of comprehensibility.

5.3.1 Assumption 1: Share of emissions of the battery and the vehicle

The battery accounts for a significant proportion of the weight and emissions of an electric vehicle. To illustrate the different potential savings of emissions for the battery and the rest of the vehicle, the calculation must be carried for each part respectively. Therefore, it is necessary to discuss how high the respective share of emissions from the battery and the rest of the vehicle is compared to the overall manufacturing process. In this context, the studies presented in Chapter 4 are used to determine the percentage shares. Table 5-1 shows the distribution of the individual studies, sorted by different weight classes of the vehicle. Since a large part of the data is available for the weight category from 1500 to 1650 kg (weight category 2), the best comparability is possible in this area. The average values were compared with the other weight categories and no significant deviations are apparent. For a simplified presentation, the values were rounded to the nearest unit value. Consequently, the battery accounts for 35 % and the rest of the vehicle for 65 % of the total emissions of the manufacturing process.

	Battery				Vehicle			
Weight Category[73] in kg	1	2	3	4	1	2	3	4
Hall and Lutsey (2018)	-	50%	-	-	-	50%	-	-
Messagie (2017)	43,8%	-	-	-	56,3%	-	-	-
Wolfram and Wiedmann (2017)	-	30,8%	-	-	-	69,2%	-	-
Ellingsen *et al.* (2016)	29,6%	32,4%	40,4%	45,6%	70,4%	67,6%	59,6%	54,4%
Nealer *et al.* (2015)	-	24,0%	-	36,0%	-	76,0%	-	64,0%
Hawkins *et al.* (2013)	-	36,3% 41,1%	-	-	-	63,7% 58,9%	-	-
Average Value	**36,7%**	**35,8%**	**40,4%**	**40,8%**	**63,3%**	**64,2%**	**59,6%**	**59,2%**
Assumption for calculation		**35%**				**65%**		

Table 5-1: Share of emissions of the battery and the vehicle in the manufacturing process

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[73] Category 1: 1100 – 1200 kg; Category 2: 1500 – 1650 kg, Categroy 3: 1750 kg; Categroy 4: 2100 – 2350 kg

5.3.2 Assumption 2: Share of emission of the manufacturing phases

Savings through EOL-strategies can be evaluated in relation to the entire manufacturing process. The higher the share of the respective manufacturing phase, the more EOL-strategies should be used to avoid it.

Values for the vehicle

The corresponding values for the allocation of emissions to the manufacturing phases are taken from the research results of the Institute for Economics and Transport at the TU Dresden. Based on the presented values in the publication, it is possible to determine the percentage values shown in Table 5-2.

Resource Mining	Resource Refining	Component Manufacturing
28%	56%	16%

Table 5-2: Allocation of emissions to the individual phases of the vehicle manufacturing process[74]

Values for the battery

Romare and Dahlöf (2017) have listed in detail the distribution of emission load over the individual phases of a battery manufacturing process. After comparing several studies, the authors succeeded in establishing average values for the individual manufacturing phases. The distribution of emissions per manufacturing phase can be seen in Table 5-3.

Resource Mining	Resource Refining	Component Manufacturing
16%	32%	52%

Table 5-3: Allocation of emissions to the individual phases of the battery manufacturing process[75]

5.3.3 Assumption 3: Current distribution of emissions for P1, P2 and P3

EOL-strategies (especially recycling) are already applied today. Therefore, it is necessary to determine the current recovery rates at the three optimisation points P1, P2 and P3.

Values for the vehicle

The values for the vehicle are taken from the annual report on EOL vehicle reuse/recycling/recovery rates in Germany for 2016, published by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the German Federal Environment Agency. In accordance with the requirements of the directive[76] of EOL-vehicles these percentages refer only to weights and not emissions. To be able to transfer the percentages

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[74] Data based on Martin and Treiber (2014, p. 6) See annex A.9.

[75] Data based on Romare and Dahlöf (2017, pp. 19–25) See annex A.9A.10.

[76] pursuant to Art. 7 (2) of the End-of-Life Vehicles Directive 2000/53/EC (European Parliament and the Council, 2000).

to emission loads, it is assumed that the emissions in the manufacturing process are evenly distributed over the weight of the vehicle. The corresponding distribution of emissions of the vehicle is illustrated in Figure 5-4, which are transferred accordingly in tabular form below[77].

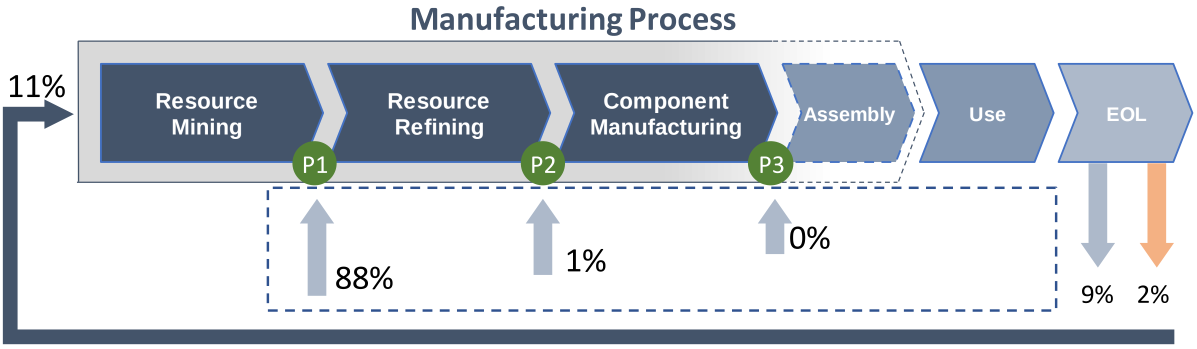

Figure 5-4: Visual presentation of the distribution in the manufacturing process

Vehicle	New	P1	P2	P3
Distribution of recovery rates related to the single manufacturing stages	11 %	88 %	1 %	0 %

Table 5-4: Tabular presentation of the distribution in the manufacturing process[78]

Values for the battery

Due to the novelty of electromobility, no valid data for the corresponding distribution of the battery and its components are published to date. The data for batteries presented in the above-mentioned annual report are related to low-voltage car batteries[79]. An extrapolation of the values is excluded, since the battery chemistry of a low-voltage car battery is significantly different from the high-voltage battery used to power an electric vehicle. Furthermore, extracted metals with current recycling technologies (especially cobalt, copper, lithium and nickel) cannot be reused for battery manufacturing. Batteries in electric vehicles are currently used primarily for energy production through pyrometallurgical processes. The recovered metals of this process do not comply with the quality standards for a new battery. Hence, a large part of the components of a battery must pass through the entire manufacturing process (Romare and Dahlöf, 2017, pp. 32–34).

To determine values for the recycling rates of batteries current legal requirements are applied. According to Directive 2006/66/EC of the European Parliament and of the Council, Member

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[77] This graphical representation of the distribution is presented only once as a visual aid understanding and serves to ensure that there are no misunderstandings in the interpretation of the tabular values during the scenario analysis.

[78] Data based on (BMU, 2016, pp. 6–9) See annex A.10.

[79] Even if this is not explicitly defined in the report, it can be assumed that the values refer to low-voltage batteries due to the ratio of the weight of all batteries to the weight of all recycled components.

States must achieve a collection rate[80] of at least 45% for purchased and distributed batteries and accumulators by 26 September 2016. In this context, a wide range of battery types, from small button cells to batteries for driving electric vehicles, is grouped and considered together (European Parliament and the Council, 2006). Due to the size of the battery in electric vehicles and the unusual situation that users remove the battery of an end-of-life vehicle on their own responsibility and return it to the appropriate collection points, it can be assumed that 100% of the batteries in electric vehicles are collected by the manufacturer after use. This assumption is important because the model assumes that any new vehicle can be manufactured with recovered components. If not every used battery is recollected, the number of vehicles that require a completely new battery and the number of vehicles that can use a recycled battery would have to be calculated proportionally. According to Directive 2006/66/EC Annex III, the recycling of lithium-ion batteries must have a resource efficiency[81] of at least 50%[82] (European Commission, 2006). Hence, this legal minimum requirement is assumed to be the current value for battery recovery.

Battery	New	P1	P2	P3
Distribution of recovery rates related to the single manufacturing stages	50 %	50 %	0 %	0 %

Table 5-5: Distribution of the battery recovery rates per scenario

5.3.4 Assumption 4: Emissions produced by EOL- processes

This assumption refers to emissions generated by EOL-processes and is needed to assess whether there is actual potential for decrease of emission. In this area the literature publishes strongly diverging values. Romare and Dahlöf (2017) describe that according to their analysis the recycling process of a battery requires 70% of the emissions compared to a new production. Accordingly, there would be a potential of savings of 30% within P1 (Romare and Dahlöf, 2017, p. 46, Table 23). However, Ahmadi *et al.* (2017) rate the potential savings significantly higher. According to their research remanufacturing and recycling processes can generate savings potentials of up to 80% (Ahmadi *et al.*, 2017, pp. 116–118). Both studies do not differentiate in detail in their assessment between the respective manufacturing phases and the moment at which EOL-strategies take place. Nevertheless, this distinction is essential. The assumption that emissions are identical at each stage of the manufacturing phase may be too simplistic. It is highly probable that there are different opportunities for each optimisation potential, which will develop differently in the future.

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[80] The collection rate only indicates how many of the distributed batteries have to be collected. Recovery processes are not included here.

[81] ‘recycling efficiency’ of a recycling process means the ratio obtained by dividing the mass of output fractions accounting for recycling by the mass of the waste batteries and accumulators input fraction expressed as a percentage (Article 2 (3))

[82] In accordance with Regulation (EU) No 493/2012 regarding the calculation of recycling efficiencies

Eventually, any data selection is arbitrary according to the current state of research (and due to the limited validity of current environmental assessments). Hence, a first approach to assume a certain number of different saving potentials (e.g. 30%, 50% and 70%) and combine them for every respective optimisation potential is discarded. Due to the distinction between battery and vehicle as well as three distribution scenarios for the recovery rates, the total number of combinations increases exponentially[83] (see Annex A.13). The illustration of all possibilities is inevitably at the expense of clarity. Furthermore, it is more likely that today the savings are relatively small and will increase in the future due to technological developments and lower emissions from energy production. Therefore, it is assumed that there are three different levels of emissions associated with P1, P2 and P3, which will decrease accordingly in the future due to enhancement of technology and decarbonisation of energy production (see Table 5-6) [84]. Overall, the remaining emissions for the battery are currently assumed higher than for the rest of the vehicle due to the novelty and continuous development of the technology. These options are combined within a scenario analysis in chapter 5.5.

	Vehicle			Battery		
Scenario	Low	Medium	High	Low	Medium	High
Today	60%-40%	70%-50%	80%-60%	70%-50%	80%-60%	90%-70%
Scenario 1	40%-20%	50%-30%	60%-40%	50%-30%	60%-40%	70%-50%
Scenario 2	20%-5%	30%-10%	40%-20%	30%-10%	40%-20%	50%-30%

Table 5-6: Percentage of EOL-processes compared to original manufacturing stage

5.4 Procedure for the calculation

To explain the calculation in a comprehensible way, the procedure with selected and exemplary parameters is presented below. For a simplified representation it is assumed, that EOL-strategies generate 50% of emissions for both the battery and the rest of the vehicle, regardless of whether they refer to P1, P2 or P3. If the share of material mining for the battery amounts to 16% of total emissions the new share for the material mining phase for this component amounts to 8%. Hence, compared to a component that passes through the entire manufacturing process, the total emissions are reduced to 92% (=100%-8%) by replacing the phase of resource mining with an EOL-strategy. With the application of EOL-strategies for P2, resource mining could be completely omitted and resource refining would account for only 50% of emissions. In total, this means that only 68% (=100%-16%-0.5*32%) of the original emissions are released. The more manufacturing phases can be substituted by EOL-

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[83] The comination of three saving potentiasl leads to 6561 possible combination. The more assumptions are made about savings (e.g. 20%, 40%, 60% and 80%) and development scenarios, the greater the number of combinations. For more information please refer to Annex A.13.

