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Abstract

The reduction of Carbon Dioxide (CO2) is a central topic of environmental policies in Europe and worldwide, with a large focus on sustainable mobility. Initiatives are taken to enable sustainable mobility by optimising existing vehicle powertrain technologies such as conventional combustion engine vehicles and developing alternative powertrains such as electric vehicles, (plug-in) hybrid electric and fuel cell electric vehicles. Given the conceptual difference of energy deployment where vehicles convert primary energy into operating (propulsion) energy on-board or use loaded already converted energy for propulsion, environmental assessment of vehicles based only on direct emissions is not adequate. New methods are needed to determine the environmental burden whereas life cycle assessment provides the most comprehensive information.

The work provides a data inventory for production and operation of vehicles with conventional and alternative powertrains for four geographical regions: United States, European Union, Germany and Austria. Through vehicle simulation and data inventories the CO2 emissions of vehicles have been assessed for their full life cycle.

The results show that according to the simulated current test procedures, electric vehicles provide the most potential for enabling CO2 sustainable mobility, currently resulting in an average of 30% less CO2 compared to the most inefficient vehicle. However, the electric vehicle is highly dependent on local conditions of used electricity generation and CO2-efficiency of traction battery production. It is found that the regulated assessment procedures for electric and fuel cell vehicles in Europe do not accurately reflect on the actually caused CO2-emission associated with their propulsion, but only on the local emissions. Significant differences are exhibited in production and operation of vehicles between the regions, whereas the case of Austria demonstrated the importance of CO2-efficient electricity mix through multiple sensitivity analyses.

Electric vehicles provide a great potential, however, further improvements are urgently required to enhance its actual environmental profile. Primarily, the global CO2 efficient electricity generation from renewable sources must be increased and the supply chain impact of battery production improved. Also, environmental assessment regulations of vehicles require urgent improvement as to take into account the environmental cost of primary energy conversion used for propulsion.

Zusammenfassung

Die Reduktion der Emission von Kohlendioxid (CO2) ist ein zentrales Thema der europäischen sowie weltweiten Umweltpolitik. Dabei steht unter anderem nachhaltige Mobilität im Fokus, welche durch die Optimierung vorhandener Antriebstechnologien, vor allem die der Verbrennungsmotorfahrzeuge, sowie die Entwicklung alternativer Antriebsstränge, wie Elektrofahrzeugen, (Plug-in) Hybridfahrzeugen sowie Brennstoffzellenfahrzeugen, ermöglicht werden soll. In Anbetracht des konzeptionellen Unterschieds des Energieeinsatzes bei Fahrzeugen welche Primärenergie in mechanische Antriebsenergie an Bord übertragen und solchen die bereits umgewandelte Energie für den Antrieb verwenden, ist die rein auf direkte Emissionen basierende Umweltbewertung von Fahrzeugen nicht ausreichend. Für die Ermittlung der Umweltbelastung sind neue Methoden erforderlich, wobei die Ökobilanzierungsmethode hierbei die umfassendsten Informationen liefert. Die vorliegende Arbeit liefert eine Datenbestandsaufnahme der Produktion und des Betriebs von Fahrzeugen mit herkömmlichen sowie alternativen Antriebssträngen für vier geografische Regionen: USA, Europäische Union, Deutschland und Österreich. Durch Fahrzeugsimulation und Datenbestände wurde hierbei der CO2-Ausstoß für den vollen Lebenszyklus der Fahrzeuge erfasst.

Ergebnisse die durch die Simulation der derzeit gültigen Prüfverfahren erzielt wurden, zeigen dass das Elektrofahrzeug mit einer Reduktion des CO2 Ausstoßes um 30% im Vergleich zum ineffizientesten Fahrzeug, das höchste Potenzial für CO2-nachhaltige Mobilität bietet. Leider ist das Elektrofahrzeug stark abhängig von den lokalen Bedingungen der Stromerzeugung und der CO2-Effizienz der Batterieproduktion. Das momentan gültige Prüfverfahren für Elektro- und Brennstoffzellenfahrzeuge in Europa spiegelt nicht exakt die tatsächlich verursachten CO2-Emissionen wieder, sondern nur die lokalen Emissionen dieser Fahrzeuge. Signifikante Unterschiede zwischen den Regionen zeigen sich in der Produktion und beim Einsatz der Fahrzeuge, während im Fall von Österreich die Bedeutung eines CO2-effizienten Strommixes durch mehrfache Sensitivitätsanalysen aufgezeigt wurde.

Das Elektrofahrzeug bietet hohes Potenzial, bedarf jedoch weiterer Verbesserungen seines tatsächlichen Umweltprofils. So müsste weltweit die Stromerzeugung CO2-effizient aus erneuerbaren Energiequellen stattfinden, sowie die Supply Chain Auswirkungen der Batterieproduktion verbessert werden. Darüber hinaus sollen die Prüfverfahren angepasst werden um die Umweltkosten der Primärenergieumwandlung für die verwendete Betriebsenergie zu berücksichtigen.

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Abbreviations:

Abbreviation / term	Definition
ΔSOC	Change (balance) of the State of Charge
ADAC	Allgemeiner Deutscher Automobil-Club / German Mobility Club
ADR	Assembly, Disposal and Recycling
ADVISOR	ADvanced VehIcle SimulatOR
AER	All-Electric Range
AIT	Austrian Institute of Technology
Argonne	Argonne National Laboratory (United States Department of Energy Office of Science)
ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems
ASM	Automotive Simulation Models (dSpace)
CI	Compression Ignition
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPERT	Computer Programme to Calculate Emissions from Road Transport
DOE	Department of Energy of United States
DSG	Direct Shift Gearbox
ECE	Economic Commission Europe
EEA	European Environmental Agency
ELCD	European Life Cycle Database
EM	Electric Motor
EMEP	European Monitoring and Evaluation Programme
EPA	United States Environmental Protection Agency
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle (Battery electric vehicle)
FASTSim	Future Automotive Systems Technology Simulator
FCEV	Fuel Cell Electric Vehicle
FP5 / FP7	5th and 7th Framework Programme for Research and Innovation
GEMIS	Global Emissions Model for integrated Systems
GHG	Greenhouse Gasses
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation (Referring to the entire model)
GREET1	Referring to the fuel cycle GREET model
GREET2	Referring to the vehicle cycle GREET model

Abbreviation / term	**Definition**
GUI	Graphical User Interface
HBEFA	Handbook of Emission Factors for Road Transport
HEV	Hybrid Electric Vehicle
HRS	High Response Synchronous
HVAC	Heating Ventilation and Air Conditioning
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IINAS	International Institute for Sustainability Analysis and Strategy
ISO	International Organization for Standardization
JRC	Joint Research Center of European Commission
LCA	Life Cycle Assessment
Li-ion	Lithium-ion
LPG	Liquid Petroleum Gas
MOVES	MOtor Vehicle Emission Simulator
MPG	Miles Per Gallon
NEDC	New European Drive Cycle
NiMH	Nickel-Metal-Hydride
NOx	Nitrogen Oxides
NREL	National Renewable Energy Laboratory of United States
NTNU	Norwegian Institute of Science and Technology
OTAQ	Office of Transportation and Air Quality of Unites States
PFSA	PerFluoroSulfonic Acid
PHEM	Passenger car and Heavy duty vehicle Emission Model
PHEV	Plug-in Hybrid Electric Vehicle
PM_{10}	Particulate Matter diameter 10
PMS	Permanent Magnet Synchronous
PROBAS	PRozessOrientierte Basisdaten für Umweltmanagement (Life cycle data inventory source maintained by German Federal Environmental Agency)
SI	Spark Ignition
SOC	State of Charge
SOx	Sulphur Oxides
UML	Unified Modeling Language
US	United States
VBA	Visual Basic for Applications
VMT	Vehicle Miles Travelled
VOCs	Volatile Oxygen Compounds
WLTP	Worldwide-harmonized Light-vehicles Test Procedure

1 Introduction

Central topics of the environmental policies in Europe and worldwide stand for a reduction of Carbon Dioxide (CO_2) and other emissions causing the global warming and climate change. Measures for reduction of anthropogenic CO_2 emissions are in the strong focus of development of the automotive and other industries. All major governments and automotive manufacturers target their strategic development on improving the mobility to a sustainable extent having in mind the scarcity of resources on the one side and the negative environmental effects on the other.

However, the trend of personal transport activity is still projected with significant growth, as presented in Figure 1 by the “Sustainable Mobility Project” calculations [1]:

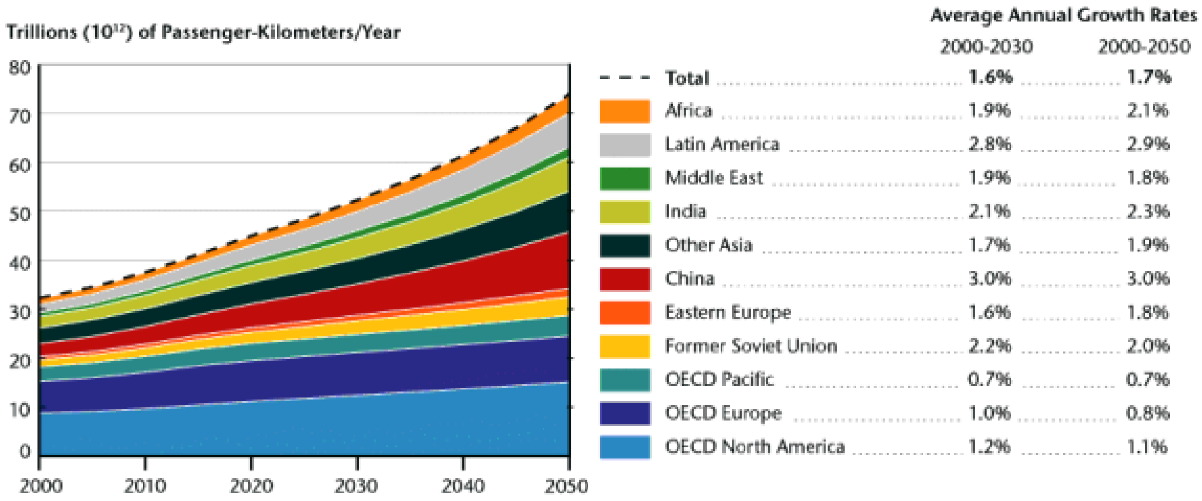

Figure 1: Personal transport activity by region; [1]

As stated in introductory chapters of [2], in the second half of 20th century the car and therewith the personal mobility has become an inextricable part of the society. With that being said and considering the significance of the figure above, the expectations of ecological pressure caused by the car are reasonably high.

After more than 100 years of automotive development, in the early 70-ties, first actions in direction of environmental improvement are evident whereas efficient use of available resources and protection of environment represent the main targets. These particular movements are noted simultaneously with the first oil crisis. However, significant environmental improvement of the automotive technology used today is obvious. Relevant literature exhibits several research and production trends of environmentally conscious and more sustainable powertrain technologies. Popular, widely developed and already used vehicles with alternative powertrains are Electric Vehicles (EV), Plug-in Hybrid Electric Vehicles (PHEV), Hybrid Electric Vehicles (HEV) and Fuel Cell Electric Vehicles (FCEV). In the meantime, efficiency improvements of conventional Internal Combustion Engine Vehicles (ICEV) are showing promising results, however, such improvements are gradual and will reach their limits at some stage. Nevertheless, the reduction of consumption of fossil and other fuels as well as minimizing CO_2 emission remains the main topic of environmental development in the automotive industry. [2]

A Recent study has proven, that for example in Austria, it is possible to save up to 60% CO_2 emission including the supply of the energy, in one year, using electric vehicles in comparison with the use of similar vehicles with a conventional internal combustion engine [3]. Several additional studies [4], [5], [6] have also proven an actual reduction of CO_2 Emission in the use cycle of vehicles with alternative powertrains such as FCEV and EVs. Most of these papers focus on the determination of CO_2 reduction considering the fuel and use cycle of the vehicles. This being said, the terms use, fuel and vehicle cycle are introduced with reference to detailed description of the terms in sub-chapter 2.2. The use cycle encompasses the accounting of emissions accrued in association with vehicle use (direct emissions). The fuel cycle considers accounting of emissions associated with production and delivery of the fuels needed for vehicle operation. In the vehicle cycle, emissions accrued during the production of materials used for vehicle components, the production of vehicle components, assembly, recycling and disposal of vehicles are considered. The use, fuel and vehicle cycle constitute the full vehicle life cycle.

Actual environmental assessment of vehicles based only on direct emissions is not considered to be sufficient anymore, especially for a comparison of different propulsion and fuel systems. New methods are needed to provide complete information sets on environmental burden caused by the vehicles with conventional and alternative powertrains [7]. A comprehensive method for an ecological analysis of a vehicle is represented by the Life Cycle Assessment (LCA) which is used to determine the environmental pressure provided by the product system (Production, Energy supply, Use, Disposal). Considering that definite environmental measures on production vehicles are, as a rule, bound with high investments [8], computer simulations and pre-evaluations are of great importance for automotive research and development.

The open source software market offers tools that are used in different ways for LCA and other studies. On the one hand, software tools are used for vehicle simulation to gain the fuel consumption data (i.e. ADVISOR) and on the other hand, life cycle data inventory tools and databases (GREET, GEMIS, PROBAS, etc.) are used to complete the vehicle life cycle studies with fuel and vehicle cycle data.

1.1 Objective

Hence, the main goal of this study is to develop a unique calculation model which uses vehicle simulation and the vehicle life cycle data inventory to enable accounting of CO_2 emissions over the full vehicle life cycle for conventional and different alternative powertrains as well as to establish data inventories and assess the resulting CO_2 emission for 4 geographical regions: United States (US), European Union (EU), Germany and Austria. Combining the results of vehicle simulation with vehicle life cycle data inventory, the calculation model enables an examination of the entire environmental burden of the full vehicle life cycle in terms of CO_2 emissions. Based on the parameters defined for the simulated vehicle, provided data inventory on emissions associated with the production of fuels and production and recycling of the vehicle and finally results of the vehicle simulation, the calculation model shall provide results for use, fuel and vehicle cycle which in total constitutes the full vehicle cycle. The calculation model shall be implemented as a software tool so that it allows an input of own assumptions and data inventories and therewith customized sensitivity analyses against different vehicle specific or LCA specific parameters.

In order to be able to develop the tool and perform the analysis as above stated, preliminary research work has been done to insight the basic concepts of the LCA and applied software tools for simulation and CO_2 accounting for the considered product system and geographical regions. Hence, the basic concept of the LCA methodology in scope needed for CO_2 accounting of this study is given in chapter 2. A general introduction to emission modeling, a detailed description of the tools used for emission modeling and vehicle simulation as well as types of vehicle examined are described in chapter 3.

As the preliminaries for the implementation work have been elaborated, consequently chapter 4 presents the implementation concept and description of the extension of the ADVISOR simulation tool as well as the details of data collection for 4 geographic regions. Chapter 5 presents the resulting work where representatives of all vehicle types were parametrized, simulated with the modified ADVISOR tool in a base case and with a row of sensitivity analyses. The study is finalized with the summary of the work and outlook in chapter 6.

2 Vehicle Life Cycle Assessment – Method to determine the environmental burden of a product system

Provision of products and services is in general connected to resource consumption which usually results in negative environmental impacts. However, the price of goods hardly reflects the impairment of the environmental performance as such services of the ecosystem are usually taken free of charge. With this said, aftereffects such as excessive use of resources, climate change and overuse of ecosystem are inevitable. [7]

In order to raise the awareness about the environmental burden caused by the current economic system procedures, methods such as the life cycle assessment have been developed to provide measurable information regarding the resource consumption, pollution and environmental degradation through pollution emissions and resource use. LCA is able to describe and evaluate the complete product system („cradle-to-grave“) and represents a scientific tool with a process standardized by the International Organization for Standardization (ISO 14040 ff). An LCA provides comprehensive information about a product system used to identify improvement priorities and potential problems in terms of environmental pressure. Additionally, the LCA represents a support instrument for evaluating and controlling environmental improvement goals [7]. The following sub-chapters address general LCA definitions, specific goals and methods of vehicle LCA.

2.1 Life Cycle Assessment Definition

Considering that the LCA is one of the main preliminaries of this study, in the following, a definition of the LCA given by the ISO 14040 is quoted as presented in the handbook of industrial ecology:

“LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a system; evaluating the potential environmental impacts associated with those inputs and outputs; and interpreting the results of the inventory and impact phases in relation to the objectives of the study.” [9]

The handbook of industrial ecology explains that products in the ISO 14040 LCA definition also include services which provide a given function and that in general the term product is taken as “pars pro toto” for all objects of LCA, if not otherwise specified for the given study. The product is studied during its whole life cycle including all processes related to the product’s life cycle called the “product system”. Therewith, the product delivers a function which is taken as reference for the LCA studies, meaning that in the end all environmental impacts are related to this function [9].

The key concept of the cradle-to-grave analysis is simplified illustrated in Figure 2:

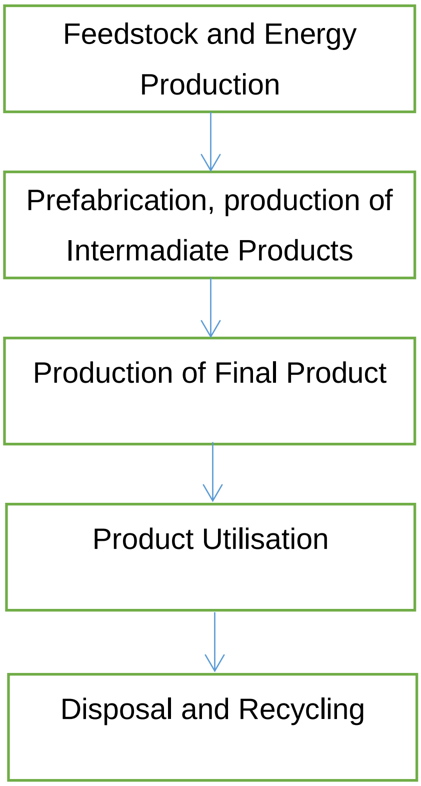

Figure 2: Simplified life cycle of a product, translated original from [10]

The connected process modules of the product life cycle tree form a system which focuses on a product, process and service or in the most general formulation a human activity. LCA analyses systems which perform designated functions oriented to product utilization. Therefore, the evaluation of the system utilization provides proper benchmarks for comparing the product’s environmental burden and provides appropriate means for definition of a "functional unit".

2.2 Vehicle Life Cycle Assessment and Data Inventory

The application of LCA methodologies in the automotive industry occurs at various levels. However, the great significance of the LCA implies that the LCA methodologies and processes are constantly further developed. Increasingly precise measuring instruments are deployed in order to gain new findings on the further improvement of the environmental performance of vehicles through the entire life cycle - from raw material extraction to the disposal of used cars. [2].

A recent LCA study elaborated by the Austrian Federal Environmental Agency [7] and preliminary chapters of the ISO 14040 appraise that ideal LCAs features following attributes:

- Complete data inventory and factual accuracy
- Unambiguous statement setting and clear definition of goal and scope,
- Resilient definition over time
- Comprehensable assumptions and elaboration
- Proper documented and creatable at reasonable cost and effort

Considering the noticeably spread supply chain, such LCA studies are in praxis usually creatable only partially or stepwise [7].

Hence, the crucial part of any LCA is the life cycle data inventory. The data inventory has to contain all input and outputs of material and energy flows required in the product life cycle. This can be presented as physical withdrawal of materials from the environment (feedstock of oil or iron) or emission associated with this activity (CO_2, Nitrogen Oxides (NOx) etc.).

Since the early 1980s, the Center for Transportation Research of Argonne National Laboratory (Argonne) has performed a lot of research regarding the assessment of fuel cycle related emissions for various fuels and transportation technologies. In 1996, Argonne developed and published a fuel cycle model based on a comprehensive spreadsheet called GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation). The main goal was to provide a computer tool that enables researchers to assess and evaluate the fuel-cycle energy consumption and emission impacts. Since its development, the model was extensively used as the basic data inventory for LCAs and other studies by many institutions and researchers. A comprehensive list of publications which use the GREET Model is given in [11]. Later, Argonne researchers included also the production, recycling and disposal of vehicles with different powertrain technologies. In order to keep the life cycle models manageable, they were split into GREET1 - representing the fuel-cycle model and GREET2 – representing the vehicle cycle model. In the further text, the “GREET model” refers as superordinate to the GREET1 fuel cycle and GREET2 vehicle cycle model. The concept of the GREET model is illustrated in Figure 3 and presented in detail in sub-chapter 3.4 as the basic vehicle cycle data inventory for this study.

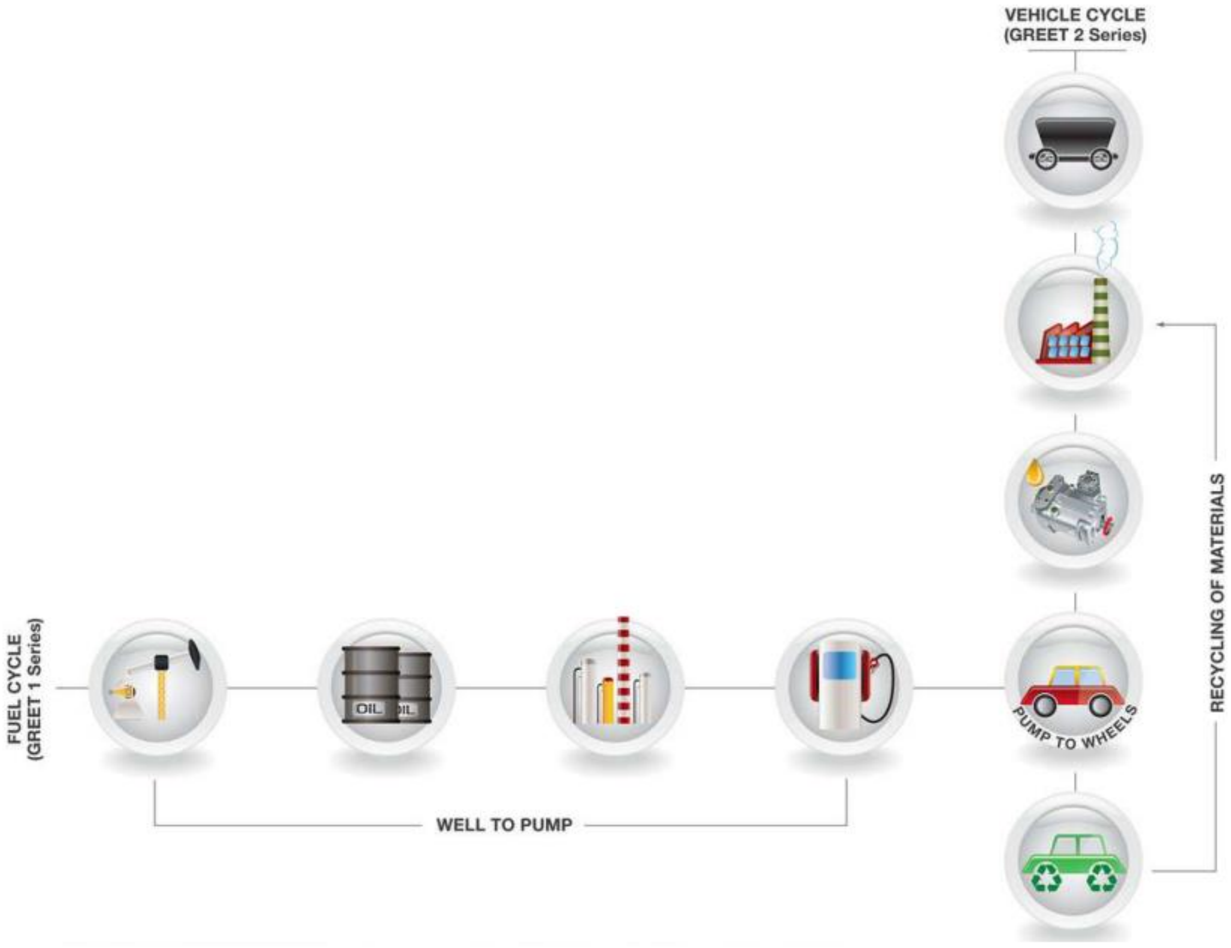

Figure 3: GREET vehicle cycle model; [12]

The illustration of the GREET model demonstrates the full vehicle life cycle, representing a two-dimensional basic cradle-to-grave scheme as defined in Figure 2. In order to present a simplified implementation process in this study, for the case of passenger vehicles, the two-dimensional scheme will be broken down into three main parts:

- Vehicle cycle – for accounting emissions associated with production and recycling of the vehicle [12]
- “Well-to-pump” - for accounting indirect emissions associated with production and supply of the fossil fuels or other energy sources [13]

- Pump-to-wheels - for accounting direct emissions associated with the fuel combustion [13]

Further terms used in the literature are well-to-tank and well-to-wheels whereas the Figure 4 adopted from [14] presents a very good outline of these terms.

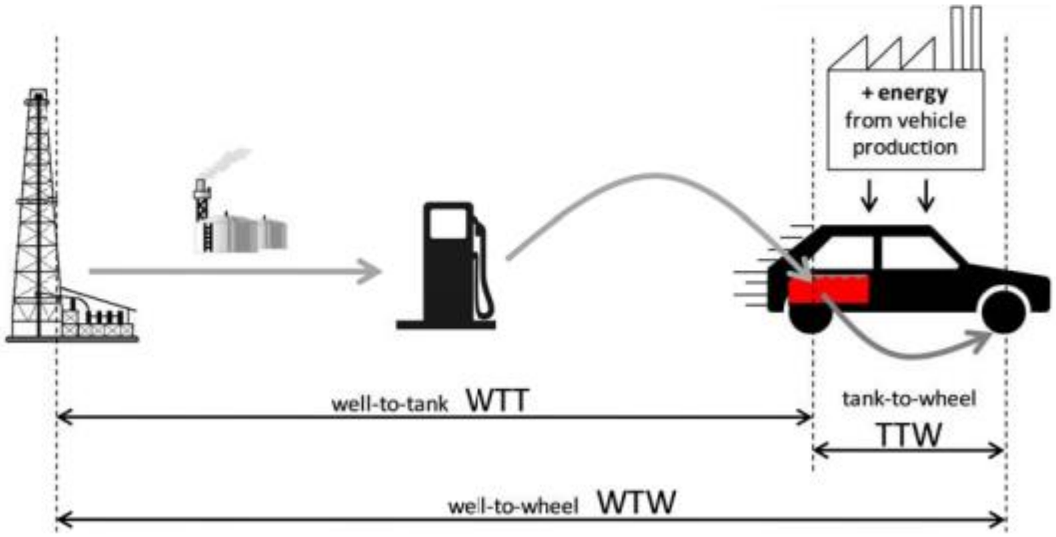

Figure 4: Definition of fuel cycle terms; [14]

The full life cycle analysis presented in [5] structures the data inventory as follows:

- Material cycle: material extraction, parts manufacturing, assembling, and recycling (vehicle cycle)
- Fuel cycle: raw fuel extraction, refining, and pump transportation (well-to-pump)
- Use cycle: affected by the driving, route topography and powertrain technology (Pump-to-wheels)

Based on the above-mentioned definitions, this study will make use of following terms forming the data inventory of a full vehicle life cycle:

- Vehicle cycle
- Fuel cycle
- Use cycle.

These terms are explained in detail in following sub-chapters.

2.2.1 Vehicle cycle

The existing literature exhibits several methodologies for a determination of the vehicle cycle data inventory. For example, in [5] and [7] top-down methodologies are used where the vehicles are broken-down into material types and energy requirements and emissions per material are defined including assembling and dismantling.

On the other hand, the approach used in the GREET2 Model provides a detailed bottom-up specification of the data inventory for the following phases of a vehicle life cycle:

- Raw material recovery
- Material processing and fabrication
- Vehicle component production
- Vehicle assembly
- Vehicle disposal and recycling [12]

Thus, for the vehicle cycle data inventory, it is required to specify the emissions for all phases as given above. As the first step, the quantity of materials used in the production of vehicle components is required together with the emissions associated with the processing and fabrication of the specified materials. In the next step, the energy used and emissions associated with the production of vehicle components and assembling of the vehicle need to be determined. Finally, the determination of energy used and emissions associated with the disposal and recycling of vehicles rounds up the vehicle cycle.

2.2.2 Use cycle

The use cycle, in [12] referred to as “pump-to-wheels”, indicates the specific emissions of vehicles associated only with the combustion (use) of on-board fossil fuels used for propulsion or operation of auxiliaries. Hence the required information for the data inventory of the use cycle are CO_2 emission factors of the combusted fuel and fuel consumption figures. The CO_2 emission factors are uniquely defined for fossil fuels and are obtained from the specification in [15]. The determination of powertrain efficiency is going to be simulated by a vehicle simulation, resulting finally in the fuel consumption figures.

Hence, for the use cycle data inventory, the determination of the fuel economy figures is crucial. The fuel CO_2 emission factors are depending on the characteristics of the respective fuel type as given in [15].

2.2.3 Fuel cycle

The fuel cycle accounts for associated emissions in the steps required to deliver the finished fuel to the vehicle refueling stations [16]. The pathway of the fuel cycle includes recovery or production of the feedstock used to produce the respective fossil fuel, transportation and storage of the energy source through conversion of the feedstock to the fuel and the subsequent transportation, storage, and distribution of the fuel to the refueling stations [17].

Considering the regional aspect, the emissions associated with the production and supply of fossil fuels and other energy sources such as electricity and hydrogen exhibit great differences even when neighboring countries are compared. Especially for the case of electricity and hydrogen production, different methods can be deployed resulting in different CO_2 emission scenarios. These facts are understood as crucial when conceiving the fuel cycle data inventory and shall be considered carefully in the implementation phase.

2.3 Scope and limitations of this study regarding the life cycle assessment

According to ISO 14044 there are four phases of an LCA study [18]:

- The goal and scope definition phase
- The inventory analysis phase
- The impact assessment phase
- The interpretation phase.

In consideration of the LCA structure according to ISO 14044, the main limitation of this study is that it is concentrating on the CO_2 footprint associated with the full life cycle of vehicles with alternative powertrains and has a limited scope of the typical assessment and interpretation phase. The study concentrates on the establishment of a comprehensive data inventory for different geographical regions and enhancing a simulation tool for determination of the amount of CO_2 emissions in the full vehicle life cycle. Accordingly, set-up of the data inventory covers the first two phases of the LCA according to ISO 14044 and the impact and interpretation of results focus on confrontation with current regulations and procedures.

According to [10], which is also based on the ISO 14040 series, an LCA should consider following boundaries:

- Geographical
- Time
- Functional and
- Technical system boundaries

One of the results of this study shall be a comparison of the full vehicle life cycle between 4 different geographical regions, which are in the further text referred to as “locational references” for harmonization of terminology with the examined data inventory sources. The locational references for US, EU, Germany and Austria are considered as geographical boundaries in a wider sense since the supply chain in automotive is not easily limitable.

Timewise the study will consider to the extent deemed possible the up-to-date data representing the present technological status. A further time constraint considered is a 10 year vehicle lifetime, as usually found in similar literature, for example in [7].

Technical system boundaries are set to the following:

- Main focus of the study are the CO_2 emissions and passenger vehicles,
- The vehicle types are passenger vehicles with conventional and alternative powertrains as defined in the sub-chapter 3.6.

The unit for the data inventory is CO_2 per kg of material product and cumulative energy used in MJ per kg of material product. The resulting unit used also as the basis for the sensitivity analyses is in grams of CO_2 per vehicle kilometer (g CO_2 / km). Specification of the detailed analysis framework following these guidelines is given in chapter 5, together with the details of the simulation framework.

3 Approach – Selection of tools for accounting of CO_2 emissions and definition of vehicle types

Following the introduction of the life cycle assessment methodology presented above, this chapter addresses means to facilitate the implementation of the presented methodology, emission modeling and respective data inventories, vehicle simulation tools and examined vehicle types.

Hence, the following sub-chapters present a state of the art on emission modeling (sub-chapter 3.1) and vehicle simulation tools (sub-chapter 3.4) as well as a rationale for the selection of tools used in the implementation process (sub-chapter 3.3). Further in sub-chapters 3.4 and 3.5 the chosen tools for implementation are presented in detail followed by definitions of the vehicle types examined by this study in sub-chapter 3.6.

3.1 Emission modelling

Reduction of CO_2 emissions including awareness raising of the excessive CO_2 overproduction is a central topic of initiatives and policies of environmental protection in Europe and worldwide. Hence, numerous initiatives, projects and actions are being or have been implemented, with the aim to estimate the actual amount of CO_2 being produced in association with the production of different goods, energy types and transportation means in a wide spectrum of human activities.

For example, in Europe, the JEC[1] research collaboration has elaborated well-to-wheel analyses containing respective well-to-tank and well-to-pump sub-analyses reflecting on greenhouse gas emissions, energy efficiency, and industrial costs [19]. The European Monitoring and Evaluation Programme (EMEP) and the European Environmental Agency (EEA) developed the "EMEP/EEA air pollutant emission inventory guidebook", which provides comprehensive technical guidance for the elaboration of emission inventories developed primarily for policymaking [20]. Another example is the "EC-METI" Task Force which was formed as a collaboration of the European Commission and the Ministry of Trade and Industry of Japan to develop a "*common methodology for assessing the impact of ITS on the energy efficiency and CO_2 emissions*" [21].

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[1] Initiative of the European Commission joining JRC, EUCAR and CONCAWE (http://iet.jrc.ec.europa.eu/about-jec/short-portrait)

The United States Environmental Protection Agency's (EPA) Office of Transportation and Air Quality (OTAQ) has developed a series of emission models during the past two decades [22]. Notably, the EPA's current official model "MOVES" (MOtor Vehicle Emission Simulator) is used for estimating air pollution emissions from mobile sources. As referred to in the sub-chapter 2.2, Argonne has been conducting research on fuel cycles since the early 1980s, financed by the US Department of Energy's (DOE's) Office of Transportation technologies. Argonne has developed a full life-cycle model called GREET based on spread-sheets containing data inventories on fuel and vehicle cycles where the energy used and weight of the different vehicle types are pre-defined by means of statistical assessments [12].

The literature exhibits numerous further examples of such projects and initiatives, which often aim at measurement, modeling or estimation of emissions from mobile or otherwise more precisely classified sources, such as road traffic, railway traffic, heavy duty vehicles etc. In [23] a distinction is introduced between emission models and databases, whereas in a later report from the same research organization [24], instantaneous emission modeling is presented with further classification into adjusted and unadjusted instantaneous emission models. Instantaneous models are elaborated as a possibility to calculate emissions for any operation profile of the vehicle giving such emission modeling much more precision in comparison with models based on average speed driving cycles. Thus, in [24] it is explained that in consideration of significant difficulties to continuously measure emissions with a high degree of precision and problems with consequent allocation of measurements to correct operating conditions, some emission models take into account such distortions and are classified as adjusted or otherwise as unadjusted emission models.

Based on the overviews in [24] and [25] and supported by further literature research, a summary of the state-of-the-art on emission modeling is provided in the following sub-chapters concentrating on input, output and basic functionality of each emission model. Conciliating with the requirements of this study, the emission modeling tools are structured in:

- tools which only present the resulting output for a certain functional unit (referred to as output oriented emission modeling tools)
- tools which present all process stages, pathways and calculations resulting in the output (referred to as fully fledged emission modeling tools).

3.1.1 Output oriented emission modeling tools

3.1.1.1 MOVES

MOVES is a modeling tool developed by the EPA which is under constant development and is currently available in its version “2014a”. The tool is used for the estimation of a wide range of mobile source emission factors and inventories. Initial information required for the modeling comprises “*vehicle type, time period, geographical areas, pollutants, vehicle operating characteristics, and road types*” [26]. MOVES has one of the largest and most detailed databases covering a broad range of pollutants, reflects on different vehicle operating states and allows multiple scale analysis. The MOVES model provides a database with relevant default information on emissions for the US, however, the MOVES user guide encourages that up-to-date local inputs should be used in order to increase model accuracy [25] [26].

3.1.1.2 ARTEMIS

The ARTEMIS (Assessment and Reliability of Transport Emission Models and Inventory Systems) emission model was a considerably large project financed by the European Commission within the 5th Framework Research Programme with the aim to provide a consistent model on national and regional levels covering the main transport means: road, rail, air and ship transport. The objectives of the project were to grasp the differences and uncertainties in emission modeling and model predictions and to address these as well as to provide a methodological uniformity in emission modeling giving a framework for decision and policy making in regard to air quality improvement [27]. The results of the project are presented by a comprehensive report in [27] and summarized by [28] as follows:

- Elaboration of “*The common ARTEMIS driving cycle*” comprising real-world test procedures for the passenger cars and heavy duty vehicles enabling coherent measurement tests between the project partners. Furthermore, a systematic methodology analysis is provided to minimize methodological uncertainties such as vehicle sampling, test conditions etc. The application of defined procedures took place under the ARTEMIS project, but also under national programs of the project partners, resulting in a significantly larger emission database. Hence, these developments resulted in significant improvement of coherent test procedures for emissions measurements;

- Extensive research on areas which were not thoroughly examined by the time of the development of ARTEMIS, i.e. non-regulated pollutants, cold start and evaporative emissions and implications of the auxiliaries tested on duty vehicles, single-track vehicles (2-wheelers) and recent car models;
- Ability to facilitate consistent modeling at several scales, (i.e. local, national, regional) and subsequent estimation of vehicles fleets and their emissions;
- Large database containing relevant statistical data for elaboration of rational assumptions on main characteristics of the traffic situation;
- Validation of the simulation activities with real data collected through executed experimentations.

ARTEMIS comprised research on non-road transport as well, however, the level of development is not the same for all transport means, whereas the road transport package is elaborated to highest detail [25].

[28] presents the ARTEMIS tools as a composition of an emission data sets, fleet models, emission factor processors, traffic data set modules and an emission computation module.

3.1.1.3 COPERT

The Computer Programme to Calculate Emissions from Road Transport (COPERT) series of software solutions, has a long history beginning in 1989 when the initial version of the software was developed by the EEA with the name “COPERT 85”. The calculations in this version of the software were based on average speeds and software has been widely used to estimate official national data inventories from road transport [29]. The software was constantly developed supported by the EEA meaning that the development states of the software were connected with the results of larger European projects such as dedicated projects of the European Commission’s Joint Research Center (JRC), like ARTEMIS (FP7), “PARTICULATES” project (FP5) and many other. The latest version of the software uses emission factors developed by “HBEFA” which is presented in the next sub-chapter [30].

The software is able to calculate emissions of European countries’ regulated and non-regulated pollutants from road transport and covers conventional vehicle classes such as passenger cars, light and heavy-duty vehicle as well as two-wheelers [31]. An initial database is provided with the software, however, users can feed data into the system through excel forms or manual input. Finally, the software enables the creation of reports on different scales as well as options for visualization of the data. The software is mainly used by experts in the field for the compilation of national or regional inventories, scientific/study purposes, estimations of fleets etc. [32].

Development and maintenance of the software are provided by “EMISIA”, a spin-off company of the Aristotle University of Thessaloniki which offers a range of inventories and specific solutions for emission modeling [30].

3.1.1.4 HBEFA

The Handbook of Emission Factors for Road Transport (HBEFA) was originally a project of Environmental Protection Agencies of Germany, Switzerland and Austria aimed to provide emission factors for all current vehicle categories. In the meantime, further European countries joined this project (Sweden, Norway, France) as well as the JRC. The handbook provides emission factors, i.e. the specific emission in g/km, per traffic activity at different levels of disaggregation such as the type of emissions or vehicles, year, pollutants and similar. The official webpage of HBEFA offers now an online version of the tool, providing emission factors for main vehicle categories and traffic situations [33].

In its latest version “3”, HBEFA uses the Passenger car and Heavy duty vehicle Emission Model (PHEM) for calculation of the emission for all in HBEFA possible simulations of traffic and drive situations. PHEM is a cooperative development in the frame of the ARTEMIS project, aiming at simulating of emission factors for heavy-duty vehicles which would ultimately be used for passenger vehicles as well and forms a part of HBEFA and the ARTEMIS inventory model.

The basis of PHEM ‘s calculations is the engine power demand which is being computed in 1 Hz frequency from input such as vehicle data (i.e. mass), transient engine maps, transmission ratios and gear-shift models and driving cycle data input such as speed, road gradient and drive resistances. In addition, transient correction functions for engine and emission maps are used in order to take transient influences into consideration and a Selective Catalytic Reduction module was developed to reflect real behavior of the system on the simulation of NOx emissions.

In the current HBEFA versions, hybrid vehicles have not been considered as a separate segment in the fleet structure but the increasing market of such vehicles and their specific emission behavior should be considered in more detail in the future developments [34].

3.1.2 Fully fledged emission modeling tools

3.1.2.1 GEMIS

GEMIS – “Globales Emissions-Modell Integrierter Systeme” – is a standalone application enabling analysis and comparison of environmental and cost effects of energy, transportation, and material systems. GEMIS facilitates a comparison of the primary energy consumption, pollutant emissions and material flows of different energy and transport systems, as well as understanding of fuel consumption and emissions at each stage of energy production, conversion, and utilization. This open source software product has been developed by the International Institute for Sustainability Analysis and Strategy (IINAS) and was used extensively in life cycle assessments and transport emission analysis studies with European context. [35]

The hubs of the GEMIS software functionality are products, processes, and scenarios. In GEMIS, products are inputs and outputs of processes, which are as rule technological processes, defined in GEMIS as activities to convert certain energy / material into the required output energy / material or transportation activities. An example of this structure is power plants using fuels as input, producing electricity as output through energy conversion process and vehicles providing transportation services. Scenarios are used in GEMIS to allocate processes or at least one process which has a demand for certain energy, material or transportation service whereas the different combination of processes enables different scenario options. With an allocation of scenarios, the calculation of results for different scenario-options / combination of processes is enabled, whereas the software offers options for visualization, comparison, and disaggregation of gained results.

As presented in [7], the GEMIS software was adapted by the Environment Agency Austria (Umweltbundesamt) with respect to the inventories in Austria and is kept constantly up-to-date.

3.1.2.2 GREET

As indicated in the sub-chapter 2.2, since its first release in the mid-1990s GREET has developed to a vehicle life cycle model, intended for use as an analytical tool by researchers and practitioners for estimation of fuel, use and vehicle cycle emissions.

According to the GREET modeling approach, the product system which should be assessed for evaluation of vehicle technologies includes two different energy cycles, fuel and vehicle, considering production and use for both energy cycles. This modeling approach was realized by developing the vehicle cycle model GREET2 building upon the established fuel cycle model GREET1 and related experiences.

For a given transportation fuel and/or vehicle type, the GREET model is able to calculate the energy consumption, Greenhouse Gasses (GHG) emissions and typical pollution indicators such as (Volatile Oxygen Compounds) VOCs, Carbon Monoxide (CO), NOx, Particulate Matter diameter 10 (PM_{10}), Sulphur Oxides (SOx). The GREET model relies on the energy flow as the main parameter in the calculation process, computing the throughput of the total energy used in the processes which the model is covering. The model comprises a large database of emission factors based on official data provided by the EPA, own research of Argonne or other referenced sources as well as detailed structuration of processes and products the model makes use of. All processes, product compositions and data inventories in the GREET model are provided as excel sheets, enabling the user to reconstruct the process paths and use the itemization of materials used [36].

As a result, the GREET model provides information on energy used and emission associated with:

- use and production of 5 vehicle types: ICEV, HEV, PHEV, EV and FCEV in conventional and light-weight production (GREET2),
- production of fuels required for the propulsion of the comprised vehicles types with several production specification options (GREET1).

Furthermore, GREET contains abundant raw data for emission modeling, providing the most comprehensive data inventory in comparison with other emission models examined.

The GREET model is being maintained and updated regularly by Argonne as well as widely used and quoted by numerous studies and papers on this topic.

3.1.3 Smaller projects and applications

The Canadian National Railway Company developed a very simple tool for an estimation of GHG emissions associated with the transportation of products. The calculator estimates the equivalent of CO_2 emissions for the transportation cycle of products with consideration of nationally aligned assumptions such as emission factors extracted from studies elaborated on transportation covering Canada only [25].

The Emission Calculator for Urban Transport ("CELTU") is another Canadian emission accounting tool. It comprises the production, refining and transport of fuel and production of electricity considering the increasing number of electric cars. Against the provision of input data such as activity type, evaluation year, place, road type, fleet composition and expansion it can calculate annual GHG emissions and some air pollution indicators associated with vehicle use and transportation in the urban context. [25]

The International Vehicle Emission ("IVE") Model is a java-based application designed to estimate emissions from motor vehicles with the accent on the setup of regional or national constraints to enable accounting of emissions on this level. Possible input information is divided into three groups: "*1) the engine technology and add-on control distribution (including maintenance); 2) the driving behavior of the different types of on-road vehicles traveling on the local road; 3) vehicle emission factors specific to the local vehicles."* [25]

The "MOPSEA" project was conceived by the Belgian Science Policy out of the needs to comply with requirements for international and European agreements. After elaboration of initial inventories for environmental air legislation and international reporting obligations, the course of the project was more directed to the model mapping of historical emissions enabling elaboration of emission projections for the future. [25]

3.2 Vehicle simulation tools

Adapting to the increasingly changing determination factors, associated effects and sustainability challenges, the automotive industry is currently in a transition phase. The basis of this progressing transition are detailed analyses of the various factors influencing the society, general behavior and expectations on the product system, including global trends and correspondingly changing customer requirements. Besides the direct effect the changing conditions have on the product system itself, increased focus is given to necessary adaptations of the development process and the use of new methods in order to remain competitive with optimal use of resources. Hence, the key to optimizing the development process is the enhanced and consistent use of virtual development methods; both in the early development phase of the vehicles as well as to test and ensure the quality of the software versions and hardware components installed [37].

Simulation as one of the broadly used virtual development methods was investigated in [38], focusing on present applications, progressing developments and advantages of simulation methods and tools. In [38] one of the most prominent definitions of simulation is cited: "*Simulation modeling and analysis is the process of creating and experimenting with a computerized mathematical model of a physical system*". The evolvement of the simulation in the past decades is presented in Figure 5, showing the number of related papers in the respective period.

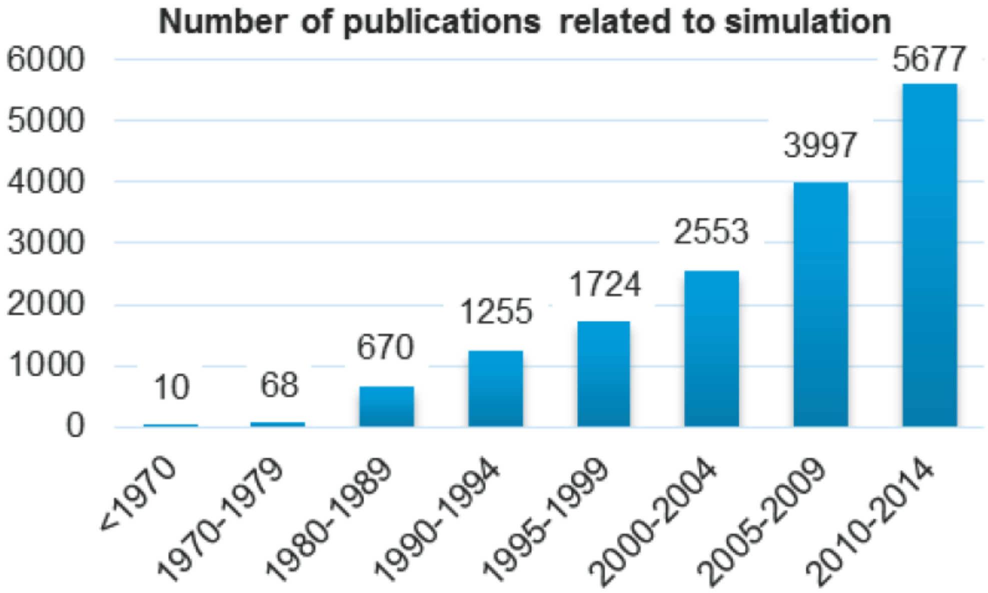


Figure 5: Number of publications related to vehicle simulation; [38]

[38] classifies simulation models in accordance with following 3 dimensions: (i) timing of change, (ii) randomness and (iii) data organisation, whereas all three dimension are further classified based on determining factors such as: static or dynamic for timing, deterministic or stochastic for randomness and grid-based and mesh-free for data organisation.

