Estimated Greenhouse Gas Emissions and Primary Energy Demand of Passenger Vehicles – 3rd edition

Life Cycle Assessment Methodology and Data

green ncap

July 2024

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The forecast of electric energy supply for all European Countries was kindly made available for free by Ricardo, under the condition that the data are used exclusively for the needs of Green NCAP LCA projects. Green NCAP highly values the provided data and appreciates RICARDO's gesture.

The PAUL SCHERRER INSTITUTE (PSI) in Switzerland reviewed the methodology, basic data and draft results [Bauer 2022] of the LCA Expert Tool 2.1 [Jungmeier et al. 2022], which is the basis for this document.

Ricardo reviewed document 'Life Cycle Assessment Methodology and Data (2nd edition)' and analysed some results for correctness and consistency. A summary of the findings was provided [Hill 2022], no issues were identified, several recommendations for improvement were made.

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CONTENTS

1. INTRODUCTION

1.1. Background

There is international consensus that the environmental effects of transportation systems can only be analysed and compared on the basis of Life Cycle Assessment (LCA) including the production, operation and the end-of-life treatment of the various facilities.

Life cycle assessment is a method to estimate the material and energy flows of a product (e.g. transportation service) to analyse environmental effects over the entire lifetime of the product 'from cradle to grave'.

Based on the methodology of 'Life Cycle Assessment' (LCA) an LCA Expert Tool (Version 2.1) was developed and documented in a report and a handbook in 2022 to estimate the greenhouse gas (GHG) emissions and the primary energy demand (PED) of different transportation systems with a passenger vehicle using different fuels, propulsion systems and state of technologies in different countries [Jungmeier et al. 2022]. This tool was already used to calculate and publish the LCA based GHG emissions and primary energy demand of 61 vehicles tested in Green NCAP in April 2022 [Jungmeier et al. 2022a]. Since then, Green NCAP tested vehicles have received a package of LCA calculations produced by the further developed versions of the tool. This document summarizes the methodology and data used in the 3rd edition, applicable as of July 2024.

The LCA Expert Tool (v2.1) is updated (v2.4) [Jungmeier et al. 2024] and is used to assess the life cycle based GHG emissions and primary energy demand of vehicles available on the current European market as a basis to provide this information to consumers.

1.2. Project Aim

The aim of the project is to provide the LCA data and results for an online life cycle based environmental information system of vehicles for European consumers and preparing to roll out this interactive tool internationally. For that purpose, the calculation methods and basic data from the LCA Expert Tool (v2.4) are used [Jungmeier et al. 2024] as input for the web pages of the different FIA mobility clubs and consumer organisations.

The goal of the Life Cycle Assessment (LCA) is to estimate the greenhouse gas emissions and the primary energy demand of vehicles currently available on the European market. The Life Cycle Assessment is done for generic global supply chains of vehicle production and energy supply in Europe between 2024 and 2039. The main focus is to estimate significant differences between the vehicles and the main influencing parameters among:

- Propulsion system
- Type of fuel
- Energy demand
- Vehicle mass
- Battery capacity
- CH_4 and N_2O emissions from vehicles equipped with an ICE.

No brand specific calculations for the vehicle production are made. The calculation is done for different total lifetime mileages ranging up to maximum 240,000 km in maximum 16 years vehicle lifetime. The annual millage can be selected by the users of the online LCA Consumer Tool on www.greenncap.com/lca-tool/.

The life cycle based environmental information about passenger vehicles include the GHG emissions in CO_2-equivalent (sum of CO_2, CH_4 und N_2O) and the total cumulated primary energy demand (PED) with its fossil and renewable shares. This environmental information is estimated and documented per driven kilometre and in absolute values over the entire life cycle, using the shares of vehicle production, operation and end-of-life treatment in Europe. For the electric vehicles (BEV and PHEV) the current and future national electricity mixes for each of the 27 countries in EU27, the UK and CH, EU27 and a 100% renewable electricity mix from wind, photovoltaics and hydro power in Europe, are made available. For conventional ICE, HEV and PHEV vehicles using fossil fuel (with biofuel blending diesel B7 and petrol E10), for all countries, the same assumptions regarding the fuel supply are made as in the EU27 average situation. The approach is consistent with LCA Expert Tool 2.4 [Jungmeier et al. 2024].