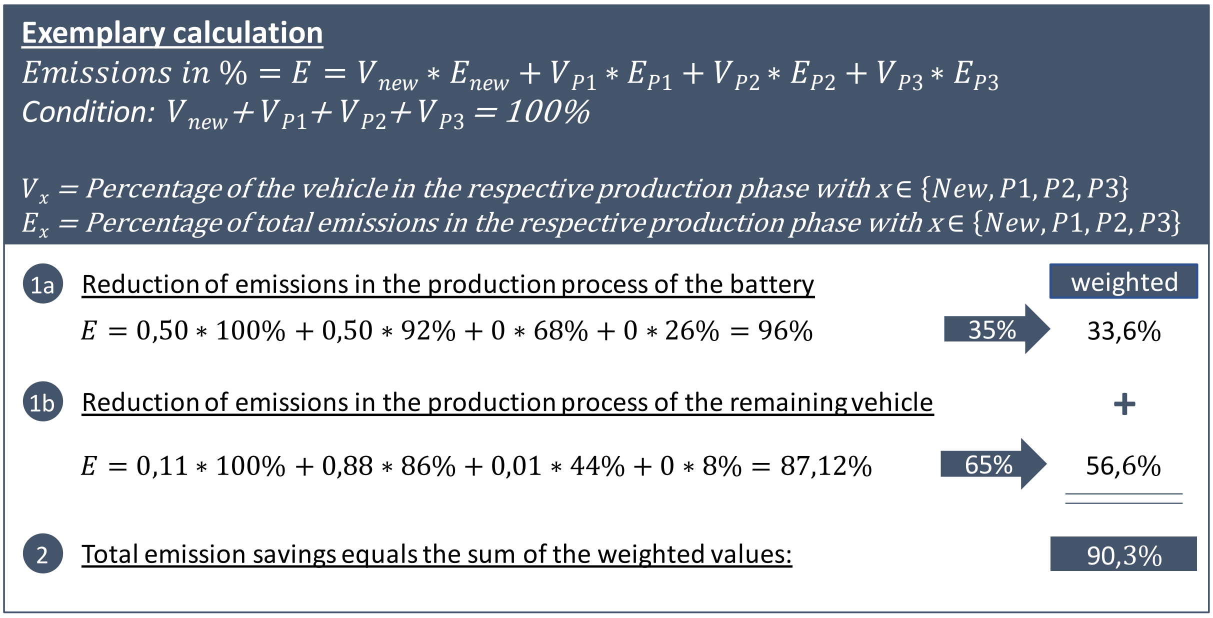
[84] A ratio of 60% implies a potential of savings of 40%. For this reason, the percentage values 90% - 5% in Table 5-6 are reciprocally related to the resulting savings potentials of 10% to 95%.

processes, the lower the emissions are. Table 5-7 shows these values for the battery and the vehicle, depending on whether the EOL-strategies are based on P1, P2 or P3.

	Resource mining		Resource Refining		Component Manufacturing	
	Battery	Vehicle	Battery	Vehicle	Battery	Vehicle
Original values	16%	28%	32%	56%	52%	16%
Multiplication by factor 0,5	8%	14%	16%	28%	26%	8%
New values including EOL-strategies	92%	86%	68%	44%	26%	8%

Table 5-7: Possible savings of emissions through the application of EOL-strategies

Using this data, the calculation can now be carried out and is explained by using the current distribution of recovery rates for a vehicle in accordance with chapter 5.3.3 (see Figure 5-5). Hence, when a new car is produced, 11% of its components must pass through the entire manufacturing process. 88% of the required material is produced from recycled materials. This means that 88% no longer have to pass the phase of resource mining and the generated emissions amount to only 92% of the complete manufacturing process. According to this logic, the values for all manufacturing phases are multiplied by the percentage emission share and the interim results are added. Finally, both results (of the vehicle and battery) are subsequently weighted by the share of the battery or vehicle in the overall manufacturing process and added. In this example, the application of EOL-strategies can reduce emissions by 9.8% to 90,2%.



Exemplary calculation

$$Emissions\ in\ \% = E = V_{new} * E_{new} + V_{P1} * E_{P1} + V_{P2} * E_{P2} + V_{P3} * E_{P3}$$

$$Condition{:}\ V_{new} + V_{P1} + V_{P2} + V_{P3} = 100\%$$

V_x = Percentage of the vehicle in the respective production phase with $x \in \{New, P1, P2, P3\}$

E_x = Percentage of total emissions in the respective production phase with $x \in \{New, P1, P2, P3\}$

1a Reduction of emissions in the production process of the battery

$$E = 0{,}50 * 100\% + 0{,}50 * 92\% + 0 * 68\% + 0 * 26\% = 96\%$$

1b Reduction of emissions in the production process of the remaining vehicle

$$E = 0{,}11 * 100\% + 0{,}88 * 86\% + 0{,}01 * 44\% + 0 * 8\% = 87{,}12\%$$

2 Total emission savings equals the sum of the weighted values:

Figure 5-5: Explanation of the procedure of the calculation

5.5 Scenario analysis

5.5.1 Definitions of the scenarios - possible improvements of Assumption 3

The fundamental objective regarding EOL-strategies is to shift the recovery rates as far as possible from optimisation potential P1 to P3. Thus, it is necessary to make assumptions regarding the potential development of current recovery rates, which can be compared within a scenario analysis. For both, the battery and the vehicle, a conservative (1) and an optimistic (2) scenario is defined.

Values for the vehicle

Contrary to the suggestion defined in chapter 4.5 to use a fictitious vehicle, a Mitsubishi i-MiEV (see Table 5-8) is used as a reference for calculating the theoretically possible improvement potentials of the rest of the vehicle. This selection is justified on two grounds. Firstly, there is no data for a fictitious vehicle so far. Secondly, only percentage potentials will be displayed. Hence the results can be extrapolated to other vehicles. The values of the Mitsbushi i-MiEV are used to perform a possible allocation of the components to the three optimisation potentials. To determine the new values, it is estimated for each component whether they could be used in the future for optimisation potential P1, P2 or P3. The detailed listing of the individual components, including the corresponding weights and allocation to the optimisation potentials, is explained in detail in the annexes A.11 and A.12.

Vehicle	New	P1	P2	P3
Today	11 %	88 %	1 %	0 %
Scenario 1	3,6 %	42,4 %	34,9 %	19,1 %
Scenario 2	3,6 %	35,5 %	20,9 %	40,0%

Table 5-8: Development of the recovery rates of the vehicle[85]

Values for the battery

Literature review does not provide currently verified data regarding the potential developments in battery manufacturing. Therefore, as a first desirable scenario, it is assumed that the recycling and recovery rates for low-voltage car batteries can also be achieved for high-voltage batteries of electric vehicles. In 2017, 82.8% of the weight of car batteries has been recycled in the Federal Republic of Germany[86] (Umweltbundesamt, 2018a). This means that 32.8% are transferred from New to P1. Hence, for the second scenario, it is assumed that the same amount can be shifted again in a next step to P2 and P3 (with the ratio 2:1).

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[85] Own estmation based on Fuchs (2014, xxxiv).

[86] This values corresponds to the general recycling efficiencies of all spent batteries and accumulators according to Directive 493/2012

Battery	New	P1	P2	P3
Today	50 %	50 %	0 %	0 %
Scenario 1	17,2%	82,8 %	0 %	0 %
Scenario 2	17,2%	50 %	21,9 %	10,9 %

Table 5-9: Development of recovery rates of the battery

5.5.2 Number of calculations to estimate potential benefits by EOL-strategies

The uncertainty regarding the emissions produced during EOL-processes is still remaining. Due to the large number of possible combinations, the presentation of all results is not effective. Since the main goal of the calculation is to highlight the potential ecological benefits, it is important to make a specific selection. For this reason, four options are defined for which the scenarios are calculated respectively. This allows to evaluate whether the estimation that the savings are mainly influenced by the shift from P1 to P2 or P3 is accurate.

Option I assumes that the savings per optimisation potential are congruent with the share of the respective manufacturing phase. Since the process of resource refining causes the greatest part of emissions, the respective emissions during EOL-process must also cause the most emissions. However, an opposite argumentation is also valid. The manufacturing phase with the highest percentage also obtains the highest absolute value. Therefore, higher savings may be generated more easily in percentage terms. Thus, option II describes the exact opposite of option I.

Option III assumes that emissions for EOL-strategies will decrease the later they take place in the manufacturing process. According to this scenario, emissions would be lowest for P3. Again, the reciprocal argumentation is justifiable. The complexity and effort of the EOL-strategies may decrease the smaller the closed loop is. Hence, the smaller the cycle, the higher the emissions, since simple processes can be improved more difficultly. Thus, option IV describes the opposite of option III.[87]

	Emissions of EOL-strategies compared to original manufacturing					
	Vehicle			Battery		
	P1	P2	P3	P1	P2	P3
Option I	Medium	High	Low	Low	Medium	High
Option II	Medium	Low	High	High	Medium	Low
Option III	High	Medium	Low	Option II		
Option IV	Low	Medium	High	Option I		

Table 5-10: Options to estimate the emissions caused by EOL-processes

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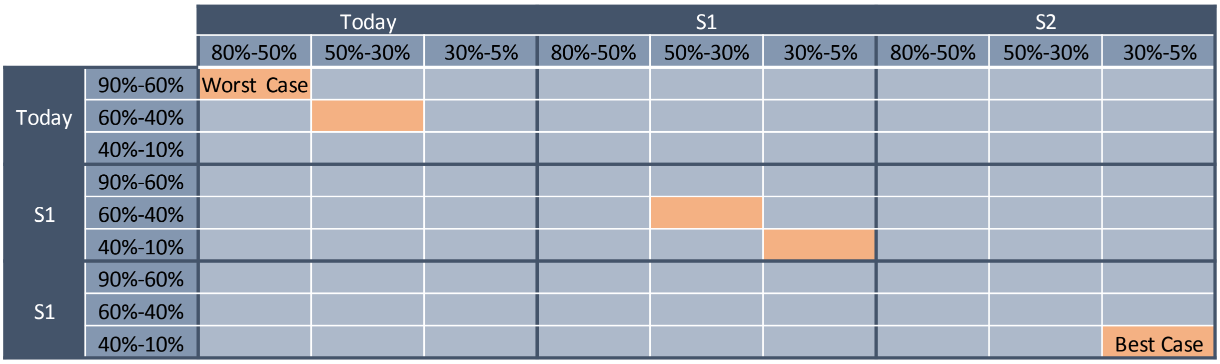
[87] Since the share of emissions in the overall process for the battery increases congruently from P1 to P3, the distribution of options II and I applies to options III and IV of the battery.

All theoretically possible results are between the two orange boxes at the top left and at the top right in Figure 5-6. Based on these calculations, it is now possible to cover specific areas of all possible combinations. In the context of the scenario analysis potential savings of emissions within the tagged ranges can be pictured within the calculation for each option.