For the purpose of this study, a free and open source software simulation tool is required which:

(i) provides as much as possible information on vehicle characteristics, structure and operation parameters, in particular, fuel economy, enabling therewith the calculation of CO_2 emissions for the full vehicle life cycle.

(ii) Enables code modification to facilitate the process of the calculation of the full vehicle life cycle.

The literature review and internet research were thus focused to the described extent however results of the research provided in the following sub-chapters provide descriptions of proprietary vehicle simulation software to exemplify the current industry status. Hence, for the purpose of this study simulation tools are classified as (i) free and open source and (ii) proprietary software. The examples from the industry are based on the summary given in [39] and further literature research.

3.2.1 ADVISOR

ADVISOR (Advanced Vehicle Simulator) is an open source software tool for vehicle simulation developed by the US DOE's, National Renewable Energy Laboratory, implemented in the Matlab/Simulink environment. ADVISOR is a convenient, flexible but robust software used in the first place to quantify the fuel economy, the performance, and the emissions of vehicles that use alternative powertrain technologies. ADVISOR's structure and default data enables simulation and analysis of ICEV, HEV, PHEV, EV and FCEV and provides a variety of options for modeling different forms of these vehicles. One of the main assets of ADVISOR is the possibility to quantify the expected changes, which result from implementation of new technology and compare them with the baseline data. Further, ADVISOR facilitates parametrization of the simulation environment enabling detailed representation of vehicle operation state in different settings. ADVISOR's modular structure and design provide connectivity possibilities with other proprietary tools and models as well as the possibility to integrate simulation results of components of such proprietary tools and models [40].

ADVISOR has been used in a wide spectrum of studies and notably in the life cycle analysis study - [5] and a large well-to-wheel fuel analysis - [16] elaborated for the European contexts.

In 2003 the National Renewable Energy Laboratory of the US (NREL) established a partnership with "AVL List GmbH", Graz/Austria to further develop and commercialize ADVISOR whereas the further developed versions were held proprietary by AVL List and used also as instantaneous emission models as reported in [24]. ADVISOR is still openly available in its version from 2003, used and supported by a large community in research and development.

3.2.2 FASTSim

The Future Automotive Systems Technology Simulator (FASTSim) is an open source software tool developed and maintained by NREL / US DOE. The tool is designed to support the evaluation of impacts on efficiency, performance, cost, and battery life through technology improvements for the development of vehicles with conventional

(ICEV) and alternative powertrains (HEV, PHEV, EV). Thus, besides technical powertrain typical questions such as battery size, FASTSim considers the cost efficiency associated with component parameters and fuel economy [41].

The tool was developed in Excel and Visual Basic for Applications (VBA), which is used for management of models, editing of parameters and running the simulation through its Graphical User Interfaces (GUI). This open source approach of available calculation in Excel worksheets and VBA code enables customizing of the tool to required detailed specifics. One of the important aspects and innovations of the tool is the inclusion of the cost model into the simulation. The cost model estimates the present price of the vehicle, fuel and battery replacement based on the simulated specified components and a row of customizable economic parameters whereas the fuel costs estimations are based on further input and results of simulated vehicle efficiency. The tool provides possibilities of direct analysis of simulated results by means of Powertrain Comparison and Parametric Study. The Powertrain Comparison looks at the impacts of using different powertrains (ICEV, HEV, PHEV and EV) by swapping the powertrain of the observed vehicle whereas for each powertrain, the specified characteristics are considered and control and sizing of relevant components and its cost are compared, including the fuel costs. The Parametric Study extends the Powertrain Comparison through replacing the chosen parameters/variables with a range of values for which the simulation is renewed and recorded [42].

3.2.3 AVL Cruise

AVL Cruise is a proprietary simulation tool developed and maintained by AVL List GmbH, Graz/Austria. AVL Cruise provides means for vehicle system simulation for the entire development range facilitating a spectrum of tasks of the vehicle system and driveline analysis from conceptual design to the application on hardware test systems. The flexibility of AVL cruise enables adjustment to the conformity of the application requirements throughout the development process. The modeling starts with a small quantity of input data, whereas the models scale with the development process in accordance with the simulation needs. AVL Cruise models are developed to enhance the productivity of common “Hardware in the loop” procedures and to be reusable in terms of iterating or successive development processes aiming at optimal use of resources, unvarying decision-making support and retaining the focus on optimization of the vehicle key performance attributes [39].

In consideration of the diversity of the powertrain concepts explored today, the adaptable “System/Sub-system” structure enables prompt changing of drivetrain concepts in the highly complex simulation models. Through the modular structure of the powertrain integration system, compatibility with other simulation tools is comprised through developed interfaces for other simulation tools like Matlab/Simulink, CarMaker, CarSim etc. Beside the interfaces, Cruise models can be compiled and exported for direct use in Matlab/Simulink environment for further/ulterior development [39].

In the example of the HEV development with AVL Cruise, very detailed and advanced models can be created whereas, in the case of validation against measurements, a realistic picture of the vehicle’s consumption, emissions, energy flow and performance is provided. In consideration of the development of novel powertrains, the assets of CRUISE simulation models are the possibilities to make a detailed analysis of powertrain components independently and virtually determine requirements and “load profiles” for the individual system components. Such characteristics of the CRUISE models combined with simulating various drive cycles, provides comprehensive information on the maximum loads of the system components, an output information crucial for component life-time estimation [39].

3.2.4 Autonomie

Autonomie is a software environment and framework developed and maintained by Argonne US DOE, in cooperation with General Motors. Based on Matlab/Simulink, Autonomie facilitates means for design, simulation, analysis and control of automotive control-systems. Autonomie is designed to readily manipulate models ranging from low to high degree of detail, conceptualizing systems/sub-systems and complete architectures as well as final development processes such as calibration and validation. Autonomie is construed to facilitate automotive engineering support for the entire development process, such as:

- Support from early stage of embedded system development starting with “model in the loop” and throughout further stages; “software in the loop” and “hardware in the loop” as well as rapid control prototyping;
- Integration of all levels of math-based development tasks;
- Building up on existing models through industry-wide reuse and exchange;
- Communication with other proprietary vehicle modeling software packages and;

- Management of databases and configuration data including options for protection of rights on models and developed processes [39].

Through the given flexibility and automatic model building, Autonomie supports exploring various drivetrain configurations or individual component technologies. Exemplifying the possible outputs, some of the typical applications of Autonomie are:

- Simulation of entire vehicles to assess the key performance characteristics or for analysis of drivetrain configuration setups for alternative (HEV, PHEV, EV) and conventional vehicle types;
- Simulation of systems/sub-systems to assess the properties of individual components such as sizing optimization for the chosen drivetrain configuration;
- Examination of virtual calibration and confirmation of tested hardware models and developed algorithms [39].

The functionality of Autonomie has been validated for several examples of configuration and vehicle types through the “Argonne’s Advanced Powertrain Research Facility vehicle test data” and with other sources of data [39].

3.2.5 Simulation with Dymola/Modelica developed by Austrian Institute of Technology

Beside the above-presented developments of Argonne which is based on Matlab/Simulink and AVL’s standalone application which offers practical interfaces for Matlab, [39] presents further simulation model development based on Modelica and Dymola. Modelica is a modeling language used for component-oriented modeling of technical systems which uses differential, algebraic, and discrete equations to model the behavior of technical systems. Modelica offers several proprietary and free simulation environments whereas Dymola is currently licensed under “Dassault Systèmes” [43].

For the purpose of simulation of complex alternative drive train vehicles, the Austrian Institute of Technology (AIT) has developed a simulation environment based on Dymola/Modelica, providing libraries which enable flexible simulation of entire vehicles and comparisons of the given concepts. Supporting the entire development process, the developers at AIT integrated the simulation and the test environment and giving the possibility to perform “hardware in the loop” testing [39].

As for other simulation modeling tools described in [39], the structure of the simulation environment developed at AIT begins with components which can interact as objects over interfaces. Components can be grouped into sub-system and systems with the highest level being the vehicle model itself. A focus of the usability is design and sizing primarily of electrical components and other tasks such as fuel economy, range and load behavior of components [39].

3.2.6 dSpace Automotive Simulation Models and ModelDesk

Automotive Simulation Models (ASM) is a proprietary set (suite) of simulation tools developed by “dSPACE GmbH”, Paderborn/Germany. ASM is implemented with Matlab/Simulink covering simulation of vehicles (systems) and their components and sub-systems such as combustion engines and electric components. ASM’s modular concept supports an entire range of simulation modeling possibilities beginning with a simulation of individual components, component sub-systems, whole vehicles to overall traffic scenarios. The pre-defined / default simulation models represent the performance of the devices, components or systems, whereas the implementation of individual requirements takes place through amendment, customizing or replacing of components, sub-systems, and systems or their properties. Besides running on Matlab/Simulink ASM simulation models support multiple simulation platforms (“SCALEXIO”, “dSpace Simulation”, “VEOS”) and multiple development stages in simulation processes including “hardware in the loop” testing in the final development stages [44].

For parametrisation of vehicle dynamics models outside of the Matlab/Simulink environment and provision of data for ASM simulation models, dSpace provides an additional simulation tool referred to as ModelDesk, which is a user interface providing a graphical representation of modeled components with an intuitive interface for parameterization of the simulation models and simulation environment. Developers can therewith manage entire test drives including whole vehicles, streets, and maneuvers as well as repeat simulation results. The most important function of ModelDesk is a coherent parameterization of models with one tool for rendering simulations whereas the parameter sets can be used by the above-stated platforms without prior code generation and even during the simulation run [45].

3.3 Rationale for selection of tools

For the implementation of objectives set in this study, the tools used in the implementation need to comply with the following criteria and requirements:

(i.) Open source software providing full code and allowing further development;

(ii.) Code with replicable calculation methods not dependent of any external databases;

(iii.) Segregated data structures providing relevantly detailed information and enabling respective linkages;

(iv.) Consideration of the currently established alternative powertrains (HEV, PHEV, FCEV, EV);

(v.) Range of available information adequate to consider the full vehicle life cycle;

(vi.) Adequate baseline input information and data provided with the tool, which enables initial testing and function confirmation.

In consideration of the emission models and tools presented in sub-chapter 3.1 and the above criteria, the GREET model excels as the tool of choice for the implementation of the aimed calculation model for the full vehicle life cycle. The GREET model complies with all above criteria with its features such as; modular structure (ii,iii), taking into account all required conventional and alternative powertrains (iv), precise definition of the vehicle cycle (v), input information segregated to the very detail developed in MS Excel showing every calculation step with an input-output material and emissions overview (i,ii,iii,vi). In addition, the GREET Model has been widely used in the relevant literature and studies, notably in [5], [17], [46] and [47] with a comprehensive list of technical papers given in [11]. More detailed description of the GREET model is given in the following sub-chapter 3.4.

Other emission models identified and presented in sub-chapter 3.1 lack at least one or more of the above-stated criteria. For instance, MOVES, COPERT and HBEFA are applications which depend on remote databases (ii) having in focus provision of aggregated data (iii, v) i.e. for fleets and changes on a more global level. ARTEMIS provides comprehensive and detailed information on required types of emission, however, the model is as well oriented to provide global figures aggregated for all powertrain types of passenger vehicles and does not consider the vehicle cycle (v). GEMIS is, on the other hand, a process-oriented emission modeling tool providing comprehensive information on emission associated with production of material products, however, the software does not provide any usable information for structuring the vehicle cycle. Hence, the information delivered by GEMIS for material products comprised in the vehicle material composition will be used to collect data for locational references other than the US.

Considering the presented vehicle simulation tools, the selection narrows to two open source vehicle simulation tools; ADVISOR and FASTSim. Both tools are able to perform most of the functions essential for implementing the objectives of this study. However, the degree of detail which is achievable by modeling with ADVISOR, and the fact that FASTSim does not consider FCEV and gas in any form for conventional powertrains, as present leaves ADVISOR as the vehicle simulation tool of choice. ADVISOR was used for simulating vehicle fuel economy performance in life cycle assessment and various studies in respective literature, i.e. [5] and [16]. Notably, ADVISOR was used in [48], for simulating vehicles in differently specified environments to predict CO_2 emissions for analysis and further development of CO_2 reduction policies. The simulated numerical results gained from ADVISOR were validated against chassis dynamometer tests, whereby the overall results performed by ADVISOR were proven reliable [48]. A detailed description of ADVISOR is given in sub-chapter 3.5.

3.4 GREET – Excel tool for accounting of energy use and emissions of fuel and vehicle cycle

Coherent to its chronological evolvement the GREET model, in its overall structure, is divided into GREET1 – the primarily developed fuel cycle model and GREET2 vehicle cycle model developed relying on the experiences and results gained from GREET1.

For a given type of transportation fuel, the GREET1 fuel cycle model is able to calculate the energy consumption, GHG emissions and typical pollution indicators such a VOCs, CO, NOx, PM_{10} and SOx. Processes covered by the GREET1 fuel cycle model include production, transportation and storage of primary energy sources as well as production, transportation, storage and distribution of produced fuels [13]. The calculated throughput of total energy used is divided among the different process fuels (e.g., NG, residual oil, diesel, coal, electricity) used in the stage. This means that the energy flow is the main parameter in the calculation process, whereas emissions and indicators are calculated from the comprised database of emission factors. The emission factor database included in GREET1 Model relies mostly on official data provided by EPA, own research of Argonne or other referenced sources. [36]

The GREET2 vehicle-cycle model is able to calculate energy consumption, GHG emissions and typical pollution indicators for materials and material compositions used in the production of different vehicle types. However, the model does not consider fuels used in the transportation of such materials and material compositions. The vehicle cycle in the GREET2 Model is defined for 5 vehicle types: ICEV, HEV, PHEV, EV and FCEV, featuring a modular structure which includes following processes: "*raw material recovery and extraction, material processing and fabrication, vehicle component production, vehicle assembly, and vehicle disposal and recycling".*

In the below-presented Figure 6, the GREET2 vehicle-cycle model simulation logic is illustrated, showing the data requirements and end results.

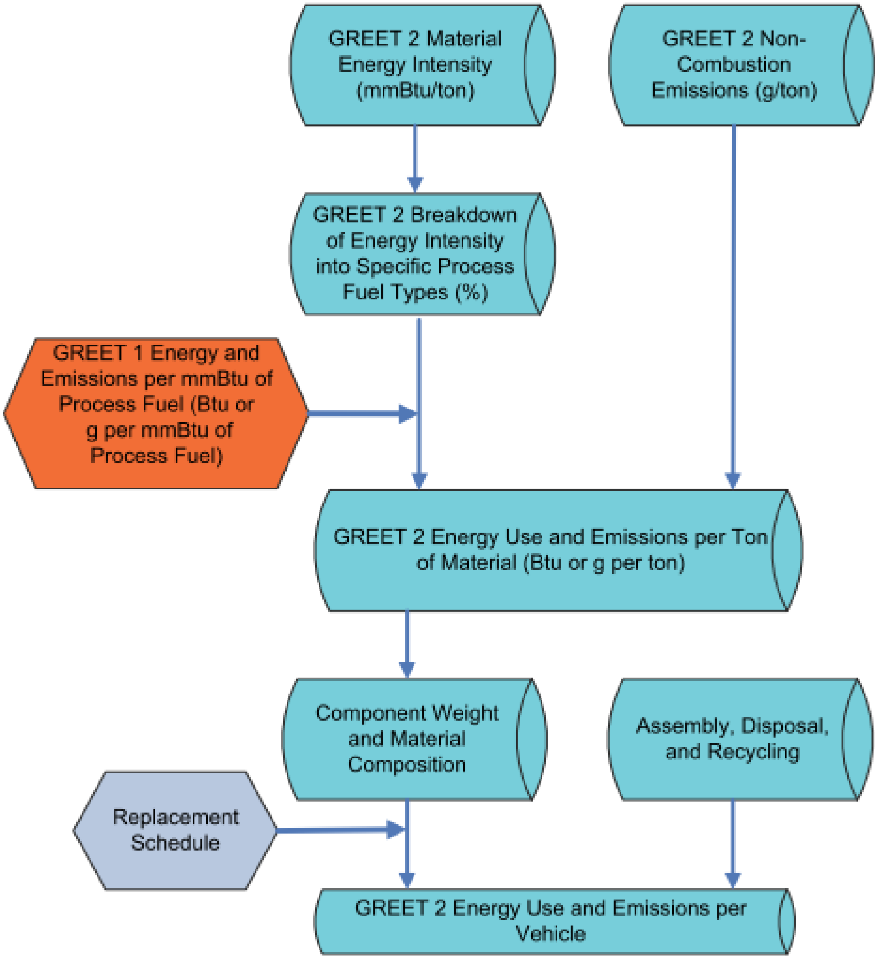


Figure 6: Simulation logic of the GREET2 vehicle cycle model; [36]

The first and most important step to start the analysis of the vehicle-cycle is to determine the vehicle component weight. The weight estimation in GREET2 model comprises following components: *"… body (including body-in-white [BIW], body interior, body exterior, and glass), chassis, batteries, fluids, powertrain, and transmission or gearbox"* [36]. The powertrain components include the weight of a motor, controller or generator depending on the vehicle type chosen for vehicle cycle modeling. In the second step, the GREET2 model allocates specific material compositions for each vehicle component.

GREET2 incorporates replacement schedules for vehicle components that should be replaced within the vehicle lifetime (batteries, tires, fluids etc.). Energy used and emissions associated with recycling of scrap materials to a useful state are included as well in the disposal and recycling stage of the vehicle-cycle model. As a final step of the vehicle cycle simulation, the energy used during the processes from raw material recovery to vehicle assembly is accounted and accompanying emissions are calculated. The energy use and emission calculation occur separately in four major groups:

- Vehicle materials:
  raw material recovery; raw material transportation and processing; and material production, fabrication, and processing.
- Battery:
  material production and fabrication for the start-up and storage batteries.
- Fluids:
  production and disposal of coolants, engine oil, windshield fluid, steering fluid, brake fluid, and transmission fluid.
- Assembly, Disposal and Recycling (ADR):
  vehicle assembly, painting, disposal, and recycling [36].

The grouping of calculation will play a major role in the implementation process considering that important data input for these groups will come from parameters of simulated vehicles in ADVISOR.

3.5 ADVISOR – Matlab tool for vehicle simulation

ADVISOR's vehicle simulation functionalities are founded on elementary principles of propulsion and vehicle dynamics and a large spectrum of input data on the performance of specific vehicle components and detailed characteristics. The input data is structured in “performance maps” required for each essential component of the simulated vehicle. ADVISOR provides a large set of input data by default for each of the powertrain combinations available [49].

The backbones of the tool’s usability are the three main GUIs serving to setup and follow-up the simulation process. The GUI sequence and the simulation flow is structured in a way that users can make iterative assessments of vehicle performance, fuel economy and emissions, affected by adjustments of vehicle parameters and drive cycle requirements. Direct interaction with the raw input and output data loaded into the Matlab workspace is enabled over the GUI as well. Simulink block diagrams were used to define the relations between components as well as to present graphically and therewith more clearly the simulation flow. When a simulation is initiated, the input data loaded in Matlab workspace is acquired by the simulation functions, consequently, the output results are loaded also into Matlab workspace and in the results window. [40]

Thus using ADVISOR with all its flexibility occurs on two levels; through the GUI and manipulation of the block diagrams programmed with Simulink. The GUI controls, described in more details in following paragraphs, can be used to address 85 components including a library of their performance map and control logic files. However, GUI controls are limited in terms of developing new or amending drivetrain architectures. For this purpose, ADVISOR needs to be modified on the level of Simulink block diagrams. [50]

The sequence of the three main GUIs follows the simulation and tool’s workflow in general. The first GUI facilitates the main configuration of the vehicle and its components by selecting default, amending or uploading new component or characteristic detail data and the option to save or create new instances of vehicle configurations. Visualizations showing performance maps of respective components are aligned in the GUI to help in optimization processes. After the desired vehicle is “build” the GUI sequence leads to the configuration of simulation parameters. Simulations can be initialized as single/multiple drive cycles, specific test procedures and gradeability and acceleration tests. The second GUI enables selection of existing, further adjustment and creation of new drive cycles and test procedures, whereby internationally defined and used drive cycles (i.e. New European Drive Cycle (NEDC)) are provided by default. After the simulation is initialized and completed, the third GUI shows the simulation results. The result GUI provides a spread of possibilities for analysis, visualization, detailed review and comparison of results [40].

For the scope of this study, simulation of typical vehicle use is of great importance for accurate fuel economy figures. Therefore, this study will only consider the drive cycle simulation functionality of ADVISOR. However, it is important to emphasize that ADVISOR provides means to create any desired drive cycle function.

State of Charge (SOC) balancing is also an important aspect to consider for processing simulations in ADVISOR. There is a possibility that the battery SOC difference between the beginning and the end of a drive cycle is too large, resulting in simulated fuel economy to be very high or low because of the net discharge or charge of the battery, respectively. ADVISOR provides two methods to ensure the SOC remains balanced for the simulated vehicle and drive cycle such that multiple simulation scenarios can be compared on a consistent basis. The detailed options of the SOC balance methods presented in [40] were considered in more detail in the resulting chapter 5, where the parameterized vehicles were simulated in different drive cycles.

3.6 Vehicles with conventional and alternative powertrains

With legal requirements regarding the emission compliance getting stricter from year to year, more research and development of alternative powertrains is being fostered. The automotive industry is rendering large investments in research and development, whereby often old and well-known technologies and processes are re-examined and checked against the enacted environmental aspects [2]. Alternative powertrains have been classified in [2] in the following two major groups:

1. The first group covers heat engines that use the combustion process to turn the fuel’s chemical energy to mechanical, whereof following are most notable:
    - Two-stroke engine
    - Wankel / rotary engine
    - Gas turbine
    - Stirling engine
    - Steam engine
2. The second group covers powertrains that are able to directly convert chemical energy to electric energy or to store the electric and mechanical energy:
    - Electric battery
    - Flywheel storage
    - Fuel cell.

However, taking into consideration the overall picture and the sum of characteristics needed for propulsion of vehicles, in particular, the broad range of load and speed required over the long service life, none of the above-mentioned alternative powertrains could supersede the conventional Spark Ignition (SI) and Compression Ignition (CI) engines. For example, the conclusion of the latest research on the two-stroke engine was that the power, fuel economy, NOx emission and service life could not fulfill the requirements of the today's modern vehicle. Beside the improvement of the mechanical aspect, the developments on the Wankel Engines could not achieve an optimal combustion process and therewith no significant contribution to optimizing fuel economy, emissions or service life. Developments of the gas turbine, stirling and steam engine in the field of automotive could not reach the appropriate balance of fuel economy, emission and manufacturing costs [2].

Most of the currently researched alternative powertrains rely on direct conversion or storage of electric energy and some also include combination with conventional combustion engines. In accordance with the basic structure of powertrains, conversion or storage of electric energy or the combination of the combustion engine with electric power drive, a vehicle with electric, hybrid and fuel-cell powertrains are presented in [2] as vehicles with alternative powertrains. Thereof, hybrid vehicles have several further classifications in serial and parallel and in micro, mild, full and plug-in hybrids.

The LCA methodology used in this study is primarily concerned with input and output of fuels/energy and emissions. Pursuant to the requirements of the study, the classification of vehicles shall be partially aggregated in consideration of the simulation possibilities of specific powertrain assemblies, as presented in the following sub-chapters.

Further, the classification of vehicles, as presented in the following text, is typical for LCA studies on vehicles with alternative powertrains and exhibited in similar literature, i.e. [5].

3.6.1 Conventional Vehicle – Internal Combustion Engine Vehicle

The term conventional vehicle is used in this work for typical ICEVs as depicted in Figure 7, where the powertrain is based solely on the Internal Combustion Engine (ICE). Considering that the vehicles shall be modeled in ADVISOR it is important to note that ADVISOR supports data input for diesel, gasoline, Compressed Natural Gas (CNG) and Liquid Petroleum Gas (LPG) engines. There are no other specific implications of the ICEV design for the emission modeling in ADVISOR.

With regard to the definition of micro-hybrid vehicles in the respective literature (i.e. [51]), and the fact that these are closely related to conventional vehicles with only slight modification of the powertrain components, micro-hybrids are classified as conventional vehicles for the scope of this study. According to [14], micro-hybrid vehicles have no actual electric propulsion involved, but the only conventional electric starter and the alternator are replaced by one combined starter-alternator. Additionally, an electric machine is used for recovery of braking energy with special energy managements units and is, therefore, a more comprehensive system than an ordinary start-stop system. Micro Hybrid is considered to be a popular measure to raise the efficiency of conventional drive systems with many manufacturers offering these systems in a wide range of vehicle types. [14]

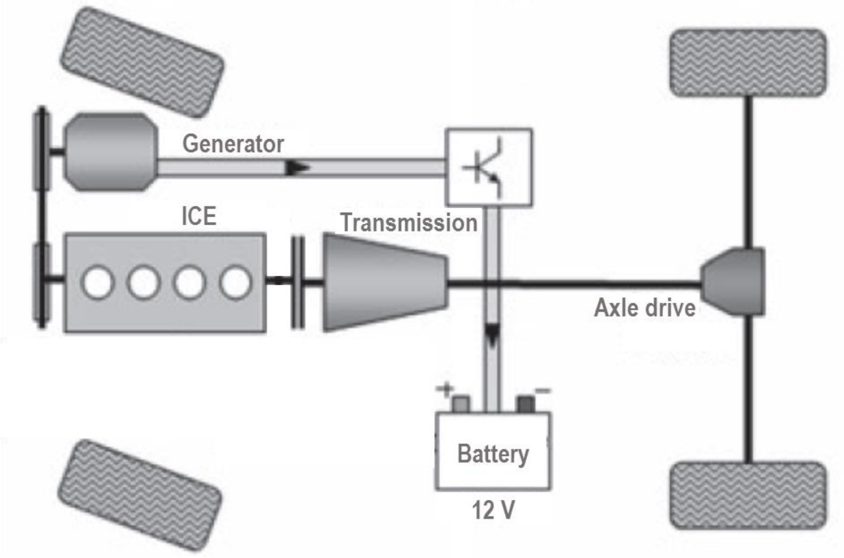


Figure 7: Conventional Internal Combustion Engine Vehicle Scheme; adapted from [51]

The greatest potential of the ICEV is at the same time environmentally it's biggest problem as the ICE enables very high autonomy of the vehicle with operating ranges of modern vehicles up to 1200 km. At the same time, the low efficiency and significant direct emissions of ICE are becoming a massive problem, especially in metropolitan areas. Furthermore, the scarcity of fossil fuel resources urges for the development of new propulsion technologies. [14]

3.6.2 Hybrid Electric Vehicle

The initial idea of electrifying vehicle powertrains comes from attempts to enable the ICE to run only at its optimal operating point to attain finally more efficiency (out if the ICE). For example, in a normal driving cycle with several acceleration points, an ICEV achieves an efficiency rate of approximately 20%. Engagement of electric motors at least for acceleration movements can lead to an increase of efficiency. In terms of definitions for simulations in ADVISOR, an HEV is defined as a vehicle which uses an ICE and the support of electric machines and energy storage systems for propulsion [14].

In the context of this study, the HEVs are defined according to the categorization of the system as parallel, series and power-split hybrids and according to the hybridization level as defined in the relevant literature, i.e. [51].

The concept of parallel hybrid is that both, the ICE and the electric motor are mechanically linked to the drivetrain and can operate in parallel. The main characteristic of series hybrid systems is that the ICE is not mechanically linked to the drivetrain, but only runs a generator that produces electricity. The power-split hybrids, on the other hand, have the characteristic that their mechanical power is separated into a mechanical and an electric path. [51]

HEVs can be also categorized in accordance with the respective degree of hybridization, as follows:

- Micro-Hybrid
- Mild-Hybrid
- Full-Hybrid
- Plug-In-Hybrid

Applying the above classification to the context of this study, Micro-Hybrids are fit rather to ICEV as mentioned in sub-chapter 3.6.1, while Plug-In-Hybrid represents an individual type of alternative powertrain described in the following sub-chapter (3.6.3). Mild-hybrid and Full-hybrid vehicles are described in the category of HEVs in the following.

A mild hybrid is characterized through the set-up of the electric motor on the crankshaft between the ICE and transmission – as presented in Figure 8. According to its component layout, mild-hybrid can be categorized as a parallel hybrid. The electric systems in mild-hybrids are usually designed to support the ICE by a so-called boost function as the electric motors feature high torque. Support to the ICE comes in its inefficient work range, for example, in the start-up or acceleration phase. The batteries used to save the energy are of higher voltage 42 -150 volts, increasing the efficiency and enabling the recuperation of break energy. [51] [14]

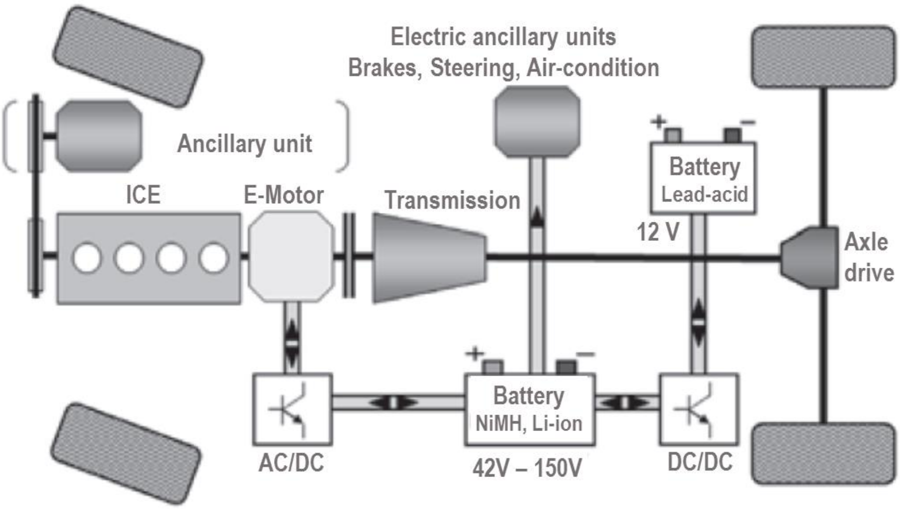


Figure 8: Mild hybrid electric vehicle scheme; [51]

The main feature of the full hybrid vehicles is the fact that they can be driven either solely by the means of electric motor, internal combustion engine or combined. Different from the mild-hybrids, further construction modifications are necessary such as, an additional clutch, one or more electric motors with a high electrical drive power and a high-voltage battery ready for saving kinetic energy with high maximum capacity [51]. A scheme of a full hybrid vehicle, commonly available as parallel or power-split hybrid, is given in Figure 9.

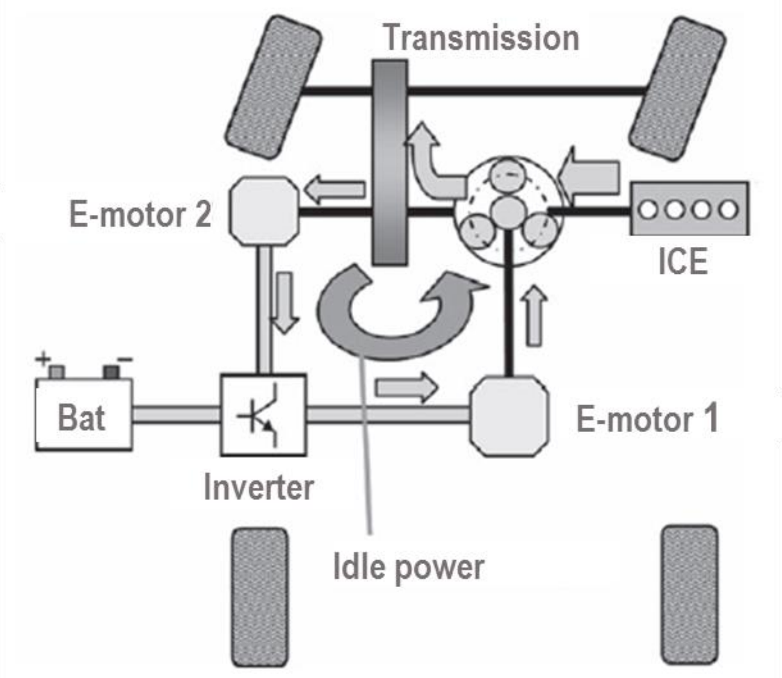


Figure 9: Power-split hybrid electric vehicle scheme; [51]

Implicitly, the full hybrid features more torque from the electric motor and is through the combination of the motors and intelligent operating strategies able to provide good acceleration and high driving pleasure with significant fuel savings [51].

However, the system complexity increases the costs implicitly which is one of the main problems of complex and full hybrid systems. With the increase of efficiency of the ICE, direct emissions are decreased, whereas the plug-in hybrid represents a convenient possibility to reduce the direct and especially urban emission even more. [14]

3.6.3 Plug-in Hybrid Electric Vehicle

PHEV is a hybrid electric vehicle which enables the loading of the energy storage battery externally via the power grid. PHEV has usually a larger battery installed then HEV and thus provides a combination between an EV and an ICEV. A possible PHEV configuration is presented in Figure 10.

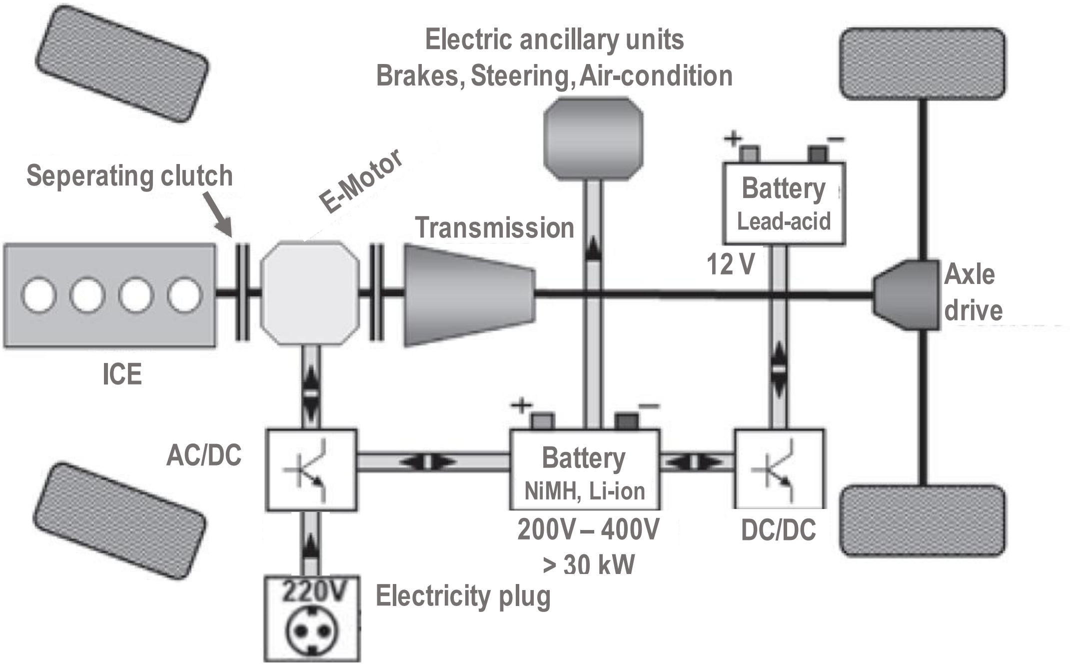


Figure 10: Parallel configuration of a Plug-in hybrid; [51]

The main idea of this combination is to incorporate both main advantages of the ICE and electric motor; the high autonomy given by the ICE and, high efficiency and zero direct emissions given by the electric motor. Perfect scenario of a parallel PHEV would be emissionless and silent propulsion in the urban area and utilization of the ICE only if longer driving ranges are required where the ICE operates much more efficiently.

PHEV are constructed in different powertrain configurations. Similar as for HEV, the parallel configuration of PHEV, as presented in Figure 10, features an extra clutch between the ICE and the electric motor. For PHEV configured as series architecture, the ICE is permanently decoupled from the powertrain and it serves only to produce electricity for the electric propulsion motors. [14]

The categorization in parallel systems and series system is important for PHEVs in ADVISOR because of the energy flow. For modelling emissions in ADVISOR important conclusion of this categorization, as it will be needed in further chapters, is that the series hybrid delivers all the energy to the wheels only out of the energy storage system, and on the other hand the parallel hybrid can deliver energy from ICE and energy storage system to the wheels at the same time.

3.6.4 Electric Vehicle

The EV relies completely on electric propulsion, having as a drive source an electric motor and a battery as energy storage, which is to be charged at the electric grid. Essentially, due to the electric drive, EVs produce no emissions during the use cycle which is defined in the literature as the zero direct emissions term. The production and supply of the electric energy and the vehicles, especially the batteries, are on the other hand indeed associated with emission production. As shown in Figure 11, the EV eliminates components such as internal combustion engine, transmission or exhaust line, compared to ICEV, HEV, or PHEV. The saved material usage and weight are compensated by the high weight of batteries needed for the energy storage. Additional advantages of the EV are very good dynamic characteristics and efficiency performance of the electric motor. [52] [7]

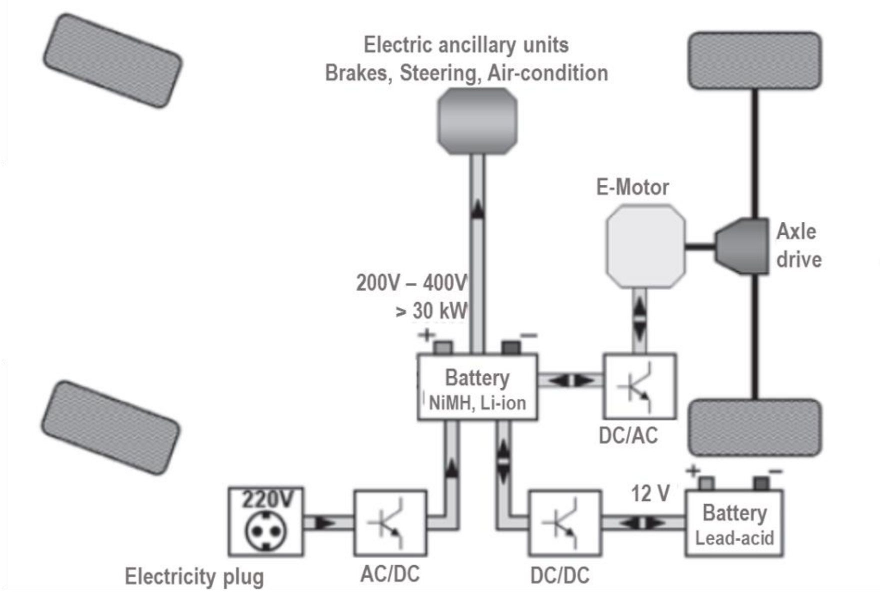


Figure 11: Electric vehicle scheme; adapted from [14] and [51]

The local/direct zero emission is a great advantage, especially in the polluted metropolitan areas. An additional advantage for the urban area is the noise level, which compared to the conventional vehicle is well reduced. The main problems of the EV are the relatively small overall range compared to conventional cars and the high costs of batteries. Electric cars on the market today are mostly made in compact design aiming weight minimization in general. The final goal is to enable sufficient range with battery performance as available in the present stage of development. [7]

The implications of the design of electric vehicles for emission modeling in ADVISOR are straightforward; zero direct emissions and energy used from the storage system is to be accounted for CO_2 calculations.

3.6.5 Fuel Cell Electric Vehicle

The FCEV has actually a pure electric drive train as well, with the main difference in comparison with EVs that it produces the energy on-board and does not rely on the energy stored. Electricity is generated by a fuel cell by a controlled reaction of hydrogen and oxygen, producing water as the direct exhaust emission [14]. According to [51], also other energy sources can be used for generation of electricity such as CNG, LPG, Methanol, Ethanol, etc.

The scheme presented below demonstrates the structure of the FCEV, with a possibility to store the energy from the grid as well, considering that apart from the fuel cell system an FCEV needs a battery in order to be able to store the energy to cover the demand that is caused by supply peaks when for example acceleration movement is required [14].

The main goal of the FCEV architecture depicted in Figure 12 is the direct zero emission goal, which the FCEV completes also for longer ranges in difference to the EV. Unfortunately, the production of hydrogen and the vehicle itself are associated with a significant amount of emissions produced and energy used.

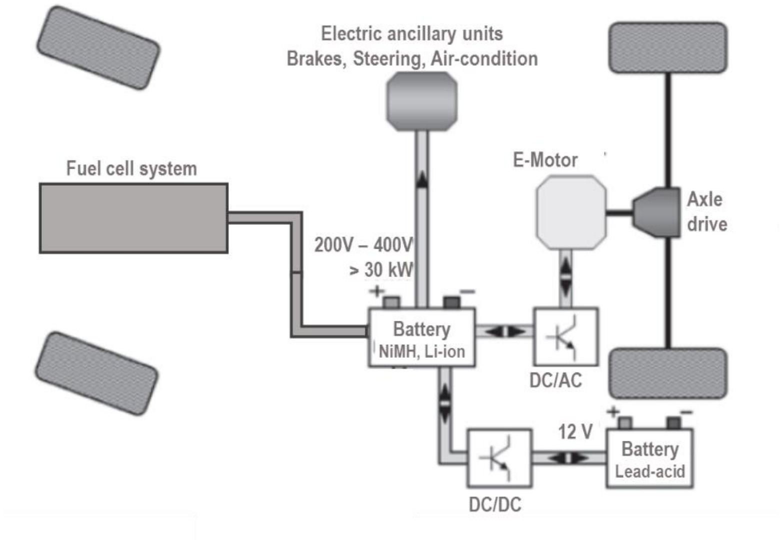


Figure 12: Fuel cell electric vehicle scheme adapted from [14] and [51]

For emission modeling in ADVISOR, only “classical” fuel cell vehicles are considered without the possibility to store energy from the grid. Hence, the implications of the FCEV design for emission modeling in ADVISOR are similar to ICEV, meaning that the fuel used for energy supply and the conversion relevant for the calculation of emissions is given in a vector, the same way as for ICEV.

3.6.6 Summary of vehicle configurations considered in this study

The above presented vehicle configurations will be represented by specific vehicle models, leading the market share of the C segment and parametrized for simulation in ADVISOR as presented in chapter 5.2. Since the ICEV type constitutes the majority of the vehicle market share, whereas the compression and spark ignition engines both take significant parts and have different propulsion energy characteristics, the ICEV as presented in Figure 7, will be considered with both engine versions. Majoring the market with its power-split configuration, the HEV configuration depicted in Figure 9 and PHEV in Figure 10 represent these vehicle types in this study. The EV and FCEV typical configurations presented in Figure 11 and Figure 12 are contemplated as such in further work.

4 Implementation – Modification of ADVISOR and furnishing of data-sets

The key parts of this study are the modification of ADVISOR simulation tool to calculate the CO_2 intensity of the different vehicle types and the collection of respective data for materials composing the vehicles and propulsion energy/fuels for different locational references to enable a rational comparison. Hence, this chapter provides an overview of the “ADVISOR modification” and the details on collected data for different locational references of the vehicle life cycle assessment. A detailed description of ADVISOR Modification including documentation of the amended code is given in Appendix A while Appendix B provides details on the data collection process, especially for cases where single entries required a rather comprehensive survey and calculations.

4.1 Implementation concept

In the chapters above, the fundamental items were described needed to commence the implementation process of the ADVISOR modification. Thus, the main concept is to extend the simulation in ADVISOR so that the end results present the full vehicle life cycle according to the simulation parameters set. The simulation parameters include vehicle modeling data as given by ADVISOR originally, and extensions of ADVISOR’s GUI to enable editing of the main parameters for the full vehicle life cycle calculation. This means that besides the fuel economy figures, ADVISOR shall give basic weight data for the modeled vehicle as well as for significant components such as battery packs.

Other information needed for the *vehicle cycle* such as vehicle material composition, shall be inherited from the GREET2 Model and normalized to fit the vehicle weight, as modeled in ADVISOR. Furthermore, the structure of the data inventory for emissions associated with the production of materials will also be used from the GREET2 vehicle cycle model. Overall the vehicle cycle calculation and the baseline dataset for the US relies on the GREET2 Model, whereas the required vehicle cycle data, in the further text referred to as “*vehicle cycle data-set*”, has been collected for scenarios with locational reference to Germany, Austria and the EU. In consideration of the large amount of data which needs to be collected for the vehicle cycle data-sets, the ADVISOR modification shall enable importing these data from excel.

The *use cycle* shall be calculated by utilizing the fuel consumption figures calculated by ADVISOR simulations and respective CO_2 emission factors, energy source heating and density values, as presented in the GREET model. To ensure consistency and following the coding structure of ADVISOR, these values will be coded in the Matlab calculation functions.

Similar as for the vehicle cycle, the *fuel cycle* calculation foresees loading of energy supply scenarios containing the emission data per unit of energy source type used for propulsion in the simulation. Considering that ADVISOR is able to process simulation for 6 energy source types, this smaller amount of data on emission associated with the production of fuels and energy used shall be retained as input Matlab m-files and referred to in the further text as "*fuel cycle data-set*". Within the frame of this study, the data for the fuel cycle data-set will be collected for same 4 locational reference scenarios as for the vehicle cycle: United States, Germany, Austria and the EU.

Figure 13 illustrates the implementation concept, referring especially to the data sources within the implementation.

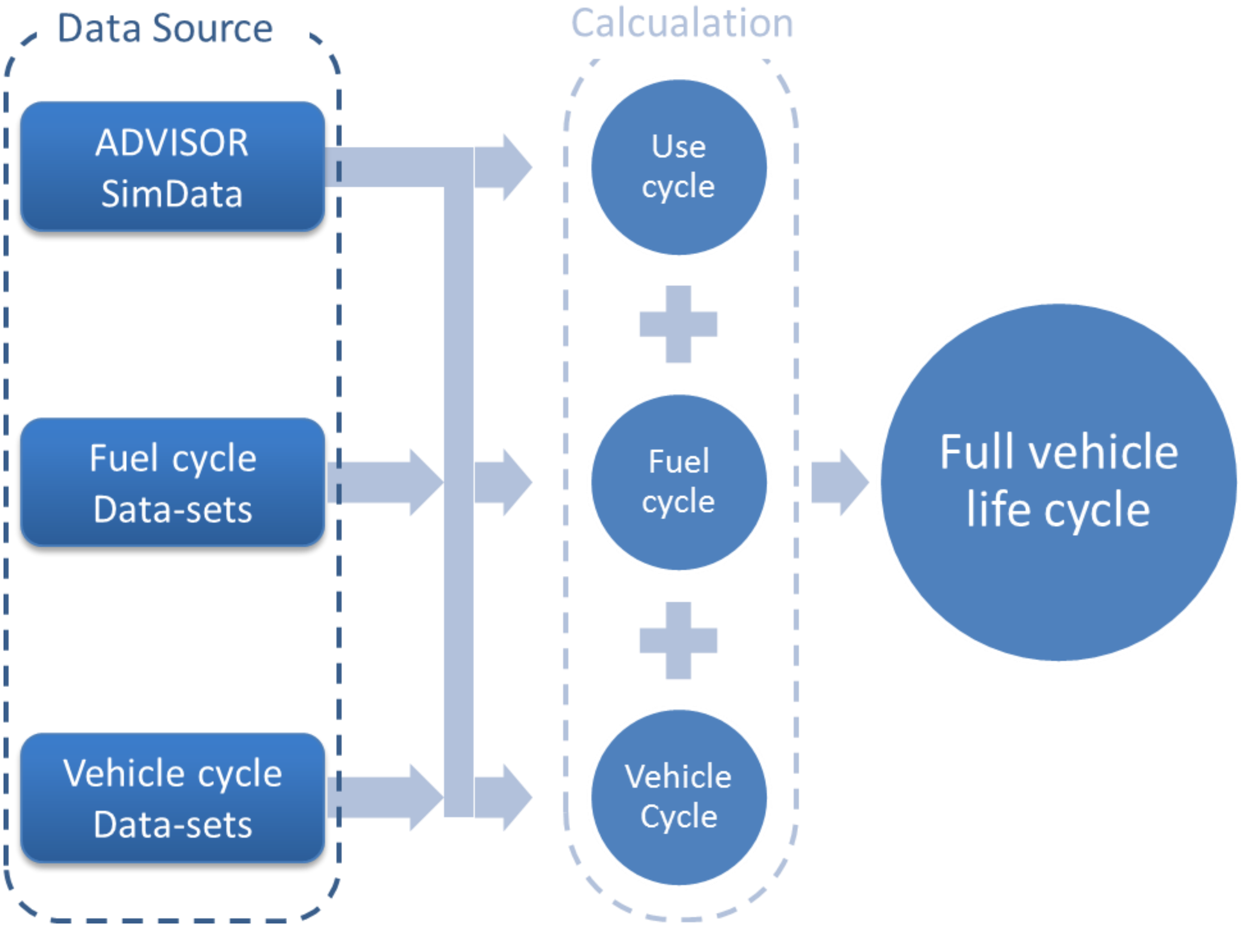


Figure 13: Implementation concept of ADVISOR modification

In light of the functional principle of ADVISOR the simulation flow can be defined as follows:

- In the vehicle input GUI, the user defines the vehicles by choosing the pre-defined vehicle, customizing the presets or modeling a completely new vehicle as originally provided in ADVISOR. When this step is finished the input data from ADVISOR for calculating the vehicle cycle is ready.
- In the simulation setup GUI, the user defines the drive cycle as originally provided in ADVISOR and shall be able to edit following parameters and data sets:
    - Basic simulation parameters: vehicle longevity (service kilometers over the life cycle), number of battery packs used in the life cycle and distinguish between commercial and passenger vehicles
    - Choosing preset, adjusting or developing new data sets with vehicle and fuel cycle emission factors
- After ADVISOR has completed the simulation fuel economy figures are used to calculate the fuel and use cycle.
- In the Results GUI, the user can view the simulation and full vehicle life cycle results. Results can be exported for further processing.