		Today			S1			S2		
		80%-50%	50%-30%	30%-5%	80%-50%	50%-30%	30%-5%	80%-50%	50%-30%	30%-5%
Today	90%-60%	Worst Case								
	60%-40%		🟧							
	40%-10%									
S1	90%-60%									
	60%-40%					🟧				
	40%-10%						🟧			
S1	90%-60%									
	60%-40%									
	40%-10%									Best Case

Figure 5-6: Illustration of the presented results within the scenario analysis

5.5.3 Presentation and evaluation of the results

In the context of the scenario analysis all assumptions are used and the theoretically possible savings by the application of EOL-strategies are calculated according to the presented calculation method. The results of the scenario analysis confirm the expected outcome. By using EOL-strategies, emissions can be significantly reduced during the manufacturing process of (future) electric vehicles. Already today, certain savings can be generated by EOL-strategies and should be mentioned in current LCAs. As part of the calculation, it is estimated that the current application of EOL-strategies can already save between 3.8% and 11.4% of emissions of the manufacturing process. By shifting the percentage distribution from P1 to P2 or in the best case P3 and simultaneous improvement of emissions generated by the EOL-strategies, decreases up to 47,7 % are possible compared to the already achieved savings.

Furthermore, all results of the respective four options do not differ greatly. Marginal deviations between the four calculations regarding the savings per battery and vehicle compensate each other, so that the total savings of emissions remain similar. Hence, the shift from P1 to P2 or P3 represents the key factor in order to enhance the ecological improvement of an LCA. Depending on whether the vehicle or the battery displays greater savings, the percentage shares in the manufacturing process change. Nevertheless, a clear trend can be identified. Due to a more conservative estimation of the recovery rates for batteries, the savings for the battery are lower. Possible savings in percent are up to two to three times lower for the battery than for the vehicle. Hence, the share of the battery will increase or even exceed the emissions of the manufacturing process of the rest of the vehicle. In addition, a comparison of the vehicle and the battery shows the influence of the energy-intensive manufacturing stages. Regarding the vehicle this phase corresponds to resource refining. The shift of the recovery rates from P1 to P2 is greater in scenario 1 than in scenario 2. Hence, the decrease from scenario today to scenario 1 is greater than from scenario 1 to scenario 2. The same effect can be observed for the battery in scenario 2, where more recovery rates for P3 are considered and the energy-intensive manufacturing phase of component manufacturing is replaced. Accordingly, the greatest impacts can be achieved as soon as the most energy intensive manufacturing step can be substituted by EOL-strategies. To enable better comprehensions and due to the small deviations, the respective maximum and minimum values of the four calculations were combined and presented in Figure 5-7. A detailed presentation of the individual results can be found in annexes A.14 to A.17.

Nevertheless, the calculated savings of emissions solely refer to the manufacturing process. The impacts on the emissions produced by the entire life cycle of an electric vehicle are not considered. In line with the decreasing emissions during the manufacturing process, the decarbonisation of energy production will also reduce emissions produced by the use phase. If one imagines that a future electric vehicle is powered only by renewable energy throughout its entire life cycle, any emissions from the use phase will be eliminated. Therefore, future emissions of the entire vehicle can be reduced up to a much larger extent by the combined enhancement of the decarbonisation of energy production and application of EOL-strategies.

Figure 5-7: Aggregated results of the scenario analysis

5.6 Presentation of necessary changes

5.6.1 Design for remanufacturing and reuse

To achieve the desired shift from P1 to P2 or even P3, fundamental changes are necessary in the way current vehicles are designed and produced. In accordance with the concept of CE and especially C2C one possible approach is to design the components of a vehicle in such a way that EOL-strategies are in focus of manufacturing. Thus, the components can be optimally recovered after the use phase. At present, there are no concrete limits to manufacturers in terms of design, dimensions and materials used. This certainly increases the variety of offered products, but also limits the possibilities of reusing or remanufacturing components, parts and materials as optimally as possible. To increase the ecological assessment of automobiles, standardised sizes and specifications need to be developed to transfer the concept of C2C to the automotive industry. The more components comply with certain standards, the easier they can be reintegrated into the manufacturing process.

The basis for such an approach has already been created by certain car manufacturers. E.g., Daimler and Toyota have established corresponding concepts. Daimler already opened “smartville”, an innovative manufacturing facility for the Smart, in Hambach, France, in 1997. To enable a time-optimised manufacturing process the components are designed for fast (dis)assembly. Thus, a sustainable manufacturing process is possible which at the same time supports the closing of loops within the framework of CE (Daimler, 2007). Furthermore, Toyota promotes the use of remanufactured components as part of repair services. This requires that EOL-vehicles are returned to Toyota after use so that they can be appropriately remanufactured (Toyota, 2019b). These examples show that implementation is feasible. However, such concepts have to be uniformly introduced across manufacturers.

A concrete implementation proposal could look as follows: In a new standard or regulation the two main categories “dimensions of components” and “allowed materials” are defined. Accordingly, large components such as windows, metal parts like doors, the bonnet or fuel filler cap, interior alignment like ceiling panelling, seat cushions, or glove compartments have to adhere to defined dimensions. After use, a component from one vehicle can be used for the manufacturing of another model (and in best case even for a different manufacturer). Hence, automobile manufacturers are automatically forced to build their models around the corresponding components. However, to maintain future competitiveness through individual design possibilities there should be several choices regarding the dimensions. E.g., for the design of a window for a small vehicle the manufacturer can choose between two or three predefined dimensions.

Furthermore, the definition of dimensions has to be supported by regulations regarding the processed materials. In this context, the concrete example of varnished components can be used to clarify the approach. Varnishing is often difficult to remove from the metal and the recycling processes consequently cause ecological conflicts. Due to melting processes, the metals no longer meet the quality requirements for a new vehicle[88] . A new directive could oblige to only use adhesive film to colour vehicles[89]. Even if this may cause optical losses, it would be more advantageous from a sustainable perspective, as the metal components can be recovered (between different manufacturers). Moreover, the Monitoring and Controlling of resource mining and refining of ores can be improved. Combined with clear guidelines regarding the specific materials the verifiability of quality and safety standards are enhanced. Further, the guarantee of successful crash tests is also increased because it is no longer possible to select components of lower quality.

However, such changes may meet with resistance by the industry. The implementation of new standards inevitably goes hand in hand with the measure that automobile manufacturers have to publish some of their product design and material compositions. Even if new standards soften competitive advantages to a certain extent, affected components usually do not represent a unique selling point for automobile manufacturers. A clear differentiation from the competition would still be possible and is not a valid counterargument against the introduction of new standards regarding the manufacturing to support the concept of a CE.

Besides the ecological advantages, it is possible to enable positive economic effects. Either way, the market for recovered components is growing rapidly due to the intention of establishing a CE. By implementing these new standards or regulations, the supplier industry is strengthened. The market power of suppliers increases because they can simultaneously deliver to several automotive suppliers without having to manufacture individual components. Universal solutions as well as individually expandable components (e.g. through plug-in kits or modular designs) may expand the product portfolio. Automotive suppliers can use their expertise in component manufacturing to develop new and innovative business models to enhance recovery rates of vehicles.

Such business models are in alignment with the concept of the CE. Manufacturers or suppliers are intrinsically motivated to make recovery as (cost) efficient as possible. The more the product design is oriented towards possible recovery, the lower will be the effort to implement it. In this way, a continuous improvement and optimisation process in the sense of CE can be created. Furthermore, government-supported incentive systems should provide additional support for such business models. By introducing certifications, the public perception can be emphasised that a company carries out recovery in an outstanding manner. Such certificates offer manufacturers the potential to differentiate themselves from (international) competition and to defend and establish new quality-related price models in spite of lower manufacturing

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[88] The same conflict applies for the recovering of small electrical components. Cables or connections are partially melted down. The result is a mixture of different metal and plastic materials. Uniform specifications for the simple dismantling of these electrical components could solve this problem (Braungart and McDonough, 2008, p. 54).

[89] In this context, research and development of alternative varnishes has to be intensified due to the introduction of material requirements.

costs. Eventually, this approach can provide the basis to combine the current widespread focus on price and cost efficiency with a focus on long-term ecological impacts.

5.6.2 Service as a business model

Nevertheless, some complex components of a vehicle may be difficult to recover. These encompass above all the powertrain including the engine, braking and steering technologies and, in the case of electric vehicles, the battery. Such components are associated with much greater research expenditure and often represent a unique selling point for the respective automobile manufacturers. New standards or regulations could cause great resistance among automobile manufacturers, as they would have to publish some of their competitive advantages and accordingly lose market dominance. To be able to guarantee competition in the future, the concept of the Performance Economy can be applied for such components. Based on the example of Rolls Royce[90], this model can be transferred to automobile manufacturers. The entire drive train or only the electric motor and the battery remain in the possession of the car manufacturer. In addition to the mutual interest in the sustainable functionality of the respective components, remanufacturing, refurbishing, repair or reuse processes can also be optimised internally. With the help of predictive maintenance, it is possible to detect and prevent defects at an early stage and to maintain functionality in the long term. This offers innovative potential for developing future competitive advantages and enables the creation of a continuous and independent process of improvement of complex components. In addition, a proven long-term quality with correspondingly low interaction with the manufacturer can also be a reason for a higher purchase price.

Automobile manufacturers may also benefit from internal synergy effects. Many automotive manufacturers have technological overlaps between individual models and engines. For example, powertrains can theoretically be designed for several models, which considerably reduces the complexity of an established service model. The same applies to batteries. According to the current state of the art, remanufactured batteries cannot reach the maximum power of a new battery. However, such batteries do not necessarily have to be reused in an identical model. The integration of second use batteries in other areas of the vehicle fleet models such as car sharing models, logistics transport vehicles or company-owned vehicles can represent feasible implementation scenarios. Furthermore, cross-sector cooperation is becoming more and more feasible. Used vehicle batteries can be repurposed as stationary power storage units for households[91] or as large storage units[92] to stabilise the power grid with control. Such application demands less performance of the battery due to fewer and longer charging cycles.

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[90] To recap the advantages see Chapter 2.2.6.

[91] First concepts and joint ventures have already been established, e.g. with the cooperation of BMW and Vissmann. For more information please refer to: https://www.digital-energysolutions.de/

[92] Experts estimate that by 2035 a total of 65 GWh of spent batteries will be available on the market. https://mobilitymag.de/batterien-second-life-elektroautos/

If the automobile industry can be persuaded of the necessity to establish collective solutions, innovative business models from external suppliers are also conceivable. A major criticism of electric vehicles to date is their short range and the associated frequency of charging cycles. This process is much more time-consuming than refuelling an ICEV. Therefore, electric vehicles must be designed in such a way that the battery unit can be easily replaced. This requires internationally uniform standards regarding the size and connection of the battery. Such norms are already successfully applied in the automotive or further industries. Low voltage batteries of passenger vehicles[93] or the establishment of the Schuko plug (type F plug), which is used in large parts of Europe, can serve as examples for the feasibility. This approach makes it possible to quickly replace the battery unit at service stations. Depending on the vehicle, different battery types with varying capacities have to be available, just as a distinction is currently made between different fuels. A modular battery design ensures that a vehicle can be charged even if the full capacity of the batteries has not been used yet. In this context, Toyota has developed a modular battery system for electric forklift trucks that ensures that each customer receives exactly the battery capacity they need to meet their actual performance requirements. Such a concept could serve as a basis and be transferred to the automotive industry (Toyota, 2019a). Hence, the problem of the range and environmentally damaging disposal of used batteries, which belong to the main arguments against electromobility, would be eliminated abruptly. Maintenance, charging and care of the batteries belong subsequently to the responsibility of the service station operator or another external service provider. Batteries can be charged under optimum conditions to maximise battery life. It is also possible to charge the batteries solely with renewable energy. As a result, WTW emissions would no longer exist. Used batteries are collected in a controlled manner and can be optimally recovered through the application of EOL-strategies.