The process diagram in Figure 14, established according to the Unified Modelling Language (UML) notation as presented in [53], illustrates the above-described simulation flow.

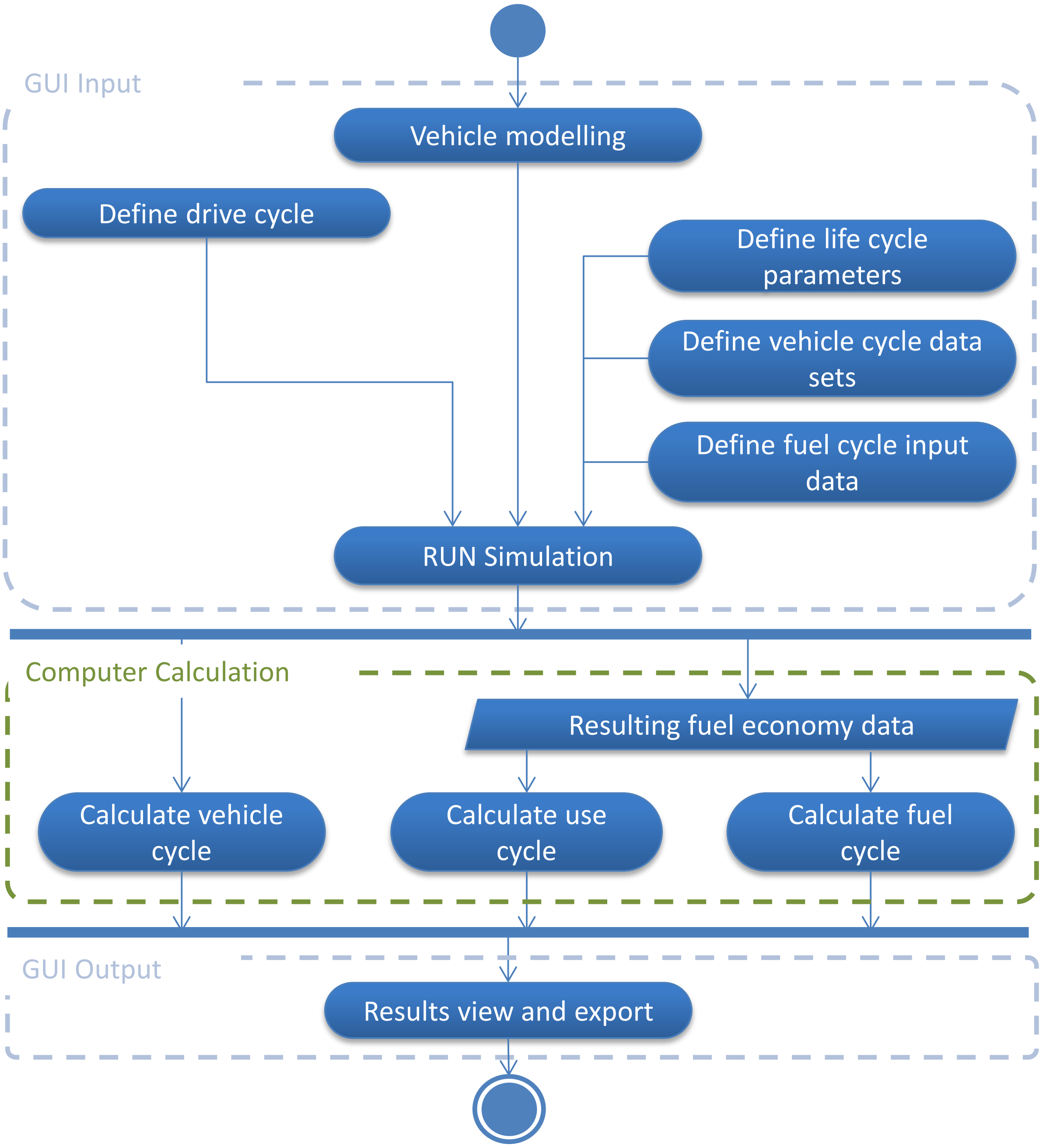


Figure 14: ADVISOR Modification process chart

4.2 Implementation description

The modification of ADVISOR took place in five major steps:

1. Definition and specification of the required data for accounting emissions for:
    a. the vehicle cycle (vehicle cycle data-sets)
    b. the fuel cycle (fuel cycle data-sets) – indirect fuel emissions
    c. the use cycle (tank-to-wheel emission factors) – direct fuel emissions

2. Modifying the simulation setup GUI of ADVISOR for editing the full vehicle cycle calculation parameters along with the simulation parameters as well as enabling selection of the vehicle and fuel data-sets
3. Implementing the vehicle cycle as given by the GREET2 Model into the Matlab source code
4. Developing a calculation for the direct and indirect emissions (use cycle and fuel cycle)
5. Modifying the results GUI of ADVISOR for displaying the results of Simulation and results of full vehicle life cycle

The presented steps are described in the following sub-chapters, while detailed documentation of the modification is given in Appendix A.

Furnishing data required for the vehicle and fuel cycle was the final implementation step which is further described in sub-chapter 4.3 and Appendix B respectively.

4.2.1 Definition and specification of the required data

In this step, the processes of the GREET model and the ADVISOR simulation calculations have been thoroughly analyzed for the vehicle, fuel and use cycle.

4.2.1.1 Vehicle cycle

The calculation of the vehicle cycle in the GREET2 model is structured into following main items:

- Materials used for the production of vehicle, excluding batteries and fluids (materials);
- Materials used for the production of the batteries (batteries);
- ADR;
- Fluids used during the vehicle lifetime (fluids) [36].

The vehicle cycle data-set developed in form of a spreadsheet to be imported by the ADVISOR modification contains a separate sheet for each of the above items. The data collection referred to in sub-chapter 4.3., with different locational references, will take place in accordance with the specification of materials and compositions presented in the next sub-chapters.

4.2.1.1.1 Materials

The core of the vehicle cycle calculation in the GREET2 model is Table 1 listing the materials used and shares of the respective materials in the overall weight of the vehicle, excluding the batteries and fluids. The shares of the materials used are defined for 5 vehicle types considered in this study including lightweight construction scenario which are presented in Appendix A.

Table 1: Vehicle Material Composition in percent of vehicle weight, excluding batteries and fluids; [36]

	ICEV	HEV	PHEV	EV	FCV
Steel	62.9%	64.8%	64.3%	65.5%	58.9%
Stainless Steel	-	-	-	-	3.4%
Cast Iron	10.3%	7.1%	7.2%	2.0%	1.7%
Wrought Aluminum	1.9%	1.3%	1.2%	1.5%	2.3%
Cast Aluminum	4.5%	5.9%	6.7%	5.6%	3.5%
Copper/Brass	1.9%	3.9%	4.5%	5.8%	3.3%
Zinc	-	-	-	-	-
Magnesium*	0.0%	0.0%	0.0%	0.0%	0.0%
Glass	3.0%	2.7%	2.5%	3.1%	3.0%
Average Plastic	11.3%	10.4%	9.8%	11.9%	11.9%
Rubber	2.2%	1.8%	1.9%	1.7%	2.0%
Carbon Fiber-Reinforced Plastic*	-	-	-	-	-
Carbon Fiber-Reinforced Plastic for High Pressure Vessels	-	-	-	-	5.8%
Glass Fiber-Reinforced Plastic	-	-	-	-	0.6%
Nickel	-	-	-	-	1.63 E-06
Perfluorosulfonic acid (PFSA)	-	-	-	-	0.1%
Carbon Paper	-	-	-	-	0.2%
Polytetra-fluoroethylene	-	-	-	-	0.2%
Carbon & PFSA Suspension*	-	-	-	-	-
Platinum	4.94 E-06	4.50 E-06	4.78 E-06	-	1.50 E-05
Silicon	-	-	-	-	0.1%
Carbon*	-	-	-	-	0.0%
Others	2.0%	2.1%	1.9%	2.8%	2.8%
*used in lightweight construction only – see Appendix A					

Table 1 is imported by the ADVISOR modification from the vehicle cycle data-set, together with the respective information on associated emission for each of the materials listed. Tire replacements are also included under the item materials, whereas the number of replacements and the share of rubber and steel (33,3% / 66,7%) in tire production is imported from the vehicle cycle data-set. Information on vehicle weight and type is taken over from the ADVISOR simulation parameters.

For each of the material products, the GREET2 defines process stages specifying energy and resource requirements, shares of recycled and virgin materials or shares of different material types as applicable for the respective material product. Considering the data collection for the different locational references, the stated detailed information on material products shall be taken into account especially when comparing process stages and composition shares of each material product.

4.2.1.1.2 Batteries

The GREET2 model defines the material composition of 3 types of batteries; lead-acid starter batteries, Nickel-Metal-Hydride (NiMH) and Lithium-ion (Li-ion) traction batteries.

The material composition of the lead-acid battery is given in Table 2. GREET's default assumptions of 2 replacements in vehicle lifetime and battery weights of 16.32 kg for ICEV, 10.61 kg for lightweight ICEV, 10.02 for conventional and 6.52 for lightweight construction of the remaining vehicle types are applied in this study. The energy inputs required for the battery assembly amounts to 2.67 MJ per kilogram of the battery.

Table 2: Material composition of lead-acid batteries in percent of battery weight; [36]

Material	Share
Plastic (polypropylene)	6.1%
Lead	69.0%
Sulfuric Acid	7.9%
Fiberglass	2.1%
Water	14.1%
Others	0.8%

The material composition of the NiMH traction battery is given in Table 3. According to the preset assumptions in GREET HEV and FCEV use the NiMH battery with no replacements during the vehicle lifetime. The energy inputs required for the battery assembly is the same as for the lead-acid battery.

Table 3: Material composition of NiMH batteries in percent of battery weight; [36]

Material	Share
Iron	12.0%
Steel	23.7%
Aluminum	0.5%
Copper	3.9%
Magnesium	1.0%
Cobalt	1.8%
Nickel	28.2%

Rare Earth Metals	6.3%
Average Plastic	22.5%
Rubber	0.1%

The material composition of the Li-ion traction battery is modeled separately for each of the vehicle types with alternative powertrains, as presented in Table 4. According to the preset assumptions in GREET, PHEV and EV use the Li-ion battery with no replacements during the vehicle lifetime. The energy input required for the Li-ion battery assembly is accounted as a flat-rate per battery irrelevant of the weight and amounts to 474,5 MJ per battery unit.

Table 4: Material composition of Li-ion batteries in percent of battery weight per vehicle type; [36]

Li-Ion Battery Materials	**HEV**	**PHEV**	**EV**	**FCV**
Lithium Manganese Oxide (LiMn2O4)	25.0%	27.0%	33.6%	25.0%
Nickel	0.0%	0.0%	0.0%	0.0%
Cobalt	0.0%	0.0%	0.0%	0.0%
Manganese	0.0%	0.0%	0.0%	0.0%
Graphite/Carbon	11.0%	12.0%	14.7%	11.0%
Silicon as anode material	0.0%	0.0%	0.0%	0.0%
Binder	1.9%	2.1%	2.5%	1.9%
Copper	12.0%	15.0%	10.9%	12.0%
Wrought Aluminum	20.0%	22.0%	18.7%	20.0%
Cast Aluminum	0.0%	0.0%	0.0%	0.0%
Electrolyte: LiPF6	1.4%	1.7%	1.9%	1.4%
Electrolyte: Ethylene Carbonate	4.1%	4.8%	5.4%	4.1%
Electrolyte: Dimethyl Carbonate	4.1%	4.8%	5.4%	4.1%
Plastic: Polypropylene	1.8%	2.2%	1.7%	1.8%
Plastic: Polyethylene	0.2%	0.4%	0.3%	0.2%
Plastic: Polyethylene Terephthalate	2.0%	1.7%	1.2%	2.0%
Steel	3.3%	2.0%	1.4%	3.3%
Thermal Insulation	0.4%	0.3%	0.3%	0.4%
Coolant: Glycol	1.9%	1.3%	0.9%	1.9%
Electronic Parts	10.9%	2.7%	1.1%	10.9%

The weight of the traction batteries will be retrieved from the ADVISOR simulation parameters for each simulation, whereas the assumption for a number of batteries per vehicle lifetime can be edited in the simulation setup.

The CO_2 emissions and energy used for the production of batteries will be summarized in kg and MJ per battery type.

4.2.1.1.3 ADR

For the vehicle ADR, the GREET2 model calculates a total for an average mid-size passenger car, based on process stages compiled from the literature [36]. The same total for ADR energy used and emission is deployed for all vehicle types considered. The processes and energy input amount required and respective share of process fuels are presented in Table 5.

Table 5: ADR Process stages, energy input required and share of process fuels; [36]

		Shares of process fuels	
Process stage	**Energy input [MJ per vehicle]**	**Natural gas**	**Electricity**
Paint Production	302.80	0.0%	100.0%
Vehicle Assembly - Painting	2,910.90	83.4%	16.6%
Vehicle Assembly - HVAC & Lighting	1,044.51	56.1%	43.8%
Vehicle Assembly - Heating	3,146.18	100.0%	0.0%
Vehicle Assembly - Material Handling	216.29	0.0%	100.0%
Vehicle Assembly - Welding	288.03	0.0%	100.0%
Vehicle Assembly - Compressed Air	431.52	0.0%	100.0%
Vehicle Disposal	1,560.76	0.0%	100.0%

4.2.1.1.4 Fluids

Replacement of fluids is also considered in the GREET2 Model based on the estimated weight of the fluids according to the Table 6. The GREET2 Model calculates a total for each vehicle type based on the assumptions for a number of replacements within the vehicle lifetime.

Table 6: Weight of fluids per vehicle type in kg; [36]

Fluid	ICEVs	HEVs	PHEVs	EVs	FCVs
Engine Oil	3.86	3.86	3.86	0.00	0.00
Power Steering Fluid	0.00	0.00	0.00	0.00	0.00
Brake Fluid	0.91	0.91	0.91	0.91	0.91
Transmission Fluid	10.90	0.84	0.84	0.84	0.84
Powertrain Coolant	10.43	10.43	10.43	7.15	7.15
Windshield Fluid	2.72	2.72	2.72	2.72	2.72
Adhesives	13.61	13.61	13.61	13.61	13.61

The main assumption in the GREET model regarding vehicle fluids is that oil based fluids such as engine oil, power steering, brake and transmission fluids have the same emissions and energy consumption as for the production and provision of gasoline. The assumption for powertrain coolant is that it is constituted of ethylene glycol and water in the proportion of 50% each, while the windshield fluid is constituted of 50% methanol and 50% water. Emission characteristics for adhesives are accounted for as average plastic. Oil based fluids are assumed to be burned in the disposal phase with a 67% product to waste ratio.

For vehicle cycle calculations, the CO_2 emissions and energy used associated with production and disposal of fluids will be summarized as a flat-rate for each vehicle type, based on the respective number of replacements.

4.2.1.2 Fuel cycle

Simulations in ADVISOR can be performed for all vehicle types considered in this study and respective propulsion energy sources as presented in Table 7.

Table 7: Propulsion energy supported in ADVISOR and required units for the fuel cycle data

Propulsion energy source	Required units for emission data
Electricity	g/KWh
Gasoline	g/l
Diesel	g/l
Compressed Natural Gas	g/KWh
Liquefied Petroleum Gas	g/l
Hydrogen	g/KWh

The data with different locational reference shall be collected for the fuel cycle data-sets in accordance with the Table 7 and presented in sub-chapter 4.3.5

4.2.1.3 Use cycle

ADVISOR's output variables for fuel consumption of fossil fuels return a vector indicating the consumption in grams for each second of simulation. Analogously for the case of electricity ADVISOR returns an output vector indicating the consumed or regenerated electricity as positive or negative values. Hence, data on density, heating values and CO_2 emissions associated with the combustion of fuels is required to calculate the emissions in the use cycle. Comparing such data from different sources like the State Office for Environment of Bavaria / Germany in [54], the Austrian Federal

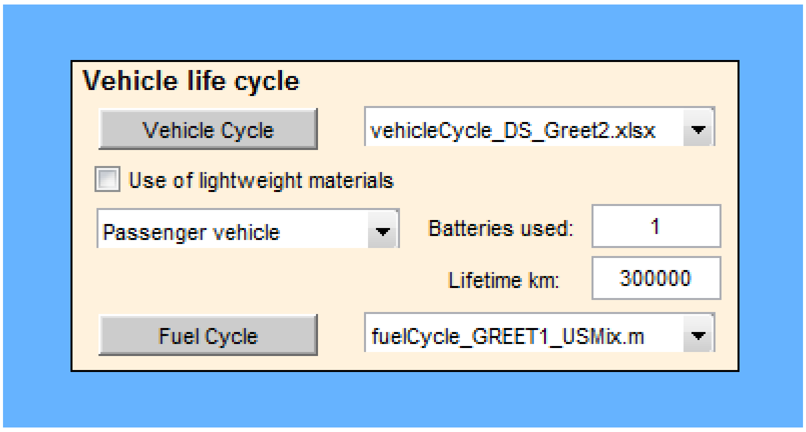
Environmental Agency in [55] and GREET1 [56], the specification of different values can be noticed. Considering that the data inventory established in this study refers in the majority to the European region, the data provided by the European Commission's Joint Research Centre in [57] is going to be used for the calculation of the use cycle, as presented in the following Table 8.

Table 8: Heating values, density and CO_2 emissions associated with combustion of fuels; [57]

	Lower heating value	Density	Combustion CO_2 exhaust
Gasoline	32.28 [MJ/l]	1.34 [l/kg]	2361.52 [g/l]
Diesel	35.86 [MJ/l]	1.20 [l/kg]	2626.62 [g/l]
CNG	35.10 [MJ/kg]	n.a.	71.20 [g/MJ]
LPG	23.68 [MJ/kg]	n.a.	65.70 [g/MJ]
Hydrogen	120.10 [MJ/kg]	n.a.	n.a.

4.2.2 Modification of the simulation setup GUI of ADVISOR

In this step, the ADVISOR GUI was modified to enable the editing of simulation parameters and selection of the fuel and vehicle data-sets to be processed in the calculation of the full vehicle life cycle. The following Figure 15 presents the batch of interface elements added to the simulation setup figure of ADVISOR.



vehicleCycle_DS_Greet2.xlsx

☐ Use of lightweight materials

Passenger vehicle

Batteries used: 1

Lifetime km: 300000

fuelCycle_GREET1_USMix.m

Figure 15: Added interface elements to the simulation setup GUI

The buttons "Vehicle Cycle" and "Fuel Cycle" enable management of the dropdown lists from which the data-sets can be chosen. Detailed specification of the modified code is given in Appendix A.

4.2.3 Implementing the calculation of the vehicle cycle from GREET2

After the required data coming from GREET and ADVISOR has been defined and means have been developed to pass the data to the calculation function, the consequent step was to implement the GREET2 vehicle cycle calculation. The vehicle cycle calculation was implemented as a typical Matlab function invoked in the simulation setup file as other ADVISOR functions.

The implementation of the GREET vehicle cycle calculation into ADVISOR was developed on the basis of following concepts and assumptions:

- The current calculation of CO_2 emissions should be easily extendable for maps of other emissions;
- The vehicle cycle data-sets required for the calculation, represent the base of the calculation and are retrieved by ADVISOR in a way so that they are readable as look-up tables. Following the above-stated assumption, the basic concept was to load the look-up tables from spreadsheet data-sets to Matlab, with the names of rows and columns saved as separate vectors. This way a value from the look-up table can be retrieved by entering the name of emission of indicator for the desired value.

The GREET2 Model incorporates the life cycle calculation of the lightweight construction of the different vehicle types as well. This option has also been incorporated into the ADVISOR calculation and the option can be chosen in the simulation setup interface.

After the data-set has been loaded and the required function input parameters processed, the next step was to calculate the weight of the materials used in the production of vehicle components depending on the vehicle mass value provided from ADVISOR simulation. The calculation multiplies the vehicle mass, excluding battery weight vehicles with energy storage systems, with the percent share of the material used for the production of vehicle components. After the weight of the materials used for the production of vehicle components has been calculated the next step was to calculate how much emissions emerge in the production of these materials. This calculation is based on the loaded look-up table containing the values for emissions in grams per pound of material product.

In order to be able to complete the calculation for the vehicle cycle, it remains to determine the emissions which arise through the production of batteries and to retrieve the values for vehicle ADR and Fluids which are loaded from the spreadsheet data-set. As mentioned in the sub-chapter 4.2.1.1, the emission associated with the production of batteries is loaded as total for Lead-acid (starter) batteries and for Li-ion (traction) batteries, the mass of the batteries as modeled in ADVISOR is multiplied with the respectively loaded coefficients.

The result of the vehicle cycle calculation function is a vector which contains the overall result of the vehicle cycle and the results for each of the 4 main items as specified in sub-chapter 4.2.1.1; materials, batteries, ADR and fluids. According to the main implementation assumption, the calculation is set to be able to deliver results for other emissions and emission indicators as well. However, in this stage of development only results for CO_2 emissions are further processed.

4.2.4 Implementing the calculation of the fuel and use cycle

The calculation of the fuel and use cycle relies on actual simulation results of ADVISOR, especially the fuel economy figures and on the loaded fuel cycle data-set as mentioned in the sub-chapters above. ADVISOR's simulation results provide vectors with consumption values and a vector containing the distance achieved through the propulsion effort for each second of simulation processed. Depending on the vehicle type and the respective propulsion energy source, the resulting vectors contain consumption of fuel in grams, consumption of electric energy in Joule or both in the case of hybrid vehicles. Further, the output results also provide ΔSOC of the energy storage system, which is crucial for PHEV consumption calculations. In following the calculation of the cycles is shortly described, while detailed description and code documentation are given in Appendix A.

4.2.4.1 Use and fuel cycle for ICEV, HEV and FCEV

For the case of ICEV, HEV and FCEV where only one type of fuel is the source of propulsion energy, the use and fuel cycles are calculated by multiplication of the consumption with the respective fuel and use cycle coefficients.

4.2.4.2 Use and fuel cycle for EV

The consumption calculation for EV makes use of an existing function in ADVISOR which in addition to the energy circulation accounts the columbic effect if specified in the simulation parameters. In addition, the grid charger efficiency of 90% is added to obtain the overall value of energy taken from the grid. The value for the grid charger efficiency is taken from [3] as the down rounded average of all measurements of on board grid charger efficiency.

Finally, the total energy consumed from the grid is divided with the distance which the vehicle has achieved in course of the simulation to calculate the indirect CO_2 emissions in gram per kilometer. The variable for direct CO_2 emission has been set to a zero value as EV has no CO_2 emissions associated with the use of the vehicle. In the end, the average consumption was calculated as additional information in the added part of results GUI.

4.2.4.3 Use and fuel cycle for PHEV

The PHEV calculation of the use and fuel cycle is a combination of calculation for ICEV and EV, whereas the energy used from the grid is determined by an existing ADVISOR function which was developed as one of the results of the work presented in [58] and provides the energy used only from the energy storage based on the ∆SOC value. As for the electric vehicle, the columbic effect and the grid charger efficiency are considered in the calculation of the total energy used from the grid.

The emissions associated with the energy used from the grid and energy from the fuel converter are calculated separately and aggregated in the final step building the total result of the use and fuel cycle.

4.2.5 Modification of the results GUI of ADVISOR

For displaying the results of the simulation and the results of the full vehicle life cycle, a batch of interface elements was added to the results GUI of ADVISOR as presented in the following Figure 16.

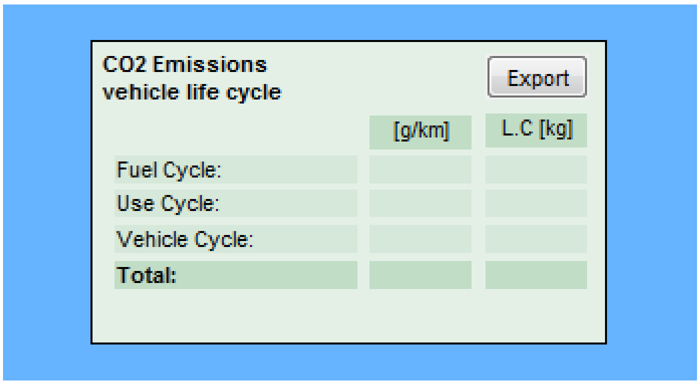


Figure 16: Added interface elements to the results GUI

The full vehicle life cycle results can be exported to a spreadsheets file for further processing of the data.

4.3 Data inventory: Elaboration of vehicle and fuel cycle data-sets

Industrial processes, resource availability and environmental policies are vastly different when compared between regions or even bordering countries as the following sub-chapters will demonstrate. Comparing the full vehicle life cycle in scenarios of production and use in different regions and countries is a valuable part of this study. Since the data provided in the GREET model on emissions associated with the production of materials and performance of industrial processes refers to the United States, it was required to acquire data for further sampling regions and countries. Hence in addition to the baseline data for US taken over from GREET, the data will be collected for following locational references:

- Germany as the largest producer of passenger cars in Europe [59],
- Austria as one of the countries with highest shares of renewable energy in gross energy consumption in Europe [60] and the location where this study is elaborated, and
- The EU, to exemplify comparisons with larger regions such as the Unites States.

The main sources of the data collection for Germany and EU are the GEMIS [35] and PROBAS[2] databases both maintained by the German Federal Environmental Agency and the IINAS. Furthermore, the work of the European Commission's Joint Research Centre[3] including the European Life Cycle Database (ELCD)[4] is going to be used while collecting data for the vehicle cycle. The Austrian Federal Environmental Agency provides and maintains its own version of GEMIS database which was specially developed to cover scenarios in Austria. This version of GEMIS Austria database was thankfully provided by the Institute for Powertrains and Automotive Technology of Technical University Vienna.

During the data collection, process stages of production of each material product were compared to contain the same or similar processing stages for material products as the baseline data from GREET. In cases where the comparison of process stages for a certain material product exhibited significant differences, the amount of energy requirement and the type of energy/fuels consumed in the process was taken as defined in GREET. In a further step, comparable processes for utilization of such energy/fuels were retrieved from GEMIS for the respective locational reference. These

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[2] http://www.PROBAS.umweltbundesamt.de/php/index.php
[3] https://ec.europa.eu/jrc/en/publications
[4] http://eplca.jrc.ec.europa.eu/ELCD3/processList.xhtml

emission factors were finally used to calculate the emissions and energy used for the missing process stages. The emissions are presented in kilogram of CO_2 per material product and the energy used in Megajoule per kilogram of material product. Other than for the baseline data for US, each entry of vehicle cycle data-set is referenced to a specific process in GEMIS, link to PROBAS/ELCD or to respective Annex were additional calculations were required.

4.3.1 Baseline vehicle cycle data-set for the United States

4.3.1.1 Materials

The GREET model provides all data with the locational reference for US required for the vehicle cycle, as presented in Table 9, starting with the summary of CO_2 emissions and energy consumption for material products composing the vehicle.

Table 9: Summary of Energy Consumption and Emissions of Material Products for the US; [61]

Material Product	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Steel	3.57	40.15
Stainless Steel	1.94	26.99
Cast Iron	0.90	31.32
Wrought Aluminum	6.97	117.40
Cast Aluminum	2.69	44.06
Copper/Brass	3.00	40.97
Zinc	2.97	40.64
Magnesium	9.22	122.05
Glass	1.68	20.95
Average Plastic	3.20	80.03
Rubber	3.71	50.07
Carbon Fiber-Reinforced Plastic	18.39	288.97
Carbon Fiber-Reinforced Plastic for High-Pressure Vessels	33.05	485.43
Glass-Fiber-Reinforced Plastic	4.60	78.96
Nickel	5.21	74.91
Perfluorosulfonic acid (PFSA)	1.37	19.93
Carbon Paper	132.75	1909.56
Polytetra-fluoroethylene	7.70	102.41
Carbon & PFSA Suspension	1.34	19.51
Platinum	103.74	1028.72
Silicon	216.46	3464.53
Carbon / Graphite	4.81	82.71

4.3.1.2 Batteries

CO_2 Emissions and energy consumed associated with the production of all battery types considered in this study is presented in Table 10, per kg of battery weight. It is noted that the calculations in GREET foresee a flat-rate amount of energy and emission associated with the assembly of the Li-ion batteries which amounts to 49,132.24 g of CO_2 and 786.01 MJ of energy used per Li-ion battery unit. Different from the lead-acid and NiMH batteries, the "per kilogram" values for Li-ion batteries presented in Table 10 do not include battery assembly.

Table 10: Energy Consumption and Emissions Related to the production of batteries for US; [61]

Vehicle / Battery	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Lead-acid battery for all vehicles	0.75	17.07
NiMH battery for all vehicles	4.97	86.40
HEV Li-ion battery	6.51	107.68
PHEV Li-ion battery	4.70	79.72
EV Li-ion battery	4.27	71.71
FCEV Li-ion battery	6.51	107.68

4.3.1.3 ADR

The emissions and energy used for the process stages considered in GREET for vehicle ADR are presented in Table 11.

Table 11: Energy Consumption and Emissions related to vehicle ADR for the US, per vehicle lifetime; [62]

Process	CO_2 Emissions: kg per vehicle lifetime	Total energy: MJ per vehicle lifetime
Paint Production	43.20	659.45
Vehicle Assembly - Painting	221.14	3,751.77
Vehicle Assembly - HVAC & Lighting	149.03	2,274.75
Vehicle Assembly - Heating	197.25	3,498.34
Vehicle Assembly - Material Handling	30.86	471.03
Vehicle Assembly - Welding	41.10	627.28
Vehicle Assembly - Compressed Air	61.57	939.77
Vehicle Disposal	222.68	3,399.06
Total ADR per vehicle lifetime	**966.83**	**15,621.45**

4.3.1.4 Fluids

In accordance with the assumptions described in sub-chapter 4.2.1.1.4, CO_2 emissions and energy used accounted for production and disposal of fluids is presented in Table 12.

Table 12: Energy Consumption and Emissions Related to production of fluids for US; [61]

Fluid	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Engine Oil	3.15	54.47
Power Steering Fluid	3.15	54.47
Brake Fluid	3.15	54.47
Transmission Fluid	3.15	54.47
Powertrain Coolant	1.60	20.01
Windshield Fluid	0.20	15.54
Adhesives	3.20	89.08

4.3.2 Vehicle cycle data-set for Germany

4.3.2.1 Materials

GEMIS and PROBAS databases provide a solid basis for data collection on material products for Germany. However, as mentioned in the introduction of the sub-chapter 4.3 for some material products the process stages accounted for in GEMIS were not comparable with the process stages specified in GREET's baseline data. Hence, these stages were additionally included whereas the calculations are presented in the referenced Annexes. Some material products, used especially for the FCEV and lightweight vehicle production were not available in any of the databases or through literature research and are consequently inherited from GREET, as presented in the following Table 13.

Table 13: Summary of Energy Consumption and Emissions of Material Products for Germany

	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]	Source:
Steel	3.44	53.74	See Appendix B.1.1
Stainless Steel	4.26	75.43	*
Cast Iron	0.82	12.86	GEMIS: metal\iron-cast-DE-2005
Wrought Aluminum	12.33	176.03	See Appendix B.1.2
Cast Aluminum	4.12	63.66	See Appendix B.1.3
Copper/Brass	3.29	43.11	metal\copper-DE-mix-2010
Zinc	4.82	69.67	GEMIS: metal\zinc-DE-2010
Magnesium	10.69	145.85	*

Glass	1.06	11.89	GEMIS: nonmetallic minerals\glass-flat-DE-2000
Average Plastic	4.23	69.78	See Appendix B.1.4
Rubber	3.16	93.55	GEMIS: chem-org\rubber_EPDM-DE-2000
Carbon Fiber-Reinforced Plastic	18.39	288.97	**
Carbon Fiber-Reinforced Plastic for High-Pressure Vessels	33.05	485.43	**
Glass-Fiber-Reinforced Plastic	4.60	78.96	**
Nickel	4.72	59.89	GEMIS: metal\nickel-DE-2010
Perfluorosulfonic acid (PFSA)	1.37	19.93	**
Carbon Paper	132.75	1,909.56	**
Polytetra-fluoroethylene	7.70	102.41	**
Carbon & PFSA Suspension	1.34	19.51	**
Platinum	26,448.70	305,900.00	GEMIS: Precious metal\Pt-primary-Western-world
Silicon	435.61	8,241.10	See Appendix B.1.5
Carbon / Graphite	4.81	82.71	**

* Same source and data as in Table 21
** Same source and data as in Table 9

The production stages of steel, wrought and cast aluminum are presented in detail and illustrated with a flowchart in [36]. Comparing these process stages with the equivalent GEMIS processes following discrepancies were ascertained and considered in the calculations in appendices as referenced in the table above:

- Steel production processes in GEMIS do not include the Stamping process stage in any of the available steel processes,
- Aluminum production processes do not differentiate between wrought and cast aluminum production;
    - For wrought aluminum production Hot Rolling, Cold Rolling, Stamping and Extrusion process stages need to be added,
    - For cast aluminum, Shape Casting and Machining process stages need to be added.

Due to data unavailability for Germany, the locational reference for the production of stainless steel and magnesium is the EU.

Data for all plastic types defined in GREET was collected from GEMIS and PROBAS. The average calculation and the references for each type are provided in Appendix B.1.4.

In comparison to the baseline data from GREET, an outlying value is identified for the platinum material product. The GREET documentation explains that during their research a study of the German Öko Institute from 1997 estimating the energy required for production of platinum at “82,535 million Btu/ton” (95,988.2 MJ/kg) was considered, but that finally an estimation from other literature at “77.2 million Btu/ton” (89.8 MJ/KG) was used for the model. This vastly larger value is confirmed in [7] where the same GEMIS process for platinum is quoted as in Table 13. However, the share of platinum in overall vehicle weight is less than 0.01% in any of the vehicle types (Table 1), making this divergence not highly significant.

Data for more than 95% of average vehicle weight share, as per Table 1, has been collected with locational reference for Germany.

4.3.2.2 Batteries

The materials specified in the composition of lead-acid and NiMH batteries are in majority also used in the vehicle material composition or are largely available in the used databases. Detailed references to data sources and calculation of the CO_2 emissions and energy used are presented in appendices referenced by the summary of results presented in Table 14.

On the other hand, data for the majority of material products used for the production of Li-ion batteries as per Table 4 are not available in the used databases for Germany, therefore the value for production in Europe is applied for this data-set whereas no distinction is made for the different vehicle types.

Table 14: Energy Consumption and Emissions Related to the production of batteries for Germany

Vehicle / Battery	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]	Source:
Lead-acid	1.33	23.43	Appendix B.1.6
NiMH	5.20	79.63	Appendix B.1.7
Li-ion	5.04	104.00	*
* Same source and data as in Table 22			

4.3.2.3 ADR

The emissions and energy used for vehicle ADR were calculated taking into consideration the amounts of the energy input required and the respective types of energy/fuels specified in Table 5 as well as the emissions and energy used for the respective energy utilization processes specified in GEMIS for Germany. Details of the calculation and the process references are presented in Appendix B.1.8 with the summary presented in the following Table 15.

Table 15: Energy Consumption and Emissions related to vehicle ADR for Germany, per vehicle lifetime; Source: Appendix B.1.8

Description	CO_2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production	46.96	811.08
Vehicle Assembly - Painting	223.77	4,020.57
Vehicle Assembly - HVAC & Lighting	106.88	1,883.47
Vehicle Assembly - Heating	192.87	3,533.09
Vehicle Assembly - Material Handling	33.54	579.35
Vehicle Assembly - Welding	44.67	771.52
Vehicle Assembly - Compressed Air	66.93	1,155.86
Vehicle Disposal	242.06	4,180.64
Vehicle ADR	**957.69**	**16,935.59**

4.3.2.4 Fluids

The assumptions from GREET explained in sub-chapter 4.2.1.1.4, were applied for calculating the emissions and energy used for fluids, taking the respective underlying processes for provision and disposal of resources from GEMIS. The calculation and references to single processes used from GEMIS are given Appendix B.1.9. with the summary presented in the following Table 16.

Table 16: Energy Consumption and Emissions Related to production of fluids for Germany; Source: Appendix B.1.9

Fluid	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Engine Oil	3.34	52.15
Power Steering Fluid	3.34	52.15
Brake Fluid	3.34	52.15
Transmission Fluid	3.34	52.15
Powertrain Coolant	1.01	35.07
Windshield Fluid	0.28	11.02
Adhesives	4.23	69.78

4.3.3 Vehicle cycle data-set for Austria

4.3.3.1 Materials

The version of GEMIS developed and maintained by the Austrian Federal Environmental Agency is the main source for collection of data for Austria enabling the establishment of the data-set for Austria (Table 17) in analogy to the above.

Table 17: Summary of Energy Consumption and Emissions of Material Products for Austria

	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]	Source:
Steel	2.44	35.80	See Appendix B.2.1
Stainless Steel	4.26	75.43	*
Cast Iron	1.80	24.68	GEMIS: metal\pig-iron-DE-2005-KRAWI
Wrought Aluminum	8.33	131.25	See Appendix B.2.2
Cast Aluminum	4.28	66.83	See Appendix B.2.3
Copper/Brass	3.29	43.11	**
Zinc	3.88	53.99	GEMIS: metal\zinc-A
Magnesium	10.69	145.85	*
Glass	0.94	10.66	GEMIS: Steine-Erden\Flaschenglas-primär-Österreich
Average Plastic	4.26	84.20	See Appendix B.2.4
Rubber	3.16	93.55	**
Carbon Fiber-Reinforced Plastic	18.39	288.97	***
Carbon Fiber-Reinforced Plastic for High-Pressure Vessels	33.05	485.43	***
Glass-Fiber-Reinforced Plastic	4.60	78.96	***
Nickel	4.72	59.89	**
Perfluorosulfonic acid (PFSA)	1.37	19.93	***
Carbon Paper	132.75	1,909.56	***
Polytetra-fluoroethylene	7.70	102.41	***
Carbon & PFSA Suspension	1.34	19.51	***
Platinum	26,448.70	305,900.00	**
Silicon	435.61	8,241.10	**
Carbon / Graphite	4.81	82.71	**

* Same source and data as in Table 21
** Same source and data as in Table 13
*** Same source and data as in Table 9

The same assumptions for the addition of production stages for steel, wrought and cast aluminum are taken as in the data-set for Germany, whereas all underlying processes are respectively applied for Austria as presented in the referenced appendices.

Apart from the data used especially for the production of FCEV and lightweight vehicles inherited from the baseline data-set, data for stainless steel and magnesium is inherited from the EU data-set, while copper, rubber, nickel, platinum and silicon refer to the data-set for Germany.

In comparison to the baseline data-set from GREET, the collected data does not contain any outlying values other than platinum which is already described in sub-chapter 4.3.2.

Data for more than 89% of average vehicle weight share, as per Table 1, has been collected with locational reference for Austria.

4.3.3.2 Batteries

The materials specified in the composition of lead-acid and NiMH batteries are in majority also used in the vehicle material composition or are largely available in the used databases. Detailed references to data sources and calculation of the CO_2 emissions and energy used are presented in appendices referenced by the summary of results presented in Table 18.

On the other hand, data for the majority of material products used for the production of Li-ion batteries as per Table 4 are not available in the used databases for Germany, therefore the value for production in Europe is applied for this data-set whereas no distinction is made for the different vehicle types.

Table 18: Energy Consumption and Emissions Related to the production of batteries for Austria

Vehicle / Battery	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]	Source:
Lead-acid	1.25	22.88	Appendix B.1.6
NiMH	4.99	79.27	Appendix B.1.7
Li-ion	5.04	104.00	*
* Same source and data as in Table 22			

4.3.3.3 ADR

In analogy to the vehicle data-set above, Table 19 summarizes the emissions and energy used related to vehicle ADR with respective data of underlying processes applied for locational reference of Austria.

Table 19: Energy Consumption and Emissions related to vehicle ADR for Austria, per vehicle lifetime; Source: Appendix B.2.7

Description	CO_2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production	17.46	549.58
Vehicle Assembly - Painting	202.95	4,084.37
Vehicle Assembly - HVAC & Lighting	68.64	1,604.50
Vehicle Assembly - Heating	226.91	4,156.58
Vehicle Assembly - Material Handling	12.47	392.56
Vehicle Assembly - Welding	16.61	522.77
Vehicle Assembly - Compressed Air	24.88	783.20
Vehicle Disposal	89.98	2,832.75
Vehicle ADR	**659.89**	**14,926.30**

4.3.3.4 Fluids

In analogy to the vehicle data-set above, Table 20 presents a summary of the emission accrued and energy used for production and disposal of vehicle fluids, with respective data of underlying processes applied for locational reference of Austria as referred to in detail in Appendix B.2.8.

Table 20: Energy Consumption and Emissions Related to production of fluids for Austria; Source: Appendix B.2.8

Fluid	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Engine Oil	3.14	46.88
Power Steering Fluid	3.14	46.88
Brake Fluid	3.14	46.88
Transmission Fluid	3.14	46.88
Powertrain Coolant	1.47	36.32
Windshield Fluid	0.15	14.64
Adhesives	4.26	84.20

4.3.4 Vehicle cycle data-set for the EU

4.3.4.1 Materials

The main sources for the data collection for the EU are also the GEMIS and PROBAS databases. The ELCD was used for retrieving data on Zinc material product and plastic material types which compose the average plastic as presented in the Appendix B.3.4. In analogy to the data-sets above the overview of material product emissions is given in Table 21.

Table 21: Summary of Energy Consumption and Emissions of Material Products for the EU

	CO_2 Emissions: [kg/kg]	**Total energy: [MJ/kg]**	**Source:**
Steel	2.92	33.78	See Appendix B.3.1
Stainless Steel	4.26	75.43	PROBAS[5]
Cast Iron	0.82	12.86	*
Wrought Aluminum	9.92	168.12	See Appendix B.3.2
Cast Aluminum	2.54	44.14	See Appendix B.3.3
Copper/Brass	3.97	52.96	GEMIS: metal\copper-wire-EU-2005
Zinc	3.04	n.a.	ELCD[6]
Magnesium	10.69	145.85	PROBAS[7]
Glass	0.58	12.65	PROBAS8
Average Plastic	3.80	n.a.	See Appendix B.3.4
Rubber	3.16	93.55	*
Carbon Fiber-Reinforced Plastic	18.39	288.97	**
Carbon Fiber-Reinforced Plastic for High-Pressure Vessels	33.05	485.43	**
Glass-Fiber-Reinforced Plastic	4.60	78.96	**
Nickel	4.72	59.89	*
Perfluorosulfonic acid (PFSA)	1.37	19.93	**
Carbon Paper	132.75	1,909.56	**
Polytetra-fluoroethylene	7.70	102.41	**
Carbon & PFSA Suspension	1.34	19.51	**
Platinum	26,448.70	305,900.00	*
Silicon	435.61	8,241.10	*
Carbon / Graphite	4.81	82.71	**

* Same source and data as in Table 13
** Same source and data as in Table 9

Steel production processes delivered by GEMIS for the EU are similar to the processes specified in GREET but also do not contain stamping process stage. Since GEMIS does not comprise average shares of recycled and virgin steel for the EU, the GREET shares have been accounted for the average steel. For aluminum production, same assumptions are raised as described for vehicle data-set for Germany (sub-chapter 4.3.2). The ELCD does not provide explicit information on cumulative energy requirement for the data on different types of plastic.

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[5] http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={FE002BA2-414C-4F42-8FB4-F1DA84EB9B0B}

[6] http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=fd9db252-4998-11dd-ae16-0800200c9a66&version=03.00.000&stock=default

[7] http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={DB90ABC6-4C10-49DD-9328-AA308536DDCF}

[8] http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={47368082-B100-4FB4-9BA4-81C6331D6904}

Data for more than 80% of average vehicle weight share, as per Table 1, has been collected with locational reference for the EU.

In comparison to the baseline data-set from GREET, the collected data does not contain any outlying values other than platinum which is already described in sub-chapter 4.3.2.

4.3.4.2 Batteries

In analogy to the data-set for Germany, data has been collected for the materials specified in the composition of lead-acid and NiMH batteries with a respective summary of calculations and references provided in Table 22.

The data for material products used for the production of Li-ion traction batteries as per Table 4 are in majority not available in the used databases for the EU. However, [62] considers in detail production of the Li-ion batteries with comparable material composition as in Table 4 taking the assumption that the battery assembly takes place in Europe. Hence, the value resulting from the study of 6.0 kg CO_2 equivalent per kg of Li-ion battery will be considered multiplied by the factor 0.84, in accordance with [63], to gain the share of CO_2 emission associated with the production of Li-ion batteries. [62] provides information for a single Li-ion battery type which will be deployed for all vehicle types in this data-set.

Table 22: Energy Consumption and Emissions Related to the production of batteries for EU;

Vehicle / Battery	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]	Source:
Lead-acid	1.36		
NiMH	4.98		Appendix B.3.6
Li-ion	5.04	104.00	[63]

4.3.4.3 ADR

In analogy to the vehicle data-sets above, Table 23 summarizes the emissions and energy used related to vehicle ADR with respective data of underlying processes applied for locational reference of EU.

Table 23: Energy Consumption and Emissions related to vehicle ADR for EU; Source: Appendix B.3.7

Description	CO_2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production	36.07	817.88
Vehicle Assembly - Painting	224.68	4,399.26

Vehicle Assembly - HVAC & Lighting	94.83	1,982.52
Vehicle Assembly - Heating	216.59	4,009.81
Vehicle Assembly - Material Handling	25.76	584.20
Vehicle Assembly - Welding	34.31	777.98
Vehicle Assembly - Compressed Air	51.40	1,165.55
Vehicle Disposal	176.01	3,991.35
Vehicle ADR	**859.65**	**17,728.55**

4.3.4.4 Fluids

In analogy to the vehicle data-sets above, Table 24 presents a summary of the emission accrued and energy used for production and disposal of vehicle fluids, with respective data of underlying processes applied for locational reference of EU as referred to in detail in Appendix B.3.8.

Table 24: Energy Consumption and Emissions Related to production of fluids for EU; Source: Appendix B.3.8

Fluid	CO_2 Emissions: [kg/kg]	Total energy: [MJ/kg]
Engine Oil	3.64	50.91
Power Steering Fluid	3.64	50.91
Brake Fluid	3.64	50.91
Transmission Fluid	3.64	50.91
Powertrain Coolant	0.58	n.a.
Windshield Fluid	0.28	11.02
Adhesives	3.80	n.a.

4.3.5 Fuel cycle data-sets

Information for the fuel cycle is available from numerous sources. Considering that most of the data for the vehicle cycle were collected from GREET and GEMIS, the fuel cycle data-set (Table 25) is also constituted from these sources as far as possible. Fuel cycle data for the EU relies on the study of the JRC - [57]. The collected fuel cycle data complies with following criteria:

- The generation mix of electricity production (electricity mix) is used for electricity as the main propulsion energy source and in the process chain of production of other fuels;
- The data for fossil fuels considers conventional fuel types and conventional production processes;
- In accordance with process chain information from GREET and GEMIS, hydrogen production is considered to take place through natural gas reforming

and to be in a gaseous state, since ADVISOR simulations handle hydrogen in this state for FCEV.

Table 25: CO_2 emission associated with provision of fuel and energy (fuel cycle)

Fuel	Unit	US	Src.	Germany	Src.	Austria	Src.	EU	Src.
Gasoline	g/l	438.83	[56]	491.43	[9]	344.77	[10]	421.25	[57]
Diesel	g/l	488.87		420.70	[11]	356.01	[12]	524.27	
LPG	g/KWh	38.94		27.43	[13]	46.00	[7]	27.32	
CNG	g/KWh	35.29		27.23	[14]	34.00		30.53	
Hydrogen (GH2)	g/KWh	379.73		287.00	[64]	217.00		385.56	
Electricity	g/KWh	514.06		558.34	[15]	207.55	[16]	428.80	[17]

Table 26 presents the upstream energy used for the provision of the fuels and electricity from the same source as the Table 25.

Table 26: Upstream energy used for the provision of fuel and energy (fuel cycle)

Fuel / [MJ/MJ]	US		Germany		Austria		EU	
Gasoline	1.23		1.21		1.09		1.18	
Diesel	1.20		1.15		1.16		1.20	
LPG	1.16		1.10		1.19		1.12	
CNG	1.18		1.16		1.23		1.36	
Hydrogen (GH2)	1.82		1.54		1.23		1.99	
Electricity	2.43		2.68		1.81		2.71	

At this point, it is noted that [65] describes the CO_2 emissions for the electricity mix as a reflection on the average amount of electricity produced from available primary energy sources considering a specific locational reference. A significant change of the electricity demand and respectively the change of the load to the electricity power grid would have an impact on the CO_2 intensity of its production which is referred to as electricity generation "marginal mix". Deployment of marginal mix CO_2 emission factors can have a significant impact on impact assessments.

Specific studies such as [66] address this issue for a sample region of the US providing an analysis of the marginal mix, however, it was not feasible to perform a homogenous

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[9] GEMIS: filling-station\gasoline-DE-2010 (excl. bio)

[10] GEMIS: Tankstelle-Benzin-A-2014 (inkl. Beimischung)

[11] GEMIS: filling-station\Diesel-DE-2010 (excl. bio)

[12] GEMIS: Tankstelle-Diesel-A-2014 (inkl. Beimischung)

[13] GEMIS: filling-station\LPG-DE-2010 (excl. bio)

[14] GEMIS: filling-station\natural-gas-CNG-DE-2010

[15] GEMIS: el-generation-mix-DE-2010

[16] GEMIS: el-generation-mix-AT-2010

[17] GEMIS: el-generation-mix-EU-27-2010 (PRIMES)

data survey of the marginal grid CO_2 emission factors through the used databases or literature sources for the 4 locational references considered in this study.

4.4 Comparison of data-sets

The vehicle cycle data-sets presented above consistently follow the structure and vehicle material composition as presented in the GREET2 model, however, the first eleven material products comprise in average more than 95% of the vehicle composition. Considering that these materials are the most relevant for the vehicle cycle, the following Figure 17 presents an overview of the CO_2 emissions for the most relevant material products and all locational references considered.

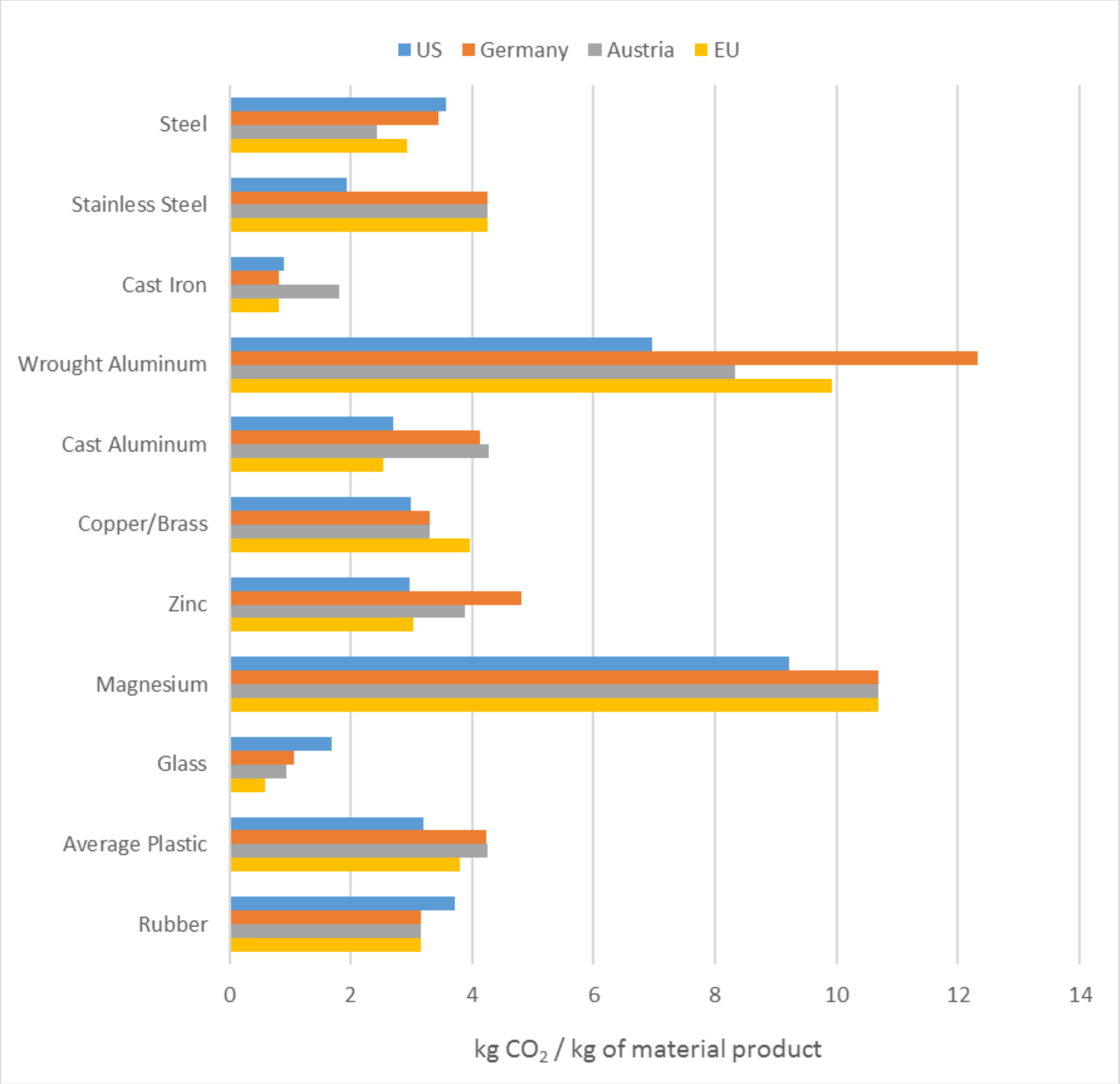

Figure 17: Summary of CO_2 emissions of materials comprising more than 95% of the vehicle composition

Looking at each material product, it can be stated that a general correlation of the values between the locational references exists. The differences between the locational references are mainly influenced by industrial processes specific for the region, availability of basic resources such as ore mines, energy types used for processing, electricity mix and further factors specific for the processing stages and supply chain characteristics. Beside the large divergence of the platinum material products emissions mentioned in chapter 4.3.2.1, the largest divergence in the comparison above is exhibited by the wrought aluminum material production with locational reference for Germany. According to the original data retrieved from GEMIS, Germany's mixed aluminum production is 54% more CO_2 inefficient than the comparable process in Austria. Further analysis resolved that the German and the Austrian processes include different supply resources which as a base provide significantly distinct emissions causing this large difference.

The fuel cycle data presented in chapter 4.3.5 is depicted in following Figure 18 and presents the emission values grouped per fuel/energy type.

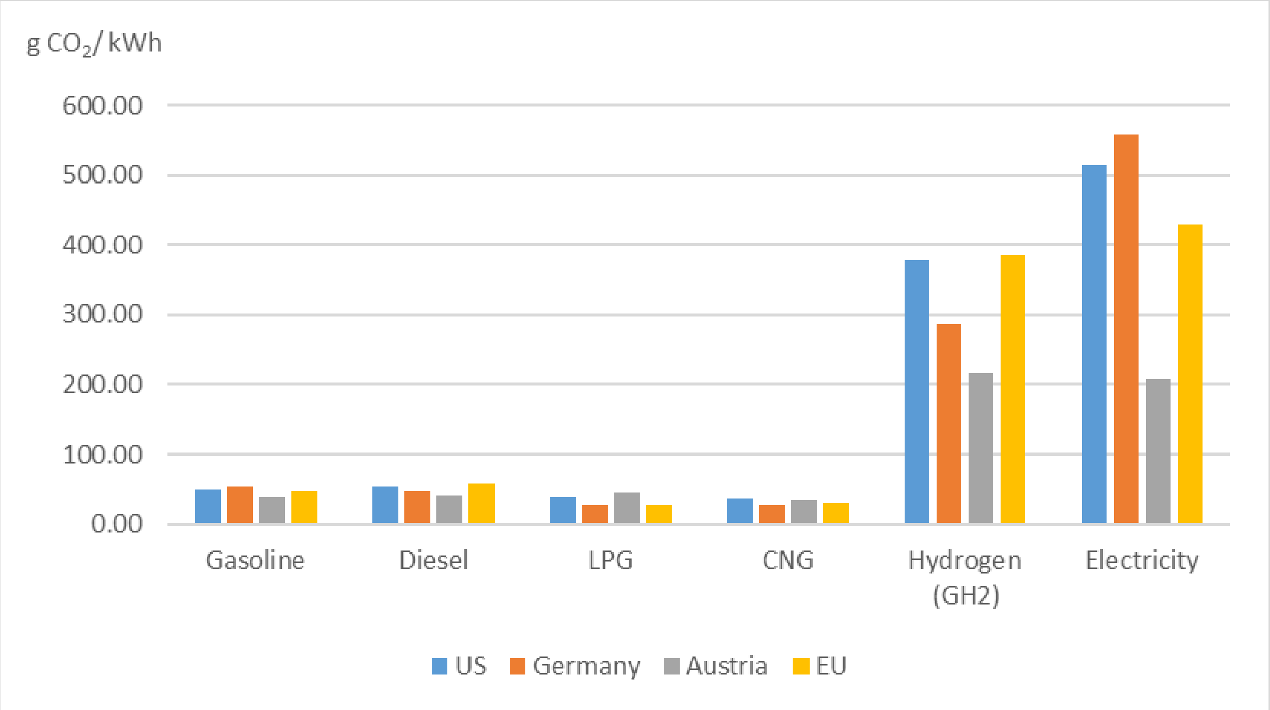

Figure 18: Fuel cycle data-set grouped per fuel energy/type

All fossil fuel data lays in a similar range, whereas the electricity and hydrogen exhibit significant divergences. The share of renewable energy in the electricity generation mix is decisive for the CO2 efficiency. According to [60], Austria has one of the highest shares of renewable energy deployment in Europe which explains this high divergence. Since more massive hydrogen production is generally a rather young process and considering that the data for hydrogen originates from different sources, the data can be interpreted to have a certain extent of coherency.

4.5 Proof of function

The functionality of the added life cycle calculation module in ADVISOR was tested against the corresponding results provided by the GREET model. As described in the above sub-chapters, the baseline dataset for the vehicle cycle derives from the data provided in the GREET2 and a fuel cycle dataset is made available based on the GREET1. Other required coefficients used in the life cycle calculations such as fuel density, heating values and specific CO_2 emission coefficients for fuel combustion are per default based on the values provided in the GREET model.

In consideration of the above and to obtain the exact same values for the full vehicle life cycle in GREET and ADVISOR, following main input parameters have been equalized in both tools for these testing purposes:

- Vehicle weight;
- Average consumption equivalents or energy used per distance as applicable for vehicle type;
- Energy supply scenarios / fuel cycle CO_2 factors;
- Lifetime in kilometers;
- Battery weight as applicable for vehicle type;
- Number of battery packs in vehicle lifetime;
- Number of tire-sets changed in vehicle lifetime.

Furthermore, the figures for lower heating values, density and combustion CO_2 emissions have been adjusted to correspond to the values as provided in GREET1 as presented in Table 27.

Table 27: Heating values, density and CO_2 emissions associated with combustion of fuels; [56]

	Lower heating value	Density	Combustion CO_2 exhaust
Gasoline	31.27 [MJ/l]	1.33 [l/kg]	2273.85 [g/l]
Diesel	36.09 [MJ/l]	1.18 [l/kg]	2705.12 [g/l]
Hydrogen	117.68 [MJ/kg]	n.a.	n.a.

The test procedure to verify the functionality of the life cycle calculation was executed as follows:

- The simulation was executed in ADVISOR with default parameters and an overridden vehicle weight as assumed in the GREET model for the specific vehicle type
- The consumption simulated in ADVISOR was transformed to the units used in GREET such as MPG and Btu/Mile and entered in the vehicle specification sheets in GREET1
- The SOC correction option was enabled for FCEV and HEV so that the same SOC of batteries is provided in the beginning and at the end of the simulation with a tolerance range of +-0,5 %.
- The results presented in the Table 28 below were gained for comparison

Table 28: Results of the proof of function

Vehicle			ADVISOR [g CO_2 / km]			GREET [g CO_2 / km]		
Type	Fossil Fuel	Weight [kg][18]	Vehicle cycle	Use cycle	Fuel cycle	Vehicle cycle	Use cycle	Fuel cycle
ICEV / SI	CG	1427.00	21.32	187.21	36.12	21.32	187.21	36.12
ICEV / CI	CD	1427.00	21.32	158.87	28.71	21.32	158.87	28.71
HEV	CG	1505.00	22.88	132.65	25.60	22.88	132.65	25.60
PHEV	CG	1585.00	24.18	158.80[19]	78.16	24.18	158.80	78.16
EV	-	1308.00	20.09	0.00	105.10	20.09	0.00	105.10
FCEV	-	1595.00	33,71	0.00	134.89	33,71	0.00	134.89

It is noted that the GREET model determines the emissions for PHEV based on the fuel economy calculated as an average of 3 PHEV operation modes: (i) charge depleting only of electricity resources, (ii) charge depleting of electricity and fuel resources and (iii) charge sustaining mode. The consumption average of the operation modes is calculated by the share of Vehicle Miles Traveled (VMT) in charge depleting and charge sustaining mode whereas the VMT curve is defined in the GREET Model and depends on the entered All-Electric Range (AER). Hence, the three operation modes were simulated in ADVISOR whereas the results for emission were validated with those from GREET for each operation mode. The final average consumption and emissions presented in the table above were calculated in GREET based on the consumption values and AER simulated with ADVISOR and in accordance with the VMT defined in GREET.

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[18] Assumptions for vehicle weight are taken over from GREET.

[19] Indirect results from ADVISOR. Detailed description of the process is given in the paragraph following the table.

4.6 Plausibility comparison with similar studies

Several life cycle studies of different vehicle types were assessed for possible comparisons, however, the majority of the life cycle studies have arguably untransferable frameworks and limitations or very specific interpretation of results. Nevertheless, some rough comparisons are possible whereas also one specific study provides means for a more precise comparison.

In the work of Norwegian Institute of Science and Technology (NTNU) presented in [67] and corrected in [68] an ICEV with SI and CI engine and an EV are examined. The corrected version of the article ([68]) accounts for 81 grams of CO_2 equivalents per kilometer (g CO_2-eq / km) in the EV vehicle cycle and 190 g CO_2-eq / km for the EV full vehicle life cycle. The ICEVs with SI and CI engines considered in the study account for 258 and 228 g CO_2-eq / km for the full vehicle life cycle, noting an estimate of 43 g CO_2-eq/km for the ICEV vehicle cycle. Adopting the basic vehicle and LCA parameters from [67] in the modified ADVISOR tool combined with the vehicle and fuel-cycle data-set established for the EU, 120, 229 and 216 grams of CO_2 emissions per kilometer (g CO_2 / km) of EV, ICEV SI and ICEV CI are asserted in the full vehicle life cycle with 43, 37 and 40 g CO_2 / km accounted for the vehicle cycle. The differences for ICEV SI and CI are attributed to the consideration that [68] accounts for CO_2 equivalents and modified ADVISOR CO_2 emissions only, especially with respect to a share of CO_2 emission of 84% in total CO_2 equivalents given in [63]. The results are depicted in following Figure 19.

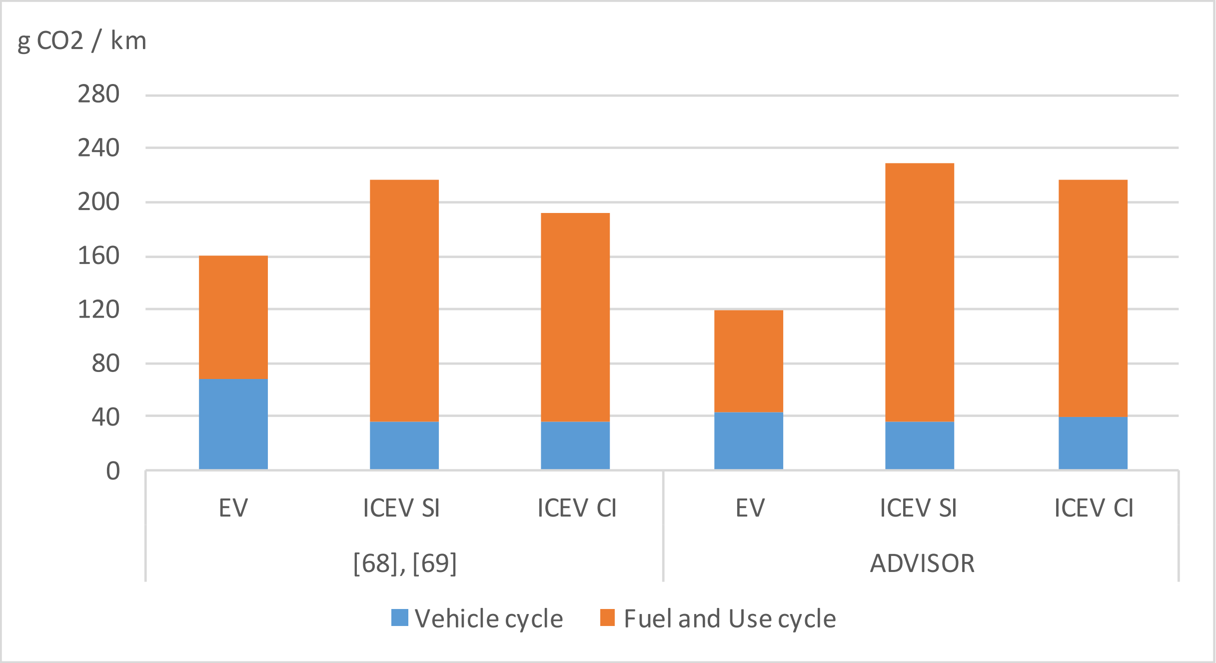


Figure 19: Comparison of the LCA study [67] / [68] with results from the modified ADVISOR

Beyond the different target units, the significant difference, however, is noticed for the EV for both the vehicle and fuel cycle. The main difference in the vehicle cycle is the battery data inventory which [67] uses from [69] and which accounts for 4 times more emission per kg of Battery than the figures according to [62] this study is principally using. [69] is going to be considered in more detail in the sensitivity analysis. Regarding the EV's fuel cycle, the European electricity mix mentioned [67] is not referenced but obviously reflects on own calculations of NTNU.

Going out of the four locations considered in this study, the study in [70] was analyzed, presenting a solidly structured study, considering the full vehicle life cycle with the locational reference being New Zeeland. Data for the fuel cycle are also not explicitly presented in the study, except for generation of electricity. However, accommodating the vehicle weight, battery weight and the number of replacements, consumption and service life, a rough comparison is made with the baseline data for the US. Thus, [70] accounts for 0,26 and 0,25 kg of CO_2-eq/km per vehicle kilometer for ICEV SI and ICEV CI, while the results of the ADVISOR simulation account for the same values for the given parameters for the CO_2 emissions only. For the case of EV [70] estimates 0,11 kg CO_2 equivalents per vehicle kilometer, while the ADVISOR simulation accounts for 0,10 kg of CO_2 emissions providing therewith relatively coherent results considering the rough balance of the framework conditions. [70] considers also PHEV, however, the weighting factor for shares of propulsion on grid-loaded electricity and fuel are not explicitly stated and unable a direct comparison.

A detailed analysis of an FCEV is presented in [71] with a range of scenarios including hydrogen production from different primary energy sources and future simulated representations of vehicle production scenarios. Comparing the "current" scenario representing the current state of industry and hydrogen production via gas reforming, [71] conveys that about 0,27 kg CO_2-eq / km is emitted in the full vehicle cycle by FCEV, thereof 0,17 kg CO_2-eq / km referring to the fuel and 0,10 kg CO_2-eq / km to the vehicle cycle. Taking the same LCA parameters such as vehicle and battery weight, service life and consumption combined with the fuel and vehicle data-sets for the EU, modified ADVISOR simulates results of 0,14 kg CO_2 / km for fuel and 0,07 kg CO_2 / km for the vehicle cycle. Taking into consideration that according to [63] 84% of the CO_2-eq / km from [71] can be accounted as CO_2 emission and the level of detail the data from [71] is enabling a comparison, a certain coherency of the results can be noted.

A summarized comparison of the studies [70] and [71] is provided in following Figure 20.

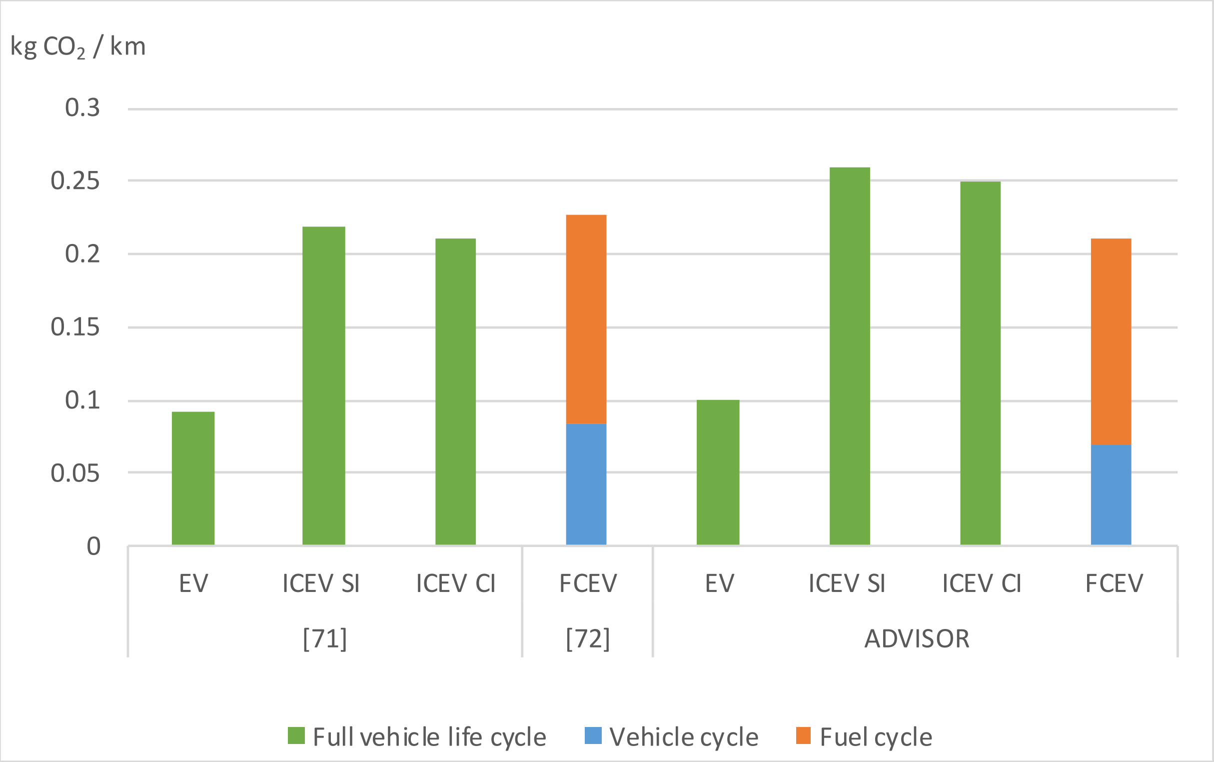
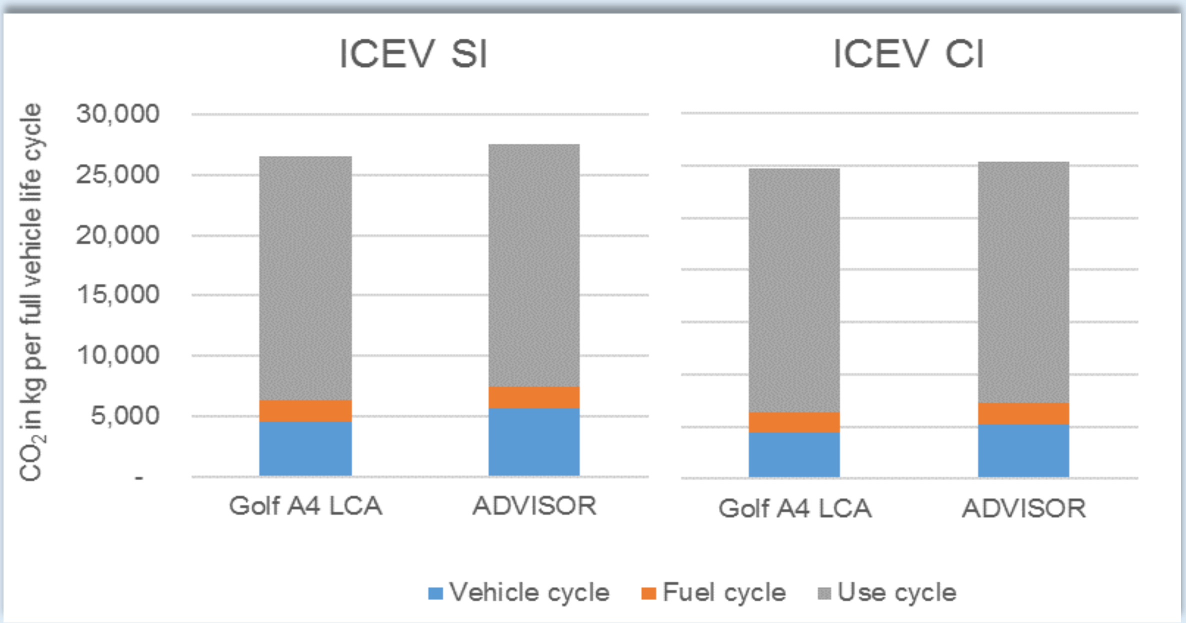


Figure 20: Comparison of the LCA study [70] and [71] with results from the modified ADVISOR

The study presenting the largest amount of details enabling a most rational comparison is presented in [72]. For the vehicle cycle, the study provides a precise material composition inventory which compared to the one used from GREET provides a very similar representation of the material composition. The structure of the presentation of results is also similar to the full vehicle life cycle structure used in this study. The Figure 21 below presents the results from [72] and modified ADVISOR with the same parameters such as vehicle weight, consumption, service life, fuel cycle and with the vehicle data-set defined for Germany as presented above.



Emissions [kg CO_2 / vehicle]				
Vehicle cycle	4,402	5,160	4,577	5,580
Fuel cycle	1,991	1,990	1,748	1,799
Use cycle	23,339	23,195	20,277	20,067
Full vehicle cycle:	**29,732**	**30,345**	**26,602**	**27,446**

Figure 21: Comparison of the LCA study [72] with results from the modified ADVISOR

A difference in the vehicle cycle is noted for both vehicle types. [72] states that "*Commercially available tables are used for material mining and production*" and does not reference or provide details on the data used for vehicle materials nor details on the electricity production used in the vehicle/parts production process. Considering that in accordance with the results of [72], the counted back CO_2 emissions associated with the production of fuel amount to 238 and 204 g CO_2/l for diesel and gasoline, while the above presented fuel cycle for Germany accounts for 421 and 491 g CO_2/l of diesel and gasoline, it is assumed that [72] calculated rather conservative estimates of CO_2 emission for provision of energy and material resources.

Looking at further studies provided directly from the manufacturer such as [73], it is noted that some of the assumptions used for the expressive graphs are rather unrealistic. For example, [74] presents a graph with the assumption that a "BluePower" electricity is used with practically 99% of saving of CO_2 emission in the use phase. In the small print further on it is however stated that using the European electricity mix the savings reduce to 26% of CO_2 emissions. On the other hand, the study of the FCEV in [73] presents results which seem implausible in comparison to any of the research works or inventories referenced in this study ([7], [61], [72]).

Summarizing the comparison of the different studies with the modified ADVISOR, it is notable that a direct comparison is rather difficult since all studies make use of different data inventories, input parameters and in the end have slightly different objectives. However, after the input parameters are balanced to a comparable extent, modified ADVISOR provides results which are by all means plausible and comparable with those of the observed studies. The following chapter 5 addresses in detail how the different data inventories and input parameters bias the results of full vehicle life cycle for particular vehicles parametrized.

5 Results and sensitivity analysis

As presented in the chapters above, the production of fuels, electricity and material products, requires different source energy types and implicitly associates different emission amounts. Based on the collected data inventory above and on the modification of ADVISOR simulation tool presented, this chapter is going to present the results of the performed simulations in the specifically defined framework.

Hence, the sub-chapter 5.1 presents the “base case” framework conditions defined for the simulations, while the parametrization and the procedure of the simulation are explained in the sub-chapter 5.2.

The results of the study including a sensitivity analysis in accordance with the data collected is presented in sub-chapter 5.3., comparing the full vehicle life cycle scenarios for different regions / countries as well as by analyzing sensitivity cases such as vehicle life and battery sizing. The results are presented in grams of CO_2 emission per vehicle kilometer (g CO_2 / km).

Finally, the CO_2 reduction goals of the EU are analyzed in a confrontation with the main finding of the study with an outlook of possible developments to achieve the emission goals stated.

5.1 General framework for the simulations

The vehicle types addressed in this study are going to be represented by specific C segment (medium cars) vehicle models according to categorization in [75]. Specific vehicles are chosen based on the European market share relevance obtained from [76] for ICEV and HEV and from [77] for PHEV, FCEV and EV. Accordingly, the Volkswagen Golf is selected as the representative for ICEV SI and CI vehicle, in its environmentally representative “Bluemotion“ 1,2 TSI and 1,6 TDI versions, as mentioned in [74] HEV is represented by the Toyota Prius model while the meaning role of PHEV in C segment is again held by a Volkswagen Golf in its GTE version. Due to its significant market penetration, Nissan Leaf is selected as the comparable EV. The number of marketed FCEV vehicles in Europe constrains the selection to the Toyota’s Mirai model easily.

The indications in the literature regarding the vehicle service life considered in life cycle studies is rather split. For example, [67] assumes that vehicles can achieve a service life of 10 years and 150,000 km. On the other hand, [78] takes the assumption that the vehicle service life is 180,000 (~300,000 km) whereas the electric vehicles have to account a full battery pack replacement. Both assumptions are considered in the sensitivity analysis in further sub-chapters, whereas the base case assumption is 10 years and 150.000 km.

According to the German Institute “DEKRA” [79], the service life of a tire set amounts to 40,000 km. Hence, 4 tire sets for the vehicle life of 150.000 are considered with 10 replacements of engine oil according to [80] and default number of replacements of other fluids as presented and starter batteries as in GREET2 [61].

The simulations are going to be run in the NEDC, defined by the regulation [81]. which defines the consumption testing procedure for PHEV as presented in the following equation 5.1:

$$C = \frac{De * C1 + Dav * C2}{De + Dav} \tag{5.1}$$

$\mathrm{C} = \text{fuel consumption in l/100 km.}$

$\mathrm{C1} = \text{fuel consumption in l/100 km with a fully charged electrical energy/power storage device.}$

$\mathrm{C2} = \text{fuel consumption in l/100 km with an electrical energy/power storage device in minimum state of charge (maximum discharge of capacity).}$

$\mathrm{De} = \text{vehicle's electric range}$

$\mathrm{Dav} = 25\ \text{km (assumed average distance between two battery recharges).}$

Considering that in accordance with the stipulations of [81] the approval method of NEDC considers the measurement of electricity from the socket, the simulations of PHEV and EV will be calibrated to achieve the declared overall consumption. Although [82] does not foresee any SOC balancing during the NEDC test drive cycle, the initial SOC for simulation of HEV and FCEV will be calibrated to achieve the resulting ∆SOC less than 0,5% for all base case and sensitivity analysis simulations to ensure the same determining factors in all cases.

Changes to the above-described base case simulation framework made in course of the sensitivity analysis are described in the respective sub-chapters below.

5.2 Parametrization of the selected vehicles

Key technical data required for parametrization of the vehicle models selected for analysis is summarized in Table 29 below.

Table 29: Key technical data required for simulation of representative vehicles

Vehicle type:	**ICEV SI**	**ICEV CI**	**HEV**	**PHEV**	**EV**	**FCEV**
Vehicle model:	Volkswagen Golf 1.2 TSI	Volkswagen Golf 1.6 TDI	Toyota Prius	Volkswagen Golf GTE	Nissan Leaf	Toyota Mirai
Production year:	2014 -	2014 -	2009 - 2015	2014 -	2013 -	2015
Fuel converter (FC) type:	SI	CI	SI	SI	n.a.	Fuel cell
FC Displacement [cm³]:	1,197	1,598	1,798	1,395	n.a.	n.a.
FC Torque [Nm / rpm]:	175/1400	250/1500	142/4000	250/1600	n.a.	n.a.
FC Output [kW/rpm]:	81/4600	81/3200	73/5200	110/5000	n.a.	114
Transmission:	M/6	M/5	CVT	DSG/6	Single speed	CVT
Electric Motor (EM) type:	n.a.	n.a.	PMS	PMS	HRS	PMS
EM Torque [Nm]:	n.a.	n.a.	207	330	254	335
EM Output [kW]:	n.a.	n.a.	60	75	80	113
Energy storage type:	n.a.	n.a.	NiMh	Li-Ion	Li-Ion	NiMh
Energy storage capacity (nominal) Ah:	n.a.	n.a.	6.5	25	66.2	6.5
kWh:			1.3	8.8	24.7	1.6
Nominal voltage:			201.6	352	360	244
Number of modules (m):/ cells (c)	n.a.	n.a.	168 c (28m x 6c)	96 c (8m x 12c)	192 c (48m x 4c)	204 c (34m x 6c)
Energy storage mass [kg]:	n.a.	n.a.	29.35	120.00	290.00	35.64*
Vehicle curb weight [kg]:	1,210	1,299	1,380	1,572	1,580	1,850
Consumption (ECE/NEDC) combined:	4.9 l/100km	4.0 l/100km	4.0 l/100km	1.5l+ 11,4KWh /100km	15 KWh /100km	0,8 kg /100km
AER (ECE):	n.a.	n.a.	n.a.	50	n.a.	n.a.
Source:	[83]	[84]	[85], [86]	[87], [88]	[89], [90]	[91], [92]

CVT Continuously variable transmission
DSG Direct Shift Gearbox
PMS Permanent Magnet Synchronous
HRS High Response Synchronous
"c" – cell
"m" – module
*Calculated in accordance with the weight of the module of the Toyota Prius Battery

Considering the unavailability of the specific data for simulation of the vehicles in ADVISOR such as maps of brake specific fuel consumption, speed range, torque range, efficiency of electric motors and fuel cells, such data is estimated and interpolated based on the above presented key technical data of the vehicles and default data structures available in ADVISOR. The framework for the estimation of the simulation data is based on guidelines from the literature depicted in the following paragraphs. Other simulation specific data such as battery configuration is going to be construed on data available in ADVISOR and adjusted in accordance with descriptions and definitions from [51] and [93].

As the essential requirement for simulation of the vehicles, the brake specific fuel consumption diagrams for direct injection SI and CI engines presented in Figure 22, taken over from [93], delineate the main tendencies applied as frames for the estimation.

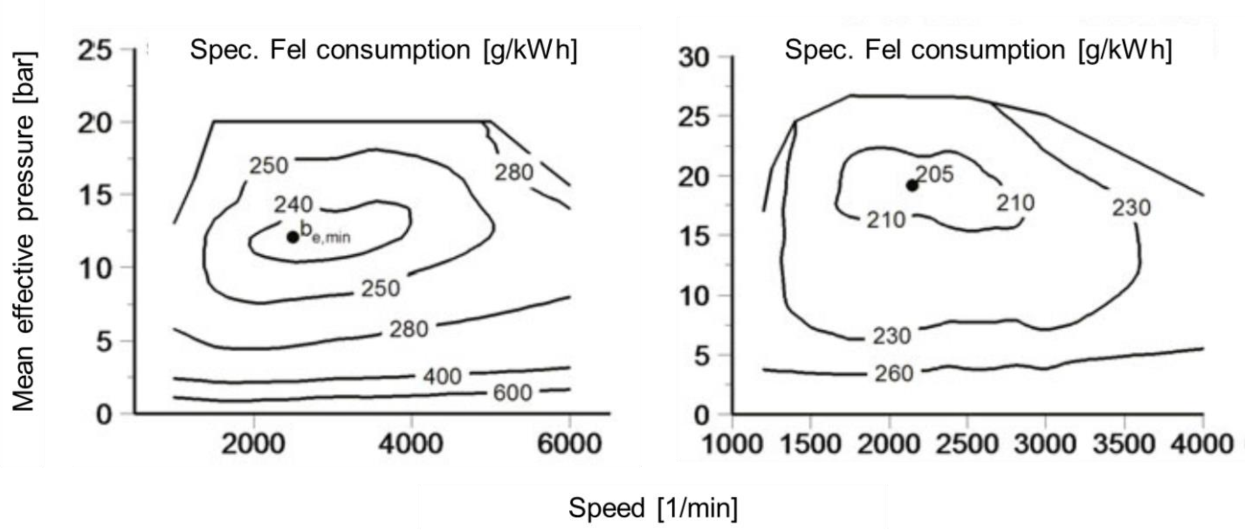


Figure 22: Brake specific fuel consumption diagrams for direct injection SI (left) and CI (right) engines; [93]

The comprehensive study of a hybrid electric drive system presented in [94], provides a range of specific information on the examined drive train and a good example of a synchronous motor/inverter efficiency contour map presented in Figure 23.

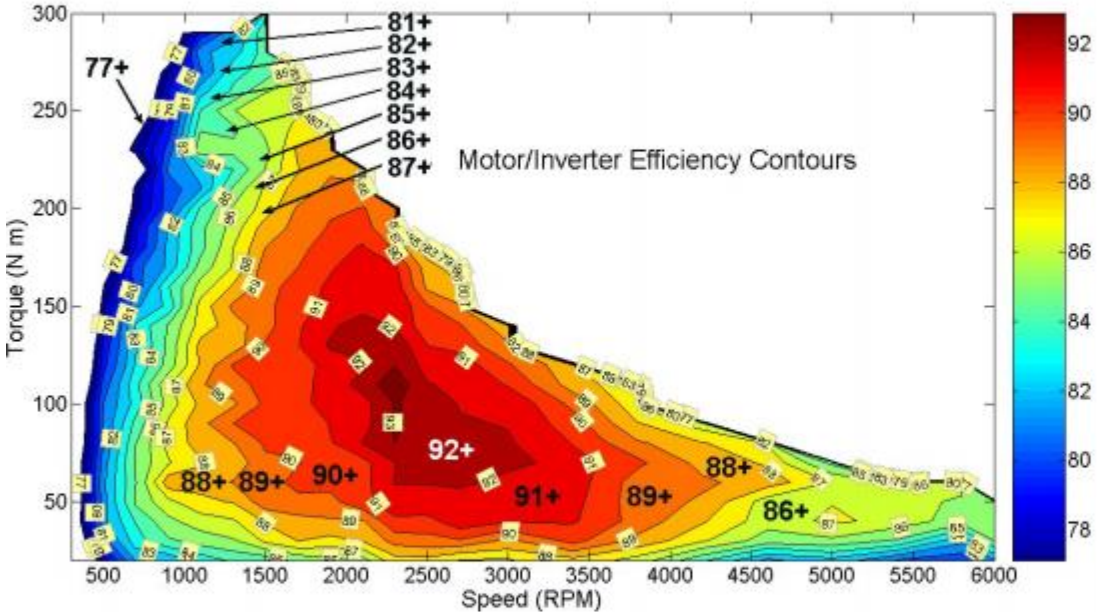


Figure 23: Combined motor/inverter efficiency contour map; [94]

The above map is used as an orientation point for estimating efficiency ranges of synchronous electric motors for the specified vehicles.

As presented in [95], the constant development of the fuel cell technology focuses on the consumption optimization through the optimization of the partial efficiencies and minimizing the activating losses. The diagram presented in Figure 24 presents general efficiency overview as well as an overview of developments according to [95].

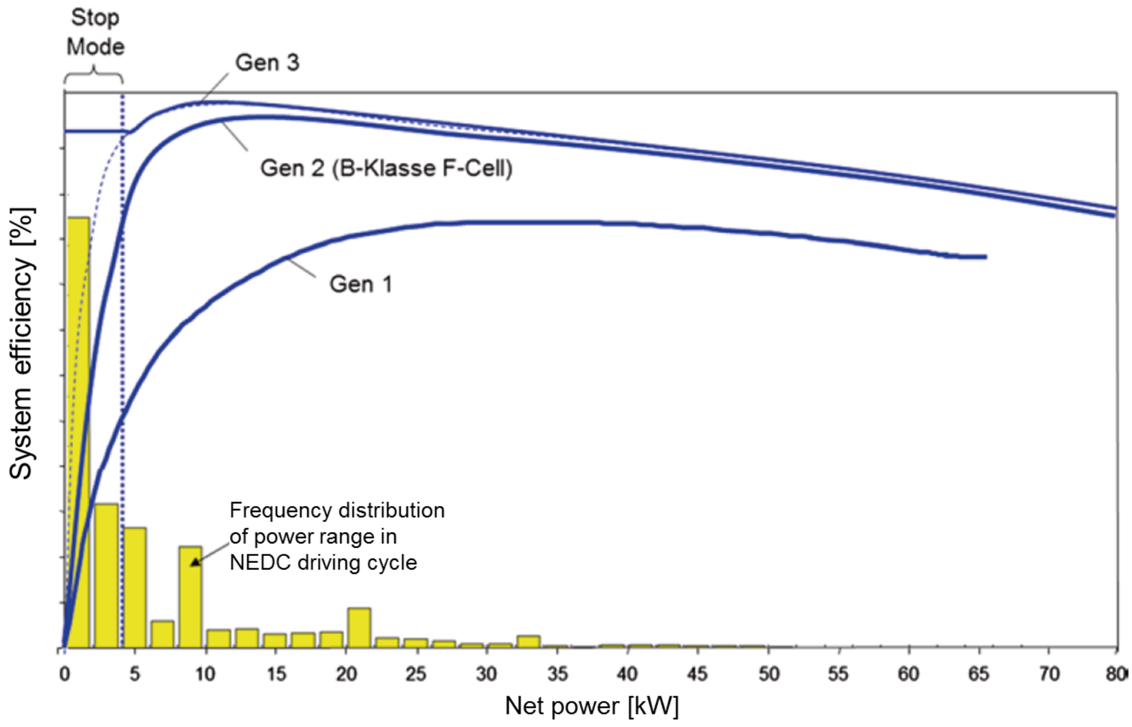


Figure 24: Fuel cell efficiency, optimization and potentials; [95]

The fuel/energy consumption resulting from the simulation tests performed in modified ADVISOR with the NEDC for all specified vehicles shall have an accuracy of at least 95 percent in comparison to the above-presented manufacturer fuel consumption information.

5.3 Simulation results and sensitivity analysis

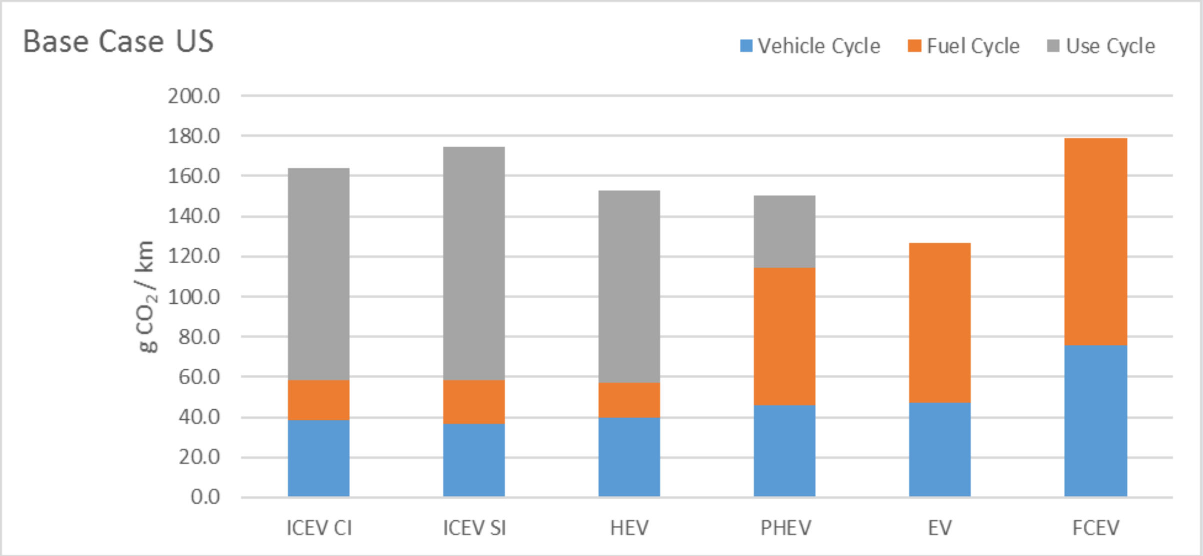
The above-described simulation setup together with the elaborated data sets enables a wide range of scenarios and sensitivity analyses. In following an overview is provided per region/country analyzing the results in accordance with data-set used, as well as analyzing sensitivity for some special cases such as the driving cycle, service life, replacement and enlargement of battery packs and other, as presented in the sub-chapters below.

5.3.1 Base case simulation results

The base case results represent the impacts accounted for the CO_2 efficiency of production of materials and resources used in the full vehicle life cycle for considered geographical regions. The results are presented per geographical region focusing on advantages of different vehicle types and in an overview for all geographical regions focusing on differences between the regions and respective impacts on vehicle types.

5.3.1.1 Baseline data-set for the US

The simulation results of the selected representative vehicles with the assumption of production and use under the general conditions for resource provision of US are presented in Figure 25.