However, such a model may not be in the economic interest of the individual automobile manufacturers, as it only works if an agreement is reached on an identical technology. Nevertheless, car manufacturers often work together with experienced partners in battery technologies. Therefore, the introduction of a uniform battery technology must be politically demanded and promoted (e.g. through restrictions on framework agreements between automobile and battery manufacturers or the establishment of a central platform for further research into battery technologies). Consequently, it is possible to persuade the automotive and battery industries to work together on a sustainable solution. Possible competitive disadvantages resulting from the introduction of a common battery standard are not a sufficient counter-argument. Quality characteristics such as general wear and tear or consumption remain the responsibility of the automobile manufacturer and offer the opportunity to position itself on the market. Thus, the development and introduction of standardised battery technology can strongly support the ecological sustainability of electric vehicles.

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[93] The requirements for low voltage car batteries are defined in DIN EN 50342

6 Summary and outlook

6.1 Summary

The aim of this thesis was to develop a model to evaluate End-of-Life strategies in the context of Lifecycle Assessment of electric vehicles. For this purpose, the urgent necessity of the transformation from a linear to a CE is shown. This transformation requires fundamental structural changes in the way society produces, consumes and exploits goods and services. For this reason, all phases of a product life cycle have to be analysed. The integration of EOL-strategies is essential, since manufacturing characterises the indispensable main element of a CE. In this context, LCAs are an important measurement tool. Hence, current literature is analysed to compare the status-quo of ecological assessments. It makes clear that the current norm for LCAs offers too much scope for subjective assumptions. Accordingly, the results diverge widely, and the determination of an adequate range regarding the generated emissions during an electric vehicles lifetime as well as the manufacturing of the battery is not feasible. To enable the comparability of LCA results in the future, stricter and uniform specifications are required. Therefore, proposals are presented to enhance the informative value of future LCAs. Furthermore, it is elaborated that the current approach of assessing existing technologies should be developed to focus on what framework conditions and parameters need to be applied to define certain environmental objectives. However, assessments of current technologies can still serve as a benchmark to measure short- and long-term feasibility.

By using the developed model in Chapter 5, it is possible to demonstrate possible savings and to sensitise for the need of EOL-strategies. In this context, it is clarified that the assessment of EOL-strategies as a credit for an existing vehicle can cause a redundant consideration in LCAs. Therefore, improvements of EOL-strategies should always be related to the next generation of a vehicle.

The assumption-based calculation shows that great savings of emitted GHGs are feasible through the application of EOL-strategies. However, the potential for reducing emissions within the battery manufacturing process is not fully exploited due to the novelty of the technology. Hence, the estimated savings for the remaining vehicle are much greater than for the battery. Consequently, it can be assumed that the greater focus of research will remain focused on battery technology. Furthermore, structural changes are necessary to enable a successful implementation and establishment of EOL-strategies. These have to be supported and accelerated by political and legal regulations. By introducing guidelines based on the concepts of a CE, new markets will emerge which can be used by participants through disruptive innovations in product design and innovative business models.

6.2 Limitations and further research

The results of the calculation are currently based on simplified assumptions. Hence, based on the results and findings of this thesis, the advantages of EOL-strategies must be further researched. To obtain reliable results, actual values have to be determined. For this purpose it is firstly necessary to determine which components can be optimally recovered with EOL-strategies in practice and how this percentage can be improved in the future by new design concepts and business models. In order to achieve short-term results, the focus should be on EOL processes, which replace the most energy-intensive stages of the respective manufacturing process. In a second step this knowledge should be used to carry out a detailed data analysis of EOL-processes to assess the exact potential for savings of emissions. Only in this way it is possible to generate quantifiable meaningful values that do not allow global political decision-makers to argue differently and encourage society to act.

However, the current standard for LCA has not been revised since 2009, although it provides the scientific basis for an ecological assessment. Thus, the problem of subjective assumptions in LCA remains. Therefore, the entire procedure for the ecological evaluation of products and goods has to be revised. A basic prerequisite for the calculation of a valid data basis is that the standard for the implementation of LCA is reevaluated and guidelines are created to enable future comparability. As soon as EOL-strategies are integrated into the manufacturing process and ecologically valid assessments can be made, the model must also be expanded for cross-sectoral benefits. Thus, it is possible to meet the demands of a well-operating CE in the long term.

6.3 Outlook

Although this thesis focuses on electric vehicles, it is likely that similar potentials can be achieved for all kinds of vehicles. The integration of EOL-strategies can make an important contribution to achieve our climate targets and subsequently relieve the climate of our planet. This presupposes that the necessity of the establishment of EOL-strategies is moderated in a global environment. It is not expedient if the application is introduced by local legal regulations which can be avoided, e.g. by outsourcing manufacturing facilities. To understand the significance of these findings, the results must be placed in an overall context. Outcomes of the scenario analysis apply to the reduction of emissions during the manufacturing of a new electric vehicle, independent of the absolute values within the manufacturing process. In 2017, 93 million vehicles were sold globally (OICA, 2018). Hence, if such measures can be established, the sum of the emission load of all newly registered vehicles would be reduced accordingly.

Recent developments raise optimism to enhance the political and social awareness for the necessary savings of emissions. The Climate Change Conference in Katowice in 2018 adopted the Climate Change Rule Book. It specifies in detail how individual nations must report on climate protection and what minimum standards need to be set for the activity of the data. These regulations now also apply to Developed countries and create a basis for an international legal order (Ehlerding and Zaremba, 2018). The implementation is now in the responsibility of the individual states and belongs in particular to industrial nations, where 20 percent of the world's population consume 80 percent of all resources. Therefore, Walter Stahel already in 2010 emphasised that “[i]t is industrialised countries that need innovative business models to show the paths towards a competitive and sustainable growth in future” (Stahel, 2010, p. 3).

In this context, the EU Parliament has formulated a clear objective. By 2030, automobile manufacturers will be committed to reduce their fleet CO_2 emissions by 37.5 % (European Commission, 2019). Hence, the manufacturers are forced to place many electric vehicles on the market in the next 11 years. This goal creates political pressure on the automotive industry and accelerates the replacement of the internal combustion engine. In this context the industry has to adapt itself to the new market conditions by creating innovative business models and develop cost-effective manufacturing concepts in accordance with the CE. This development can be supported by further political regulations and incentives. The establishment of adequate price and taxation models, e.g. through higher prices for CO_2 certificates, can contribute to enhance the economic incentives of reducing LCA results of electric vehicles.

Hence, the replacement of the internal combustion by an electric engine offers unique potential to introduce structural changes within an entire industry based on the concept of CE. Due to the rising demand for transportation worldwide, a successful implementation of EOL-strategies in the automotive industry can serve as a model and represent an important synergy effect for other industries. If the hurdles of the global multilateral system can be overcome and congruent national regulations created, the automotive sector can be revolutionised in order to shape the future of electromobility.

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VI. Attachment

A.1 Detailed results of Hall and Lutsey, 2018

A.2 Detailed results of Messagie, 2017

A.3 Detailed results of Wolfram and Wiedmann, 2017

A.4 Detailed results of Ellingsen *et al.*, 2016

A.5 Detailed results of Nealer *et al.*, 2015

A.6 Detailed results of Hawkins *et al.*, 2013

A.7 Detailed results of Lombardi *et al.* (2017)

A.8 Estimation of the emissions during battery manufacturing for Nealer *et al.* (2015)

A.9 Data for Assumption 2

A.10 Data for Assumption 3

A.11 Data for Scenario 1 - Vehicle

A.12 Data for Scenario 2 - Vehicle

A.13 Derivation of possible combinations in the Scenario Analysis

A.14 Results option I

A.15 Results option II

A.16 Results option III

A.17 Results option IV

A.1. Detailed results of Hall and Lutsey, 2018

Hall and Lutsey, 2018; The International Council of Transportation (ICCT)			
Emission Electric vehicle in g CO_2-eq / km			ICEV (Diesel) in g CO_2-eq / km
100-150			**250-260**
Parameter	**Value**	**Source**	**Comments**
Battery in kWh	30	No source mentioned	
Battery manufacturing in kg CO_2-eq/kWh	175	*Romare and Dahlöf (2017).*	Calculation of an average value
Chemistry	n/a	n/a	
Consumption in kWh/ 100km	15,2	No data mentioned	Values based on own research: https://www.nissan.de/fahrzeug
Emission ICEV in g CO_2-eq/ 100km	120	*ICCT, 2015*	The chosen value applies to the general vehicle fleet and consequently to all technologies. However, a diesel engine is considered. https://www.theicct.org/sites/default/files/publications/ICCT_Pocketbook_2016.pdf https://ec.europa.eu/clima/policies/transport/vehicles/cars_en
Distance in '000 km	150	*Wolfram and Wiedmann (2017); Ellingsen et al. (2016)*	
Number of batteries	1	*Wolfram and Wiedmann (2017); Ellingsen et al. (2016)*	No battery exchange during lifetime because there is no evidence to suggest that a replacement is necessary
EV: Car weight in kg	1580-1640	No data mentioned	Own research based on data by manufacturer: https://www.nissan.de/fahrzeuge/neuwagen/leaf/varianten-preise.html#grade-LEAFZE1A-2|specs
ICEV: Car weight in kg	1050-1161	No data mentioned	Own research based on data by manufacturer: https://www.peugeot.de/modelle/modellberater/208-5-turer/technische-informationen.html (calculations with 110 g instead of 120 g CO_2.eq in accordance with dat of the manufacturer)
E-Mix in g CO_2-eq/kWh	275,9	No data mentioned	Own research. Main analysis with EU Mix 2014 (European Environment Agency); link with data for 2015 is not avialable. https://www.eea.europa.eu/data-and-maps/indicators/overview-of-the-electricity-production-2/assessment
Impact Category	Global Greenhouse Emissions		
System boundaries	Not specified		
LCI data	Not specified; Further manufacturing processes are not mentioned.		
EOL	Not included due to high uncertainty		
Sensitivtiy Analysis	Use calculated with average grid electricity in different regions (France, Germany, Netherland, Norwwy and UK – because they represent ¾ of the European electricity mix		

A.2. Detailed results of Messagie, 2017

Messagie, 2017			
Emission EV in g CO_2-eq / km			ICEV (Diesel) in g CO_2-eq / km
87			**206**
Parameter	**Value**	**Source**	**Comments**
Battery in kWh	30	Peters *et al.* (2017)	
Battery manufacturing in kg CO_2-eq/kWh	55	Peters *et al.* (2017)	
Chemistry	LMO	Peters *et al.* (2017)	
Consumption in kWh/ 100km	20	De Cauwer et.al.	Extrapolation of the published value of 0,2 kWh/km: http://www.evs28.org/event_file/event_file/1/pfile/EVS28_Full%20paper_Cedric%20De%20Cauwer.pdf
Emission ICEV in g CO_2-eq/ 100km	165	Fontaras et. al 2015	Ref. Diesel: 120g CO2/ km on NEDC with 35% augmentation to reflect real life driving conditions
Distance in ‘000 km	200	No source mentioned	
Number of batteries	1,5	Aguirre 2012, Hooftman et. al 2014	
EV: Car weight in kg	1200	No source mentioned	
ICEV: Car weight in kg	n/a	No data mentioned	Assumption: Data regards to electric vehicle and ICEV
E-Mix in g CO_2-eq/kWh	300	European Comission 2016	EU 28 Mix 2015
Impact Category	Global Greenhouse Emissions		
System boundaries	Not specified		
LCI data	No further data is specified		
EOL	Not mentioned, if EOL-strategies are inclueded or not.		
Sensitivtiy Analysis	Study was executed with electricity mix of different countries, theoretical electricity mixes per energy source and forecast values for the EU.		