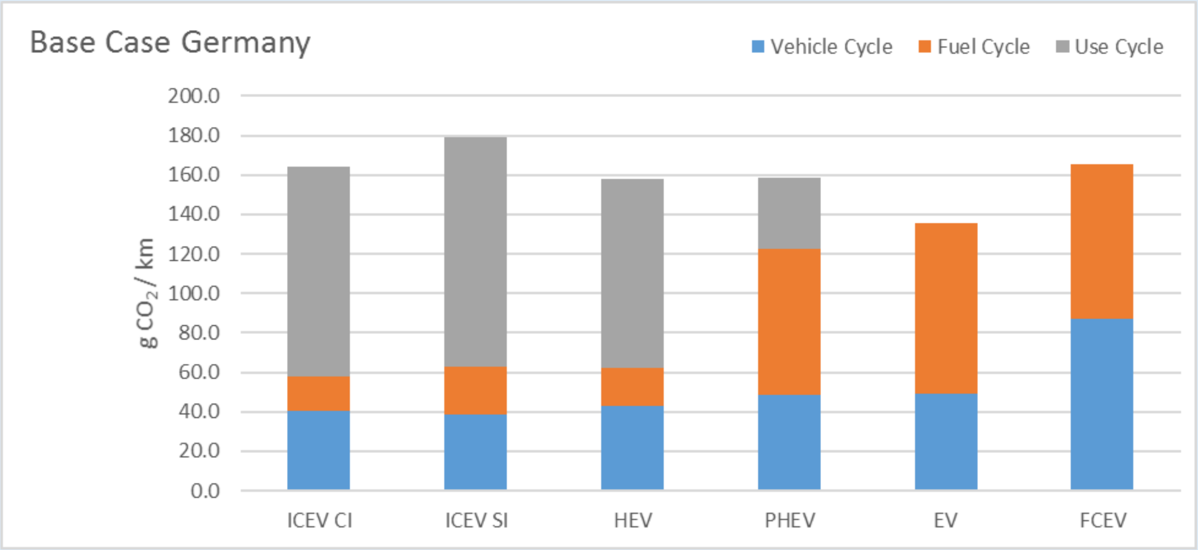
Emissions [g CO_2 / km]						
Vehicle cycle	38.4	36.5	39.7	45.9	47.0	75.8
Fuel cycle	19.8	21.7	17.7	68.2	79.6	103.4
Use cycle	106.1	116.7	95.2	36.2	0.0	0.0
Full life cycle	**164.30**	**174.88**	**152.56**	**150.27**	**126.60**	**179.16**

Figure 25: Comparison of base case results per vehicle type, gained with US data-set

The results for the US show that the highest CO_2 emission intensity per km is accounted for FCEV, followed by ICEV SI and ICEV CI. Beside the rather inefficient production of hydrogen causing the high fuel cycle value, the FCEV's vehicle cycle has the highest share in comparison, constituting 42% of the full vehicle life cycle which is caused by CO_2 intensive material composition and high curb weight. HEV and PHEV exhibit a very small overall difference whereas the PHEV's load is on fuel and vehicle accordant to the electrification grade of the powertrain. The use of EV accounts for 16% less CO_2 than the most efficient combustion engine vehicle with no external electricity charging possibility. Considering that the mostly urban NEDC goes in favor of the efficiency range of the electric motor [96], this saving may not cover for higher loads in real-life use and is considered a tight advantage in comparison with HEV and PHEV.

5.3.1.2 Data-set for Germany

The simulation results of the selected representative vehicles with the assumption of production and use under the general conditions for resource provision of Germany are presented in Figure 26.



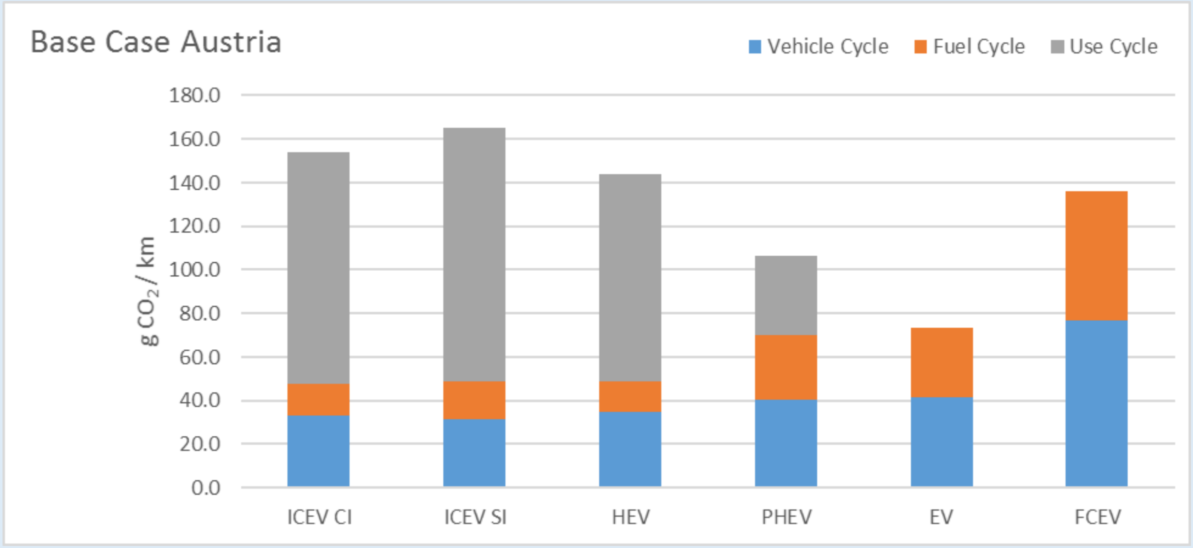
Emissions [g CO_2 / km]						
Vehicle cycle	40.7	38.7	42.9	48.3	49.4	87.1
Fuel cycle	17.1	24.1	19.6	74.2	86.4	78.2
Use cycle	106.1	116.7	95.2	36.2	0.0	0.0
Full life cycle	**164.0**	**179.4**	**157.7**	**158.7**	**135.9**	**165.2**

Figure 26: Comparison of base case results per vehicle type, gained with Germany data-set

The results for Germany show that the highest CO_2 emission intensity per km is accounted for ICEV SI, followed by FCEV and ICEV CI. In addition to the emissions accrued in the use cycle, data for gasoline production in Germany accounts for a rather large amount of CO_2 emissions intensifying the difference to other vehicle types. In these terms, the HEV is slightly more efficient than the PHEV whereas it can be said that ICEV CI, HEV, PHEV and FCEV are all on a very similar scale. The use of EV accounts in this case for 14% less CO_2 than the most efficient vehicle containing a combustion engine which is again considered as a tight advantage probably not covering the real-life use differences.

5.3.1.3 Data-set for Austria

The simulation results of the selected representative vehicles with the assumption of production and use under the general conditions for resource provision of Austria are presented in Figure 27.



Emissions [g CO_2 / km]

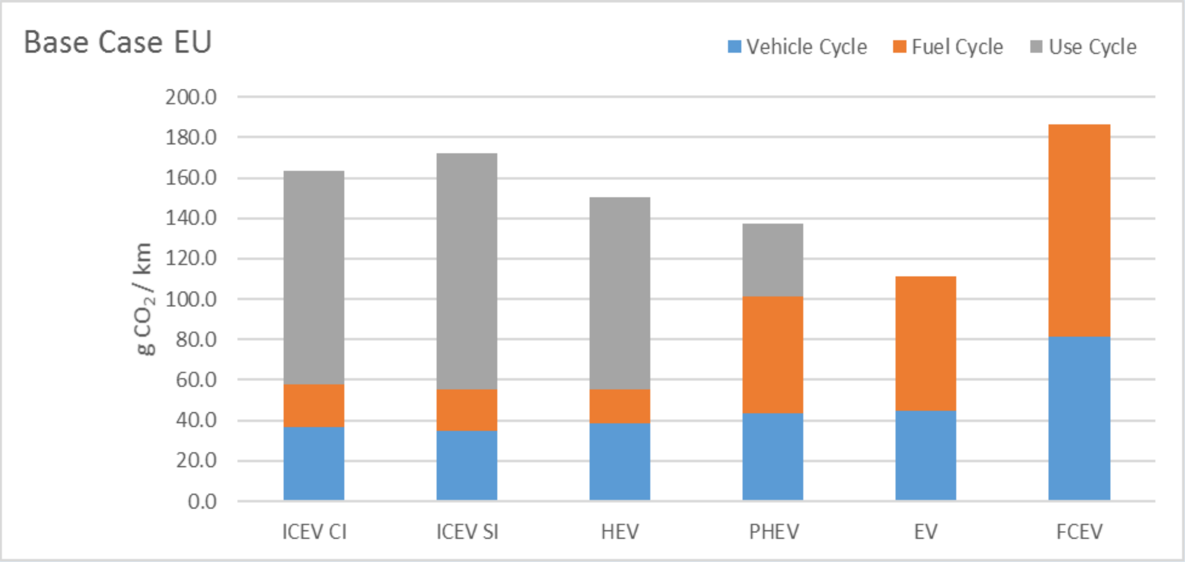
Vehicle cycle	33.4	31.7	35.1	40.2	41.4	76.9
Fuel cycle	14.4	17.0	13.9	30.1	32.1	59.1
Use cycle	106.1	116.7	95.2	36.2	0.0	0.0
Full life cycle	**153.9**	**165.4**	**144.1**	**106.5**	**73.5**	**136.0**

Figure 27: Comparison of base case results per vehicle type, gained with Austria data-set

The results for Austria show that the highest CO_2 emission intensity per km is accounted for the two ICEVs followed by the HEV. As a result of electricity production resulting low CO_2 emission in Austria, the vehicle and fuel cycles exhibit lower values for all vehicles which hence gives more significance to the use cycle emissions. For the same reason externally rechargeable vehicles exhibit significantly less emission in the fuel and use cycle. For the case of Austria, the use of EV accounts for almost a half of CO_2 emissions of the most efficient combustion engine vehicle without external recharging possibility. This significant saving of the EV in comparison to all other vehicle types covers for any higher loads of the EV in real life ([96]) and indicates that the fuel and use cycle have the most significant role in the full vehicle life cycle.

5.3.1.4 Data-set for EU

The simulation results of the selected representative vehicles with the assumption of production and use under the general conditions for resource provision of EU are presented in Figure 28.



Emissions [g CO_2 / km]						
Vehicle cycle	36.4	34.7	38.3	43.4	45.0	81.3
Fuel cycle	21.2	20.8	17.0	57.7	66.4	105.0
Use cycle	106.1	116.7	95.2	36.2	0.0	0.0
Full life cycle	**163.7**	**172.1**	**150.4**	**137.3**	**111.4**	**186.3**

Figure 28: Comparison of base case results per vehicle type, gained with EU data-set

The results for EU show that the highest CO_2 emission intensity per km is accounted for FCEV, followed by ICEV SI and ICEV CI. In analogy to the US results, the inefficient production of hydrogen causing the high fuel cycle value and the FCEV's high vehicle cycle rate caused by CO_2 intensive material composition and high curb weight are unfavorable for the FCEV's results. It is noted that results for the EU exhibit a widely spread difference between each vehicle type. The use of EV accounts for 26% less CO_2 than the most efficient combustion engine vehicle with no external electricity charging possibility. This saving of the EV in comparison to all other vehicle types may cover for the higher loads of the EV in real-life ([96]) but it still considered as a tight advantage in comparison to PHEV and HEV.

5.3.1.5 Comparison of results of all locations

An overview of simulation results for all above presented regions / countries is presented in Figure 29, including a weighted average per vehicle type. The weighted average is calculated in accordance with the vehicle market share obtained from [76] and [97]. It is noted that the FCEV is not separately evident in any of the statistics, hence for the FCEV a plain average has been calculated.

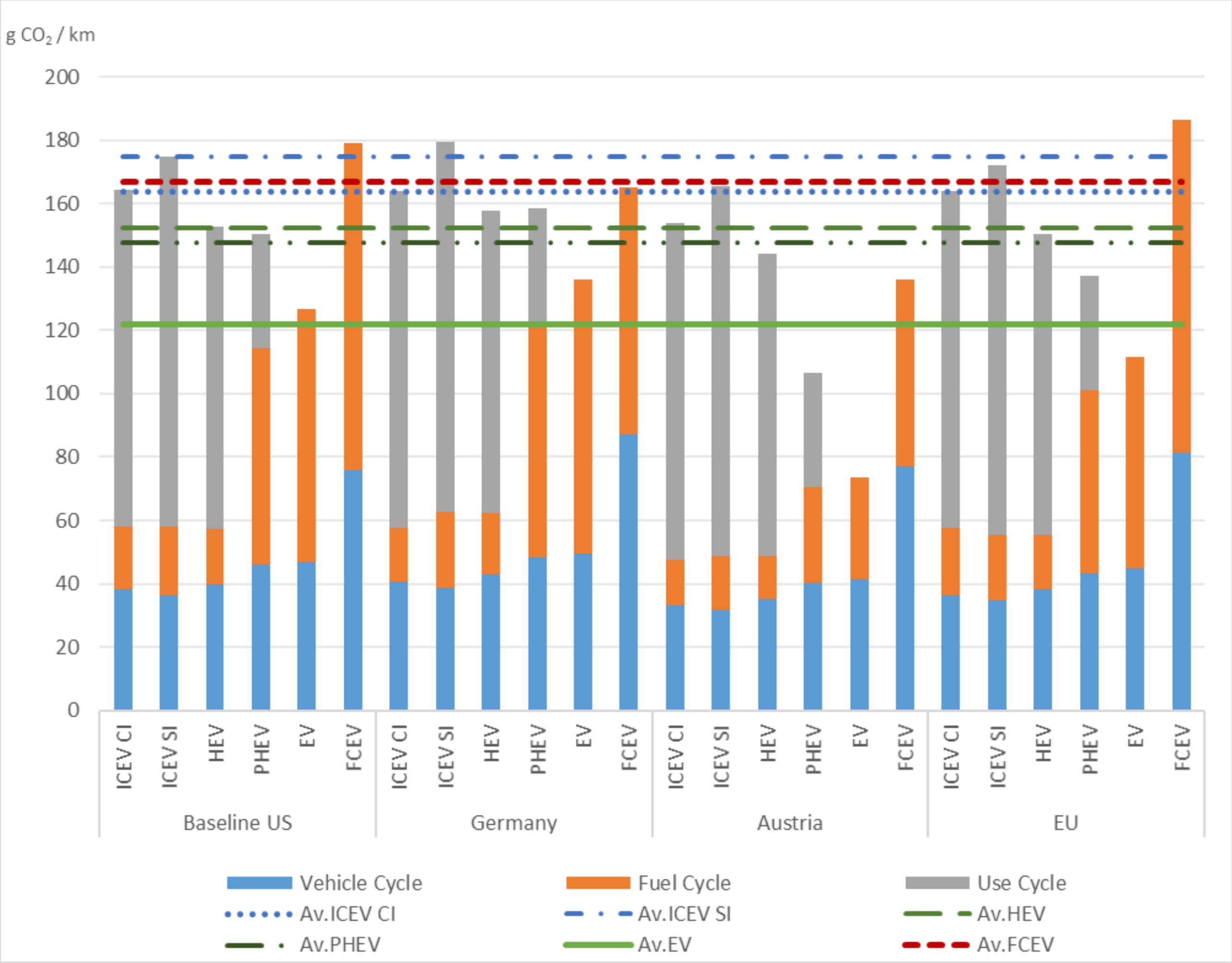


Figure 29: Overview of base case simulation results for all regions / countries

Looking at the average vehicle results, it is notable that the three most CO_2 intensive average vehicles ICEV SI, ICEV CI and FCEV are all in a 6% range of the highest average. The average FCEV emits 2% more CO_2 per km than the most efficient ICEV. A further load in the case of actual use of FCEV would be the production of hydrogen through electrolysis which according to [98] takes place using electricity with an efficiency of 70%. Combining this with the present electricity mix production, the FCEV marketed as a “zero emission vehicle” would have widely the most CO_2 intensive full vehicle life cycle. Depending on the fuel and vehicle cycle the average HEV emits 13% less than the highest average. Despite the prevalence of the charge depleting mode under the test cycle used, the PHEV emits only 3% less emission than the average HEV. The EV being the most efficient vehicle in average emits 25% less emission than the HEV as the most efficient vehicle utilizing only primary energy sources for propulsion. Full vehicle life cycle emissions of all vehicle types are in a 30% range of the most inefficient vehicle in this comparison.

Looking at the regions the most significant differences are noted for Austria which is resulting from the most CO_2 efficient mixed electricity production in this comparison. Implicitly, emissions in vehicle and fuel cycles are considerably lower than in the other countries / regions with the exception of FCEV vehicle cycle. When comparing the regions, it is noted that the variation of the vehicle cycle correlates to the variation of the electricity production mix, excluding the FCEV. The FCEV lies out of this trend because the material composition exhibits a higher rate of platinum and silicon which for the baseline data of the US reports vastly less CO_2 intensive production than the other data-sets. The trend of the vehicle cycle, combined with the electricity mix of the regions is presented in Figure 30.

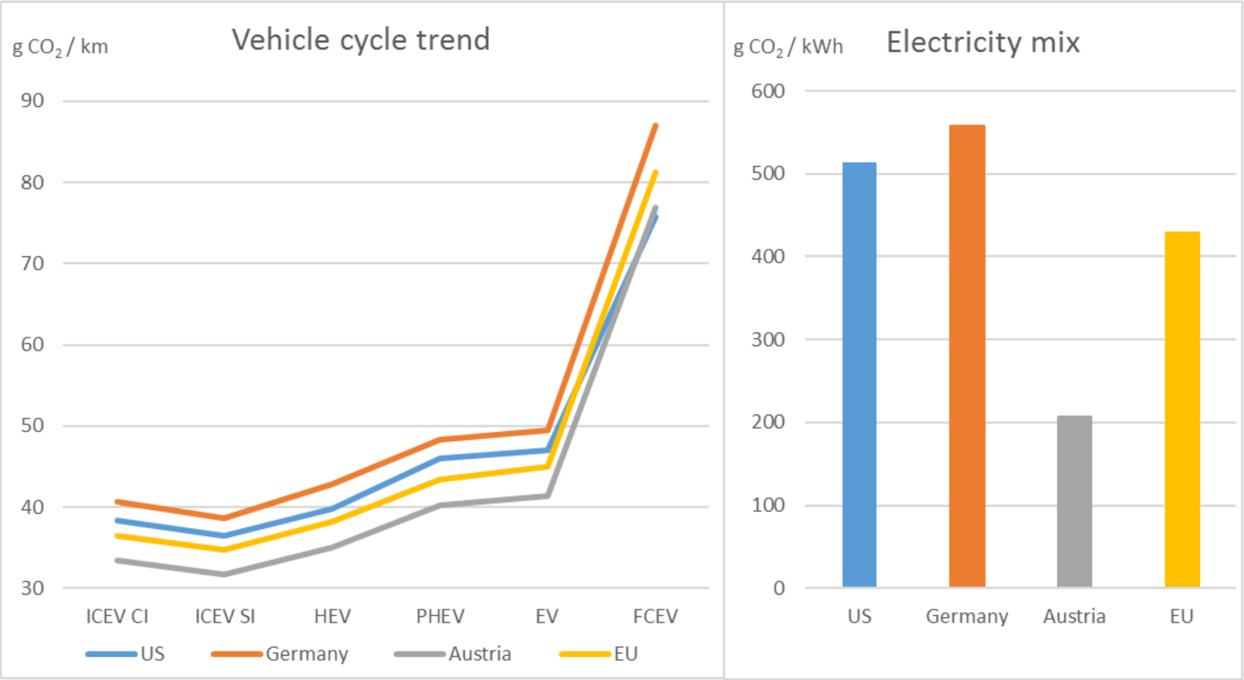


Figure 30: Overview of vehicle cycle trend and electricity mix

5.3.2 Sensitivity analysis

Combined with the data-sets surveyed, the modified ADVISOR tool enables a wide range of sensitivity analyses for the vehicles parametrized in course of this study. The following sub-chapters present sensitivity analysis for 5 different cases:

- Change of testing drive cycle
- Adjustment of the service life parameter and number of traction battery packs of externally rechargeable vehicles
- Adjustment of size / capacity of traction battery of externally rechargeable vehicles
- Traction battery data inventory
- Shares of all-electric driving range for PHEV

Considering that the series production of EVs and PHEVs is ongoing since recently and that there is only a handful of marketed models, most uncertainties concern these vehicle types as it is represented by the above cases for sensitivity analysis.

5.3.2.1 Worldwide-harmonized Light-vehicles Test Procedure drive cycle

In line with the current regulations, the NEDC represents the European type-approval procedure in accordance to which the fuel consumption and CO_2 emissions of cars are determined for the European market. The UNECE's[20] regulation concerning the definition of NEDC test procedure details "ECE 101", contains a number of flexibilities and tolerances which do not appropriately reflect the current technological developments. The EU intends to replace the NEDC with the "Worldwide-harmonized Light-vehicles Test Procedure" (WLTP) which is under development by a UNECE's working group since 2007. In 2014 a Global Technical Regulation for the WLTP was adopted were among other details the test driving cycle is defined, however, details on concerning testing of electrified vehicles have not been defined in this document [82].

To analyze the impacts of the testing procedure on the full vehicle life cycle, the driving cycle parameter has been amended in the simulation of parametrized representative vehicle. Since WLTP does not yet define the PHEV testing procedure, the shares of charge depleting and charge sustaining operating modes are applied as defined by the NEDC procedure. The results are presented in Figure 31.

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[20] United Nations Economic Commission for Europe

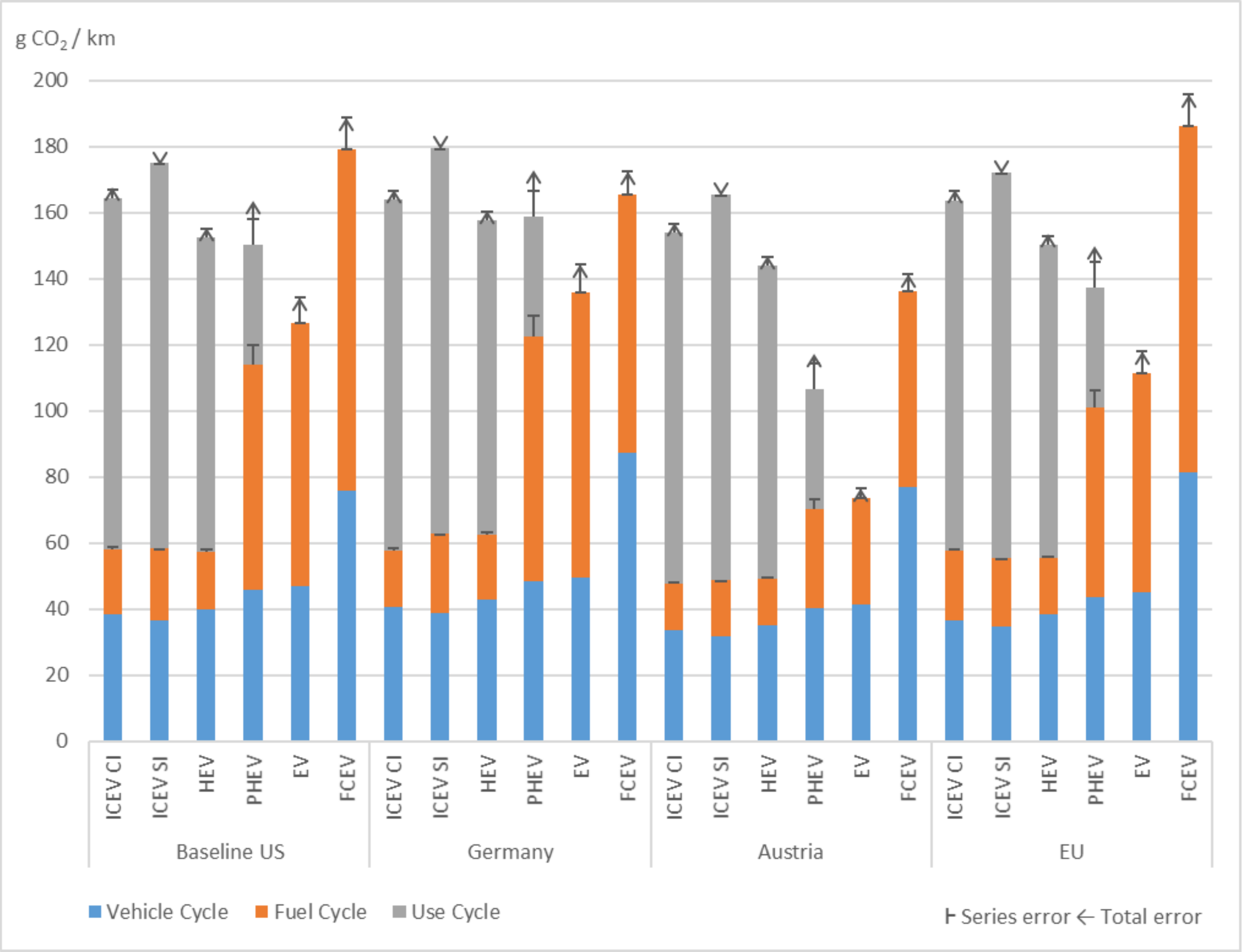

Figure 31: Overview of sensitivity against the changed testing drive cycle

Note: The diagrams presented in this and all further sensitivity analyses are based on the base case scenario represented by the stacked columns. The variations accrued through adjustment of the sensitivity parameters are represented by the error bars. Considering that the sensitivity analyses in some cases impact more than one series (vehicle, fuel or use cycle) of stacked columns, the diagrams exhibit series and total error bars. The variation of the series (vehicle, fuel and use cycle) are represented by the “series error” as labeled in the legend. The total variation of the stacked column (full vehicle life cycle) is represented by the “total error” as labeled in the legend.

The change of the drive cycle had the least effect on the consumption figures of ICEV SI, HEV and ICEV CI with an absolute change of less than 3% for all vehicle types resulting neglectable changes in the full vehicle life cycle. The simulated consumption increase for PHEV amounts 6% in charge depleting mode and for 18% in charge sustaining mode resulting in the overall average increase of 8% for the full vehicle life cycle. The EV and FCEV exhibit an excess consumption of 9% and 8%, resulting in a 5% average increase of the full vehicle life cycle. The most significant change occurs for the PHEV, as it outreaches the HEV in the case of US and HEV and ICEV CI for the case of Germany. The EV remains to have the least average CO_2 intensity per km.

Due to the change of the drive cycle, the general trend of the sensitivity analysis shows that the vehicles with a higher degree of electrification are mostly impacted. The very small absolute increase of the EV’s full vehicle life cycle in the case of Austria shows that the efficiency of the electric motor plays a largely lesser role than the CO_2 intensity of the electricity production used for propulsion. The final development of the WLTP vehicle cycle is expected with big hopes of finding a realistic solution of looking at the consumption rates, especially for hybrid vehicles as well as hoping that the environmental burden of primary energy use for electricity production will be considered in the vehicle assessment.

It is noted that efficiency maps of combustion engines and electric motors have been estimated and that the results, in general, enable an interpretation of notion what the changes will be with the implementation of WLTP.

5.3.2.2 Service life and number of battery packs

As mentioned in sub-chapter 5.1, the literature exhibits different assumptions in regard to the vehicle service life and the number of traction batteries during the life time of vehicles with externally rechargeable traction batteries. Hence, the following Figure 32 presents the impact of changing the vehicle service life to 300,000 km and accounting for one full replacement of traction batteries for externally rechargeable vehicles. Further vehicle cycle parameters such as engine oil replacements windshield fluid fill-ups and tire-sets are set to double the base case while all other parameters were left as per default.

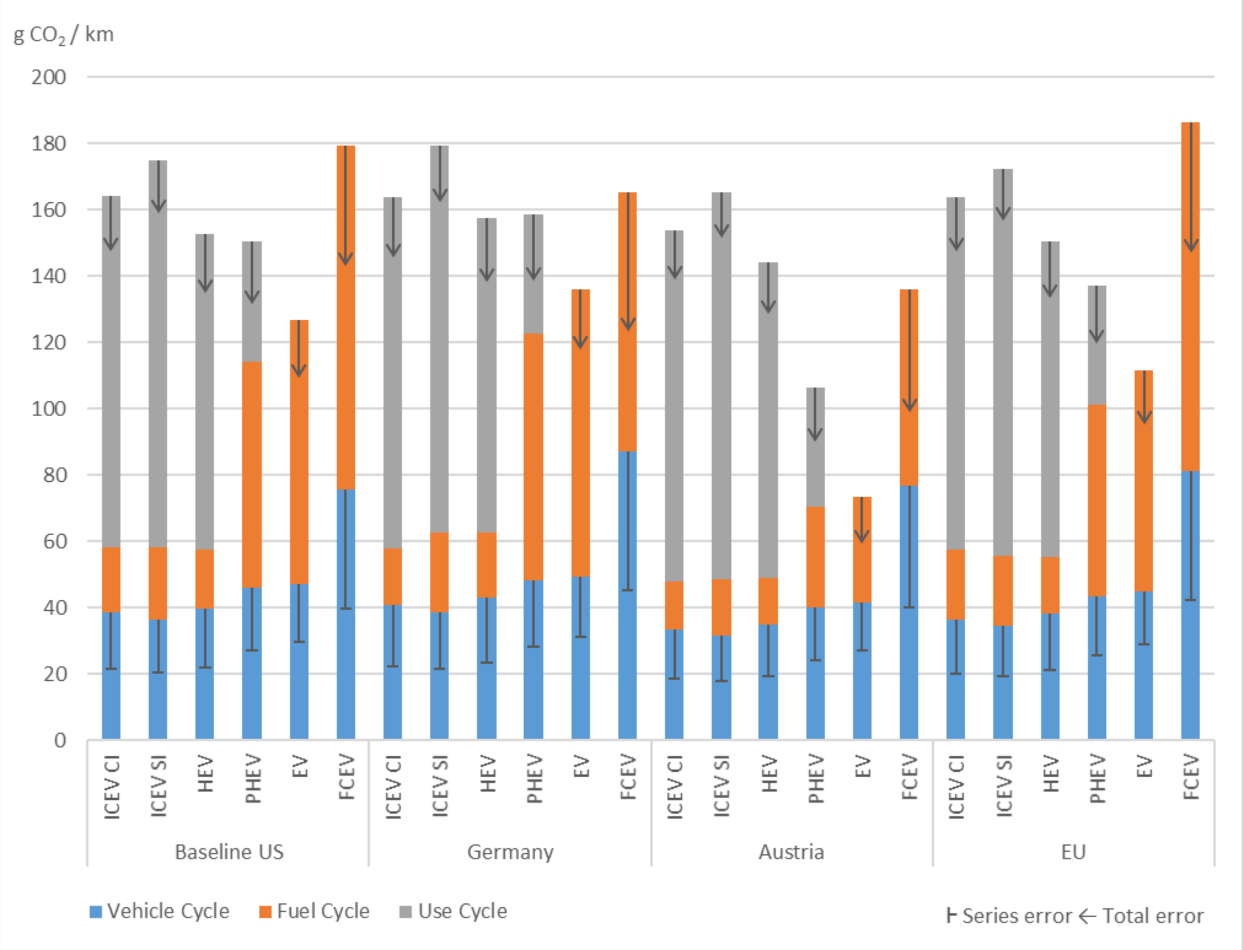

Figure 32: Overview of sensitivity in regard to the service life and a traction battery replacement

In these simulation parameter terms, the FCEV becomes less CO_2 intense than the ICEVs for the case of US and EU, and less intense than HEV and PHEV for the case of Germany while the ranking remains the same for Austria. For all other vehicle types, the change relative to the base case remains in the same range of about 16-18 g CO_2 less emission per km and vehicle type. The replacement of the traction battery pack for externally rechargeable vehicles relativizes through the extended service life and does not play a major role in the change of the full vehicle life cycle.

Hence, the assumption of double service life relativizes the impact of the vehicle cycle which is especially significant for the FCEV which implicitly only in this case becomes slightly less CO_2 intense than the ICEVs. The replacement of battery packs in combined with here assumed services life does not play a major role for externally rechargeable vehicles from the full vehicle cycle point of view.

5.3.2.3 Battery sizing of externally rechargeable vehicles

According to the NEDC testing procedure, the PHEV considered in this study can achieve an AER of 50 km [88] while the EV has a range of 199 [89]. The range of the

EV strongly constraints the vehicle usability in consideration of time efficient long-distance transportation. The main goal of the PHEV to cover daily distances with 50 km is also rather scarcely dimensioned. It is noted that the differences in the NEDC testing and the real world applicability of stated ranges are an additional constraint for the day-to-day use of the mentioned vehicles. Hence, the following figures and tables present the impact of the double capacity increase of the traction batteries for PHEV and EV. It is assumed that the nominal voltage and other general characteristics of the battery remain, whereas the capacity is increased by parallel connection of additional cells. Figure 33 presents the impacts of the double battery weight on the fuel (consumption) and vehicle (production) cycle.

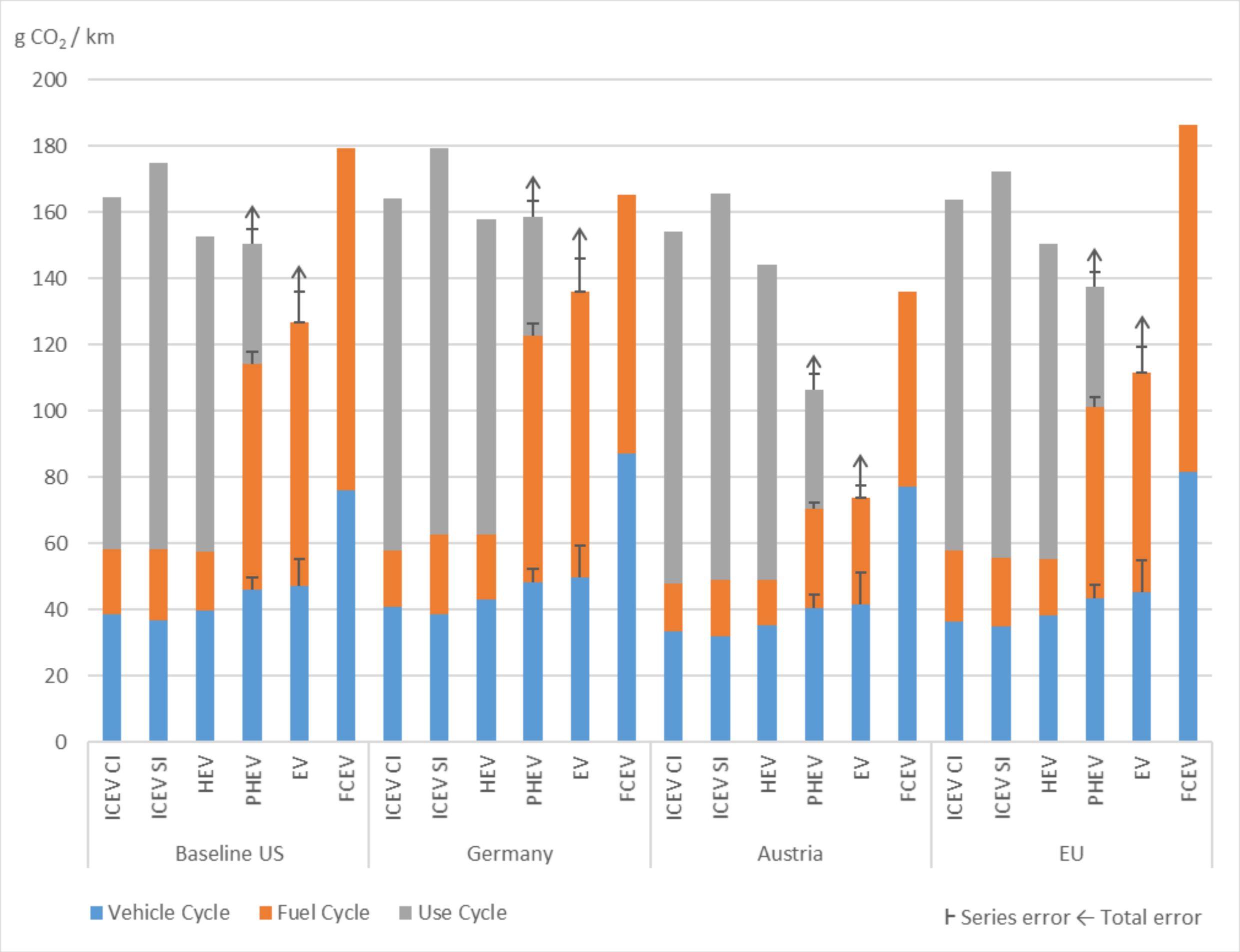

Figure 33: Overview of sensitivity in regard with enlargement of externally rechargeable battery packs

Through enlargement of battery size and capacity, the consumption increase amounts to 12% for EV, 4% and 13% for PHEV in charge depleting and charge sustaining mode. Looking at the EV, the increase in the full vehicle life cycle reaches the 1% range of the HEV for Germany, 6% range of the HEV in the US while the savings of the EV for the case EU and Austria remain over 15% compared to the HEV. The PHEV on the other side outreaches the HEV by 6% in the US, 13% in Germany and reaches the 1% range of HEV in EU while the electricity mix for Austria keeps the PHEV by 19% advantageous in comparison to HEV.

The results present a considerable trade-off in the case of enlarging the capacity and therewith the weight of the battery and vehicle. Considering the excess consumption, the EV would have a range of about 350 km which still does not represent a considerable long distance range and a full vehicle life cycle only 1% lower than the HEV for example in Germany. It is noted that the duration of the refueling process between the HEV and EV remains incomparable for the time being. The range considerations do not reflect on the core usability of PHEV, however, the outreach of the HEV in two cases (US and Germany) set its effectiveness and development effort under a question mark.

5.3.2.4 Traction battery data inventory

In course of the plausibility comparison presented in sub-chapter 4.6, the battery life cycle study [70] was identified, which finds that more emissions accrue in the upstream stage of material processing than in other comparable studies. Since the traction battery production is in constant development at the moment, it is considerably difficult to establish a comparison of the inventories used in the different studies. Nevertheless, in consideration of the significance of the work in [69], the emissions associated with the production of traction batteries presented therein are used for the following sensitivity analysis whereas the vehicle cycle data-sets are adapted in analogy to the specifications in sub-chapter 4.3. Considering that [69] takes into account in general average European conditions, the sensitivity analysis is applied only in the European context as presented in Figure 34.

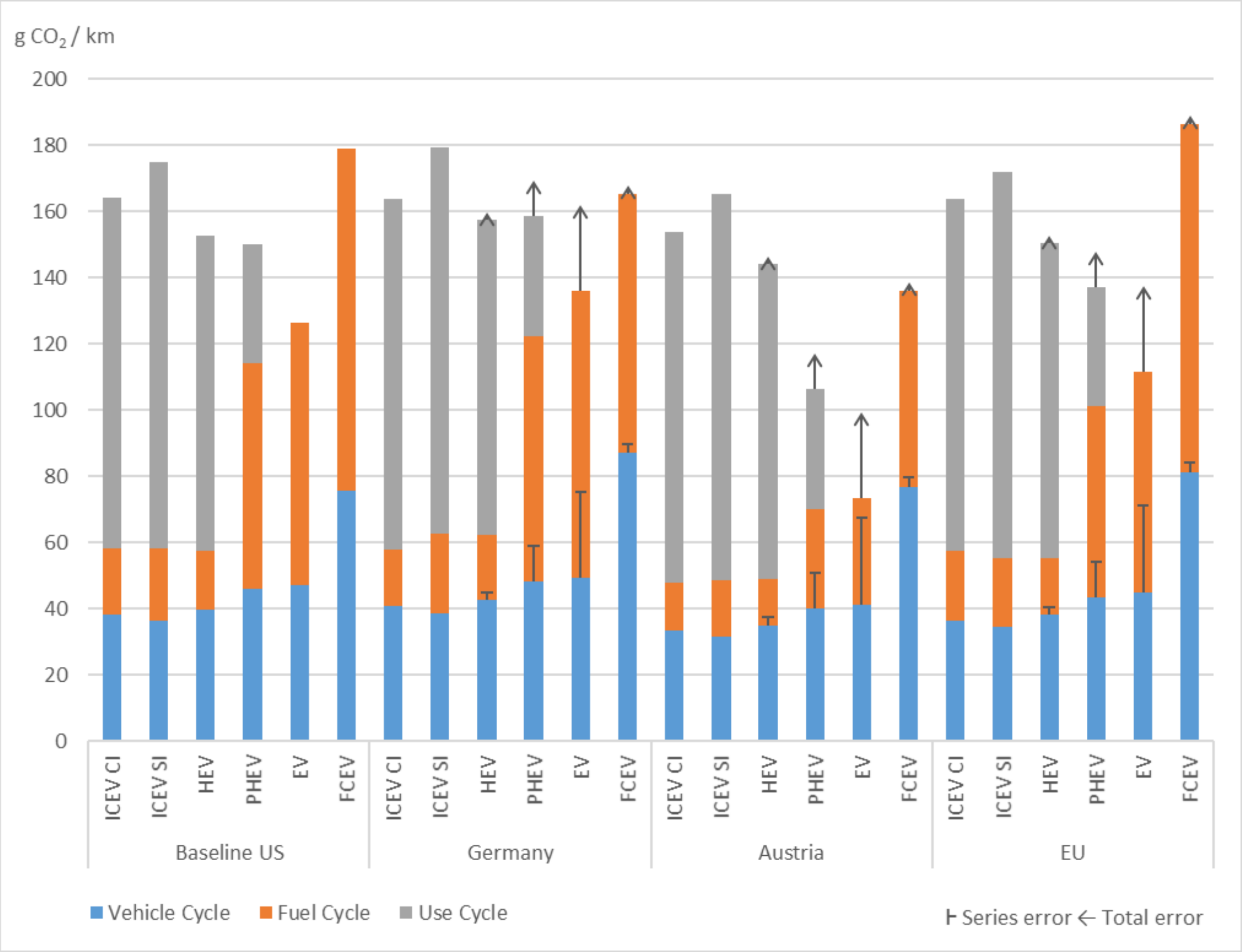

Figure 34: Overview of sensitivity in regard to the adjustment of battery data inventory

Implicitly, the results have the largest implication on the EV in accordance with its battery mass. For the case of Germany, the EV becomes more CO_2 intensive than the HEV with a total increase of 19% over the full vehicle life cycle, while the PHEV outreaches the most efficient ICEV by 3%. The relative increase in the case of Austria amounts to 35% and 10% for EV and PHEV however due to the favorable electricity mix in Austria the significant savings remain in comparison to the HEV. In the EU both the PHEV and HEV reach the 10% range of the HEV. Changes for HEV and FCEV remain neglectable for all 3 locational references.

Currently, the uncertainties of the battery production are the highest considering the rather recent mass production start and the young development stage. These uncertainties are deepening through the conclusions of the work in [69] and the results of this sensitivity analysis which present that CO_2 related impact of the EV may just be up to the height of worse than the HEV and ICEV. The case of Austria, however, denotes again the importance of the electricity production as the basis of CO_2 efficiency improvement.

5.3.2.5 Shares of all-electric driving for PHEV

The testing procedures for PHEVs are broadly different over the world, whereas the appropriacy of the above presented NEDC procedure is marked questionable, for example in [99]. As presented in [100] the main issue for fuel economy testing of PHEVs is the determination of the “utility factor” which defines the shares of charge depleting and charge sustaining operations modes within the testing cycle. Considering that the latest version of the GREET model [56] exhibits a function for determining the utility factor based on the AER of the PHEV and on the statistic of VMT, the resulting shares for 30 miles rated AER amounting to 41.3% of charge depleting operation and 58.7% of charge sustaining operation are applied for PHEV on the fuel/energy consumption figures simulated for NEDC. The impact is presented in the following Figure 35.

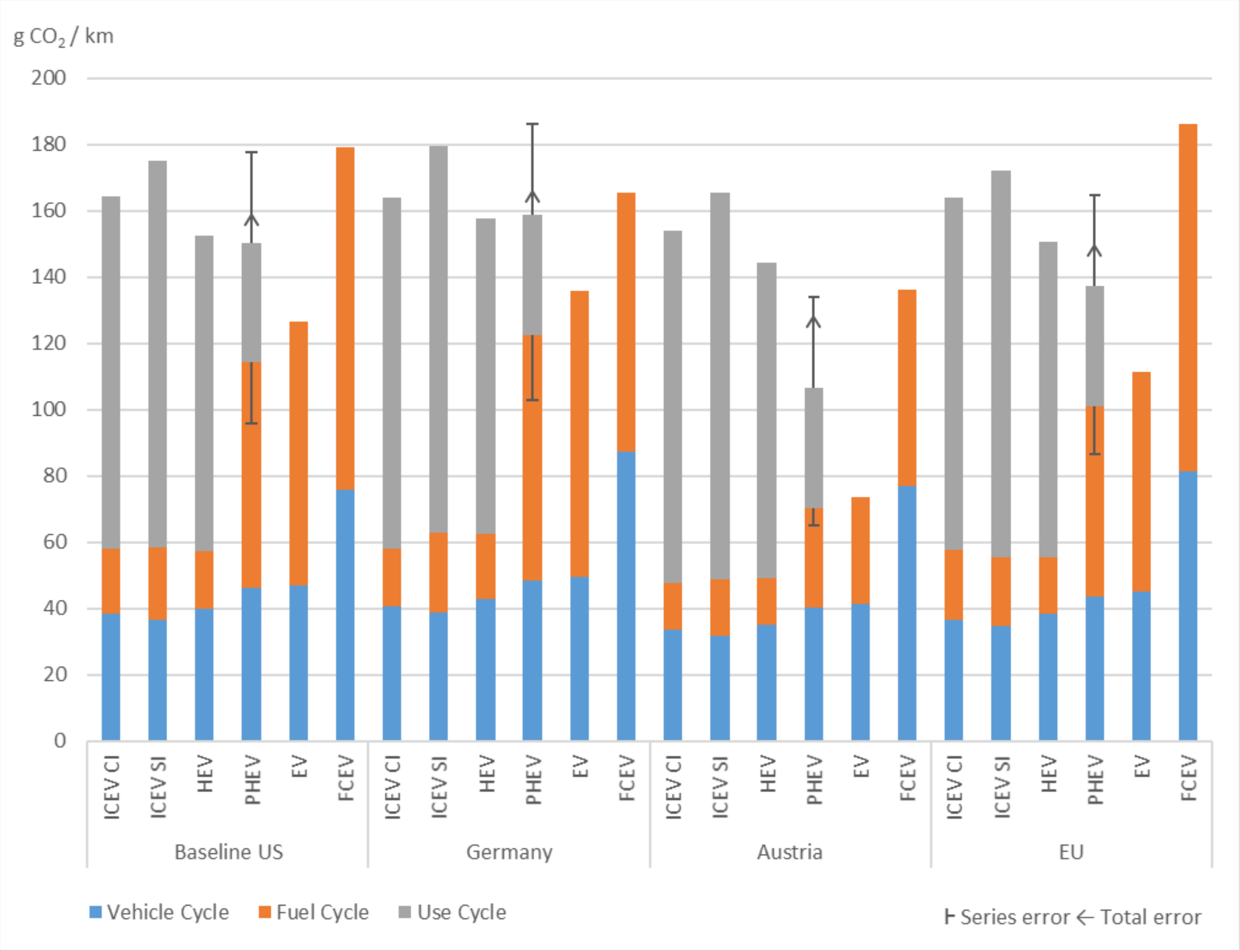

Figure 35: Overview of sensitivity in regard to changes of charge depleting and sustaining shares

Due to the increase of the charge sustaining mode in comparison to the regulation of NEDC, the fuel cycle decreases significantly because of the lower share of electricity. Consequently, the use cycle increases resulting in an overall increase of the full vehicle life cycle of 5%, 6% and 9% for Germany, US and EU as well as 20% for Austria. In these terms, the PHEV is more CO_2 intensive than HEV in US and German conditions, while it reaches almost the same value in EU and 10% range of HEV in Austria.

Testing of PHEVs is a complex topic which is rather marginally addressed with the NEDC regulations and should be comprehensively renewed with the introduction of WLTP. PHEV's CO_2 efficiency can start with being in the range of the EV or go over the ICEV depending on the individual user profile. Generalization of the driving profile, respectively defining of charge depleting and charge sustaining shares within a testing cycle on a generally applicable level is a considerably difficult task. Having in view the individuality of the user driving profile, the EPA labels PHEV separately with fuel economy figures in charge depleting and charge sustaining mode [101]. This way the consumers can at least judge if the PHEV can be accommodated to their individual driving profile with a targeted fuel economy. This, however, is not a general solution since the classification of the PHEV and respective taxation should be done within the passenger vehicle should be based on a single value.

5.4 Summary of results and sensitivity analyses

Summarizing and interpreting the base case and sensitivity analyses results, the first and most important notion demonstrated by the results is the importance of consideration of the full vehicle life cycle in the environmental assessment of alternative powertrain vehicles.

Beginning with the FCEV, a vehicle type marketed and accounted for in the European sales statistics ([76]) as a “zero emission” vehicle, which exhibits the highest CO_2 emission values in the vehicle cycle and very high values in the fuel cycle, can be classified as a rather questionable alternative powertrain solution with respect to its CO_2 emission in the full vehicle life cycle. It is noted that the results presented in this study take into account a rather optimistic scenario of hydrogen production through natural gas reforming and that a more massive use of the FCEV would probably lead to necessity of hydrogen production through electrolysis, which as stated in sub-chapter above occurs at 70% efficient use of electricity and would lead to even more CO_2 intensive values in the fuel cycle. Furthermore, the vehicle development and purchase costs need to be considered in the assessment of the effectiveness of the whole effort to deploy such an alternative powertrain in reality. In this regard a known fact is that the FCEV considered in this study, also representing one of the firstly marketed FCEV vehicles in Europe, reaches a basic purchase price of almost of 80 kEUR [91] meaning that at the present stage of development hardly any type of effectiveness can be ascertained for the FCEV.

Despite the poorly defined testing procedure in NEDC which actually puts the PHEV in a favorable position in regard to the defined utility factor, in the majority of the sensitivity cases and even in the base case for Germany, the PHEV is more CO_2 intensive than a non-externally chargeable HEV. The curb weight of this middle-class vehicle reaches almost 1,6 tons, which is some 20% more than the same vehicle model in the CI version which implies higher values of the vehicle cycle and some efficiency disadvantages which influence also the fuel and use cycle. Depending on their AER and individual driving profile of the consumer, the PHEV may just be able to cover some shorter daily distances in the mode when functioning as an electric vehicle and therewith bring the potential advantages of the EV without losing practicability for long distance ranges using the combustion engine. Considering the overall CO_2 intensity performance similar to the ones of HEV and ICEV CI, and comparing the purchase prices of the vehicles considered as an indication of affordability for more massive use, it can be ascertained that the purchase price of basic model of the PHEV is 68% and 48% higher than the ICEV CI and HEV which represents an additional detriment for serious deployment of this vehicle type.

The HEV considered in this study shows robust results in the base case and throughout the sensitivity analysis and is arguably a representative short to mid-term solution in regard to the global goals of the CO_2 intensity and considering the full vehicle life cycle. The development of the HEV is still in a relatively early stage, however, the purchase prices are in similar range to conventional vehicles whereas HEVs are meanwhile available in almost all vehicle segments.

The EV shows to have substantial potential to be the CO_2 sustainable alternative powertrain, however strongly dependent on local conditions of electricity production where the vehicle is actually in use. The example of Austria having the lowest CO_2 emission of the electricity mix in this study, shows robust results of the EV in its base case and all sensitivity analyses, reciprocating the fuel cycle. This study comprises regions with 3 similarly CO_2 intense electricity mixes (US, Germany and EU) and one with a significantly lower value (Austria). Considering that in accordance to [102], for example, the electricity mix in Poland amounts to more than a double than the EU electricity mix, the use of EV in such cases would be very contra productive in terms of

CO_2 intensity. The EVs are also marketed and accounted in the European statistics as “zero emission” vehicles. The results of this study show that the EVs can move the location of the CO_2 emissions but not significantly contribute to the global reduction of CO_2 emissions which is a global problem and irrelevant of the location of generation. Hence, the classification as “zero emission” is shown to be misleading and big hopes are raised that the introduction of the new set of regulations around the WLTP will define assessment procedures which are coordinated with the current state of technological development and among other include the fuel cycle in the overall assessment of the vehicle. An example of inclusion of the fuel cycle in the vehicle assessment is given by the German Mobility Club (ADAC) [103]. The purchase price of the basic version of the EV considered in this study is some 15% higher than the HEV and 30% higher than ICEV CI meaning that pricewise the EVs are reaching an acceptable range, however, the usability remains a detriment for a significant market share caused by the short vehicle range.

The raising of the efficiency of combustion engines is in constant development, however, its concept is bound to significant thermal losses and the physical limits of this optimization will reach its limits at some point. Nonetheless, the majority of the vehicles marketed today have some kind of hybridization / electrification level which saves or recuperates some of the energy which would be lost otherwise. In the short term the hybridization / electrification is seen as one of the solutions until the global electricity production reaches an acceptable level of renewable share and until the and efficiency at higher vehicle speeds of EVs are optimized. Having this said, in the near future it will probably be more difficult to differentiate between the ICEV and the HEV in its degree of hybridization. Hence, such studies will probably differentiate between the vehicle types only in regard to the propulsion energy source; diesel, gasoline, electricity, hydrogen or similar.

Vehicles with alternative powertrains have only recently entered mass production and their evolving development in terms of efficiency, range, production optimization and technology is notable with high expectations for further improvements. As depicted in the comparison of the vehicle cycle (Figure 30) and mentioned in several cases of the sensitivity analyses, the favorable electricity production in terms of the CO_2 is the essence of CO_2 efficiency improvement globally and in reflection to the sustainable mobility. The obviously strongly politicized movements towards the electric vehicle and declaration of the EV and FCEV as zero emission vehicles are certainly partly bound to cutting the link of regional dependencies on fossil fuels (oil) used for mobility. Introducing the star rating for vehicle environmental assessment including CO_2 efficiency for all vehicles, the ADAC went one significant step further in realistically assessing the CO_2 efficiency of the examined vehicles. According to [103], the main factor which allows a comparison between the EVs and ICEV are the CO_2 emissions from the electricity mix which ADAC takes from the German Federal Environmental Agency. In essence, the EcoTest environmental assessment protocol implemented by ADAC since 2015, includes a “class-depended” star rating scheme with threshold values for different vehicle classes (segments). Considering the vastly different electricity production pathways and implicit CO_2 intensities of the electricity mix in the different countries, it will probably be inevitable that each country applies its own electricity mix values and that vehicles are assessed differently for each country, representing the realistic circumstances. The sensitivity analyses performed to examine the robustness of the basic results against adjusting key LCA parameters show that that the EV has a robust advantage when used in regions where electricity is efficiently produced, meaning that irrelevant of technological developments and efficiency of EV the prerequisite for environmental sense of the EV and electric mobility to be called sustainable is the transformation / transition of the electricity production system towards renewable / CO_2 efficient methods.

5.5 Discussion of CO_2 reduction goals of EU

The European Commission has established a comprehensive strategy for reduction of GHG emissions where transportation and mobility emissions are addressed with high importance with the latest update of the White Paper for Transport called “Roadmap to a Single European Transport Area – Towards a competitive and resource-efficient transport system”. This roadmap provides general guidelines, goals and benchmarks for reduction of emission related to transportation based on which the European Commission has put a set of regulations providing emission target values for the new car fleets until 2020.

According to [76], the goal of the new car vehicle fleet of 130 g CO_2 / km for 2015 has been achieved already in 2014 where the new car vehicle fleet emits in average 123,3 g CO_2 / km. These statistics consider EVs as zero emission vehicles, granting them “super-credits” by counting them with a multiplication factor in the vehicle fleet statistic.

The share of EVs in the overall passenger vehicle sales is 0,3%, which means that around 37,500 EVs have been sold in 2014 and that in the sum of 12,513,670 vehicles the EVs count as 93,750 vehicles, considering that super-credits multiplier factor was 2.5 for 2014 [104]. If we roll-back the statistic with the assumption that the EV examined in this study represents an average EV and consider the fuel cycle of the EU base case scenario, the average fleet emission would raise for 0,4 g CO_2 / km, which is a rather insignificant value. The small increase of the CO_2 emission when including the fuel cycle for EV reflects, of course, the very small market share of 0,3%. Hence, it can be concluded that the average vehicle CO_2 reduction can be credited only to the optimization of ICEVs and HEVs.

Interpolating the results of the 2010 and 2014 average fleet emissions (141 g CO_2 / km and 123,3 g CO_2 km, [76]) we can say that in average a progress of 4.4 g CO_2 / km was made per year. In expectation of a more significant EV market penetration required to achieve the 2020 fleet emission goal, following scenarios for further developments are conceivable:

- In the Scenario 1 (S1) it is assumed that the average progress of 4.4 g CO_2 / km will reduce to a half in 2017 and to one-fifth in 2020, interpolating the values in-between;
- In the Scenario 2 (S1) it is assumed that the average progress of 4.4 g CO_2 / km will continue to 2020 in the same extent.

The following Figure 36 presents the market share increase of EVs until 2020 required to achieve the 95 g / CO_2 goal with both scenarios, however, including the fuel cycle interpolated for each year according to electricity mix for EU taken from GEMIS[21]. The projection in Figure 36 below assumes a stagnation of the vehicle sales (as one of the goals in the White Book for Transportation is fostering of efficient public transportation) and that the NEDC consumption of the EV examined in this study represents the average and also remains stagnating until 2020.

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[21] Processes: el-generation-mix-EU-27-2010 (PRIMES) and el-generation-mix-EU-27-2020 (PRIMES)

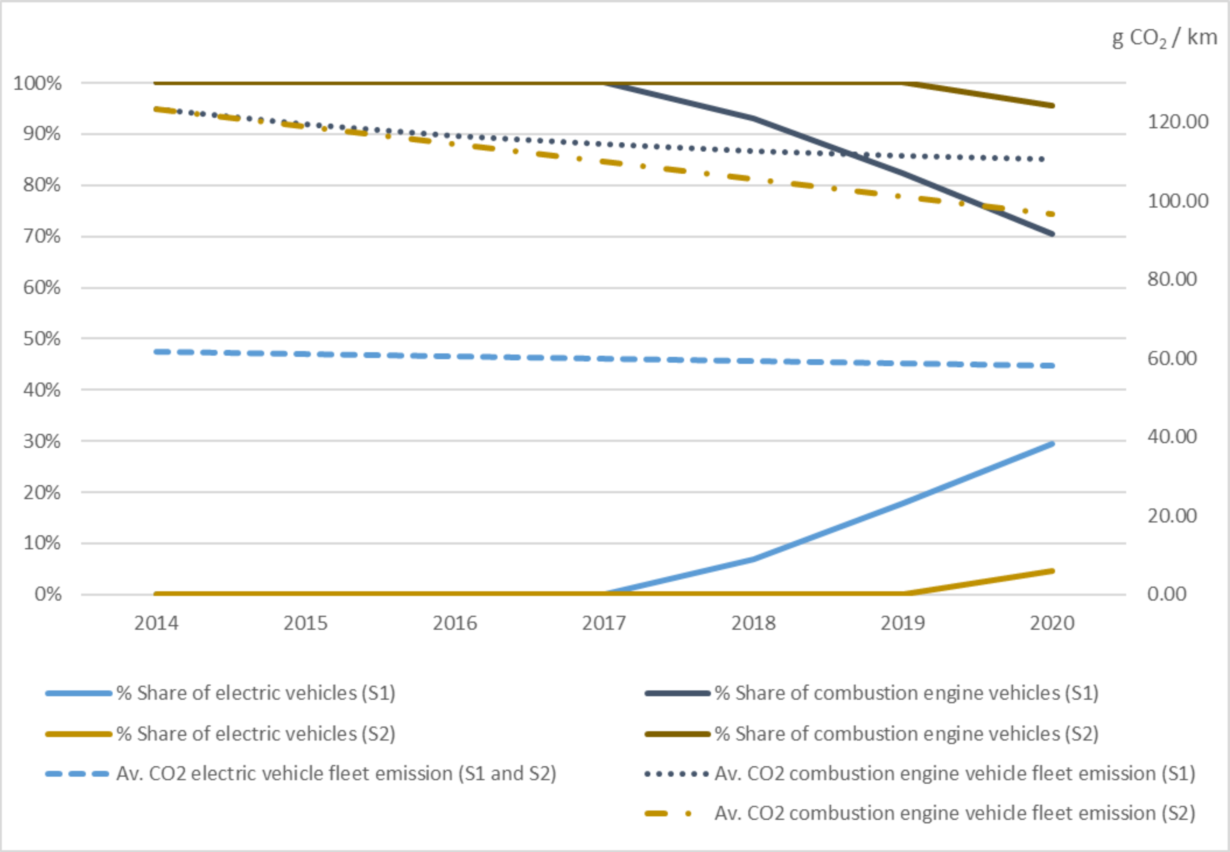

Figure 36: Projection of combustion engine vehicles and electric vehicles average fleet CO_2 emission and respective market shares to reach the 2020 average fleet CO_2 emission goal

The assumed progress of CO_2 efficiency improvement of the combustion engine vehicles requires an insignificant market share of electric vehicles until 2017 for S1 and even until 2019 for S2 for achieving the 2020 CO_2 emission fleet goal. In the S1 case, the market share of electric vehicles after 2017 would have to exhibit very significant increase to 6,7% in 2017, 17,75% in 2019 and 29,5% in 2020. In the S2 case, the share of electric vehicles needs to rise in the period from 2019 to 2020 when it should reach a value of 4.5% to reach to 2020 CO_2 emission fleet goal. The EU regulation provides a certain extent of flexibility in the first years of the implementation of the 2020 goals [76], however, all relieves including super-credits will be annulled in 2023. It remains very exciting to see what developments will stimulate the selling number of EVs to that extent or if extraordinary discoveries for optimization of combustion vehicles are found which will enable reaching the CO_2 emission target without significant market share increase of EV.

6 Summary, critical reflection and outlook

Considering the life cycle methodology, vehicle simulation, emission and vehicle cycle modeling, this work has encompassed the most relevant influencing variables for resourceful calculation of the full vehicle life cycle, and by furnishing the comprehensive data inventory with respect to the CO_2 emission, the resources for the analysis the CO_2 footprint of vehicles with conventional and alternative powertrains in various scenarios.

The enhanced vehicle simulation tool incorporating and combining the vehicle cycle and fuel cycle with the typical vehicle simulation outputs (use cycle) was developed to provide results expressed as grams of CO_2 emissions per vehicle kilometer for the full vehicle life cycle. The underlying data inventories were collected for 4 geographical regions; the United States, European Union, Germany and Austria, enabling a comparison between the regions and countries and gaining an overall overview of the current state. Vehicles leading the market share of the C segment representing the conventional internal combustion engine vehicle in a spark ignition and compression ignition version, hybrid electric vehicle, plug-in hybrid electric vehicle, electric vehicle and fuel cell vehicle were parametrized, simulated and analyzed on sensitivity with regard to adjustment of vehicle and life cycle parameters in addition to analysis of differences between the regions.

In the overall, the results show that out of all alternative powertrains considered, the electric vehicle has the most potential to make CO_2 sustainable mobility possible. However, considering the current state of electricity generation, the sustainability of electric vehicle is strongly dependent on local conditions of electricity generation where the vehicle is actually in use. The current state in most of the geographical regions considered shows a rather small share of CO_2 efficient electricity generation hindering the electric vehicle to significantly weigh-in to the reduction of CO2 emissions, especially when considering the full life cycle of the vehicle. The fuel cell vehicles show rather high CO_2 emission values in the full vehicle life cycle in most of the analyzed cases even higher than the conventional vehicles. A unique assessment of externally rechargeable (plug-in) hybrid electric vehicles seems, in general, to be an arguably difficult task considering that these vehicles can operate as electric vehicles for a certain range and otherwise as hybrid electric vehicles. Nevertheless, the analysis showed that in most of the cases such a powertrain combination may not provide optimal results looking at the full vehicle life cycle. The hybrid electric vehicle showed robust results throughout the analysis cases and is arguably a representative short to mid-term solution in regard to the global goals of the CO_2 intensity and considering the full vehicle life cycle. The conventional combustion engine vehicles considered did not exhibit large variances to the benchmarks of alternative powertrains. The European vehicle market statistics convey that the CO_2 efficiency of the combustion engine vehicles has significantly progressed over the last 5 years and that crediting these improvements the compliance with the current fleet CO_2 reduction goals has been achieved.

Concluding with addressing the regulations surrounding the vehicle certification and assessment which categorizes electric and fuel cell vehicle as “zero emission” vehicles, the results of this study show that such categorization is far from reality and that such a development will not contribute to the global reduction of CO_2 emissions as the most prevalent Greenhouse gas. The study has presented that in certain extreme cases, the use of the “zero emission” vehicles, compared to conventional vehicles, can even be contra productive in terms of CO_2 emissions. Being a part of the above-mentioned regulations, the “new” European driving cycle and accompanying procedures are predominantly outdated and do not reflect on the current state-of-the-art and technological developments in the sector. The driving cycle itself does not match the actual average driving profile which leads to vast deviations in the real life use of vehicles. Putting this aside, the lack of regulated detailed procedures for assessment of alternative vehicle types such as externally rechargeable and hybrid vehicles and especially ignoring the emissions of primary energy conversion into electric or chemical energy (fuel cycle) which than locally provides no emission in case of electric and fuel-cell vehicles does not contribute to the achievement of global emission reduction goals. Hopes are rising that the completely new set of regulations which should be effective universally and worldwide called “Worldwide-harmonized Light-vehicles Test Procedure” will reflect realistically on the assessment of emissions related to the use of primary energy which is then used for propulsion in any of the feasible forms.

The European strategy outlining the emission reduction goals compiled in the “White Paper for Transport” conveys a clear message of attempting to cut the links of European dependency on imported fossil fuels, which leaves electric powertrains as the solution of choice. However, accordant to the current state of electricity generation this does not imply realistic achievement of CO_2 reduction goals and therewith contributing to keeping the global warming in foreseen limits.

Finally, the study provides a rough estimate of a possible scenario development in the vehicle market, concluding that in order to achieve the European vehicle fleet goal 2020 of 95 g CO_2 / km, assuming that the average European fuel cycle is considered, the market share of electric vehicles will have to increase from 0.3% in 2014 29,5% in 2020 in a scenario where the efficiency improvement of combustion engine vehicles decreases. In case the improvement of combustion engine vehicle continues linearly as progressed between 2010 and 2014, the market share of the electric vehicles can remain insignificant until 2019 and raise to 4.5% in 2020 to reach the 2020 fleet goal. The regulations foresee a phasing-in period of 3 years for this strict goal to be mandatory to its full extent meaning that the exact compliance with this goal can be maximally postponed to 2023. The frame of this projection is coherent with the global projections for electric vehicles elaborated by the International Energy Agency in [105].

Nevertheless, as an outlook, it remains very exciting to see what developments will stimulate the selling numbers of electric vehicles to that extent or if extraordinary discoveries for optimization of combustion vehicles are found, enabling the reaching of the CO_2 emission target without significant market penetration of electric vehicles.

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Appendix A Detailed Description of ADVISOR Modification

Analogously to the documentation provided for ADVISOR, this Appendix provides a detailed documentation of the amendments made in ADVISORS's Matlab source code. The documentation is structured following the simulation flow, respective input and output data.

General

During the implementation of the "ADVISOR modification", the basic structure of ADVISOR has been followed including its paths and variable definitions. The following Table A-1 presents the list of prefixes used in "Advisor modification" source code.

Table A-1: Prefixes added in course of the modifications

Prefix	Meaning	Used in
vlc	Vehicle Life Cycle	Calculations
wtp	Well to Pump	Calculations
use	Use cycle	Calculations
Lbl	Label	GUI
cmd	Button	GUI
cbo	Check box	GUI
txt	Text field	GUI
ddl	Drop down list	GUI
eax	Prefix used to deviate from Advisor's variables	GUI

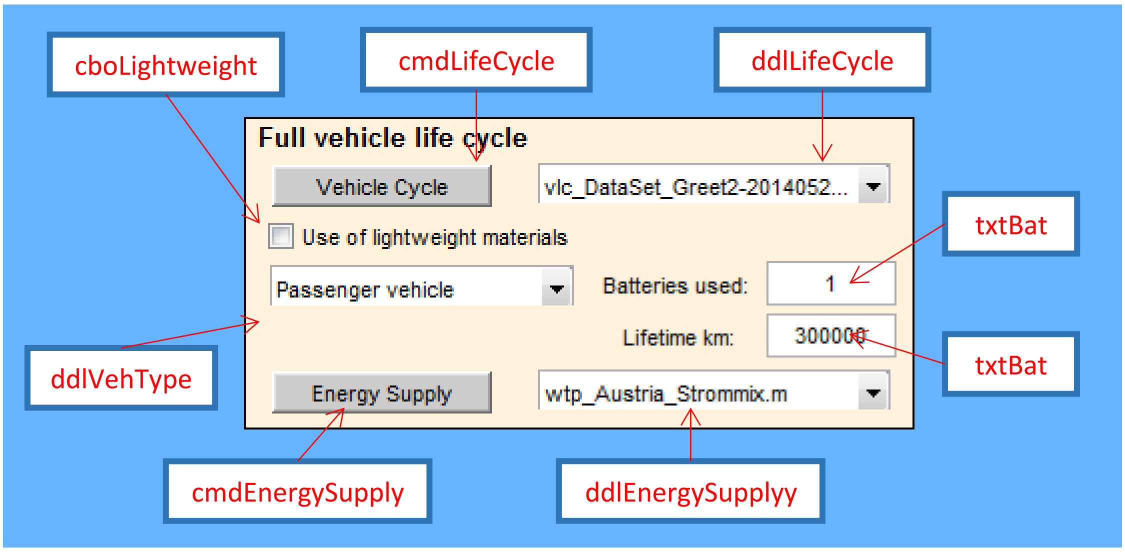
The folder structure of ADVISOR was extended by three new folders:

- The folder "advisor/extras" contains an additional folder named "LifeCycleCalculation", indicating the Vehicle Life Cycle Calculation as the modification of ADVISOR. This folder contains the functions which calculate the emission as it will be presented in further text.
- The folder "advisor/data" contains an additional folder named "vehicle_life_cycle". This folder contains the spreadsheet data-sets needed for calculation of the vehicle life cycle and a template folder with the defined pattern file inside.
- The folder "advisor/data" contains one more additional folder named "fuel cycle". This folder contains all m-files in which the fuel cycle CO_2 factors are specified for different energy supply scenarios.

Simulation Parameters window

Editing of basic simulation parameters and selection of the data-sets to be processed in the calculations which are presented in the chapter 4.3 of the main document are enabled through amendments of the GUI within the “SimSetupFig.fig” file and the code and callback of functions in the “SimSetupFig.m” file, both located in ‘<advisor>/gui’ directory as described below.

The GUIDE figure file of the Simulation setup “SimSetupFig.fig”, was amended with user interface (UI) elements and corresponding tags which are required to address the desired elements in code. The amended frame with UI elements and tags is depicted in Figure A-1.



vlc_DataSet_Greet2-2014052...

☐ Use of lightweight materials

Passenger vehicle

Batteries used: 1

Lifetime km: 300000

wtp_Austria_Strommix.m

Figures A-1: Interface elements added to the Simulation Setup GUI

The management of the spreadsheet data sets and wtp m-files was established with the means of the buttons “cmdLifeCycle” and “cmdEnergy Supply” which trigger the files management “FileList” pop-up window (described separately).

Callback functions on buttons are displayed below. First, the pop-up window is initialized after which the execution is frozen via *waitfor()* until the pop-up window is closed. File list is refreshed after that. The callback functions are presented in List 1.

…

```
% --- Executes on button press in cmdLifeCycle.
function cmdLifeCycle_Callback(hObject, eventdata, handles)
% hObject    handle to cmdLifeCycle (see GCBO)
% eventdata  reserved - to be defined in a future version of Matlab
% handles    structure with handles and user data (see GUIDATA)
h = FileList({'vlc'});
waitfor(h);
refreshFileList('vlc');

% --- Executes on button press in cmdEnergySupply.
function cmdEnergySupply_Callback(hObject, eventdata, handles)
% hObject    handle to cmdEnergySupply (see GCBO)
% eventdata  reserved - to be defined in a future version of Matlab
% handles    structure with handles and user data (see GUIDATA)
h = FileList({'wtp'});
waitfor(h);
refreshFileList('wtp');
…
---------------------------------------------------------------------------
```

List 1: “SimSetupFig.m” – added file management functions

Other interface elements serve just for passing of basic parameters to the function. The parameters passed are described in Table A-2.

Table A-2: Interface elements used for passing parameters

Tag name	Description / Returned value
ddlLifeCycle	The path of the spreadsheet file selected in the lists is passed as basic parameter to the “vlc_calculation.m.”
ddlEnergySupply	The path of the matlab file selected in the lists is passed as basic parameter to the “wtp_calculation.m.”
cboLightweight	Boolean is returned to determine if data for lightweight materials shall be used
ddlVehType	Returns an integer for the corresponding type of vehicle
txtBat	Returns the edited integer with number of batteries changed in vehicle lifetime
txtKm	Returns the edited integer with number of kilometers for which the vehicle lifetime is defined

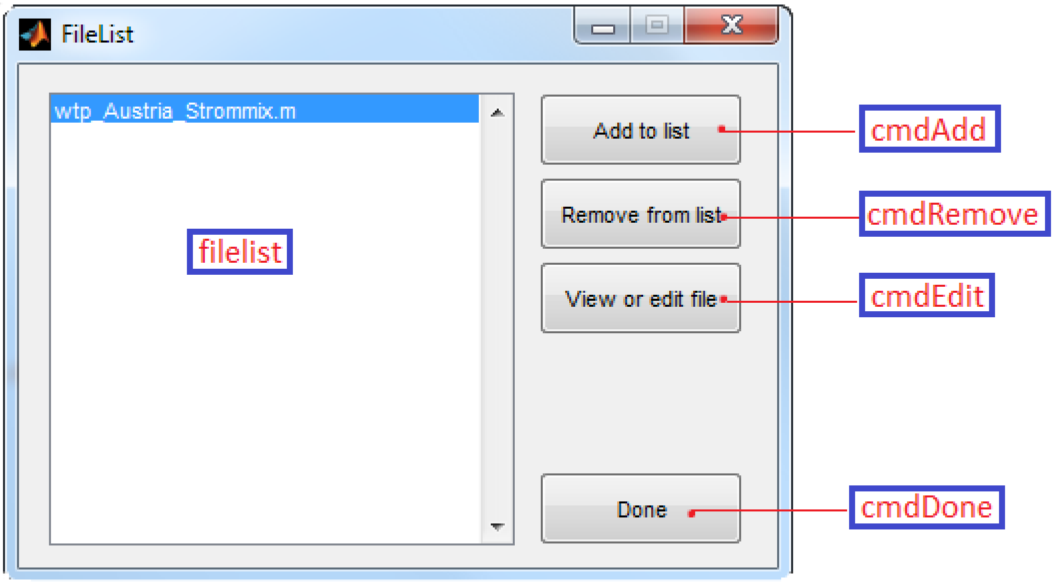
Correspondingly, the ”RUN” button callback function had to be modified so that it collects data from the new elements of the “Vehicle life cycle” GUI frame and to pass the parameters and invoke the calculation function which is based on that input. The calculation function “vlc.calculation.m” is described in detail in the section Vehicle Cycle. Vehicle mass is loaded from workspace while other parameters are collected from UI elements using “`get()`“ function. Calculation result and “Lifetime km:” (txtKm) values are exported as global variables in order to be used later. Function “`waitbar()`“ is used for progress bar implementation. The implementation of the callback in source code is presented in List 2.

```
global vinf
global eax_lc_dataset_file
global eax_dataset_path
global vlc_result
global vlc_km
eax_mass = evalin('base','veh_mass');
eax_lightweight = get(handles.cboLightweight, 'Value');
disp('milestone');
passenger_commercial_type = get(handles.ddlVehType, 'Value');
batteries_changed = str2num(get(handles.txtBat, 'String'));
addpath('extras/lifeCycleCalculation');
disp('vlc_calculation called with:');
eax_lc_dataset_file
eax_lightweight
eax_mass
passenger_commercial_type
batteries_changed

global eax_wtp_dataset_file
global eax_wtp_dataset_path
path = getPath('wtp');
contents = cellstr(get(handles.ddlEnergySupply,'String'));
file = contents{get(handles.ddlEnergySupply,'Value')};
eax_wtp_dataset_path = path;
eax_wtp_dataset_file = file;

path = getPath('vlc');
contents = cellstr(get(handles.ddlLifeCycle,'String'));
file = contents{get(handles.ddlLifeCycle,'Value')};
eax_lc_dataset_path = path;
eax_lc_dataset_file = [path file];
evalin('base','global eax_lc_dataset_path');

wHndl = waitbar(0.25,'Performing vehicle life cycle calculation...');
vlc_result = vlc_calculation(eax_lc_dataset_file, eax_lightweight, eax_mass,
passenger_commercial_type, batteries_changed)
vlc_km = str2num(get(handles.txtKm, 'String'));
evalin('base','global vlc_result');
evalin('base','global vlc_km');
waitbar(1);
pause(0.5);
close(wHndl);
…
---------------------------------------------------------------------------
```

List 2: “SimSetupFig.m” – amendment of the RUN button callback function

FileList.fig file

The management of the vehicle and fuel cycle data-sets was established with pop-up windows. The functionality of the tags is very straight forward and enables basic functions of file management. The GUIDE figure file, representing the pop-up window is illustrated in the Figure A-2 with its elements and tag names.



Figures A-2: Interface elements added to the Simulation Setup GUI

FileList.m file

The added FileList.m file is a standard file generated by the GUIDE, slightly modified for the needed features such as parsing of input parameters as well as button callbacks to enable files manipulation. Considering that the major part of the code has been automatically generated none of the code lists are presented.

Vehicle cycle

After the required data coming from GREET and ADVISOR had been defined (chapter 4.3 of the main document) and means developed to pass the data to the calculation function, the consequent step was to implement the GREET2 vehicle cycle calculation. The vehicle cycle calculation was implemented as a typical Matlab function invoked in the “SimSetupFig.m” file as other ADVISOR functions. The developed function was named “vlc_calculation.m” and located in the “<advisor>/extras/lifeCycleCalculation” directory.

The basic concept was to load the look-up tables from spreadsheet data-sets to Matlab, with the names of rows and columns saved as separate vectors. This way a value from the look-up table can be retrieved by entering the name of emission of indicator for the desired value. The Matlab function “find()” was used to retrieve the position of the specified emission of indicator from the vector where the column or row names are saved. This process of retrieving values enables easy identification of the emission values used in the calculation, considering that GREET provides a large number of types of emissions and that the calculation should be easily extendable.

Hence, the implementation of the GREET calculation in Matlab starts with loading vectors with names of materials and emissions as well as corresponding values from the defined spreadsheet data-sets. As given in the following code list the Matlab function “`xlsread`” was used for loading the text fields with names of emissions and materials from the spreadsheet as cell arrays in Matlab. The loaded strings were consequently trimmed with the “`strtrim`” function in order to avoid any precision problems. Given that this code is repeatedly used for loading all defined data from the spreadsheet data-sets, only example code lines are shown in List 3.

```
…
[ob_nums, vlc_mats, ob_raw] = xlsread(vlc_excelValues,'Materials', 'B1:BH1');
% Vector with all calculated materials used in production of vehicles
…
[ob_nums, vlc_tEm, ob_raw] = xlsread(vlc_excelValues,'Materials','A9:A19'); %
Vector with names of emissions caused during the production of materials used
in vehicle production
…
vlc_tEm = strtrim(vlc_tEm);
…
----------------------------------------------------------------------------
```

List 3: “vlc_Calculation.m” – Loading Vector with types of materials and emissions.

After loading the values from vehicle cycle data-sets was completed, the next step was to import the necessary values from ADVISOR. Since the ICEV does not have a battery pack, the battery mass was not passed as a function parameter but imported as presented below. ADVISOR does not have an explicit variable for the battery mass but calculates the mass as the product of number of battery modules and the mass of the battery module. Considering that the calculation was replicated into Matlab code exactly as processed in the model, the vehicle mass is converted to pounds as the basic mass unit in the GREET model. The “`evalin()`” Matlab function was used to evaluate if the variables were existing in the specified workspace in Matlab and if required to import the variable into the current workspace of the calculation. Importing of values and mass conversion is presented in List 4.

```
…
ess_module_mass_exist = evalin('base','exist(''ess_module_mass'')');
ess_module_num_exist = evalin('base','exist(''ess_module_num'')');
if (ess_module_mass_exist==1 && ess_module_num_exist==1)
ess_module_mass_value = evalin('base','ess_module_mass');
ess_module_num_value = evalin('base','ess_module_num');
vlc_battery_mass = ess_module_num_value*ess_module_mass_value;
end;

vlc_mass = vlc_mass/0.45359237;
…
----------------------------------------------------------------------------
```

List 4: “vlc_Calculation.m” – Loading and processing main input variables from ADVISOR

ADVISOR's input interface foresees a set of "vinf" variables which define the basic configuration of the vehicle. The developers of ADVISOR deprecated the use of variable "vinf.drivetrain" as defined in the load file "drivetrain config", because the variable name was not consistently used and therefore statements in the gui.post.proces code did not work properly. For this reason and in order to avoid the general risk for calculations to rely on manual input of variables, it was decided that vehicle types shall be determined according to the component types which must be predefined during the Simulation Setup. Following three variables were used and imported to achieve this:

- *ess_max_ah_cap (maximum A-h capacity the ESS can have, no matter how slowly it is drained)* each vehicle with energy storage system must have a variable with the maximum capacity of the ESS.
- *fc_fuel_map (fuel use indexed by fc_map_spd and fc_map_trq)* each vehicle with a fuel converter must have a fuel use matrix.
- *fc_fuel_type (description of fuel type)* each fuel converter must have a clearly defined fuel type

Importing and assigning values to these specific variables is shown in code List 5.

```
…
ess_max_ah_cap_exist = evalin('base','exist(''ess_max_ah_cap'')');
if (ess_max_ah_cap_exist==1)
ess_max_ah_cap_value = evalin('base','ess_max_ah_cap');
end;
ess_max_ah_cap_exist
fc_fuel_map_exist = evalin('base','exist(''fc_fuel_map'')');
fc_fuel_map_exist
fc_fuel_type_ext = evalin('base','exist(''fc_fuel_type'')');
if (fc_fuel_type_ext==1)
  vlc_fc_fuel_type = evalin('base','fc_fuel_type');
end;
…
---------------------------------------------------------------------------
```

List 5: "vlc_Calculation.m" – importing values for determination of vehicle type

The following code list exhibits the determination of vehicle type in accordance with the existence or values of the above imported variables. The first if-statement determines if the vehicle is commercial or passenger on hand of the variable passed from GUI, while all other if statements were used to determine the type of the simulated passenger vehicle. The code List 6 is well documented under every if-statement and clarifies the statements in details.

```
…
global vlc_vehicleType
```

```
if (passenger_commercial_type==1)
if (ess_max_ah_cap_exist==0 && fc_fuel_map_exist==1)
    %if a battery does not exist and a fuel map exists = ICEV
   vlc_vehicleType = 'ICEV';
    disp('VLC Modul detected ICEV as the vehicle modeled');
end;
if (ess_max_ah_cap_exist==1 && fc_fuel_map_exist==0)
    %if a battery exists and a fuel map does not exist = EV
    vlc_vehicleType = 'EV';
     disp('VLC Modul detected EV as the vehicle modeled');
end;
if (ess_max_ah_cap_exist==1 && fc_fuel_map_exist==1 &&
strcmp(vlc_fc_fuel_type, 'Hydrogen')==1)
    %if a battery exists and a fuel map exists and the type fuel is Hydrogen
= FCV
    vlc_vehicleType = 'FCV';
     disp('VLC Modul detected FCV as the vehicle modeled');
end;
if (ess_max_ah_cap_exist==1 && fc_fuel_map_exist==1 &&
strcmp(vlc_fc_fuel_type, 'Hydrogen')==0 && max(ess_max_ah_cap_value)<25)
    %if a battery exists and a fuel map exists and the type fuel is NOT
Hydrogen and the battery capacity is lower than 25 Ah = HEV
    vlc_vehicleType = 'HEV';
    disp('VLC Modul detected HEV as the vehicle modeled');
end;
if (ess_max_ah_cap_exist==1 && fc_fuel_map_exist==1 &&
strcmp(vlc_fc_fuel_type, 'Hydrogen')==0 && max(ess_max_ah_cap_value)>=25)
    %if a battery exists and a fuel map exists and the type fuel is NOT
Hydrogen and the battery capacity is lower than 25 Ah = PHEV
    vlc_vehicleType = 'PHEV';
    disp('VLC Modul detected PHEV as the vehicle modeled');
end;
if (vlc_vehicleType==0)
    disp('VLC ERROR: Undefined vehicle type - the Vehicle Life Cycle
calculation will not be executed')
end;
evalin('base', 'global vlc_vehicleType')
end;

if(passenger_commercial_type==2);
    disp('The Data for Commercial vehicle is not existing, but has a foreseen
placeholder in the spreadsheet dataset form');
    vlc_vehicleType = 'C_ICEV';
end;
…
---------------------------------------------------------------------------
```

List 6: “vlc_Calculation.m” – determination of the vehicle type

The GREET2 Model incorporates the life cycle calculation of the lightweight construction of different vehicle types as well. Hence, this option has also been incorporated into the ADVISOR calculation. The vehicle type variable is concatenated by the “`strcat()`” function with the lightweight variable if use of lightweight materials has been considered by enabling the respective checkbox in the Simulation Setup figure. The stated procedure is given in code List 7.

```
…
if vlc_lightweightBoolean
```

```
    vlc_lightweight = '_light';
    disp('VLC Modul detected use of lightweight materials');
else
    vlc_lightweight = '';
end;
…
vlc_vehType_lw = strcat(vlc_vehicleType, vlc_lightweight);
---------------------------------------------------------------------------
```

List 7: “vlc_Calculation.m” – processing of the lightweight parameter

Table A-3 provides the shares of the vehicle material composition for conventional and lightweight construction scenarios.

Table A-3: Vehicle Material Composition in percent of vehicle weight, excluding batteries and fluids

	ICEV	ICEV light	HEV	HEV light	PHEV	PHEV light	EV	EV light	FCV	FCV light
Steel	62.9%	30.7%	64.8%	33.1%	64.3%	34.0%	65.5%	21.7%	58.9%	19.9%
Stainless Steel	-	1.0%	-	0.8%	-	0.8%	-	-	3.4%	2.8%
Cast Iron	10.3%	3.5%	7.1%	3.3%	7.2%	3.4%	2.0%	2.9%	1.7%	2.5%
Wrought Aluminum	1.9%	6.7%	1.3%	5.8%	1.2%	4.8%	1.5%	6.9%	2.3%	6.3%
Cast Aluminum	4.5%	14.1%	5.9%	14.2%	6.7%	15.1%	5.6%	15.9%	3.5%	12.9%
Copper/Brass	1.9%	3.1%	3.9%	4.8%	4.5%	5.1%	5.8%	7.3%	3.3%	4.3%
Zinc	-	-	-	-	-	-	-	-	-	-
Magnesium*	0.0%	0.4%	0.0%	0.4%	0.0%	0.3%	0.0%	0.4%	0.0%	0.4%
Glass	3.0%	3.3%	2.7%	2.9%	2.5%	2.6%	3.1%	3.1%	3.0%	3.4%
Average Plastic	11.3%	14.2%	10.4%	12.5%	9.8%	12.3%	11.9%	15.4%	11.9%	13.7%
Rubber	2.2%	2.9%	1.8%	2.5%	1.9%	2.4%	1.7%	2.6%	2.0%	2.7%
Carbon Fiber-Reinforced Plastic	-	16.1%	-	15.5%	-	14.8%	-	18.3%	-	19.8%
Carbon Fiber-Reinforced Plastic for High Pressure Vessels	-	-	-	-	-	-	-	-	5.8%	4.8%
Glass Fiber-Reinforced Plastic	-	1.8%	-	1.9%	-	2.0%	-	2.6%	0.6%	2.7%
Nickel*	-	-	-	-	-	-	-	-	1.63 E-06	1.33 E-06
Perfluorosulfonic acid (PFSA)	-	-	-	-	-	-	-	-	0.1%	0.0%
Carbon Paper*	-	-	-	-	-	-	-	-	0.2%	0.1%
Polytetra-fluoroethylene	-	-	-	-	-	-	-	-	0.2%	0.2%
Carbon & PFSA Suspension*	-	-	-	-	-	-	-	-	-	-
Platinum *	4.94 E-06	8.58 E-06	4.50 E-06	5.13 E-06	4.78 E-06	5.32 E-06	-	-	1.50 E-05	1.23 E-05
Silicon	-	-	-	-	-	-	-	-	0.1%	0.1%
Carbon*	-	-	-	-	-	-	-	-	0.0%	0.0%
Others	2.0%	2.3%	2.1%	2.4%	1.9%	2.2%	2.8%	3.1%	2.8%	3.2%

*Note: The share of the material is smaller 0,05%

After the basic data-sets had been loaded and the required function input parameters processed, the next step was to calculate the weight of the materials used in the production of vehicle components depending on the vehicle mass value provided from ADVISOR simulation. Variables and loaded look-up tables (matrices) used for the calculation are given in Tabel A-4.

Table A-4: List of variables used for calculation of share of each material used in the vehicle production

Variable name	Type	Unit	Description
vlc_mass	Scalar	Lb	Vehicle mass provided as the function parameter
vlc_matComp_v	Matrix	%	Values of material composition of the vehicle components per vehicle type, in percent, loaded from the spreadsheet data-set
vlc_matComp	Cell Array	-	Names of materials used in the production of vehicle components, loaded from the spreadsheet data-set
vlc_vehicles	Cell Array	-	Names of vehicle types which can be simulated, loaded from the spreadsheet data-set
vlc_vehType_lw	Char	-	Definition of vehicle type including the option of lightweight materials use
vlc_tireReplacements	Scalar	No	Number of tire replacements loaded from the spreadsheet data-set
vlc_tireSteel_value	Scalar	%	Share of steel used to produce a tire, loaded from the spreadsheet data-set
vlc_tireRubber_value	Scalar	%	Share of rubber used to produce a tire, loaded from the spreadsheet data-set
vlc_wByMat_v	Vector	Lb	Results of the calculation: weight (in pounds) of each material used in the production of vehicle components

As presented by the code List 8, the calculation multiplies the vehicle mass with the percent share of the material used for the production of vehicle components. The percent share of material is taken from the loaded look-up table via the “`find()`” and “`strcmp()`” functions which return the position of the specified material from the “vlc_matComp” vector and determined vehicle from the “vlc_vehicles” vector. The values in the result vector “vlc_wByMat_v” for steel and rubber have added values, taking into account the replacement of tires including the tire material weights.

```
…
vlc_wByMat_v = [vlc_mass*vlc_matComp_v(find(strcmp(vlc_matComp, 'Steel')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
    vlc_mass*vlc_matComp_v(find(strcmp(vlc_matComp, 'Stainless Steel')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
    vlc_mass*vlc_matComp_v(find(strcmp(vlc_matComp, 'Cast Iron')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
…
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
    vlc_mass*vlc_matComp_v(find(strcmp(vlc_matComp, 'Others')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)))];
…
---------------------------------------------------------------------------
```

List 8: “vlc_Calculation.m” – weight of each material used in the production of vehicle components

After the weight of the materials used for production of vehicle components had been calculated, the next step was to calculate how much emissions emerge in the production of these materials. This calculation is based on the loaded look-up table containing the values for emissions in grams per pound of material product. The variables needed in addition to the ones described by now are given in Table A-5.

Table A-5: List of variables used for calculation of emission for each material used in the vehicle production

Variable name	Type	Unit	Description
emissionTypes	Cell Array	-	Specification of emission types used in calculation of total emission in the GREET2 Model. This is an auxiliary variable used to repeat the coded calculation for the specified emission types
vlc_mats	Cell Array	-	Names of all materials specified in the Materials sheet of the spreadsheet data-set
vlc_tEm	Cell Array	-	Names of all emissions specified in the Materials sheet of the spreadsheet data-set
vlc_tEm_mat_v	Matrix	g/lb	Matrix with values of total emissions per material product, in grams per pound, loaded from the spreadsheet data-set
vlc_totalEmissions_components_values	Vector	g	Results of the calculation showing the total emission in grams per all vehicle components produced

Considering that one of the assumptions for development of this calculation was its straightforward extendibility, the calculation delivers results for all emission types as available in the GREET2 Model, as presented in the code List 9. The Matlab functions "`find()`" and "`strcmp()`" were used again to retrieve the values from the look-up tables.

```
…
emissionTypes = {'VOC', 'CO', 'NOx', 'PM10', 'PM2.5', 'SOx','BC', 'OC','CH4',
'N2O', 'CO2', 'CO2 (VOC, CO, CO2)', 'GHGs'};

for i= 1:13
   vlc_totalEmissions_components_values(i) =
vlc_wByMat_v(find(strcmp(vlc_matComp,'Steel')))*vlc_tEm_mat_v(find(strcmp(vlc
_tEm,emissionTypes(i))), find(strcmp(vlc_mats, 'Average Steel')))+...
    vlc_wByMat_v(find(strcmp(vlc_matComp,'Stainless
Steel')))*vlc_tEm_mat_v(find(strcmp(vlc_tEm,emissionTypes(i))),
find(strcmp(vlc_mats, 'Stainless Steel')))+...
    vlc_wByMat_v(find(strcmp(vlc_matComp,'Cast
Iron')))*vlc_tEm_mat_v(find(strcmp(vlc_tEm,emissionTypes(i))),
find(strcmp(vlc_mats, 'Cast Iron')))+...
…
vlc_wByMat_v(find(strcmp(vlc_matComp,'Carbon')))*vlc_tEm_mat_v(find(strcmp(vl
c_tEm,emissionTypes(i))), find(strcmp(vlc_mats, 'Graphite')));
end
…
-----------------------------------------------------------------------------
```

List 9: "vlc_Calculation.m" – calculation of emission for all vehicle components

In order to be able to complete the calculation for the vehicle cycle it remains to determine the emissions which arise through the production of traction and starter batteries and to retrieve the values for vehicle ADR and Fluids which are loaded from the spreadsheet data-set. Main assumptions for the calculation of the battery emissions were presented in the data specification (chapter 4.3) and the battery mass value was imported as mentioned in the code List 4. Variables used in this calculation, in addition to the ones presented thereto are listed in Table A-6.

Table A-6: List of variables used for calculation of emissions associated with the traction battery

Variable name	**Type**	**Unit**	**Description**
vlc_battery_mass	Scalar	kg	The battery mass retrieved from the simulation setup variables in ADVISOR
batteries_changed	Scalar	No	Number of batteries changed in the vehicle lifetime
vlc_tractionBatery TotalEmission_values	Matrix	g/kg-battery	Total emissions for Li-Ion batteries, in grams per kg of battery, loaded from the spreadsheet data-set
vlc_starterBatery TotalEmission_values	Matrix	g	Values of total emissions for Lead-Acid batteries, in grams per vehicle lifetime, loaded from the spreadsheet data-set
vlc_CO2value_ bateryTotalEmission	Scalar	g	Result of the calculation showing the total emission in grams per all vehicle components produced

The code List 10 presents the handling of the possible battery types in different vehicle configurations. If the battery mass variable exists, the emission values are calculated by addition of the value for starter batteries and traction batteries. The value for traction batteries is gained by multiplying the battery mass, number of battery packs changed and the retrieved emission value. For the case of ICEV, where no battery packs exists except lead-acid batteries, the final emission value for the batteries contains only the values for the Lead-acid battery.

```
…
if exist('vlc_battery_mass', 'var')
vlc_CO2value_bateryTotalEmission =
vlc_LiIon_bateryTotalEmission_values(find(strcmp(vlc_tEm,'CO2')),
find(strcmp(vlc_vehicles,
vlc_vehType_lw)))*batteries_changed*vlc_battery_mass+...
    vlc_LeadAcid_bateryTotalEmission_values(find(strcmp(vlc_tEm,'CO2')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
disp('Calculation for Li-ion and Lead-Acid Batteries');
else
    vlc_CO2value_bateryTotalEmission =
vlc_LeadAcid_bateryTotalEmission_values(find(strcmp(vlc_tEm,'CO2')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
disp('only Lead Acid batteries in use');
end;
…
---------------------------------------------------------------------------
```

List 10: "vlc_Calculation.m" – calculation, retrieving values for battery emissions

Summarizing the calculation, Table A-7 and code List 11 describe the resulting variables of the calculation.