A.3. Detailed results of Wolfram and Wiedmann, 2017

Wolfram and Wiedmann, 2017				
Emission EV in g CO_2-eq / km			ICEV (Diesel) in g CO_2-eq / km	ICEV Gasoline in g CO_2-eq / km
351			**303**	**331**
Parameter	**Value**	**Source**	**Comments**	
Battery in kWh	Nominal: 42 Usable: 38,2	Not specified		
Battery manufacturing in kg CO_2-eq/kWh	273,8	Not specified	Own Calculation based on graphical presenation: 50g CO_2-eq/km → 50 g CO_2-eq/ km * 230.000 km / 42 kWh = 273,8 kg CO_2,-eq/ kWh	
Chemistry	n/a	No data mentioned		
Consumption in kWh/ 100km	15 adjusted to 23	Not specified	Application with adjustmet factor of 1,51 (Source not mentioned) to display on the road adjustment in relation to real life driving condition	
Emission ICEV in g CO_2-eq/ 100km	208 adj, to 224	International Energy Agency	• Avg. Power of 120 kw and 1,6t (International Energy Agency) • 1440 (1450 kg); Fuel Tank 500 (656)kWh; Range 750km(1000), 64(60) kWh/100km; 166 (154) g CO2/km • On road adjustement by 1,37 (1,37): Range 570 (770), 86 (81) kwH/100km; 224 (208) g CO2 / km (Data of 2009)	
Distance in '000 km	230	Ecoinvent	• Batterylife is assumed to be 150.000km (according to Bauer et.al) instead of 100.000km (Ecoinvent) • Default lifetime of 150.000km (Ecoinvent) is adjustet to 230.000 km based on Weymar 2016	
Number of batteries	1,5	Not specified	• 1,5 battery packs are needed; keine Quelle angegeben	
EV: Car weight in kg	1650	Not specified		
ICEV: Car weight in kg	1440 Gasoline 1460 Diesel	Interntaional Energy Agency	• 1,6 =: avg.of Australian LDV fleet, confirmed bei International Energy Agency	
E-Mix in g CO_2-eq/kWh	1048	No data mentioned	• Australian Energy Mix: 1048 g CO2 eq/ kWh in 2009, compared to Itten 2012: 1069-1154 gCO2 eq /kWh in 2008	
Impact Category	Global Greenhouse Gas Emission			
System boundaries	Not specifeid			
LCI data	• Dataset in Ecoinvent is limitetd. Prefered Bottom Up data of latest study out of scope this study • Sources for LCIs: Ecoinvent 3.1 database Ecoinvent. Ecoinvent 3 database. Zurich, Switzerland: Swiss Centre for Life Cycle Inventories; 2014. http://www.ecoinvent.ch			
EOL	Treatment of EOL-Strategies are not mentioned			
Sensitivtiy Analysis	Results for different kind of vehcles: ICEV-gasoline, ICEV-diesel, HEV, PHEV, BEV			

A.4. Detailed results of Ellingsen *et al.*, 2016

Ellingsen et al., 2016, Norwegian University of Science and Tecnology (NTNU)

Emission EV in g CO_2-eq / km				ICEV (Diesel) in g CO_2-eq/ km			
Mini Car	Medium Car	Large Car	Luxury Car	Mini Car	Medium Car	Large Car	Luxury Car
116,7-122,2	144,4-150	166,7	194,4-200	144,5-150	183,3	211,1	261,1

Parameter	Value	Quellen	Comments
Battery in kWh	Mini 17,7 Medium 24,4 Large 42,1 Luxury 59,9	Ellingsen et al (2014)	https://onlinelibrary.wiley.com/doi/full/10.1111/jiec.12072
Battery manufacturing in kg CO_2-eq/kWh	292 – 487,2	Ellingsen et al (2014)	Data is no directls mentioned; based in the source somewhere between 4850 und 12960 kg for an 26,6 kWh battery
Chemistry	Li-NCM	Ellingsen et al (2014)	Modification of a lithium nickel-cobalt-manganese oxide battery
Consumption in kWh/ 100km	Mini 14,6 Medium 17 Large 18,5 Luxury 20,7	Ellingsen et al (2014	
Emission ICEV in g CO_2-eq/ 100km	*Mini: 124* *Medium 149* *Large 166* *Luxury 205*	Supplementary data	Source related to several veicle manufacturer; data in kg https://iopscience.iop.org/article/10.1088/1748-9326/11/5/054010/pdf
Distance in '000 km	180	Own assumption	Avg. assumption is 150.000 km. Wihin their study they modified it to 12k km per year over 15 years. No source for this assumption is mentioned.
Number of batteries	Not specified		It can be concluded from the context that the analysis is performed without battery exchange.
EV: Car weight in kg	*1100 (mini)* *1500 (medium)* *1750 (large car)* *2100 (luxury)*	Own assumption	Own classificaton based on NEDC energy requirements of EVs as a function of vehicle curb weight
ICEV: Car weight in kg	Same as EV		
E-Mix in g CO_2-eq/kWh	521	Itten *et al.* (2014)	http://esu-services.ch/fileadmin/download/publicLCI/itten-2012-electricity-mix.pdf Data of 2008.
Impact Category	Global Greenhouse Emissions		
System boundaries	Not specified		
LCI data	BOM using data from manufacturer; Ecoinvent database (year or version are not mentioned); source of batteries works with Ecoinvent 2.2; further sources: Ellingsen et. al (2014)		
EOL	EOL: inventory based on pyrometallurgical treatment by Derwulf et al 2010 and EOL based on Hawkins		
Sensitivtiy Analysis	four different vehicle classes with different weights, Battery size, Driving range, EV energy requirement		

A.5. Detailed results of Nealer *et al.*, 2015

Nealer et al., 2015			
EV emissions in g CO_2-eq / km		ICEV in g CO_2-eq / km	
Midi: 139	**Full: 166**	**Midi: 273**	**Full: 354**
Parameter	**Value**	**Quellen**	**Comments**
Battery in kWh	Midi: 24 kWh Full: 85 kWh	Nissan, Tesla, DOE 2015A	• Based on Nissan Leaf, direct data of Nissan • Based on Tesla Models S, direct data of Tesla
Battery manufacturing in kg CO_2-eq/kWh	Midi: 90,6 Full: 85,1	Nissan, Tesla, DOE 2015A	Own calculation based on the given data; see Annex A.8
Chemistry	n/a	Not mentioned	
Consumption in kWh/ 100km	Midi: 18,6 Full: 23,6	Nissan, Tesla, DOE 2015A	Midi: 0,3 kWh/ mile → 18,6 kWh/100km; Full: 0,38 kWh/mile → 23,6 kWh/100km
Emission ICEV in g CO_2-eq/ 100km	Midi: 8,15 l/100km Full: 11,24 l/100km	DOE 2015A	Own calculation: 29 MPG bzw 21 MPG → 1 Gallon = 3,8l (in Amerika) → Also: 7,63 MPL/ 5,53 MOL → Ergibt: 12,27 km/l / 8,9 km/l
Distance in '000 km	Mid: 217 Full: 288	National Household Travel Survey	Based on National Household Travel Survey data for the first 15 years of a vehicles life time Conversion of miles were converted to km
Number of batteries	1	Hawkins *et al.* (2013)	
EV: Car weight in kg	Midi: 1650 Full: 2350	Nissan, Tesla	
ICEV: Car weight in kg	Midi: 1500 Full: 2150	Compositve of 5 ICEV data	The average gasoline vehicle comparable to the mid-size or full-size BEV was a composite of five gasoline vehicles available today
E-Mix in g CO_2-eq/kWh	480	No source mentioned	avg. US Emissions based on 2012 generation data
Impact Category	Global Greenhous Gas Emission		
System boundaries	Not specified		
LCI data	Greet 1, Greet 2		
EOL	Not mentioned		
Sensitivtiy Analysis	• Two different kind of cars • Several Electrcity Mixes of different US States		

A.6. Detailed results of Hawkins *et al.*, 2013

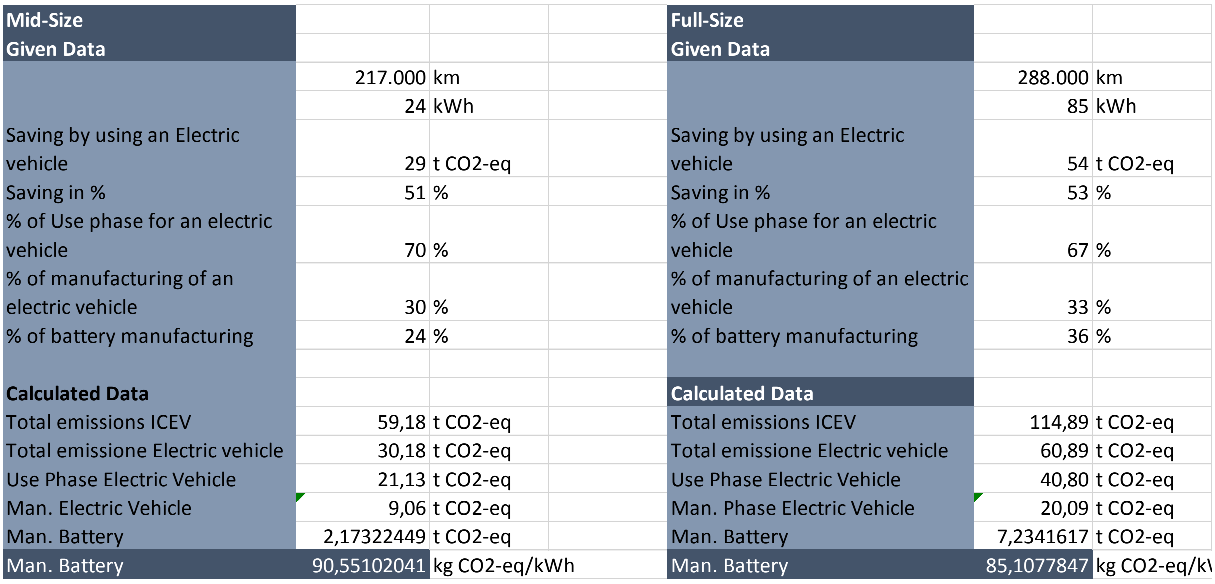
Hawkins et al., 2013

EV Emissions in g CO_2-eq / km			ICEV (Diesel) in g CO_2-eq / km	ICEV (Gasoline) in g CO_2-eq / km
Li-NCM: 196,79	**LiFePO4: 205,81**		**228,38**	**258,32**
Parameter	**Value**	**Quellen**	**Comments**	
Battery in kWh	24	Own assumption		
Battery manufacturing in kg CO_2-eq/kWh	LiNCM: 198,88 LiFePO4 259,25	Not Specified	• According to Majeau-Bettez (2011): 22 kg CO_2 per kg Batterie • 217 kg Li NCM * 22 kg CO_2-eq/ kg = 4773kg/Batterie → 198,88 kg/kWh • 273 kg LiFePO4 * 22 kg CO_2-eq/ kg = 6006kg/Batterie → 259,25 kg/kWh	
Chemistry	LiFePO4 Li NCM	Majeau-Bettez and colleagues 2011		
Consumption in kWh/ 100km	17,3	Nissan	• 0,623 MJ/km (based on data of Nissan) → 17,3 kWh/ 100 km • Incl. losses: 0,48MJ/km → 13,3 kWh/km (calculation of “real circunstances”. Specified capacity of the battery does not correspond to the real capacity used to drive the vehicle.	
Emission ICEV in g CO_2-eq/ 100km	Gasoline: 6,85 l/100km Diesel: 5,35 l/100km	Mercedes, Daimler	• Based on: Mercedes A-170, and an average of the Mercedes CDI A-160 and A-180 results • Assumption including energy losses (Energy to Wheel – TTW)	
Distance in ‘000 km	150.000	Automotive Industry	Assumptions made by the automotive industry; no further specification of the source	
Number of batteries	1	Own assumption	• Battery lifetime equivalent to that of the vehicle • Own assumption contrary to the statement by Majeau-Bettez (2011)	
EV: Car weight in kg	1521	Nissan Leaf		
ICEV: Car weight in kg	1225-1365	Mercedes A Klasse		
E-Mix in g CO_2-eq/kWh	n/a	n/a	• EU Mix; year and emissions are not specified	
Impact Category	Global Greenhouse Gas Emission			
System boundaries	Not specified			
LCI data	Ecoinvent 2-2, Greet 2.7			
EOL	End-of-life vehicle treatment is based on Ecoinvent v2.2 (Burnham et al. 2006). Battery treatment consists of dismantling and a cryogenic shattering process. The impacts associated with material recovery and disposal proceses are allocated tot he vehicle life cycle			
Sensitivtiy Analysis	Different power mixes			

A.7. Detailed results of Lombardi *et al.* (2017)

<table>
<tr><th colspan="4"><i>Lombardi et al., 2017</i></th></tr>
<tr><th colspan="3">Emission EV in g CO2 eq / km</th><th>ICEV (Diesel) in g CO2 eq / km</th></tr>
<tr><th colspan="3">225</th><th>266</th></tr>
<tr><th>Parameter</th><th>Value</th><th>Quellen</th><th>Comments</th></tr>
<tr><td>Battery in kWh</td><td>33</td><td>Zackrisson et al 2010</td><td>Zackrisson et. al 2010 uses a 10 kWh battery which was extrapolated to 33 kWh
https://www.researchgate.net/publication/222937881_Life_cycle_assessment_of_lithium-ion_batteries_for_plug-in_hybrid_electric_vehicles_-_Critical_issues</td></tr>
<tr><td>Battery manufacturing in kg CO_2-eq/kWh</td><td>166</td><td>Zackrisson et al 2010</td><td>• No data mentioned (general data for batteries based on Zackrisson et al 2010 are used)
• 1660 kg → 166 kg pro kWh ; BUT: Assumption of use of water as a solvent instead of N-methyl-2-pyrrolidone, NMP</td></tr>
<tr><td>Chemistry</td><td>LiFePO4</td><td>Zackrisson et al 2010</td><td></td></tr>
<tr><td>Consumption in kWh/ 100km</td><td>22,3</td><td>Source not specified</td><td>Given data: Consumption of 44.617 kWh over 200.000 km → 22,3 kWh/ 100km</td></tr>
<tr><td>Emission ICEV in g CO_2-eq/ 100km</td><td>5,1 l/ 100km</td><td>Not data mentioned</td><td>Only final number available which leads to 6,74 kg gasoline / 100 km; with 0,75 kg/l → 5,1 l/ 100 km</td></tr>
<tr><td>Distance in ‘000 km</td><td>200</td><td>Own assumptions</td><td>Per year: 11.000km on extra-urban/highway routes and 9000 km on urban routes</td></tr>
<tr><td>Number of batteries</td><td>2</td><td>n/a</td><td>Controversial statement of battery replacement within the study:
• <i>“The battery packs, even being of different sizes, were all considered to be replaced at least once”</i>
• <i>“avoiding its replacement during the vehicle lifetime and consequently considering the disposal of only one battery at the EoL.”</i></td></tr>
<tr><td>EV: Car weight in kg</td><td><i>1550 to 1700 kg</i></td><td>GM Chevrolet Malibu</td><td>General Motors Engine Guide (2017) GM 2.4 Liter l4 Ecotec LEA; Engine Datasheet. Available at:
http://gmauthority.com/blog/gm/gm-engines/lea/
Final weight depends on selected powertrain</td></tr>
<tr><td>ICEV: Car weight in kg</td><td><i>1550 to 1700 kg</i></td><td>GM Chevrolet Malibu</td><td>Final weight depends on selected powertrain</td></tr>
<tr><td>E-Mix in g CO_2-eq/kWh</td><td>644,9</td><td>Source not defined</td><td>• Electric Energy Mix Record (Ecoinvent database): 0.178 kgCO2eq /MJ in Italy. with. 2.983 MJ/MJ in Italy
• Conversion factor: 1kJ = 0,000278 kWh, (Physikalisch-Technische Bundesanstalt, 2007))</td></tr>
<tr><td>Impact Category</td><td colspan="3">Global Greenhouse Gas Emission</td></tr>
<tr><td>System boundaries</td><td colspan="3">Not specified</td></tr>
<tr><td>LCI data</td><td colspan="3">Impacts calculated with data from Ecoinvent Database 2015, selecting only primary materials (i.e. not recycled ones)</td></tr>
<tr><td>EOL</td><td colspan="3">• Possibility of recycling the main materials present in the considered components was included. Cases of recycled materials produced in the EOL were resolved by expanding the system boundaries to include avoided primary productions due to material recovery from waste
• Batteries were assumed to be disposed (recycling technology is not yet commercially availablev)</td></tr>
<tr><td>Sensitivtiy Analysis</td><td colspan="3">Calculation with energy mixes of different nations</td></tr>
</table>

A.8. Estimation of the emissions during battery manufacturing for Nealer *et al.* (2015)



Mid-Size				**Full-Size**		
Given Data				**Given Data**		
	217.000	km			288.000	km
	24	kWh			85	kWh
Saving by using an Electric vehicle	29	t CO2-eq		Saving by using an Electric vehicle	54	t CO2-eq
Saving in %	51	%		Saving in %	53	%
% of Use phase for an electric vehicle	70	%		% of Use phase for an electric vehicle	67	%
% of manufacturing of an electric vehicle	30	%		% of manufacturing of an electric vehicle	33	%
% of battery manufacturing	24	%		% of battery manufacturing	36	%
Calculated Data				**Calculated Data**		
Total emissions ICEV	59,18	t CO2-eq		Total emissions ICEV	114,89	t CO2-eq
Total emissione Electric vehicle	30,18	t CO2-eq		Total emissione Electric vehicle	60,89	t CO2-eq
Use Phase Electric Vehicle	21,13	t CO2-eq		Use Phase Electric Vehicle	40,80	t CO2-eq
Man. Electric Vehicle	9,06	t CO2-eq		Man. Phase Electric Vehicle	20,09	t CO2-eq
Man. Battery	2,17322449	t CO2-eq		Man. Battery	7,2341617	t CO2-eq
Man. Battery	90,55102041	kg CO2-eq/kWh		Man. Battery	85,1077847	kg CO2-eq/k

Calculations based on data provided in the study of Nealer *et al.* (2015)

A.9. Data for Assumption 2

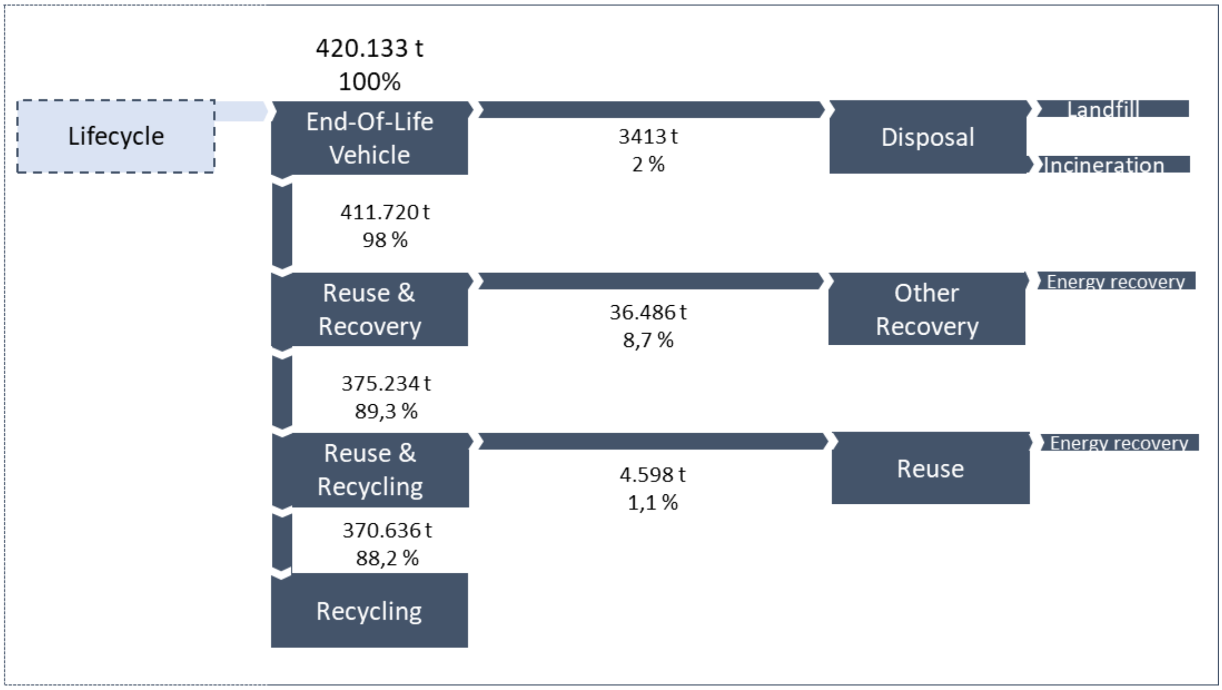
Data for the vehicle based on Martin and Treiber (2014, p. 6)

	Resource Mining	Resource Refining	Component Manufacturing
Total in kg CO_2-eq/ 100 km	1,74	3,41	0,97
Total in %	28%	56%	16%

Data for the battery based on Romare and Dahlöf (2017, p. 39)

	Resource Mining	Resource Refining	Component Manufacturing
Total in kg CO_2-eq/ kWh	18-50	48-216	20-110
Most likely value in kg CO_2-eq/ kWh	n/a	60-70	70-110
Assumption in kg CO_2-eq/ kWh	33	65	107
Total in %	16%	32%	52%

A.10. Data for Assumption 3



Source: (BMU, 2016)