Table A-7: List of resulting variables of the "vlc_calculation"

Variable name	Type	Unit	Description
vlc_CO2value_ totalEmissions_components	Scalar	g	Value of CO2 emissions for components, per vehicle lifetime, retrieved from the calculated for vehicle components
vlc_CO2value_ vehADRtotalEmission	Scalar	g	Value of CO2 emissions for ADR, per vehicle lifetime, retrieved from the loaded look-up table
vlc_CO2value_ vehFludisTotalEmission	Scalar	g	Value of CO2 emissions for Fluids, per vehicle lifetime, retrieved from the loaded look-up table
vlc_C02value_ vehicleLifetime	Scalar	g	Total CO2 emissions accrued through production of the vehicle and needed ADR and Fluids

```
…
vlc_CO2value_totalEmissions_components =
vlc_totalEmissions_components_values(find(strcmp(vlc_tEm,'CO2')));
vlc_CO2value_vehADRtotalEmission =
vlc_vehADRtotalEmission_values(find(strcmp(vlc_tEm,'CO2')));
vlc_CO2value_vehFludisTotalEmission =
vlc_vehFludisTotalEmission_values(find(strcmp(vlc_tEm,'CO2')),
find(strcmp(vlc_vehicles, vlc_vehType_lw)));
…
vlc_C02value_vehicleLifetime = vlc_CO2value_totalEmissions_components +
vlc_CO2value_vehADRtotalEmission + vlc_CO2value_bateryTotalEmission +
vlc_CO2value_vehFludisTotalEmission;
…
  vlc_result = [vlc_C02value_vehicleLifetime;
      vlc_CO2value_totalEmissions_components;
      vlc_CO2value_vehADRtotalEmission;
      vlc_CO2value_bateryTotalEmission;
      vlc_CO2value_vehFludisTotalEmission;]
…
---------------------------------------------------------------------------
```

List 11: "vlc_Calculation.m" – final calculations and

As presented by the final calculation code above, the result of the function "vlc_result" is a vector that contains variables as specified and described. According to the main implementation assumption, the calculation delivers results for other emissions and emission indicators as well. However, in this stage of development only results for CO2 emissions are further processed. The presentation of the results and the export-feature is described together with the amendments of the Results Figure in following sections.

Calculation of direct and indirect emissions

As mentioned in the chapter 4.3 of the main document, the life cycle assessment implemented in this ADVISOR modification has three main parts: vehicle cycle, use cycle (direct emissions) and fuel cycle (indirect emissions of fuel provision). After completion of the vehicle cycle calculation as presented in the sections above, the remaining use and fuel cycle are presented in this chapter. Fuel economy for EV, FCEV and PHEV is not handled originally in ADVISOR so that simply fuel economy figures could be taken and multiplied with CO2 coefficients. Nevertheless, the calculation relies on the simulation results of ADVISOR, which provide enough information to calculate exact fuel economy figures. The calculation for both use and fuel cycle had been implemented in a single function called "wtp_use_calculation.m", which is invoked in the "ResultsFig.m" file as presented in further sections. The function file itself is located in the "<advisor>/extras/lifeCycleCalculation" directory.

The function is structured so that in its beginning it imports and calculates all variables needed to determine the vehicle fuel economy and in the other part it applies corresponding coefficients or factors according to the vehicle type and fuel used. Table A-8 gives an overview of all variables used in the calculation of CO2 emission in use and fuel cycle.

Table A-8: List of variables in used for calculation of the CO2 emission in use and fuel cycle

Variable name	**Type**	**Unit**	**Description**
Vinf	Char	-	Drivetrain as specified by the simulation setup
fc_fuel_type	Char	-	Description of fuel type
fc_fuel_rate	Vector	g/s	Fuel converter fuel use in grams per second
Distance	Vector	m	Time vector containing the distance the vehicle had traveled
ess_pwr_out_a	vector	W	Power out of ess available
ess_pwr_loss_a	vector	W	The actual power loss for the energy storage system
ess_coulombic_eff	scalar	-	Average Coulombic efficiency of the energy storage system (ESS)
ess_stored_kj	scalar	kJ	Energy stored in the energy storage system over the drive cycle
ess_eff	scalar	%	Round-trip efficiency
vehicle_type	Char	-	Type of vehicle as defined by the vlc_calculation function
fuel_const	Scalar	*	Direct CO2 emission associated with combustion of fossil fuels
fuel_density	Scalar	*	Density of the used fuel type
simConsumption	Scalar	g	Fuel used over the drive cycle defined in the simulation
simDistance	Scalar	m	Distance the vehicle has travelled through the defined drive cycle
simTime	Scalar	s	Time vector defined by the drive cycle
wtp_fuel Consumption_gPm	Scalar	g/m	Average fuel consumption in grams per meter travelled
wtp_CO2_value	Scalar	g/-	Indirect CO2 emission associated with the production of the fossil fuel – well to pump, as defined by the wtp –m-files
EnergyOut_J	Scalar	J	Total energy out of the energy storage system
gridEfficiency	Scalar	%	Loss of energy consumed from the grid during the battery charging process
totalEnergyOut_KWh	Scalar	KWh	Conversion of the EnergyOut_J variable to KWh and multiplication with Grid Efficiency
energyFromUsed H2_kWHpSim	Scalar	KWh	Conversion of the fuel use by the means of net calorific value of hydrogen
use_GkmVal	Scalar	g/km	Resulting CO2 emissions associated with the use cycle in

			gram per kilometer
wtp_GkmVal	Scalar	g/km	Resulting CO2 emissions associated with the fuel cycle in gram per kilometer
Electricity Conusmption	Scalar	KWh/ km	Average electricity consumption of the EV or PHEV in KWh/100km
Hydrogen Consumption	Scalar	KWh/ km	Average hydrogen consumption of the FCEV in kg/100km
* the units vary depending on the fuel type, the units are stated in the code comments for each value assignment			

The variables had been imported the same way as presented in the vlc_calculation, with the `evalin()` Matlab function. Since every vehicle must achieve a certain distance, the existence statement was not needed for the distance vector. The “fc_fuel_rate” vector saves the amount of fuel used in grams for each second the simulation has run. In order to calculate the overall fuel consumption in the simulation, the `sum()` Matlab function was used to add up all the elements of the vector. The vector “distance” is time vector, which on the other hand saves the number of travelled meters each second of the simulation. Therefore, the distance travelled over the simulation is provided with the `max()` function, returningthe maximum value of the given vector. Finally, the average fuel consumption over the simulation was calculated as a raw value in gram per meter distance, as presented by the code List 12.

```
…
fc_fuel_rate_exists = evalin('base','exist(''fc_fuel_rate'')');
if (fc_fuel_rate_exists)
    simConsumption = evalin('base','fc_fuel_rate'); %g/s
    if (sum(simConsumption)>0)
    simConsumption = sum(simConsumption); %g/Simulation
    end
end %importing variables for calculation
…
simDistance = evalin('base','distance'); %importing variables for calculation
simDistance = max(simDistance); % m/Simulation
…
wtp_fuelConsumption_gPm = simConsumption/simDistance;
…
---------------------------------------------------------------------------
```

List 12: “wtp_use_calculation.m” – importing variables and calculation consumption

In the remaining part of the function the fuel economy is calculated for the type of vehicle simulated in accordance with “vehicle_type” variable, existing already from the vlc_calculation. The values for direct CO2 emission associated with combustion of fossil fuels and the fuel density values were defined in the main document (chapter 4.2). The resulting variables are fed to the resulting vector at the end of the function.

Use and fuel cycle for ICEV and HEV

ICEV and HEV represent the simplest cases as they have typically only fossil fuel as energy source. Actually, only for these types of vehicles ADVISOR presented the consumption of respective fuel before this modification. Since it was required to develop the calculation for other types of vehicles, the fuel consumption calculation was also developed for ICEV and HEV to provide code consistency and means to control the calculation. According to the fossil fuel specified by the simulation setup, the coefficients for direct and indirect emissions and fuel density are loaded in the corresponding variables. The statements above were implemented as given by the List 13.

```
…
if (strcmp(vehicle_type, 'ICEV') || strcmp(vehicle_type, 'HEV'))
    if (strcmp(fuel_type, 'Gasoline'))
        fuel_const = 2361.52; %gCO2/l, See Masters thesis document for source
        fuel_density = 1.34 ; %l/kg
        wtp_CO2_value = wtp_C02_ConventionalGasoline_gL;

    elseif (strcmp(fuel_type, 'Diesel') || strcmp(fuel_type, 'Deisel'))
        fuel_const =  2626.62; %gCO2/l
        fuel_density = 1.20; %l/kg
        wtp_CO2_value = wtp_C02_ConventionalDiesel_gL;
    elseif (strcmp(fuel_type, 'LPG'))
        fuel_const = 65.70*3.6; %gCO2/kWH = (gCO2/MJ*3.6)
        fuel_density = 23.68/3.6; % kWh/kg = (MJ/kg*3.6) - actually heating
value
        wtp_CO2_value = wtp_C02_LPG_gKWh;
    elseif (strcmp(fuel_type, 'CNG'))
        fuel_const = 71.20*3,6; %gCO2/kWH = (gCO2/MJ*3.6)
        fuel_density = 35.10/3,6;% kWh/kg = (MJ/kg*3.6) - actually heating
value
        wtp_CO2_value = wtp_C02_CNG_gKWh;
    end

    use_GkmVal = wtp_fuelConsumption_gPm * fuel_density  * fuel_const;
    wtp_GkmVal = wtp_fuelConsumption_gPm * fuel_density * wtp_CO2_value;
end
 ---------------------------------------------------------------------------
```

List 13: ICEV and HEV fuel and use cycle calculation

The calculation of use and fuel cycle in grams per kilometer is in the end very straightforward as all units for the input data were adjusted for the calculation.

Use and fuel cycle for EV

ADVISOR does not explicitly give the fuel economy figures for EV originally. Unmodified, ADVISOR provides an estimation of “Miles per gallon gasoline equivalent” which represents the equivalent value of gasoline used, based on the lower heating value of gasoline. Nevertheless, the first step in the “mpgge” calculation from the “gui_post_process.m” file was to determine the energy used from the energy storage system (ess). This calculation of the energy used from the ess was slightly amended as presented in the code list below. The “dE_dt” vector summarizes the energy that left the ess with loss of power associated therewith. The Matlab function `trapz()` computes the integral of all positive values of “dE_dt” with respect to “simTime” using the trapezoidal method. The energy-out values consider also the columbic effect if defined in the simulation parameters.

The total energy that left the ess is multiplied by the grid charger efficiency to obtain the overall energy taken from the grid, since the main topic of this study is the overall CO2 emission and energy consumption.

Finally, the total energy consumed from the grid is divided with the distance that the vehicle has achieved in course of the simulation to calculate the indirect CO2 emissions in gram per kilometer. The variable for direct CO2 emission is set to a zero value as EV has no CO2 emissions associated with the use of the vehicle. In the end, the average consumption was calculated as additional information to provide the users with the basic variable of the calculation. Implementation is given in the code List 14.

```
…
if (strcmp(vehicle_type, 'EV'))
    use_GkmVal = 0;
    wtp_CO2_value = wtp_CO2_Electricity_gKWh;


    dE_dt = ess_pwr_out_available+ess_pwr_loss_available; %total power 
obtained from batteries
    EnergyOut_J=trapz(simTime,dE_dt.*(dE_dt>0)); %total energy used from 
batteries
    if ~exist('ess_coulombic_eff_available'), ess_coulombic_eff_available=1; 
end %added for alternative battery models where coul. eff not defined
    EnergyOut_J=EnergyOut_J/mean(mean(ess_coulombic_eff_available)); 
%accounts for coulombic losses--mpo 26-april-2002: the extra 'mean' is used 
for cases where ess_coulombic_eff might be 2-d
    EnergyOut_J_meine = EnergyOut_J;
    totalEnergyOut_KWh = (EnergyOut_J/1000/3600)*GridEfficiency; %conversion 
into KJ (1000) and finally into kWH

    wtp_GkmVal = (totalEnergyOut_KWh / (simDistance / 1000)) * wtp_CO2_value;
    electricityConusmption = (totalEnergyOut_KWh / (simDistance / 1000)) * 
100;
```

```
    set(findobj('tag','enCoT'), 'String', 'Electricity Consumption
(kWh/100km):');
    set(findobj('tag','enCoV'), 'String', num2str(electricityConusmption));
end

…
---------------------------------------------------------------------------
```

List 14: EV fuel and use cycle calculation

Use and fuel cycle for FCEV

ADVISOR output variables enable a straight forward calculation of the fuel consumption for hydrogen as well, as presented by the code List 15, the only additional figure needed was the net calorific value of hydrogen. Subsequently the energy use was calculated in kWh with no direct (use cycle) emissions and the resulting fuel cycle emissions are fed to the result variable.

```
…
if (strcmp(vehicle_type, 'FCV'))
    use_GkmVal = 0;
    H2_ncv_KJpG = 120.10;
    wtp_CO2_value = wtp_C02_H2_gKWh;

    energyFromUsedH2_kWHpSim = (simConsumption * H2_ncv_KJpG) / 3600; %
    energyFromUsedH2_kWHpSim_meine = energyFromUsedH2_kWHpSim;
    evalin('base','global energyFromUsedH2_kWHpSim_meine');
    wtp_GkmVal = (energyFromUsedH2_kWHpSim * wtp_CO2_value) / (simDistance /
1000);

    hydrogenConsumption = wtp_fuelConsumption_gPm * 100;
    set(findobj('tag','enCoT'), 'String', 'Hydrogen consumption
(kg/100km):');
    set(findobj('tag','enCoV'), 'String', num2str(hydrogenConsumption));


…
---------------------------------------------------------------------------
```

List 15: FCEV fuel and use cycle calculation

As for the electric vehicle, the means were established for the user to be provided with the average fuel economy figures for hydrogen. The average consumption of hydrogen is given in kg/100km.

Use and fuel cycle for PHEV

In ADVISOR the PHEV represents a combination of EV and ICEV in terms of fuel economy calculations. Therefore, two basic cases were developed whereas the first one considers the fuel consumption and emissions when the PHEV overcomes the test drive cycle only in electric charge depleting mode. The second one considers the PHEV running in the “blended mode” which means that both energy saved from the grid and used from the combustion engine is deployed for vehicle propulsion. Since ADVISOR developers have implemented a function that simulated the SAE recommended PHEV test procedure J1772, a part of this function was used to calculate the amount of energy used from the batteries based on the change of the state of charge. The fuel use by the combustion engine is analogues to ICEV. Finally, the fuel cycle calculation is completed by addition of the value for fossil fuel (if any fossil fuels were used for the propulsion needs defined by the drive cycle) and electricity that was used from the ess. The use cycle calculation is the same as for ICEV and HEV and is calculated only if the vehicle used fossil fuels during the simulation test at all. The code is presented in the List 16.

```
if (strcmp(vehicle_type, 'PHEV'))

    wtp_CO2_value_Elctr = wtp_CO2_Electricity_gKWh;

    if (strcmp(fuel_type, 'Gasoline'))
        fuel_const = 2361.52;
        fuel_density = 1.34 ;
        wtp_CO2_value_fc = wtp_C02_ConventionalGasoline_gL;
    elseif (strcmp(fuel_type, 'Diesel') || strcmp(fuel_type, 'Deisel'))
        fuel_const =  2626.62;
        fuel_density = 1.20; %l/kg
        wtp_CO2_value_fc = wtp_C02_ConventionalDiesel_gL;
    elseif (strcmp(fuel_type, 'LPG'))
        fuel_const = 65.70*3.6;
        fuel_density = 23.68/3.6;
        wtp_CO2_value_fc = wtp_C02_LPG_gKWh;
    elseif (strcmp(fuel_type, 'CNG'))
        fuel_const = 71.20*3,6;
        fuel_density = 35.10/3,6
        wtp_CO2_value_fc = wtp_C02_CNG_gKWh;
    end

    if (fc_fuel_rate_exists && sum(simConsumption)>0)
           use_GkmVal = wtp_fuelConsumption_gPm * fuel_density  * fuel_const;
           wtp_GkmVal_fc = wtp_fuelConsumption_gPm * fuel_density *
wtp_CO2_value_fc;
           EnergyGivenByFuel_INFO_KJ = simConsumption*42.902372876574;
           EnergyGivenByFuel_INFO_KJ

    try
        if evalin('base','~exist(''soc_t'')')
        evalin('base','soc_t=1;');
        end
        deltaSOC_a=evalin('base','ess_soc_hist(end)-ess_soc_hist(soc_t)');

        soc1_a=evalin('base','ess_soc_hist(soc_t)');
        soc2_a=evalin('base','ess_soc_hist(end)');

        %rint model
```

```
        if strcmp(vinf.energy_storage.ver,'rint')

Ess_Delta_Energy_Stored_a=deltaSOC_a*evalin('base','max(ess_max_ah_cap)*mean(
mean(ess_voc))*ess_module_num')*3600; %Joules

        %rc model
        elseif strcmp(vinf.energy_storage.ver,'rc')

            if strcmp(vinf.energy_storage.type,'cap') % if an ultracapacitor
model:
            ess_voc_a=evalin('base','ess_voc');
            ess_cap_a=evalin('base','ess_cap');
            numCaps_a=evalin('base','ess_parallel_mod_num*ess_module_num'); %
the number of ultracaps

            V_oc_max_a = max(max(ess_voc_a));
            V_oc_min_a = min(min(ess_voc_a));
            % Q = V C (charge = voltage * capacitance), E = 0.5 C V^2 (energy
= 1/2 capacitance * oc voltage squared)
            V_init_a    = soc1_a*(V_oc_max_a-V_oc_min_a)+V_oc_min_a; %
transforming from SOC to V initial (open circuit)
            V_final_a   = soc2_a*(V_oc_max_a-V_oc_min_a)+V_oc_min_a; %
transforming from SOC to V final

            C_ave_a     = mean(mean(ess_cap_a)); % the average capacitance
over both SOC and temperature
            E1_a        = numCaps*0.5*C_ave_a*V_init_a^2; % energy at initial
state
            E2_a        = numCaps*0.5*C_ave_a*V_final_a^2;% energy at final
state

            Ess_Delta_Energy_Stored_a=E2_a-E1_a;

        % if a li-ion or NiMH etc. RC model then use below code:
        else

[ess_tmp_a,ess_soc_a]=meshgrid(evalin('base','ess_tmp'),evalin('base','ess_so
c'));
            ess_voc_a=evalin('base','ess_voc');

            temp1_a=evalin('base','ess_mod_tmp(soc_t)');
            temp2_a=evalin('base','ess_mod_tmp(end)');


            Volt1_2_a=interp2(ess_tmp_a,ess_soc_a,ess_voc_a',[temp1_a
temp2_a], [soc1_a soc2_a]).*evalin('base','ess_module_num');

            % get ess_cb and ess_cc from workspace (29-April-2002 mpo)
            ess_cb_a=evalin('base','ess_cb');
            ess_cc_a=evalin('base','ess_cc');
            ess_tmp_a=evalin('base','ess_tmp');

            if 0 % debug statement--use a find/replace for "if 0" <--> "if 1"
                keyboard
            end

            Cb1_2_a=interp1(ess_tmp_a,ess_cb_a,[temp1_a, temp2_a]);
            Cc1_2_a=interp1(ess_tmp_a,ess_cc_a,[temp1_a, temp2_a]);
```

```
Ess_Delta_Energy_Stored_a=0.5*(Cb1_2_a(2)+Cc1_2_a(2))*Volt1_2_a(2)^2 -
0.5*(Cb1_2_a(1)+Cc1_2_a(1))*Volt1_2_a(1)^2;%Joules
        end

         %nnet model
     elseif strcmp(vinf.energy_storage.ver,'nnet')

Ess_Delta_Energy_Stored_a=deltaSOC_a*evalin('base','max(ess_max_ah_cap)*mean(
ess_voc)*ess_module_num')*3600; %Joules

        %fund model
     elseif strcmp(vinf.energy_storage.ver,'fund')

Ess_Delta_Energy_Stored_a=deltaSOC_a*evalin('base','ess_cap)*ess_voc*ess_modu
le_num')*3600; %Joules

     elseif strcmp(vinf.energy_storage.ver,'saber2')

Ess_Delta_Energy_Stored_a=deltaSOC_a*evalin('base','ess_ah_nom_fun(ess_cap_sc
ale)*mean(mean(ess_voc))*ess_module_num')*3600; %Joules


        %otherwise return NaN
     else
        ess2fuel_ratio=NaN;
        %CHECK!!!
        return
     end


    catch
        Ess_Delta_Energy_Stored_a=0;
        disp(['Error in calc_ess2fuel calculating ess delta energy stored for
',vinf.energy_storage.ver ,' energy storage'])
        disp(lasterr)
        return
    end

    Ess_Delta_Energy_Stored_a=-Ess_Delta_Energy_Stored_a;
    Ess_Delta_Energy_Stored_a %Joules
    if ~exist('ess_coulombic_eff_available'), ess_coulombic_eff_available=1;
end %added for alternative battery models where coul. eff not defined

Ess_Delta_Energy_Stored_a=Ess_Delta_Energy_Stored_a/mean(mean(ess_coulombic_e
ff_available)); %accounts for coulombic losses--mpo 26-april-2002: the extra
'mean' is used for cases where ess_coulombic_eff might be 2-d

    Ess_Delta_Energy_Stored_a_kWH = Ess_Delta_Energy_Stored_a/3600000;
    Ess_Delta_Energy_Stored_a_kWH
    energyUsedFromGrid_kWH = Ess_Delta_Energy_Stored_a_kWH*GridEfficiency;
%Assumption for charging efficiency is 85%
    energyUsedFromGrid_kWH

    wtp_GkmVal_Elctr = (energyUsedFromGrid_kWH / (simDistance / 1000)) *
wtp_CO2_value_Elctr ;

    else

        use_GkmVal = 0;
```

```
        dE_dt = ess_pwr_out_available+ess_pwr_loss_available; %total power
obtained from batteries
        EnergyOut_J=trapz(simTime,dE_dt.*(dE_dt>0)); %total energy used from
batteries
        if ~exist('ess_coulombic_eff_available'),
ess_coulombic_eff_available=1; end %added for alternative battery models
where coul. eff not defined
        EnergyOut_J=EnergyOut_J/mean(mean(ess_coulombic_eff_available));
%accounts for coulombic losses--mpo 26-april-2002: the extra 'mean' is used
for cases where ess_coulombic_eff might be 2-d
        EnergyOut_J_meine = EnergyOut_J;

        totalEnergyOut_KWh = (EnergyOut_J/1000/3600)*GridEfficiency;
%conversion into KJ (1000) and finally into kWH
        totalEnergyOut_KWh_meine = totalEnergyOut_KWh;

        evalin('base','global totalEnergyOut_KWh_meine');
        evalin('base','global EnergyOut_J_meine');

        wtp_GkmVal_Elctr = (totalEnergyOut_KWh / (simDistance / 1000)) *
wtp_CO2_value_Elctr ;
        electricityConusmption = (totalEnergyOut_KWh / (simDistance / 1000))
* 100;
        set(findobj('tag','enCoT'), 'String', 'Electricity Consumption
(kWh/100km):');
        set(findobj('tag','enCoV'), 'String',
num2str(electricityConusmption));

         use_GkmVal = 0;
         wtp_GkmVal_fc = 0;


    end


     wtp_GkmVal = wtp_GkmVal_fc+wtp_GkmVal_Elctr;
     wtp_GkmVal_fc
     wtp_GkmVal_Elctr



end
 ---------------------------------------------------------------------------
```

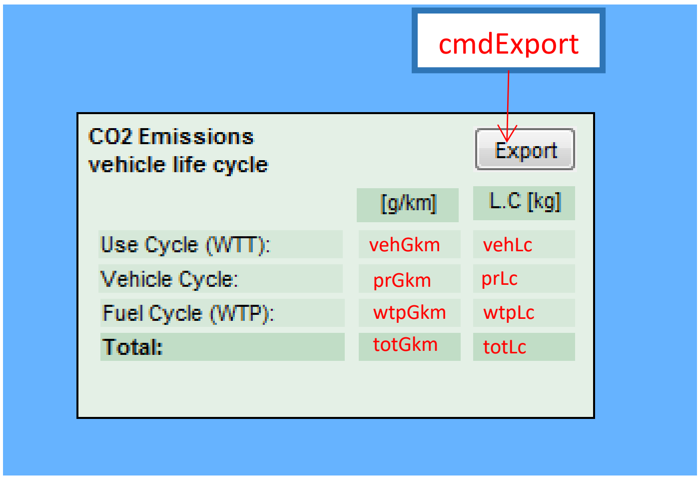
List 16: PHEV fuel and use cycle calculation

Results window

After all calculations were completed, the remaining part was to present the results in the GUI. Below are described changes in ‘ResultsFig.fig’ and ‘ResultsFig.m’ files, both located in ‘<advisor>/gui’ directory.

ResultsFig.fig file changes

The GUIDE figure file of the Results figure “ResultsFig.fig”, was amended with a frame as shown in Figure A-3 user interface elements and corresponding tags which are required to address the desired elements in code.



Figures A-3: Interface elements added to the Results GUI

ResultsFig.m file changes

As presented above, all results are put in one frame named “CO2 Emissions vehicle life cycle”. The frame contains one button used to trigger results data export to a spreadsheet file. Apart from that, in order to populate tabular result fields, the code was appended in the units4ResultsFig(), as that function is executed when the form is loaded.

As mentioned before, 'Export' button (cmdExport) is used to trigger export of results data. After a click, typical dialog for saving the results as a spreadsheet file appears. First, results data is fetched from base workspace and from tabular fields from “CO2 Emissions vehicle life cycle” frame. After that, table (xlsTable) is populated with adequate values. Finally, table is exported to as a spreadsheet file using xlswrite() function. Implementation of above statements is given in List 17.

```
% --- Executes on button press in cmdExport.
function cmdExport_Callback(hObject, eventdata, handles)
% hObject    handle to cmdExport (see GCBO)
% eventdata  reserved - to be defined in a future version of Matlab
```

```
% handles    structure with handles and user data (see GUIDATA)

global vlc_result

xlsType = evalin('base', 'vlc_vehicleType');
xlsMass = evalin('base', 'veh_mass');
xlsCo2Lt = str2double(get(handles.totLc, 'String'));
xlsCo2Gkm = str2double(get(handles.totGkm, 'String'));
xlsVehLt = str2double(get(handles.vehLc, 'String'));
xlsVehGkm = str2double(get(handles.vehGkm, 'String'));
xlsWTPLt = str2double(get(handles.wtpLc, 'String'));
xlsWTPGkm = str2double(get(handles.wtpGkm, 'String'));


xlsTable = {
            'Vehicle Type' xlsType;
            'Vehicle Mass' xlsMass;
            'Total C02 per vehicle lifetime in kg' xlsCo2Lt;
            'Total C02 in g/km' xlsCo2Gkm;
            'Vehicle Use per vehicle lifetime' xlsVehLt;
            'Vehicle Use in g/km' xlsVehGkm;
            'Energy Supply per vehicle lifetime' xlsWTPLt;
            'Energy Supply in g/km' xlsWTPGkm;
            'C02 Emissions for complete production and recycling of the
vehicle / per vehicle lifetime' vlc_result(1);
            'CO2 Emissions during production of materials for vehicle
Components  / per vehicle lifetime' vlc_result(2);
            'CO2 Emissions during Assembly, Disposal and Recycling / per
vehicle lifetime' vlc_result(3);
            'CO2 Emissions during Batery production / per vehicle lifetime'
vlc_result(4);
            'CO2 Emissions during production of Fluids / per vehicle
lifetime' vlc_result(5);
};

[file path] = uiputfile('*.xlsx','Export data', 'results.xlsx');
warning('off','Matlab:xlswrite:AddSheet');
xlswrite([path file],xlsTable,'Sheet1','A2');
…
---------------------------------------------------------------------------
```

List 17: "ResultsFig.m" – exporting of results

As for the "`units4ResultsFig()`" function, the code was amended from the 480th line of this file. The amendment populates the defined table elements of the GUI, which represent the final result of the calculations and amendments of ADVISOR. The code amended is presented in the List 18.

```
…
% set vehicle life cycle results -- tabular
wtp_result = wtp_use_calculation();
vehGkmVal = wtp_result(1);
vehLcVal = round(vehGkmVal * vlc_km / 1000);

prGkmVal = vlc_result(1) / vlc_km;
prLcVal = round(vlc_result(1) / 1000);

wtpGkmVal = wtp_result(2);
wtpLcVal = round(wtpGkmVal*vlc_km/1000);
```

```
totGkmVal = vehGkmVal + prGkmVal + wtpGkmVal;
totLcVal = vehLcVal + prLcVal + wtpLcVal;

set(findobj('tag','vehGkm'), 'String', num2str(vehGkmVal));
set(findobj('tag','vehLc'), 'String', num2str(vehLcVal));

set(findobj('tag','prGkm'), 'String', num2str(prGkmVal));
set(findobj('tag','prLc'), 'String', num2str(prLcVal));

set(findobj('tag','wtpGkm'), 'String', num2str(wtpGkmVal));
set(findobj('tag','wtpLc'), 'String', num2str(wtpLcVal));

set(findobj('tag','totGkm'), 'String', num2str(totGkmVal));
set(findobj('tag','totLc'), 'String', num2str(totLcVal));
…
----------------------------------------------------------------------------
```

List 18: “ResultsFig.m” – presentation of results

Appendix B Detailed data collection and calculations for LCA of material products

The tables provided in Appendix B provide details on data collection process, especially for cases where single entries required a rather comprehensive survey and calculations. Each sub-section of Appendix B is referenced in the respective vehicle data-set and contains details on respective processes.

Since the GREET model was used as a basis, the tables in Appendix B are structured in a way that on the left side of the table information on each process stage from GREET is given, while on the right side the equivalent of this information is provided from GEMIS, PROBAS or ELCD databases whereas each information entered is referenced with a link or an exact process name from the GEMIS database. All information which gained from the databases are marked in blue color. The final calculations are marked in grey color and contain comments explaining the calculations.

Appendix B.1 Additional calculations for vehicle cycle data-set for Germany

Appendix B.1.1 Calculation of additional process stages for Steel

Data collection for Energy Use and Emissions of material: **Steel**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2012.xls]Mat_	73.60%	26.40%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
[GREET2_2012.xls]Steel!	21.10%	19.10%	59.80%

Processes accounted for production of final material product

Reference			Processing stage
[GREET2_2012.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Steel Production
			Hot Rolling
			Skin Mill
			Cold Rolling
			Galvanizing
			Stamping

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
	metal\steel-BOF-DE-2010	metal\steel-EAF-DE-2010
Metall\Stahl-mix-DE-2010	69.80%	30.20%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processring			

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Metall\Stahl-mix-DE-2010	metal\steel-BOF-DE-2010 metal\steel-EAF-DE-2010		
metal\steel-hot rolled-DE-2010:	Metall\Stahl-mix-DE-2010	1.38	20.41
metal\steel-plate-DE-2010		1.63	25.00
metal\steel-sheet-zincing-DE-2010_PLATE	metal\steel-plate-DE-2010 (changed for this study)	2.65	40.40
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2012.xls]Steel !$W$32	Stamping (Per ton of Stamped Steel)	5.45	6.34

Shares of process fuels and energy input

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Steel !$W$35:$W$40	Natural gas	79.00%	5.01
	Electricity	21.00%	1.33

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]Steel !L$18*GREET1_Import!	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per KG] or [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.0613042	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.155094	2.68

Loss Factor (Feedstock per Ton of Output from Process stage)

Stamping	1.34

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Stamping	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.51	9.19
Average Steel excl. Stamping	shares of hot and cold rolling and galvanization as in greet	2.18	33.24
Average Steel incl. Stampi	**GREET loss factor inlcuded**	**3.44**	**53.74**

Appendix B.1.2 Calculation of additional process stages for Wrought Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Wrought**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2016.xls]Mat_	89.00%	11.00%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Extruded
[GREET2_2016.xls]W.Al!	0.00%	13.00%	87.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			Processing stage
[GREET2_2016.xls]W.Al !$B$62:$W$62, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processring			

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\Aluminum-mix-DE-2010 (Import mix)	metal\aluminium-DE-2010 (Primär- bzw. Hüttenaluminium)	12.29	172.52
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			**Processing stage**
[GREET2_2016.xls]W.Al !$B$102:$J$102, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Scrap Preparation
			Secondary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

Energy inputs required for process stage of material product

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**
[GREET2_2016.xls]W.Al !$P$53	Hot Rolling	3.63	4.22
[GREET2_2016.xls]W.Al !$R$53	Cold Rolling	3.02	3.51
[GREET2_2016.xls]W.Al !$T$53	Stamping	5.45	6.34
[GREET2_2016.xls]W.Al !$V$53	Extrusion	5.90	6.86

Processes accounted for production of final material product and respective data

Reference	**Included (source) processes / stages**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
metal\aluminium-DE-secondary-2005		1.64	26.71
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Shares of process fuels and energy input for Hot-Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
	Natural gas	90.30%	3.81
	Electricity	9.70%	0.41

Shares of process fuels and energy input for Cold Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
	Natural gas	62.50%	2.20
	Electricity	37.50%	1.32

Shares of process fuels and energy input for Stamping

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
	Natural gas	79.00%	5.01
	Electricity	21.00%	1.33

Shares of process fuels and energy input for Extrusion

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
	Natural gas	89.70%	6.15
	Electricity	10.30%	0.71

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]GREET1_Import!$B57+GREE	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.06	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.16	2.68

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	**Process stage**	**Factor**
[GREET2_2012.xls]W.Al !$G$102:$J$105	Hot Rolling	1.011
	Cold Rolling	1.007
	Stamping	1.38
	Extrusion	1.003

Calculation of energy used and associated CO2 emission including added process stages

Description	**Comment**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Hot Rolling	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.30	5.38
Cold Rolling		0.34	6.00
Stamping		0.51	9.19
Extrusion		0.49	8.80
Virgin Aluminium as per GEMIS		12.29	172.52
Virgin Aluminium incl. Hot Rolling	GREET loss factor inlcuded	12.72	179.79
Virgin Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	13.15	187.05
Final Virgin Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	18.66	267.32
Final Virgin Aluminium Wrought Product incl. Extrusion	GREET loss factor inlcuded	12.81	181.84
Average Virgin Aluminium Wrought Product	**Considering the shares of type processing [%]**	**13.57**	**192.95**
Recycled Aluminium as per GEMIS		1.64	26.71
Recycled Aluminium incl. Hot Rolling	GREET loss factor inlcuded	1.96	32.38
Recycled Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	2.31	38.60
Final Recycled Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	3.70	62.46
Final Recycled Aluminiumm Wrought Product incl. Extrusion	GREET loss factor inlcuded	2.13	35.59
Average Recycled Aluminium Wrought Product	**Considering the shares of type processing [%]**	**2.34**	**39.08**
Average Wrought Aluminium	**Share virgin / recycled from GREET**	**12.33**	**176.03**

Appendix B.1.3 Calculation of additional process stages for Cast Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Wrought**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2012.xls]Mat_	15.00%	85.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			Processing stage
[GREET2_2012.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Shape Casting
			Machining

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\Aluminum-mix-DE-2010 (Import mix)	metal\aluminium-DE-2010 (Primär- bzw. Hüttenaluminium)	12.29	172.52
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			Processing stage
[GREET2_2012.xls]C.Al!$B$125:$E$125,			Scrap Preparation
			Secondary Ingot Casting
			Shape Casting
			Machining

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\aluminium-DE-secondary-2005		1.64	26.71
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2012.xls]C.Al!$P$45	Shape Casting	7.57	8.80
[GREET2_2012.xls]C.Al!$R$45	Machining	0.54	0.63

Shares of process fuels and energy input for Shape Casting

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]C.Al!$A$48:$R$54	Natural gas	100.00%	8.80

Shares of process fuels and energy input for Machining

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]C.Al!$A$48:$R$54	Electricity	100.00%	0.63

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]GREET1_Import!$B57+GREE	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.0613042	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.155094	2.68

* Information on energy accounting in GREET not available

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	Process stage	Factor
[GREET2_2012.xls]C.Al!$G$95	Shape Casting	1.107

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Shape Casting	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.54	9.89
Machining		0.10	1.68
Virgin Aluminium as per GEMIS		12.29	172.52
Final Virgin Aluminium Casted incl. Shape casting and Machining	**GREET loss factor inlcuded**	**14.14**	**200.86**
Recycled Aluminium as per GEMIS		1.64	26.71
Final Recycled Aluminiumm CastedProduct incl. Shape casting and Machining	**GREET loss factor inlcuded**	**2.36**	**39.45**
Average Casted Aluminium Product	**Share virgin / recycled from GREET**	**4.12**	**63.66**

Appendix B.1.4 Calculation of average plastic

Data collection for Energy Use and Emissions of material: **Average Plastic**

GREET | **GEMIS**

Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt

Reference	Description	Share	Reference	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
[GREET2_2012.xls]Plastic!$A$6:$P$6	Final ABS Product: Combined	7.60%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={80AFDCFA-370D-4E0F-9293-3D3798AB99DF}	3.05	
	Final EPDM Product: Combined	7.10%	chem-org\rubber_EPDM-DE-2000	3.16	93.55
	Final Liquid Epoxy Product: Combined	10.70%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={AA7E4D9F-B6A8-40F7-947B-F7BCE1616E99}	5.71	
	Final GPPS Product: Combined	0.70%	chem-org\PS-DE-2010	2.93	87.40
	Final HIPS Product: Combined	0.70%	chem-org\PS-DE-2010	2.93	87.40
	Final HDPE Product: Combined	1.40%	Chem-Org\HDPE-DE-2010	2.46	77.54
	Final LDPE Product: Combined	1.40%	Chem-Org\LDPE-DE-2010	2.73	82.48
	Final LLDPE Product: Combined	1.40%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={80615AEE-087C-44AE-ABDB-B91B66539354}	1.49	30.30
	Final Nylon 6 Product: Combined	1.10%	http://www.probas.umweltbundesamt.de/php/prozessliste.php?do=suchen&search=Nylon	5.46	
	Final Nylon 66 Product: Combined	7.00%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={353F7BE6-940E-4F1F-964E-F59F2CCB79CB}	6.54	
	Final PC Product: Combined	3.50%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={995D4756-F53B-44EE-B80F-E86DE8BF0742}	5.94	124.48
	Final PET Product: Combined	1.70%	Chem-Org\PET-DE-2000	3.08	98.17
	Final PP Product: Combined	18.10%	Chem-Org\PP-DE-2010	3.53	95.44
	Final PUR Flexible Foam Product: Combined	12.20%	plastics\PUR-flexible foam-DE-2000	6.01	125.98
	Final PUR Rigid Foam Product: Combined	11.60%	plastics\PUR-rigid expanded-DE-2010	4.91	114.51
	Final PVC Product: Combined	13.80%	chem-org\PVC-mix-DE-2010	2.22	52.91

Final Average Plastic Product: Combined

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Average Plastic	**Share of plastic types as defined in GREET**	**4.23**	**69.78**

Appendix B.1.5 Calculation of Silicon average

Data collection for Energy Use and Emissions of material: **Silicon**

GREET

Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt

Reference	Description		Share
[GREET2_2016.xlsm]Silicon!$A$68:$A$69	Share of polycrystaline Si for PV application		50.00%
	Share of moncrystaline Si for PV application		50.00%

GEMIS / probas

Reference		CO2 [in kg per kg of material product]	Total energy [MJ per KG]
fabricatiion\silicon-cell-multi-DE-2010		453.57	8,280.90
fabricatiion\silicon-cell-mono-DE-2010		417.65	8,201.30

Silicon

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Silicon	**Shares as defined in GREET**	**435.61**	**8,241.10**

Appendix B.1.6 Calculation for lead-acid battery

Energy Use and Emissions for:			Lead-acid battery production				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**Lead-acid Battery**			**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Plastic (polypropylene)	6.1%		Data-Set Germany		3.53	95.44
	Lead	69.0%		metal\lead-DE-mix-2010		1.00	14.67
	Sulfuric Acid	7.9%		chem-inorg\sulphuric acid-2010		0.03	0.52
	Fiberglass	2.1%		http://www.probas.umweltbundesamt.de/php/p		7.67	135.90
Energy inputs required for process stage of material product							
Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67				

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66
	Electricity	38.00%	1.02

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.06	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.16	2.68

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		1.07	18.84
Battery Assembly		0.26	4.59
Lead-Acid Battery total		**1.33**	**23.43**

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.06	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.16	2.68

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		0.95	16.56
Battery Assembly		0.26	4.59
Lead-Acid Battery total		**1.20**	**21.15**

Appendix B.1.7 Calculation for NiMH battery

Energy Use and Emissions for:			**NiMH battery production**				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**NiMH Battery**	**percent of battery weight**		**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Iron	12.0%		Data-Set Germany		0.82	12.86
	Steel	23.7%		Data-Set Germany		3.44	53.74
	Aluminum	0.5%		Data-Set Germany		12.33	176.03
	Copper	3.9%		Data-Set Germany		3.29	43.11
	Magnesium	1.0%		Data-Set Germany		10.69	145.85
	Cobalt	1.8%		http://www.probas.umweltbundesamt.de/php/prozessd		7.39	103.01
	Nickel	28.2%		Data-Set Germany		5.21	74.91
	Rare Earth Metals	6.3%		[GREET2_2016.xlsm]Rare Earth'!$F$73		18.69	285.31
	Average Plastic	22.5%		Data-Set Germany		4.23	69.78
	Rubber	0.1%		Data-Set Germany		3.16	93.55

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66
	Electricity	38.00%	1.02

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.06	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.16	2.68

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		4.95	75.05
Battery Assembly		0.26	4.59
NiMH Battery total		**5.20**	**79.63**

Appendix B.1.8 Calculation of vehicle ADR

Data collection for Energy Use and Emissions for **Vehicle Assembly, Disposal and Recycling (ADR)**

GREET

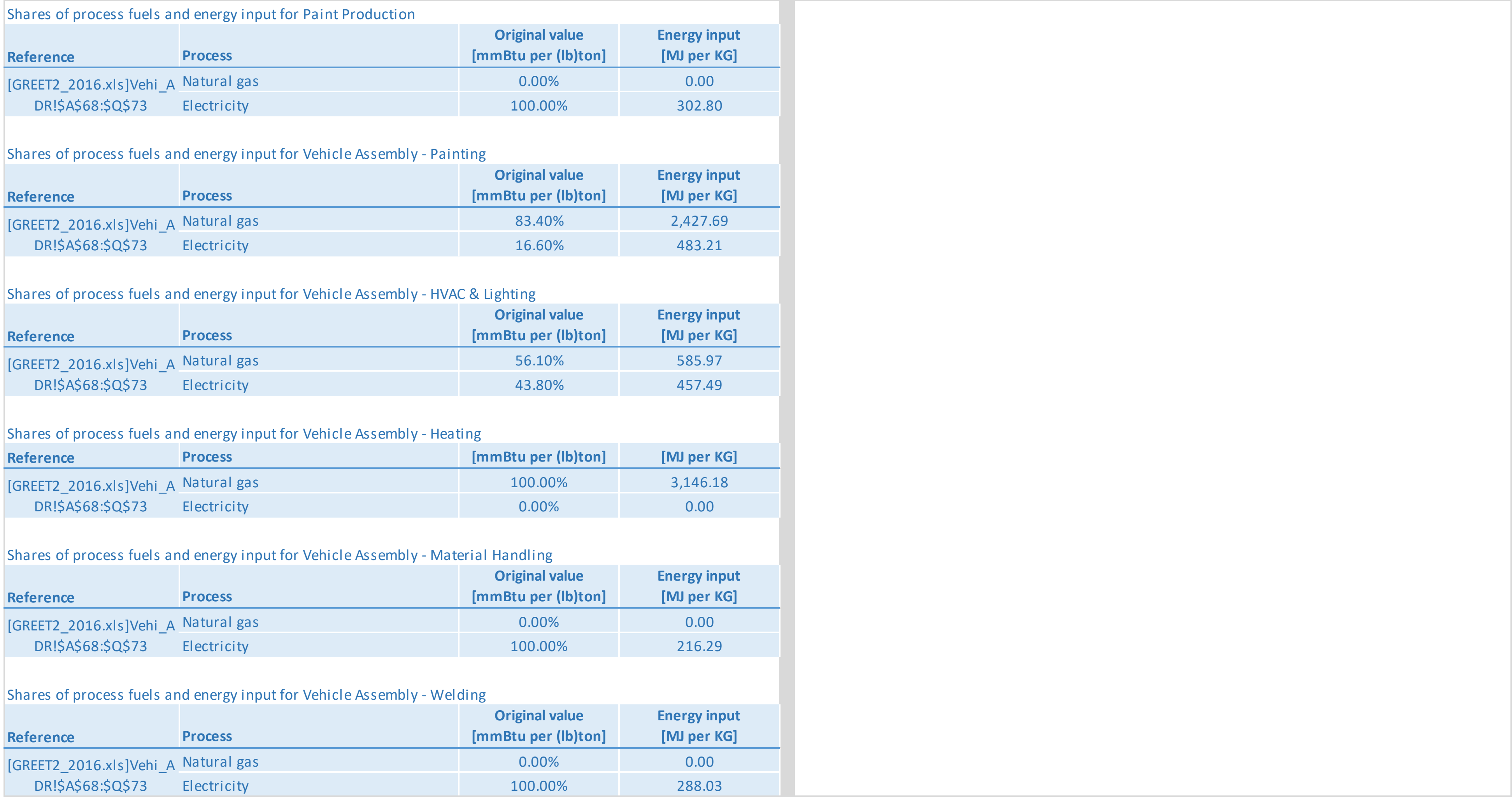
GEMIS

Processes accounted for Vehicle Assembly, Disposal and Recycling (ADR)

Reference			Processing stage
[GREET2_2016.xls]Vehi_ADR!$B$64:$Q$64			Paint Production
			Vehicle Assembly - Painting
			Vehicle Assembly - HVAC & Lighting
			Vehicle Assembly - Heating
			Vehicle Assembly - Material Handling
			Vehicle Assembly - Welding
			Vehicle Assembly - Compressed Air
			Vehicle Disposal

Energy inputs required for process stage of material product

Reference	Process stage	Original value [mmBtu per vehicle]	Conversion [MJ per vehicle]
[GREET2_2016.xls]Vehi_ADR!$B$66:$P$66	Paint Production	0.29	302.80
	Vehicle Assembly - Painting	2.76	2,910.90
	Vehicle Assembly - HVAC & Lighting	0.99	1,044.51
	Vehicle Assembly - Heating	2.98	3,146.18
	Vehicle Assembly - Material Handling	0.21	216.29
	Vehicle Assembly - Welding	0.27	288.03
	Vehicle Assembly - Compressed Air	0.41	431.52
	Vehicle Disposal	1.48	1,560.76



Shares of process fuels and energy input for Paint Production

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	302.80

Shares of process fuels and energy input for Vehicle Assembly - Painting

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	83.40%	2,427.69
	Electricity	16.60%	483.21

Shares of process fuels and energy input for Vehicle Assembly - HVAC & Lighting

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	56.10%	585.97
	Electricity	43.80%	457.49

Shares of process fuels and energy input for Vehicle Assembly - Heating

Reference	Process	[mmBtu per (lb)ton]	[MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	100.00%	3,146.18
	Electricity	0.00%	0.00

Shares of process fuels and energy input for Vehicle Assembly - Material Handling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	216.29

Shares of process fuels and energy input for Vehicle Assembly - Welding

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_A DR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	288.03

Shares of process fuels and energy input for Vehicle Assembly - Compressed Air

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	431.52

Shares of process fuels and energy input for Vehicle Assembly - Vehicle Disposal

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	1,560.76

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-DE-2010 / Gas-Kessel-DE-2010	Gas boiler for process heat in Germany	0.06	1.12
el-generation-mix-DE-2010	Electricity generation in Germany	0.16	2.68

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production		46.96	811.08
Vehicle Assembly - Painting		223.77	4,020.57
Vehicle Assembly - HVAC & Lighting		106.88	1,883.47
Vehicle Assembly - Heating		192.87	3,533.09
Vehicle Assembly - Material Handling		33.54	579.35
Vehicle Assembly - Welding		44.67	771.52
Vehicle Assembly - Compressed Air		66.93	1,155.86
Vehicle Disposal		242.06	4,180.64
Vehicle Assembly, Disposal and Recycling (ADR)	**Energy input as specified in GREET**	957.69	16,935.59

Appendix B.1.9 Calculation for vehicle fluids

Data collection for Energy Use and Emissions for **Vehicle Fluids**

GREET

Processes accounted for production of vehicle fluids

Reference	Process / production of	Disposal	Waste to product ratio
[GREET2_2016.xls]Vehi_Fluids!$B$63:$O$63	Engine Oil	Burning	66.67%
	Power Steering Fluid	Burning	66.67%
	Brake Fluid	Burning	66.67%
	Transmission Fluid	Burning	66.67%
	Powertrain Coolant	n.a	66.67%
	Windshield Fluid	n.a	0.00%
	Adhesives	n.a	66.67%

Processes accounted for disposal of vehicle fluids

			Processing stage
[GREET2_2016.xls]Vehi_Fluids!$B$63:$O$63	Engine Oil, Power Steering Fluid, Brake Fluid, Transmission Fluid		

GEMIS

Reference	CO2 [in kg per TJ of delivered Energy or Process Heat]	CO2 [in kg per kg of material product]	Total energy [in TJ per TJ of delivered material product]	Total energy [MJ per kg of material product]
filling-station\gasoline-DE-2010 (e	15,224.10	0.66	1.21	52.15
filling-station\gasoline-DE-2010 (e	15,224.10	0.66	1.21	52.15
filling-station\gasoline-DE-2010 (e	15,224.10	0.66	1.21	52.15
filling-station\gasoline-DE-2010 (e	15,224.10	0.66	1.21	52.15
chem-org\ethylene-DE-2010		2.02		70.14
chem-org\methanol-DE-2010/en	44,260.60	0.56	1.74	22.04
Average Plastic		4.23		69.78

Combustion characteristics

	LHV [MJ/l]	Density	LHV [MJ/kg]
Gasoline	32.20	1.34	43.15
Methanol	15.96	0.79	12.67

Disposal process	delivered Energy or Process Heat]	CO2 [in kg per kg of material product]	TJ of delivered material product]	[MJ per kg of material product]
oil-heavy-boiler-DE-2010 (end energy)	93362.8	4.03	1.13	

Calculation of energy used and CO2 emission associatied with production and disposal of fluids

Description	Comment	CO2 [in kg per kg of material product]		Total energy [MJ per kg of material product]
Engine Oil		3.34		52.15
Power Steering Fluid		3.34		52.15
Brake Fluid		3.34		52.15
Transmission Fluid		3.34		52.15
Powertrain Coolant	50 % ethylengl. 50% water	1.01		35.07
Windshield Fluid	50 % methanol 50% water	0.28		11.02
Adhesives		4.23		69.78

Appendix B.2 Additional calculations for vehicle cycle data-set for Austria

Appendix B.2.1 Calculation of additional process stages for Steel

Data collection for Energy Use and Emissions of material: **Steel**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2016.xls]Mat_	73.60%	26.40%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
[GREET2_2016.xls]Steel!	21.10%	19.10%	59.80%

Processes accounted for production of virgin steel

Reference			Processing stage
[GREET2_2016.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Steel Production
			Hot Rolling
			Skin Mill
			Cold Rolling
			Galvanizing
			Stamping

GEMIS

Processes accounted for production of virgin steel product and respective data

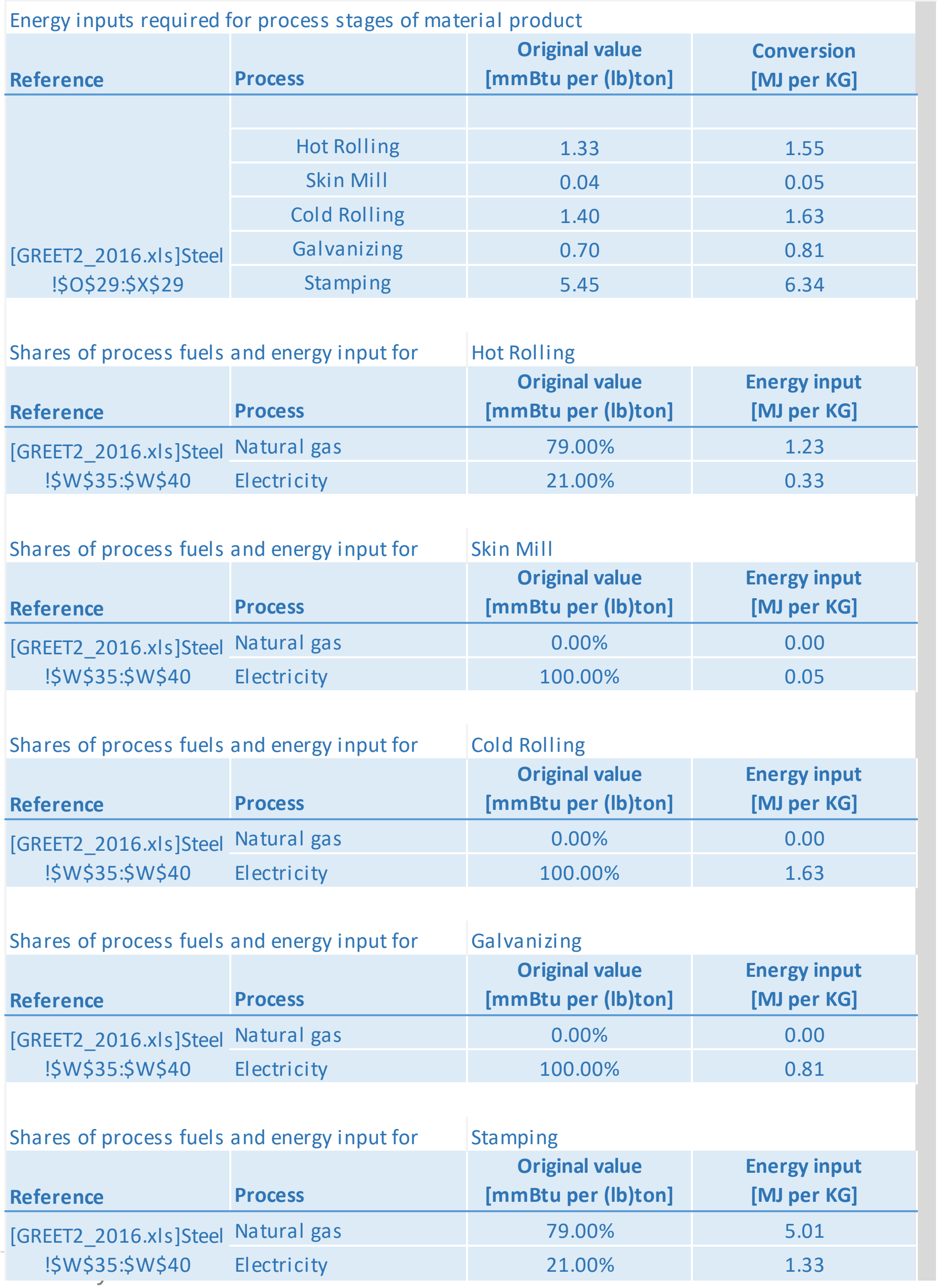
Reference		CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\steel-DE-BOF-2005 Metall\Stahl-primär-Oxygen-Österreich		1.76	21.59
Processing stages not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Production of recycled steel

Reference			Processing stage
			Steel Production

Processes accounted for production of recycled steel product and respective data

Reference		CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\steel-DE-EAF-new-2005 Metall\Stahl-sekundär-Elektro-Österreich		0.37	5.55



Energy inputs required for process stages of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2016.xls]Steel !$O$29:$X$29			
	Hot Rolling	1.33	1.55
	Skin Mill	0.04	0.05
	Cold Rolling	1.40	1.63
	Galvanizing	0.70	0.81
	Stamping	5.45	6.34

Shares of process fuels and energy input for Hot Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Steel !$W$35:$W$40	Natural gas	79.00%	1.23
	Electricity	21.00%	0.33

Shares of process fuels and energy input for Skin Mill

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Steel !$W$35:$W$40	Natural gas	0.00%	0.00
	Electricity	100.00%	0.05

Shares of process fuels and energy input for Cold Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Steel !$W$35:$W$40	Natural gas	0.00%	0.00
	Electricity	100.00%	1.63

Shares of process fuels and energy input for Galvanizing

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Steel !$W$35:$W$40	Natural gas	0.00%	0.00
	Electricity	100.00%	0.81

Shares of process fuels and energy input for Stamping

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2016.xls]Steel !$W$35:$W$40	Natural gas	79.00%	5.01
	Electricity	21.00%	1.33

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]Steel!L$18*GREET1_Import!	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Loss Factor (Feedstock per Ton of Output from Process stage)

Hot Rolling	1.031
Skin Mill	1.015
Cold Rolling	1.054
Galvanizing	1
Stamping	1.34

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per KG] or [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
(i) Hot Rolling	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.11	2.21
(ii) Skin Mill		0.00	0.09
(iii) Cold Rolling		0.09	2.95
(iv) Galvanizing		0.05	1.47
(v) Stamping		0.44	9.04
Hot Rolled steel	Incl (i), (ii), (v)	3.05	42.44
Cold Rolled steel	Incl (i), (iii), (v)	3.18	46.28
Galvanized steel	Incl (i), (iii), (iv), (v)	3.24	48.25
Virgin Steel	shares of hot and cold rolling and galvanization as in greet	**3.19**	**46.65**
Average Steel	**Share virgin / recycled from GREET**	**2.44**	**35.80**

Appendix B.2.2 Calculation of additional process stages for Wrought Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Wrought**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2016.xls]Mat_	89.00%	11.00%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Extruded
[GREET2_2016.xls]W.Al!	0.00%	13.00%	87.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			Processing stage
[GREET2_2016.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processring			

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Metall\Aluminium-DE-2005-Strom Österreich		7.96	123.09
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			Processing stage
[GREET2_2016.xls]W.Al !$B$102:$J$102,			Scrap Preparation
			Secondary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Metall\Aluminium-sekundär-Österreich Verfahren Closed well		2.47	36.94
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2016.xls]W.Al !$P$53	Hot Rolling	3.63	4.22
[GREET2_2016.xls]W.Al !$R$53	Cold Rolling	3.02	3.51
[GREET2_2016.xls]W.Al !$T$53	Stamping	5.45	6.34
[GREET2_2016.xls]W.Al !$V$53	Extrusion	5.90	6.86

Shares of process fuels and energy input for Hot-Rolling

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
	Natural gas	90.30%	3.81
	Electricity	9.70%	0.41

Shares of process fuels and energy input for Cold Rolling

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
	Natural gas	62.50%	2.20
	Electricity	37.50%	1.32

Shares of process fuels and energy input for Stamping

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
	Natural gas	79.00%	5.01
	Electricity	21.00%	1.33

Shares of process fuels and energy input for Extrusion

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
	Natural gas	89.70%	6.15
	Electricity	10.30%	0.71

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREE	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

* Information on energy accounting in GREET not available

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	**Process stage**	**Factor**
[GREET2_2016.xls]W.Al !$G$102:$J$105	Hot Rolling	1.011
	Cold Rolling	1.007
	Stamping	1.38
	Extrusion	1.003

Calculation of energy used and associated CO2 emission including added process stages

Description	**Comment**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Hot Rolling	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.30	5.78
Cold Rolling		0.23	5.29
Stamping		0.44	9.04
Extrusion		0.48	9.41
Virgin Aluminium as per GEMIS		7.96	123.09
Virgin Aluminium incl. Hot Rolling	GREET loss factor inlcuded	8.34	130.22
Virgin Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	8.63	136.43
Final Virgin Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	12.35	197.31
Final Virgin Aluminium Wrought Product incl. Extrusion	GREET loss factor inlcuded	8.46	132.87
Average Virgin Aluminium Wrought Product	**Considering the shares of type processing [%]**	**8.97**	**141.25**
Recycled Aluminium as per GEMIS		2.47	36.94
Recycled Aluminium incl. Hot Rolling	GREET loss factor inlcuded	2.80	43.13
Recycled Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	3.05	48.72
Final Recycled Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	4.65	76.27
Final Recycled Aluminiumm Wrought Product incl. Extrusion	GREET loss factor inlcuded	2.96	46.46
Average Recycled Aluminium Wrought Product	**Considering the shares of type processing [%]**	**3.18**	**50.34**
Average Wrought Aluminium	**Share virgin / recycled from GREET**	**8.33**	**131.25**

Appendix B.2.3 Calculation of additional process stages for Cast Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Cast**

GREET

Shares of virging and recycled material product [%]

Reference	**Virgin**	**Recycled**
[GREET2_2016.xls]Mat_	15.00%	85.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			**Processing stage**
[GREET2_2016.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Shape Casting
			Machining

GEMIS

Shares of virging and recycled material product [%]

Reference	**Virgin**	**Recycled**
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Processes accounted for production of final material product and respective data

Reference	**Included (source) processes / stages**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Metall\Aluminium-DE-2005-Strom Österreich		7.96	123.09
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			**Processing stage**
[GREET2_2016.xls]C.Al!$B$125:$E$125,			Scrap Preparation
			Secondary Ingot Casting
			Shape Casting
			Machining

Processes accounted for production of final material product and respective data

Reference	**Included (source) processes / stages**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Metall\Aluminium-sekundär-Österreich Verfahren Closed well		2.47	36.94
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Energy inputs required for process stage of material product

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**
[GREET2_2016.xls]C.Al!$P$45	Shape Casting	7.57	8.80
[GREET2_2016.xls]C.Al!$R$45	Machining	0.54	0.63

Shares of process fuels and energy input for Shape Casting

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Energy input [MJ per KG]**
[GREET2_2016.xls]C.Al!$A$48:$R$54	Natural gas	100.00%	8.80

Shares of process fuels and energy input for Machining

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Energy input [MJ per KG]**
[GREET2_2016.xls]C.Al!$A$48:$R$54	Electricity	100.00%	0.63

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

* Information on energy accounting in GREET not available

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	Process stage	Factor
[GREET2_2016.xls]C.Al!$G$95	Shape Casting	1.107

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Shape Casting	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.63	11.63
Machining		0.04	1.14
Virgin Aluminium as per GEMIS		7.96	123.09
Final Virgin Aluminium Casted incl. Shape casting and Machining	**GREET loss factor inlcuded**	**9.44**	**147.89**
Recycled Aluminium as per GEMIS		2.47	36.94
Final Recycled Aluminiumm CastedProduct incl. Shape casting and Machining	**GREET loss factor inlcuded**	**3.37**	**52.52**
Average Casted Aluminium Product	**Share virgin / recycled from GREET**	**4.28**	**66.83**

Appendix B.2.4 Calculation of average plastic

Data collection for Energy Use and Emissions of material: **Average Plastic**

GREET | **GEMIS / probas**

Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt

Reference	**Description**	**Share**	**Reference**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
[GREET2_2016.xls]Plastic!$A$6:$P$6	Final ABS Product: Combined	7.60%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={80AFDCFA-370D-4E0F-9293-3D3798AB99DF}	3.05	
	Final EPDM Product: Combined	7.10%	chem-org\rubber_EPDM-DE-2000	3.16	93.55
	Final Liquid Epoxy Product: Combined	10.70%	Chem-Org\EpoxyHarz-ISI	5.71	134.76
	Final GPPS Product: Combined	0.70%	chem-org\PS-A	3.94	89.25
	Final HIPS Product: Combined	0.70%	chem-org\PS-A	3.94	89.25
	Final HDPE Product: Combined	1.40%	Chem-Org\HDPE-A	3.36	79.19
	Final LDPE Product: Combined	1.40%	Chem-Org\LDPE-A		81.08
	Final LLDPE Product: Combined	1.40%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={80615AEE-087C-44AE-ABDB-B91B66539354}	1.49	30.30
	Final Nylon 6 Product: Combined	1.10%	http://www.probas.umweltbundesamt.de/php/prozessliste.php?do=suchen&search=Nylon	5.46	
	Final Nylon 66 Product: Combined	7.00%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={353F7BE6-940E-4F1F-964E-F59F2CCB79CB}	6.54	
	Final PC Product: Combined	3.50%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={995D4756-F53B-44EE-B80F-E86DE8BF0742}	5.94	124.48
	Final PET Product: Combined	1.70%	chem-org\PET	2.91	96.21
	Final PP Product: Combined	18.10%	Chem-Org\PP-DE-2010	3.53	95.44
	Final PUR Flexible Foam Product: Combined	12.20%	plastics\PUR-flexible foam-DE-2000	6.01	125.98
	Final PUR Rigid Foam Product: Combined	11.60%	plastics\PUR-rigid expanded-DE-2010	4.91	114.51
	Final PVC Product: Combined	13.80%	chem-org\PVC-mix-DE-2010	2.22	52.91

Final Average Plastic Product: Combined

Description	**Comment**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Average Plastic	**Share of plastic types as defined in GREET**	**4.26**	**84.20**

Appendix B.2.5 Calculation for lead-acid battery

Energy Use and Emissions for:			**Lead-acid battery production**				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**Lead-acid Battery**			**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Plastic (polypropylene)	6.1%		Data-Set Austria		3.53	95.44
	Lead	69.0%		metal\lead-DE-mix-2010		1.00	14.67
	Sulfuric Acid	7.9%		chem-inorg\sulphuric acid-2010		0.03	0.52
	Fiberglass	2.1%		http://www.probas.umweltbundesamt.de/php/p		7.67	135.90
Energy inputs required for process stage of material product							
Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67				
Reference	**Process**	**Shares of process fuels**	**Energy input [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66				
	Electricity	38.00%	1.02				

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		1.07	18.84
Battery Assembly		0.18	4.04
Lead-Acid Battery total		**1.25**	**22.88**

Appendix B.2.6 Calculation for NiMH battery

Energy Use and Emissions for:			NiMH battery production				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**NiMH Battery**	**percent of battery weight**		**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Iron	12.0%		Data-Set Austria		1.80	24.68
	Steel	23.7%		Data-Set Austria		2.44	35.80
	Aluminum	0.5%		Data-Set Austria		8.33	131.25
	Copper	3.9%		Data-Set Austria		3.29	43.11
	Magnesium	1.0%		Data-Set Austria		10.69	145.85
	Cobalt	1.8%		http://www.probas.umweltbundesamt.de/php/prozessd		7.39	103.01
	Nickel	28.2%		Data-Set Austria		5.21	74.91
	Rare Earth Metals	6.3%		[GREET2_2016.xlsm]Rare Earth'!$F$73		18.69	285.31
	Average Plastic	22.5%		Data-Set Austria		4.26	84.20
	Rubber	0.1%		Data-Set Austria		3.16	93.55
Energy inputs required for process stage of material product							
Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67				

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66
	Electricity	38.00%	1.02

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		4.81	75.23
Battery Assembly		0.18	4.04
NiMH Battery total		**4.99**	**79.27**

Appendix B.2.7 Calculation of vehicle ADR

Data collection for Energy Use and Emissions for **Vehicle Assembly, Disposal and Recycling (ADR)**

GREET

Processes accounted for Vehicle Assembly, Disposal and Recycling (ADR)

Reference			**Processing stage**
[GREET2_2016.xls]Vehi _ADR!$B$64:$Q$64			Paint Production
			Vehicle Assembly - Painting
			Vehicle Assembly - HVAC & Lighting
			Vehicle Assembly - Heating
			Vehicle Assembly - Material Handling
			Vehicle Assembly - Welding
			Vehicle Assembly - Compressed Air
			Vehicle Disposal

Energy inputs required for process stage of material product

Reference	**Process stage**	**Original value [mmBtu per vehicle]**	**Conversion [MJ per KG]**
[GREET2_2016.xls]Vehi _ADR!$B$66:$P$66	Paint Production	0.29	302.80
	Vehicle Assembly - Pain	2.76	2,910.90
	Vehicle Assembly - HVA	0.99	1,044.51
	Vehicle Assembly - Heat	2.98	3,146.18
	Vehicle Assembly - Mat	0.21	216.29
	Vehicle Assembly - Wel	0.27	288.03
	Vehicle Assembly - Com	0.41	431.52
	Vehicle Disposal	1.48	1,560.76

GEMIS

Shares of process fuels and energy input for Paint Production

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	302.80

Shares of process fuels and energy input for Vehicle Assembly - Painting

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	83.40%	2,427.69
	Electricity	16.60%	483.21

Shares of process fuels and energy input for Vehicle Assembly - HVAC & Lighting

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	56.10%	585.97
	Electricity	43.80%	457.49

Shares of process fuels and energy input for Vehicle Assembly - Heating

Reference	Process	Shares of process fuels	[MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	100.00%	3,146.18
	Electricity	0.00%	0.00

Shares of process fuels and energy input for Vehicle Assembly - Material Handling

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	216.29

Shares of process fuels and energy input for Vehicle Assembly - Welding

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	288.03

Shares of process fuels and energy input for Vehicle Assembly - Compressed Air

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	431.52

Shares of process fuels and energy input for Vehicle Assembly - Vehicle Disposal

Reference	Process	Shares of process fuels	Energy input [MJ per KG]
[GREET2_2016.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	1,560.76

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-AT-2010	Gas boiler for process heat in Austria	0.072	1.32
el-generation-mix-AT-2010	Electricity generation in EU	0.058	1.81

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production		17.46	549.58
Vehicle Assembly - Painting		202.95	4,084.37
Vehicle Assembly - HVAC & Lighting		68.64	1,604.50
Vehicle Assembly - Heating		226.91	4,156.58
Vehicle Assembly - Material Handling		12.47	392.56
Vehicle Assembly - Welding		16.61	522.77
Vehicle Assembly - Compressed Air		24.88	783.20
Vehicle Disposal		89.98	2,832.75
Vehicle Assembly, Disposal and Recycling (ADR)	**Energy input as specified in GREET**	659.89	14,926.30

Appendix B.2.8 Calculation for vehicle fluids

Data collection for Energy Use and Emissions for **Vehicle Fluids**

GREET

Processes accounted for production of vehicle fluids

Reference	Process / production of	Disposal	Waste to product ratio
[GREET2_2016.xls]Vehi_Fluids!$B$63:$O$63	Engine Oil	Burning	66.67%
	Power Steering Fluid	Burning	66.67%
	Brake Fluid	Burning	66.67%
	Transmission Fluid	Burning	66.67%
	Powertrain Coolant	n.a	66.67%
	Windshield Fluid	n.a	0.00%
	Adhesives	n.a	66.67%

Processes accounted for disposal of vehicle fluids

			Processing stage
[GREET2_2016.xls]V ehi_Fluids!$B$63:$	Engine Oil, Power Steering Fluid, Brake Fluid, Transmission Fluid		

GEMIS

Reference	CO2 [in kg per TJ of delivered Energy]	CO2 [in kg per kg of material product]	Total energy [in TJ per TJ of delivered material product]	Total energy [MJ per kg of material product]
Tankstelle-Benzin-A-2014 (inkl. Beim	10680.6	0.46	1.09	46.88
Tankstelle-Benzin-A-2014 (inkl. Beim	10680.6	0.46	1.09	46.88
Tankstelle-Benzin-A-2014 (inkl. Beim	10680.6	0.46	1.09	46.88
Tankstelle-Benzin-A-2014 (inkl. Beim	10680.6	0.46	1.09	46.88
chem-org\ethylene-A		2.94		72.64
chem-org\methanol	24347	0.31	2.31	29.28
Average Plastic		4.26		84.20

Combustion characteristics

	LHV [MJ/l]	Density	LHV [MJ/kg]
Gasoline	32.20	1.34	43.15
Methanol	15.96	0.79	12.67

Disposal process	delivered Energy or Process Heat]	CO2 [in kg per kg of material product]	per TJ of delivered material product]	[MJ per kg of material product]
oil-heavy-boiler-DE-2010 (end energy	92969.5	4.01		

Calculation of energy used and CO2 emission associatied with production and disposal of fluids

Description	Comment	CO2 [in kg per kg of material product]		Total energy [MJ per kg of material product]
Engine Oil		3.14		46.88
Power Steering Fluid		3.14		46.88
Brake Fluid		3.14		46.88
Transmission Fluid		3.14		46.88
Powertrain Coolant	0 % ethylengl. 50% wate	1.47		36.32
Windshield Fluid	0 % methanol 50% wate	0.15		14.64
Adhesives		4.26		84.20

Appendix B.3 Additional calculations for vehicle cycle data-set for EU

Appendix B.3.1 Calculation of additional process stages for Steel

Data collection for Energy Use and Emissions of material: **Steel**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2012.xls]Mat_	73.60%	26.40%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
[GREET2_2012.xls]Steel!	21.10%	19.10%	59.80%

GEMIS

Processes accounted for production of virgin steel

Processes accounted for production of virgin steel product and respective data

Reference			Processing stage	Reference		CO2 [in kg per kg of material product]	Total energy [MJ per KG]
[GREET2_2012.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model							
			Hot Rolled	metal\steel-hot rolled coils-EU-2005		1.97	19.98
			Cold Rolled	metal\steel-cold rolled coils-EU-2005		2.11	21.50
			Galvanized Rolled	metal\steel-hot dip galvanised-EU-2005		2.41	25.46
			Stamping	Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Recycled steel products

Processes accounted for production of recycled steel product and respective data

Reference			Processing stage	Reference		CO2 [in kg per kg of material product]	Total energy [MJ per KG]
				metal\steel-hot rolled coils-85% recycling-EU-2005		0.95	9.27
				metal\steel-cold rolled coils-85% recycling-EU-2005		1.08	10.48
				metal\steel-hot dip galvanised-85% recycling-EU-2005		1.34	13.72

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2012.xls]Steel !$W$32	Stamping (Per ton of Stamped Steel)	5.45	6.34

Shares of process fuels and energy input

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Steel !$W$35:$W$40	Natural gas	79.00%	5.01
	Electricity	21.00%	1.33

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]Steel !L$18*GREET1_Import!	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Loss Factor (Feedstock per Ton of Output from Process stage)

Stamping	1.34

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per KG] or [MJ per MJ]
gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Stamping	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.50	9.98
Virgin Steel excl. Stamping	shares of hot and cold rolling and galvanization as in greet	2.26	23.55
Virgin Steel incl. Stamping	**GREET loss factor inlcuded**	**3.53**	**41.54**
Recycled Steel	**shares of hot and cold rolling and galvanization as in greet**	**1.21**	**12.16**
Average Steel	**Share virgin / recycled from GREET**	**2.92**	**33.78**

Appendix B.3.2 Calculation of additional process stages for Wrought Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Wrought**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2012.xls]Mat_	89.00%	11.00%

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Extruded
[GREET2_2012.xls]W.Al!	0.00%	13.00%	87.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			Processing stage
[GREET2_2012.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Shares of type of material by respective processing [%]

Reference	Hot Rolled	Cold Rolled	Galvanized Rolled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processring			

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\aluminium ingots-EU-2005		10.08	169.78
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			Processing stage
[GREET2_2012.xls]W.Al !$B$102:$J$102,			Scrap Preparation
			Secondary Ingot Casting
			Hot Rolling
			Cold Rolling
			Stamping
			Extrusion

Energy inputs required for process stage of material product

Reference	Process	Original value [mmBtu per (lb)ton]	Conversion [MJ per KG]
[GREET2_2012.xls]W.Al !$P$53	Hot Rolling	1.87	2.18
[GREET2_2012.xls]W.Al !$R$53	Cold Rolling	1.93	2.24
[GREET2_2012.xls]W.Al !$T$53	Stamping	5.45	6.34
[GREET2_2012.xls]W.Al !$V$53	Extrusion	3.82	4.45

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\aluminium ingots-secondary-EU-2005		0.27	5.03
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Shares of process fuels and energy input for Hot-Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]W.Al !$A$57:$W$62	Diesel	0.10%	0.00
	Gasoline	0.00%	0.00
	Natural gas	56.10%	1.22
	Coal	0.00%	0.00
	Liquefied petroleum gas	0.00%	0.00
	Electricity	43.80%	0.95

Shares of process fuels and energy input for Cold Rolling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]W.Al !$A$57:$W$62	Diesel	0.10%	0.00
	Gasoline	3.10%	0.07
	Natural gas	40.50%	0.91
	Coal	0.00%	0.00
	Liquefied petroleum gas	0.20%	0.00
	Electricity	56.10%	1.26

Shares of process fuels and energy input for Stamping

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]W.Al !$A$57:$W$62	Diesel	0.00%	0.00
	Gasoline	0.00%	0.00
	Natural gas	79.00%	5.01
	Coal	0.00%	0.00
	Liquefied petroleum gas	0.00%	0.00
	Electricity	21.00%	1.33

Shares of process fuels and energy input for Extrusion

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]W.Al !$A$57:$W$62	Diesel	0.40%	0.02
	Gasoline	0.00%	0.00
	Natural gas	84.00%	3.73
	Coal	5.70%	0.25
	Liquefied petroleum gas	2.40%	0.11
	Electricity	7.50%	0.33

Type of utilisation of process/combustion fuels				Comparable process and values in GEMIS for utilisation process/combustion fuels			
Reference	**Process fuel**	**Utilisation**		**Reference**	**Description**	**CO2 [in kg per MJ of delivered Energy or Process Heat]**	**Total energy [MJ per MJ]**
[GREET2_2012.xls](GREET1_Import!$R57+GREE	Diesel	Medium Heavy-Duty Truck (Origin to Destination)		No comparable process for utilisation in GEMIS. Data inherited from GREET		0.09	*
[GREET2_2012.xls](GREET1_Import!$T57+GREE	Gasoline	Gasoline, Stationary Reciprocating Engine		No comparable process for utilisation in GEMIS. Data inherited from GREET		0.09	
[GREET2_2012.xls]GREET1_Import!$B57+GREE	Natural gas	Natural gas industrial boiler		gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
[GREET2_2012.xls]($B$48*GREET1_Import!$AA57+GREET1_Import!$B202)	Coal	Coal industrial boiler		coal-boiler-FBC-EU-2000	coal-fired boiler with fluidized-bed combustion (FBC) for process heat	0.12	1.26
	Liquefied petroleum gas	Liquefied petroleum gas Industrial Boiler		No comparable process for utilisation in GEMIS. Data inherited from GREET		0.08	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable		el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70
				* Information on energy accounting in GREET not available			

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	Process stage	Factor
[GREET2_2012.xls]W.Al !$G$102:$J$105	Hot Rolling	1.011
	Cold Rolling	1.007
	Stamping	1.38
	Extrusion	1.003

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Hot Rolling	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.20	4.14
Cold Rolling		0.22	4.55
Stamping		0.50	9.98
Extrusion		0.34	5.98
Virgin Aluminium as per GEMIS		10.08	169.78
Virgin Aluminium incl. Hot Rolling	GREET loss factor inlcuded	10.39	175.78
Virgin Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	10.68	181.57
Final Virgin Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	15.24	260.55
Final Virgin Aluminium Wrought Product incl. Extrusion	GREET loss factor inlcuded	10.45	176.27
Average Virgin Aluminium Wrought Product	**Considering the shares of type processing [%]**	**11.07**	**187.23**
Recycled Aluminium as per GEMIS		0.27	5.03
Recycled Aluminium incl. Hot Rolling	GREET loss factor inlcuded	0.47	9.22
Recycled Aluminium incl. Hot and Cold Rolling	GREET loss factor inlcuded	0.70	13.84
Final Recycled Aluminium Wrought Product incl. Hot Rolling, Cold Rolling and Stamping	GREET loss factor inlcuded	1.47	29.08
Final Recycled Aluminiumm Wrought Product incl. Extrusion	GREET loss factor inlcuded	0.61	11.02
Average Recycled Aluminium Wrought Product	**Considering the shares of type processing [%]**	**0.72**	**13.37**
Average Wrought Aluminium	**Share virgin / recycled from GREET**	**9.93**	**168.10**

Appendix B.3.3 Calculation of additional process stages for Cast Aluminum

Data collection for Energy Use and Emissions of material: **Aluminium - Wrought**

GREET

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
[GREET2_2012.xls]Mat_	15.00%	85.00%

Processes accounted for production of final material product: VIRGIN Aluminium

Reference			Processing stage
[GREET2_2012.xls]Steel !$B$29:$AD$29, Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model			Bauxite Mining
			Bauxite Refining
			Anode Production
			Alumina Reduction
			Primary Ingot Casting
			Shape Casting
			Machining

GEMIS

Shares of virging and recycled material product [%]

Reference	Virgin	Recycled
No reference to simillar compisition of processes in GEMIS, data inherited from GREET for further processing		

Processes accounted for production of final material product and respective data

Reference	Included (source) processes / stages	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
metal\aluminium ingots-EU-2005		10.08	169.78
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Processes accounted for production of final material product: RECYCLED Aluminium

Reference			**Processing stage**
[GREET2_2012.xls]C.Al!$B$125:$E$125,			Scrap Preparation
			Secondary Ingot Casting
			Shape Casting
			Machining

Processes accounted for production of final material product and respective data

Reference	**Included (source) processes / stages**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
metal\aluminium ingots-secondary-EU-2005		0.27	5.03
Processing stage not covered in processes defined in GEMIS. The process stage is added with energy requirement and distribution as specified in GREET2, as presented in the following calculation			

Energy inputs required for process stage of material product

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**
[GREET2_2012.xls]C.Al!$P$45	Shape Casting	7.57	8.80
[GREET2_2012.xls]C.Al!$R$45	Machining	0.54	0.63

Shares of process fuels and energy input for Shape Casting

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Energy input [MJ per KG]**
[GREET2_2012.xls]C.Al!$A$48:$R$54	Natural gas	100.00%	8.80

Shares of process fuels and energy input for Machining

Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Energy input [MJ per KG]**
[GREET2_2012.xls]C.Al!$A$48:$R$54	Electricity	100.00%	0.63

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]GREET1_Import!$B57+GREE	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Loss Factor (Feedstock per Ton of Output from Process stage)

Reference	Process stage	Factor
[GREET2_2012.xls]C.Al!$G$95	Shape Casting	1.107

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70

* Information on energy accounting in GREET not available

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Shape Casting	Emissions and energy for process stage, calculated with energy utilisation and supply from GEMIS	0.61	11.22
Machining		0.07	1.70
Virgin Aluminium as per GEMIS		10.08	169.78
Final Virgin Aluminium Casted incl. Shape casting and Machining	**GREET loss factor inlcuded**	**11.77**	**199.17**
Recycled Aluminium as per GEMIS		0.27	5.03
Final Recycled Aluminiumm CastedProduct incl. Shape casting and Machining	**GREET loss factor inlcuded**	**0.91**	**16.79**
Average Casted Aluminium Product	**Share virgin / recycled from GREET**	**2.54**	**44.14**

Appendix B.3.4 Calculation of average plastic

Data collection for Energy Use and Emissions of material: **Average Plastic**

GREET			GEMIS / probas / ELCD	
Shares of Individual Plastic in a Vehicle for Average Plastic Calculation, % by wt				
Reference	**Description**	**Share**	**Reference**	**CO2 [in kg per kg of material product]**
[GREET2_2012.xls]Plastic!$A$6:$P$6	Final ABS Product: Combined	7.60%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=76d6aaa4-37e2-40b2-994c-03292b600074&version=03.00.000&stock=default	3.05
	Final EPDM Product: Combined	7.10%	chem-org\rubber_EPDM-DE-2000	3.16
	Final Liquid Epoxy Product: Combined	10.70%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={AA7E4D9F-B6A8-40F7-947B-F7BCE1616E99}	5.71
	Final GPPS Product: Combined	0.70%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=6ed5e0f8-3914-4533-9beb-c93222bdb2cb&version=03.00.000&stock=default	2.71
	Final HIPS Product: Combined	0.70%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=aed8d428-25bc-4b69-8722-d3e26975dc5b&version=03.00.000&stock=default	2.76
	Final HDPE Product: Combined	1.40%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=0704c700-2fb0-43c5-8803-bed8a6f1b968&version=03.00.000&stock=default	1.57
	Final LDPE Product: Combined	1.40%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=46c09193-ab51-43ae-957f-e6383b67e73d&version=03.00.000&stock=default	1.69
	Final LLDPE Product: Combined	1.40%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=f35313d3-c5fa-4b97-a212-d11a122070f8&version=03.00.000&stock=default	1.49

[GREET2_2012.xls]Plastic!$A$6:$P$6	Final Nylon 6 Product: Combined	1.10%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=fad4c07f-40db-48fa-8d62-de5ae8d9fcbf&version=03.00.000&stock=default	5.46
	Final Nylon 66 Product: Combined	7.00%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={353F7BE6-940E-4F1F-964E-F59F2CCB79CB}	6.54
	Final PC Product: Combined	3.50%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=acf81ba2-1ebb-4150-9b26-06d8e2c6be10&version=03.00.000&stock=default	6.02
	Final PET Product: Combined	1.70%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=84854d79-77da-4794-9d2a-f108f7e91741&version=03.00.000&stock=default	2.92
	Final PP Product: Combined	18.10%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=0dc3d65b-7ff8-4c92-a694-748fb28070a9&version=03.00.000&stock=default	1.67
	Final PUR Flexible Foam Product: Combined	12.20%	plastics\PUR-flexible foam-DE-2000	6.01
	Final PUR Rigid Foam Product: Combined	11.60%	plastics\PUR-rigid expanded-DE-2010	4.91
	Final PVC Product: Combined	13.80%	http://www.probas.umweltbundesamt.de/php/prozessdetails.php?id={A28D6CB7-68D3-4E3E-B834-D4F600683D4D}	1.79
			Final Average Plastic Product: Combined	

Description	Comment	CO2 [in kg per kg of material product]
Average Plastic	**Share of plastic types as defined in GREET**	**3.80**

Appendix B.3.5 Calculation for lead-acid battery

Energy Use and Emissions for:			**Lead-acid battery production**				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**Lead-acid Battery**			**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Plastic (polypropylene)	6.1%		http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/proce		1.67	
	Lead	69.0%		http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/proce		1.24	
	Sulfuric Acid	7.9%		chem-inorg\sulphuric acid-2010		0.03	
	Fiberglass	2.1%		http://www.probas.umweltbundesamt.de/php/prozessd		7.67	
Energy inputs required for process stage of material product							
Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67				
Reference	**Process**	**Shares of process fuels**	**Energy input [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66				
	Electricity	38.00%	1.02				

Type of utilisation of process/combustion fuels			
Reference	**Process fuel**	**Utilisation**	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels			
Reference	**Description**	**CO2 [in kg per MJ of delivered Energy or Process Heat]**	**Total energy [MJ per MJ]**
gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70

Description	**Comment**	**CO2 [in kg per kg of material product]**	**Total energy [MJ per KG]**
Materials		1.12	
Battery Assembly		0.24	
Lead-Acid Battery total		**1.36**	

Appendix B.3.6 Calculation for NiMH battery

Energy Use and Emissions for:			NiMH battery production				
GREET				**GEMIS**			
Compisition of the NiMH Battery and respective emissions and energy used							
Reference	**NiMH Battery**	**percent of battery weight**		**Reference**		**CO2 Emissions: grams per kg of material product**	**Total energy: MJ per kg of material product**
[GREET2_2016.xlsm]Battery_Sum!$A$59:$D$68	Iron	12.0%		Data-Set EU		0.82	12.86
	Steel	23.7%		Data-Set EU		2.92	33.78
	Aluminum	0.5%		Data-Set EU		9.93	168.10
	Copper	3.9%		Data-Set EU		3.97	52.96
	Magnesium	1.0%		Data-Set EU		10.69	145.85
	Cobalt	1.8%		http://www.probas.umweltbundesamt.de/php/prozessd		7.39	103.01
	Nickel	28.2%		Data-Set EU		5.21	74.91
	Rare Earth Metals	6.3%		[GREET2_2016.xlsm]Rare Earth'!$F$73		18.69	285.31
	Average Plastic	22.5%		Data-Set EU		3.80	0.00
	Rubber	0.1%		Data-Set EU		3.16	93.55
Energy inputs required for process stage of material product							
Reference	**Process**	**Original value [mmBtu per (lb)ton]**	**Conversion [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Energy inputs: mmBtu per ton of material product, except as noted	2.30	2.67				
Reference	**Process**	**Shares of process fuels**	**Energy input [MJ per KG]**				
[GREET2_2016.xlsm]Battery Assembly'!$B$11:$B$18	Natural gas	62.00%	1.66				
	Electricity	38.00%	1.02				

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2016.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2016.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70

Description	Comment	CO2 [in kg per kg of material product]	Total energy [MJ per KG]
Materials		4.74	54.96
Battery Assembly		0.24	4.86
NiMH Battery total		**4.98**	**59.82**

Appendix B.3.7 Calculation of vehicle ADR

Data collection for Energy Use and Emissions for **Vehicle Assembly, Disposal and Recycling (ADR)**

GREET

Processes accounted for Vehicle Assembly, Disposal and Recycling (ADR)

Reference			**Processing stage**
[GREET2_2012.xls]Vehi _ADR!$B$64:$Q$64			Paint Production
			Vehicle Assembly - Painting
			Vehicle Assembly - HVAC & Lighting
			Vehicle Assembly - Heating
			Vehicle Assembly - Material Handling
			Vehicle Assembly - Welding
			Vehicle Assembly - Compressed Air
			Vehicle Disposal

Energy inputs required for process stage of material product

Reference	**Process stage**	**Original value [mmBtu per vehicle]**	**Conversion [MJ per KG]**
[GREET2_2012.xls]Vehi _ADR!$B$66:$P$66	Paint Production	0.29	302.80
	Vehicle Assembly - Painting	2.76	2,910.90
	Vehicle Assembly - HVAC & Lighting	0.99	1,044.51
	Vehicle Assembly - Heating	2.98	3,146.18
	Vehicle Assembly - Material Handling	0.21	216.29
	Vehicle Assembly - Welding	0.27	288.03
	Vehicle Assembly - Compressed Air	0.41	431.52
	Vehicle Disposal	1.40	1,477.71

GEMIS

Shares of process fuels and energy input for Paint Production

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	302.80

Shares of process fuels and energy input for Vehicle Assembly - Painting

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	83.40%	2,427.69
	Electricity	16.60%	483.21

Shares of process fuels and energy input for Vehicle Assembly - HVAC & Lighting

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	56.10%	585.97
	Electricity	43.80%	457.49

Shares of process fuels and energy input for Vehicle Assembly - Heating

Reference	Process	[mmBtu per (lb)ton]	[MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	3,146.18

Shares of process fuels and energy input for Vehicle Assembly - Material Handling

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	216.29

Shares of process fuels and energy input for Vehicle Assembly - Welding

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi _ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	288.03

Shares of process fuels and energy input for Vehicle Assembly - Compressed Air

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	431.52

Shares of process fuels and energy input for Vehicle Assembly - Vehicle Disposal

Reference	Process	Original value [mmBtu per (lb)ton]	Energy input [MJ per KG]
[GREET2_2012.xls]Vehi_ADR!$A$68:$Q$73	Natural gas	0.00%	0.00
	Electricity	100.00%	1,477.71

Type of utilisation of process/combustion fuels

Reference	Process fuel	Utilisation	
[GREET2_2012.xls]GREET1_Import!$B57+GREET1_Import!$B144	Natural gas	Natural gas industrial boiler	
[GREET2_2012.xls]GREET1_Import!$B224+GREET1_Import!$C224	Electricity	Not applicable	

Comparable process and values in GEMIS for utilisation process/combustion fuels

Reference	Description	CO2 [in kg per MJ of delivered Energy or Process Heat]	Total energy [MJ per MJ]
gas-boiler-EU-2010	Gas boiler for process heat in EU	0.069	1.27
el-generation-mix-EU-27-2010 (PRIMES)	Electricity generation in EU	0.119	2.70

Calculation of energy used and associated CO2 emission including added process stages

Description	Comment	CO2 [in kg per vehicle lifetime]	Total energy [MJ per vehicle lifetime]
Paint Production		36.07	817.88
Vehicle Assembly - Painting		224.68	4,399.26
Vehicle Assembly - HVAC & Lighting		94.83	1,982.52
Vehicle Assembly - Heating		374.75	8,497.94
Vehicle Assembly - Material Handling		25.76	584.20
Vehicle Assembly - Welding		34.31	777.98
Vehicle Assembly - Compressed Air		51.40	1,165.55
Vehicle Disposal		176.01	3,991.35
Vehicle Assembly, Disposal and Recycling (ADR)	**Energy input as specified in GREET**	1,017.81	22,216.68

Appendix B.3.8 Calculation for vehicle fluids

Data collection for Energy Use and Emissions for **Vehicle Fluids**

GREET | **GEMIS**

Processes accounted for production of vehicle fluids

Reference	**Process / production of**	**Disposal**	**Waste to product ratio**	**Reference**	**CO2 [in kg per TJ of delivered Energy or Process Heat]**	**CO2 [in kg per kg of material product]**	**Total energy [in TJ per TJ of delivered material product]**	**Total energy [MJ per kg of material product]**
[GREET2_2016.xls]Vehi_Fluids!$B$63:$O$63	Engine Oil	Burning	66.67%	JEC Well-To-Wheels Analysis / Annex 4	13050	0.56	1.18	50.91
	Power Steering Fluid	Burning	66.67%	JEC Well-To-Wheels Analysis / Annex 4	13050	0.56	1.18	50.91
	Brake Fluid	Burning	66.67%	JEC Well-To-Wheels Analysis / Annex 4	13050	0.56	1.18	50.91
	Transmission Fluid	Burning	66.67%	JEC Well-To-Wheels Analysis / Annex 4	13050	0.56	1.18	50.91
	Powertrain Coolant	n.a	66.67%	http://eplca.jrc.ec.europa.eu/ELCD3/datasetdetail/process.xhtml?uuid=45e41797-e9a1-4ee9-af29-75ae71d1943f&version=03.00.000&stock=default		1.16		
	Windshield Fluid	n.a	0.00%	chem-org\methanol-DE-2010/en	44260.6	0.56	1.74	22.04
	Adhesives	n.a	66.67%	Average Plastic		3.80		

Combustion characteristics

	LHV [MJ/l]	**Density**	**LHV [MJ/kg]**
Gasoline	32.20	1.34	43.15
Methanol	15.96	0.79	12.67

Processes accounted for disposal of vehicle fluids

			Processing stage	**Disposal process**	**CO2 [in kg per TJ of delivered Energy or Process Heat]**	**CO2 [in kg per kg of material product]**	**Total energy [in TJ per TJ of delivered material product]**	**Total energy [MJ per kg of material product]**
[GREET2_2016.xls]Vehi_Fluids!$B$63:$O$63	Engine Oil, Power Steering Fluid, Brake Fluid, Transmission Fluid			oil-heavy-boiler-DE-2010 (end energy)	107098	4.62	1.34	

Calculation of energy used and CO2 emission associatied with production and disposal of fluids

Description	**Comment**	**CO2 [in kg per kg of material product]**		**Total energy [MJ per kg of material product]**
Engine Oil		3.64		50.91
Power Steering Fluid		3.64		50.91
Brake Fluid		3.64		50.91
Transmission Fluid		3.64		50.91
Powertrain Coolant	50 % ethylengl. 50% water	0.58		0.00
Windshield Fluid	50 % methanol 50% water	0.28		11.02
Adhesives		3.80		0.00