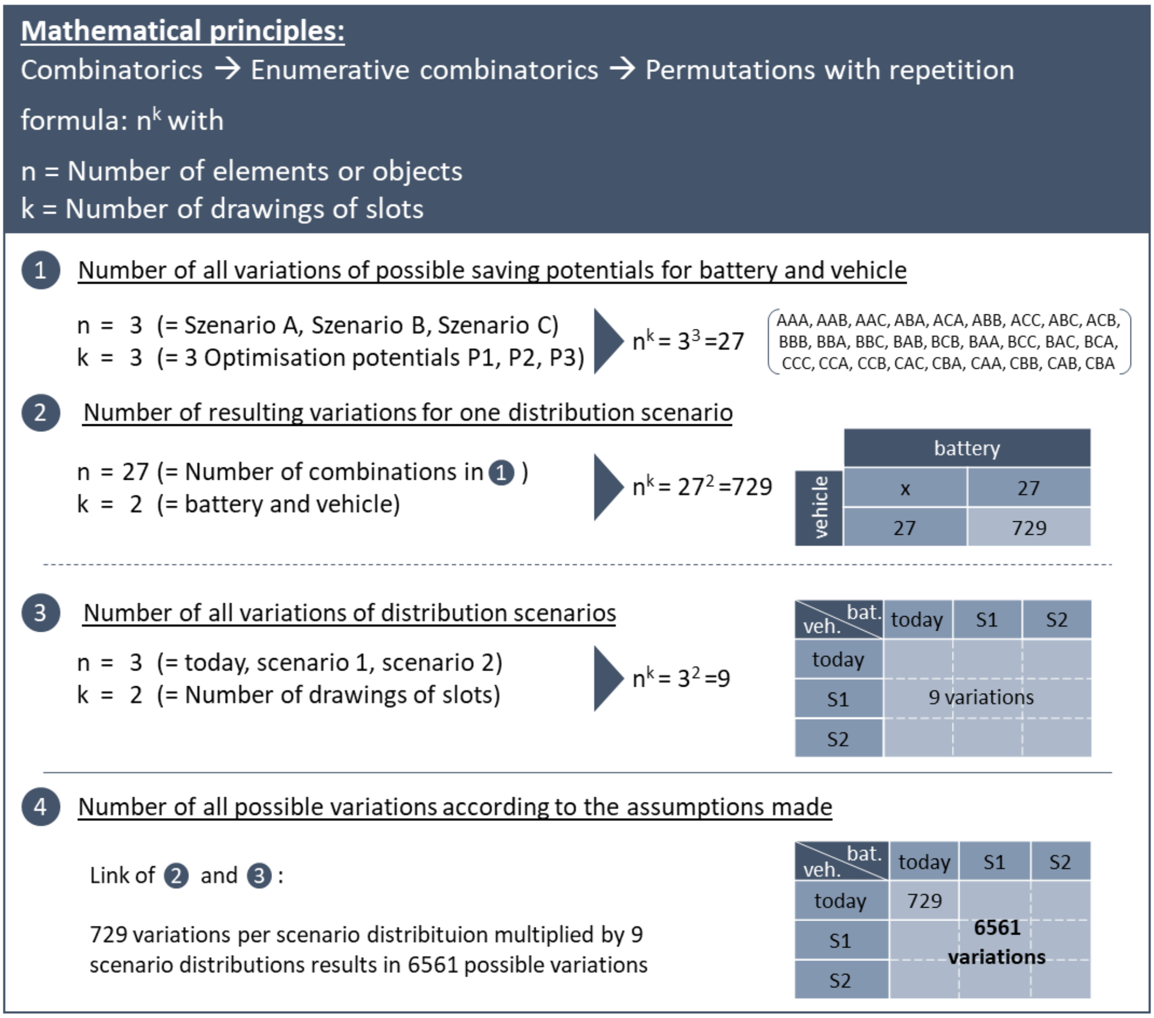
A.11. Data for Scenario 1 - Vehicle

		Weight in kg	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
Vehicle	**Mitsubishi i-MiEV**	**1089,5**				351,9	289,3	158,8
	without battery	829,9				**42,40%**	**34,86%**	**19,13%**
Structure		***187,8***						
	Frame	154,8	x			154,8	0	0
	Insulation	0				0	0	0
	Crash system	27,5	x			27,5	0	0
	Other	5,5				0	0	0
Exterior		***147,4***						
	Mudguards	4,5	x	x		0	4,5	0
	Front doors	36,8	x	x		0	36,8	0
	Back doors	36,8	x	x		0	36,8	0
	Bonnet	8,9	x	x	x	0	0	8,9
	Tailgate	11,9	x	x	x	0	0	11,9
	Windscreen wiper	4,9	x	x	x	0	0	4,9
	Bumper	7,9	x	x		0	7,9	0
	Mirror	2,5	x	x	x	0	0	2,5
	Underbody panelling	0				0	0	0
	Front windshield	17,6	x	x		0	17,6	0
	Front side windows	6,4	x	x		0	6,4	0
	Rear side windows	4,8	x	x		0	4,8	0
	Rear window	4,4	x	x		0	4,4	0
Powertrain		***342,4***						
	Motor with housing	32,8	x	x		0	32,8	0
	Gearbox without oil	14,9	x			14,9	0	0
	Oil balance	0,5	x			0,5	0	0
	Differential	8,8	x			8,8	0	0
	Side/ Drive shafts	18,8	x			18,8	0	0
	Battery	259,6				0	0	0
	Cooling system	7	x	x	x	0	0	7
Chassis		***185,3***						
	Front axle	35	x	x		0	35	0
	Shock absorbers	8,8	x			8,8	0	0
	Rear axle	22,1	x	x		0	22,1	0
	Shock absorbers	8,8	x	x		0	8,8	0
	Wheels	49,6	x	x	x	0	0	49,6
	Braking system	40,2	x			40,2	0	0
	Steering system	15,9	x	x		0	15,9	0
	ESP	2,4	x			2,4	0	0
	Pedals	2,5	x	x	x	0	0	2,5
Interior		***149,5***						
	Front seats	37,6	x	x	x	0	0	37,6
	Rear seats	20,5	x	x	x	0	0	20,5
	Interior cladding	17,1	x	x		0	17,1	0
	Carpet	0				0	0	0
	MQT	7,7				0	0	0
	Dashboard	3,7	x			3,7	0	0
	Centre console	3,1	x			3,1	0	0
	Flaps / Compartments	6	x	x	x	0	0	6
	Infotainment	4,3	x			4,3	0	0
	Instrumentation	2,5	x			2,5	0	0
	Airbags driver/passenger	3,8	x	x	x	0	0	3,8
	Airbags extended	3,6	x	x	x	0	0	3,6
	Restraint systems	8,4				0	0	0
	Other safety systems	1				0	0	0
	Other	4,3				0	0	0
	Insulation	7,4	x			7,4	0	0
	Heating system	9,7	x	x		0	9,7	0
	Climate System	8,8	x	x		0	8,8	0
Electronics		***77,1***						
	HV	40,7	x			40,7	0	0
	LV Buffer battery	12,1	x	x		0	12,1	0
	LV Cabling	13,5	x			13,5	0	0
	Exterior lighting	7,4	x	x		0	7,4	0
	Interior lighting	0,4	x	x		0	0,4	0
	LV Other	3				0	0	0

A.12. Data for Scenario 2 - Vehicle

		weight in kg	P1	P2	P3	P1	P2	P3
Vehicle	**Mitsubishi i-MiEV**	**1089,5**				294,4	173,3	332,3
	without battery	829,9				**35,47%**	**20,88%**	**40,04%**
Structure		***187,8***						
	Frame	154,8	x			154,8	0	0
	Insulation	0				0	0	0
	Crash system	27,5	x			27,5	0	0
	Other	5,5				0	0	0
Exterior		***147,4***						
	Mudguards	4,5	x	x	x	0	0	4,5
	Front doors	36,8	x	x	x	0	0	36,8
	Back doors	36,8	x	x	x	0	0	36,8
	Bonnet	8,9	x	x	x	0	0	8,9
	Tailgate	11,9	x	x	x	0	0	11,9
	Windscreen wiper	4,9	x	x	x	0	0	4,9
	Bumper	7,9	x	x	x	0	0	7,9
	Mirror	2,5	x	x	x	0	0	2,5
	Underbody panelling	0				0	0	0
	Front windshield	17,6	x	x	x	0	0	17,6
	Front side windows	6,4	x	x	x	0	0	6,4
	Rear side windows	4,8	x	x	x	0	0	4,8
	Rear window	4,4	x	x	x	0	0	4,4
Powertrain		***342,4***						
	Motor with housing	32,8	x	x		0	32,8	0
	Gearbox without oil	14,9	x	x		0	14,9	0
	Oil balance	0,5	x			0,5	0	0
	Differential	8,8	x	x		0	8,8	0
	Side/ Drive shafts	18,8	x	x		0	18,8	0
	Battery	259,6				0	0	0
	Cooling system	7	x	x	x	0	0	7
Chassis		***185,3***						
	Front axle	35	x	x		0	35	0
	Shock absorbers	8,8	x	x		0	8,8	0
	Rear axle	22,1	x	x		0	22,1	0
	Shock absorbers	8,8	x	x		0	8,8	0
	Wheels	49,6	x	x	x	0	0	49,6
	Braking system	40,2	x			40,2	0	0
	Steering system	15,9	x	x	x	0	0	15,9
	ESP	2,4	x			2,4	0	0
	Pedals	2,5	x	x	x	0	0	2,5
Interior		***149,5***						
	Front seats	37,6	x	x	x	0	0	37,6
	Rear seats	20,5	x	x	x	0	0	20,5
	Interior cladding	17,1	x	x		0	17,1	0
	Carpet	0				0	0	0
	MQT	7,7				0	0	0
	Dashboard	3,7	x	x		0	3,7	0
	Centre console	3,1	x			3,1	0	0
	Flaps / Compartments	6	x	x	x	0	0	6
	Infotainment	4,3	x			4,3	0	0
	Instrumentation	2,5	x	x		0	2,5	0
	Airbags driver/passenger	3,8	x	x	x	0	0	3,8
	Airbags extended	3,6	x	x	x	0	0	3,6
	Restraint systems	8,4				0	0	0
	Other safety systems	1				0	0	0
	Other	4,3				0	0	0
	Insulation	7,4	x			7,4	0	0
	Heating system	9,7	x	x	x	0	0	9,7
	Climate System	8,8	x	x	x	0	0	8,8
Electronics		***77,1***						
	HV	40,7	x			40,7	0	0
	LV Buffer battery	12,1	x	x	x	0	0	12,1
	LV Cabling	13,5	x			13,5	0	0
	Exterior lighting	7,4	x	x	x	0	0	7,4
	Interior lighting	0,4	x	x	x	0	0	0,4
	LV Other	3				0	0	0

A.13. Derivation of possible combinations in the Scenario Analysis



Mathematical principles:

Combinatorics → Enumerative combinatorics → Permutations with repetition

formula: n^k with

n = Number of elements or objects
k = Number of drawings of slots

① Number of all variations of possible saving potentials for battery and vehicle

n = 3 (= Szenario A, Szenario B, Szenario C)
k = 3 (= 3 Optimisation potentials P1, P2, P3)

$n^k = 3^3 = 27$

(AAA, AAB, AAC, ABA, ACA, ABB, ACC, ABC, ACB, BBB, BBA, BBC, BAB, BCB, BAA, BCC, BAC, BCA, CCC, CCA, CCB, CAC, CBA, CAA, CBB, CAB, CBA)

② Number of resulting variations for one distribution scenario

n = 27 (= Number of combinations in ①)
k = 2 (= battery and vehicle)

$n^k = 27^2 = 729$

	battery	
vehicle	x	27
	27	729

③ Number of all variations of distribution scenarios

n = 3 (= today, scenario 1, scenario 2)
k = 2 (= Number of drawings of slots)

$n^k = 3^2 = 9$

bat. / veh.	today	S1	S2
today			
S1	9 variations		
S2			

④ Number of all possible variations according to the assumptions made

Link of ② and ③:

729 variations per scenario distribituion multiplied by 9 scenario distributions results in 6561 possible variations

bat. / veh.	today	S1	S2
today	729		
S1	**6561 variations**		
S2			

Explanation of the mathematical conflict:

Assumption: The three savings potentials (A=70%, B=50% and C=30%) per manufacturing phase can be combined with the three scenarios (today, scenario 1, scenario 2). This generates a total of 27 possible combinations for the battery and also for the vehicle alone for the savings per production phase. Due to the separate consideration of battery and vehicle alone, this results in 729 possible combinations. Based on the assumption that, in addition to the current scenario, there is also a future conservative and an optimistic scenario, the number of possible combinations increases to 6561 (729 times 9) possible combinations. The more assumptions are made about savings (e.g. 20%, 40%, 60% and 80%) and development scenarios, the greater the number of combinations.

A.14. Results option I

Results of option I

① Emissions of EOL process compared to original manufacturing

	Emissions of EOL process compared to original manufacturing					
	Vehicle			Battery		
	P1	P2	P3	P1	P2	P3
Today	70%-50%	80%-60%	60%-40%	70%-50%	80%-60%	90%-70%
Scenario 1	50%-30%	60%-40%	40%-20%	50%-30%	60%-40%	70%-50%
Scenario 2	30%-10%	40%-20%	20%-5%	30%-10%	40%-20%	50%-30%

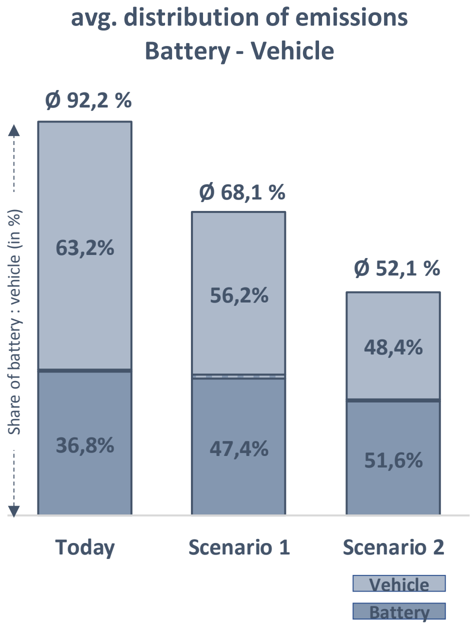
2a Emissions after application of EOL processes compared to original manufacturing

		Unweighted	Weighted	New Value
Today	Vehicle	87,18% - 92,22%	56,66% - 59,94%	90,26% - 94,10%
	Battery	96,00% - 97,60%	33,60% - 34,16%	
Scenario 1	Vehicle	51,70% - 58,60%	33,61% - 38,09%	65,36% - 70,77%
	Battery	90,73% - 93,38%	31,75% - 32,68%	
Scenario 2	Vehicle	36,16% - 41,45%	23,50% - 26,94%	49,56% - 54,46%
	Battery	74,49% - 78,63%	26,07% - 27,52%	

2b New proportion of emissions by battery and vehicle

Proportion	Vehicle	Battery
Today	62,78% - 63,70%	36,30% - 37,22%
Scenario 1	51,42% - 53,82%	46,18% - 48,58%
Scenario 2	47,41% - 49,47%	50,53% - 52,59%

③ Visualisation of the results



A.15. Results option II

Results of option II

① Emissions of EOL process compared to original manufacturing

	Emissions of EOL process compared to original manufacturing					
	Vehicle			Battery		
	P1	P2	P3	P1	P2	P3
Today	70%-50%	60%-40%	80%-60%	90%-70%	80%-60%	70%-50%
Scenario 1	50%-30%	40%-20%	60%-40%	70%-50%	60%-40%	50%-30%
Scenario 2	30%-10%	20%-5%	40%-20%	50%-30%	40%-20%	30%-10%

2a Emissions after application of EOL processes compared to original manufacturing

		Unweighted	Weighted	New Value
Today	Vehicle	87,06% - 92,10%	56,69% - 56,87%	90,75% - 94,59%
	Battery	97,60% - 99,20%	33,16% - 34,72%	
Scenario 1	Vehicle	48,40% - 55,30%	31,46% - 35,94%	64,14% - 69,55%
	Battery	93,38% - 96,03%	32,68% -33,61%	
Scenario 2	Vehicle	35,36% - 40,39%	22,99% - 26,25%	49,22% - 53,93%
	Battery	74,96% - 79,09%	26,63% - 27,68%	

2b New proportion of emissions by battery and vehicle

Proportion	Vehicle	Battery
Today	62,36% - 63,29%	36,71% - 37,64%
Scenario 1	49,05% - 51,68%	48,32% - 50,95%
Scenario 2	46,70% - 48,67%	51,33% - 53,30%

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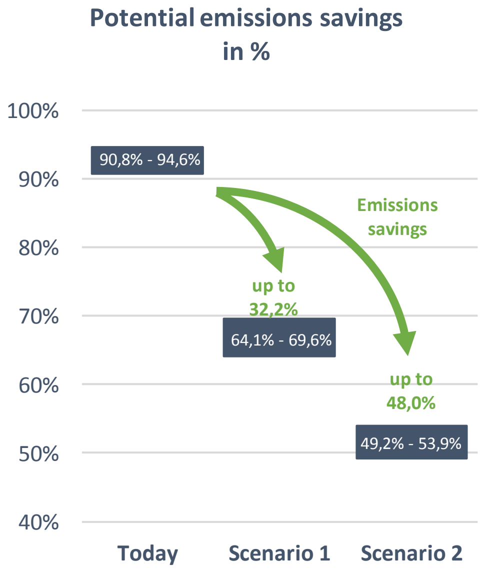
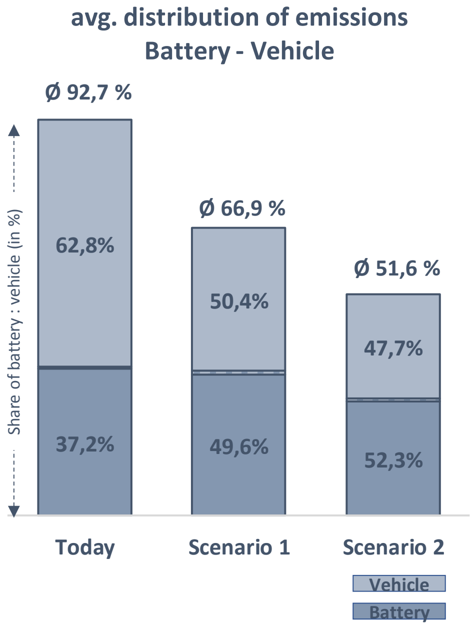
③ Visualisation of the results


Potential emissions savings in %


avg. distribution of emissions Battery - Vehicle

A.16. Results option III

Results of option III

① Emissions of EOL process compared to original manufacturing

	Emissions of EOL process compared to original manufacturing					
	Vehicle			Battery		
	P1	P2	P3	P1	P2	P3
Today	80%-60%	70%-50%	60%-40%	90%-70%	80%-60%	70%-50%
Scenario 1	60%-40%	50%-30%	40%-20%	70%-50%	60%-40%	50%-30%
Scenario 2	40%-20%	30%-10%	20%-5%	50%-30%	40%-20%	30%-10%

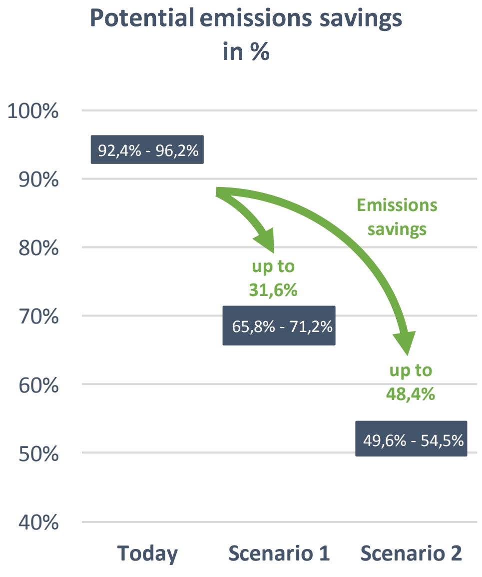
2a Emissions after application of EOL processes compared to original manufacturing

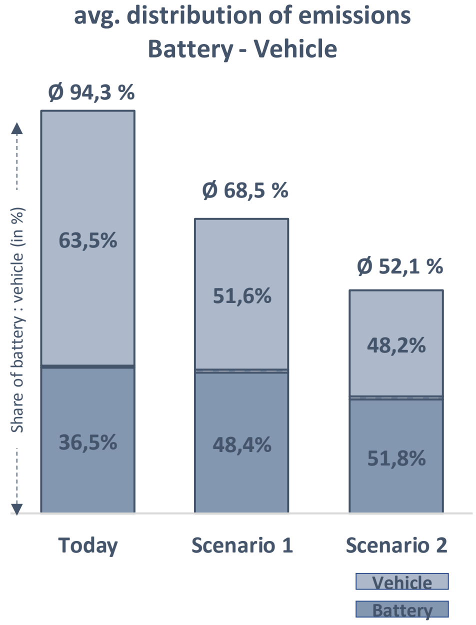
		Unweighted	Weighted	New Value
Today	Vehicle	89,58% - 94,62%	58,23% - 61,51%	92,39% - 96,23%
	Battery	97,60% - 99,20%	34,16% - 34,72%	
Scenario 1	Vehicle	50,94% - 57,83%	33,11% - 37,59%	65,79% - 71,20%
	Battery	93,38% - 96,03%	32,68% -33,61%	
Scenario 2	Vehicle	35,98% - 41,27%	23,39% - 26,83%	49,62% - 54,51%
	Battery	74,96% - 79,09%	26,23% - 27,68%	

2b New proportion of emissions by battery and vehicle

Proportion	Vehicle	Battery
Today	63,03% - 63,92%	36,08% - 36,97%
Scenario 1	50,32% - 52,80%	47,20% - 49,68%
Scenario 2	47,13% - 49,22%	50,78% - 52,87%

③ Visualisation of the results





A.17. Results option IV

Results of option IV

① Emissions of EOL process compared to original manufacturing

	Emissions of EOL process compared to original manufacturing					
	Vehicle			Battery		
	P1	P2	P3	P1	P2	P3
Today	60%-40%	70%-50%	80%-60%	70%-50%	80%-60%	90%-70%
Scenario 1	40%-20%	50%-30%	60%-40%	50%-30%	60%-40%	70%-50%
Scenario 2	20%-5%	30%-10%	40%-20%	30%-10%	40%-20%	50%-30%

2a Emissions after application of EOL processes compared to original manufacturing

		Unweighted	Weighted	New Value
Today	Vehicle	84,66% - 89,70%	55,03% - 58,30%	88,63% - 92,46%
	Battery	96,00% - 97,60%	33,60% - 34,16%	
Scenario 1	Vehicle	49,17% - 56,07%	31,96% - 36,44%	63,72% - 69,12%
	Battery	90,73% - 93,38%	31,75% -32,68%	
Scenario 2	Vehicle	35,45% - 40,56%	23,04% - 26,37%	49,11% - 53,88%
	Battery	74,49% - 78,63%	26,07% - 27,52%	

2b New proportion of emissions by battery and vehicle

Proportion	Vehicle	Battery
Today	62,09% - 63,06%	36,94% - 37,91%
Scenario 1	50,16% - 52,72%	47,28% - 49,84%
Scenario 2	46,92% - 48,93%	51,07% - 53,08%

③ Visualisation of the results