2. METHODOLOGY OF LIFE CYCLE ASSESSMENT (LCA)

2.1. Definition Life Cycle Assessment (LCA)

Life cycle assessment is a method to estimate the material and energy flows of a product (e.g. transportation service) to analyse environmental effects over the entire lifetime of the product 'from cradle to grave'.

The environmental effects of the various stages in the life cycle of the transportation systems with passenger vehicles are investigated. The stages include extraction of raw materials, manufacturing, distribution, product use, recycling and final disposal (from cradle to grave), (Figure 1). Life cycle assessment allows the comparison of different systems offering the same transportation service during the same time period and identifies those life cycle phases having the highest environmental effects.

The most important attribute in the LCA definition is 'estimated', so all environmental results based on LCA are an estimation, as it is not possible to identify all environmental contributions in the life cycle of a transportation system totally. However, due to the strong development of LCA and its databases in the last 15 years the most relevant influences on the GHG emissions and the primary energy demand of different transportation systems can be identified and calculated.

To reflect the LCA definition, all results are usually given in ranges, as by comparing different transportation systems it is only relevant if the ranges are significantly different. Partly overlapping ranges between two systems indicate that there is no significant difference between them in terms of GHG emissions and primary energy demand.

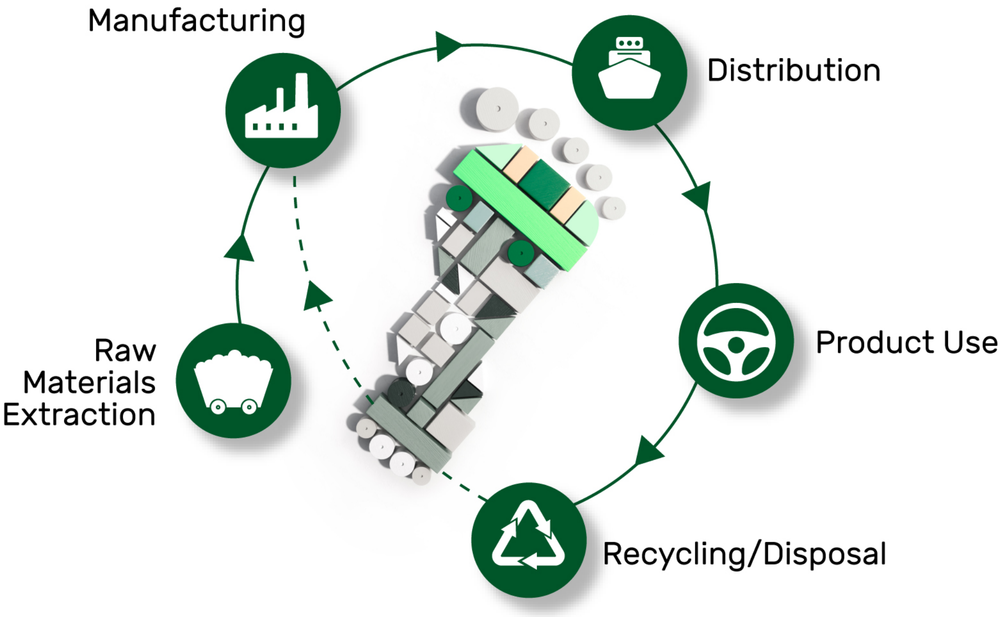

Figure 1 - Scheme of Life Cycle Assessment

According to ISO 14040, a LCA consists of the 4 following phases, which are closely linked during the whole process of applying LCA methodology (Figure 2):

- Goal and scope definition,
- Inventory analyses,
- Impact assessment, and
- Interpretation & documentation.

In the inventory analysis, the mass and energy balance is made along the whole process chain to calculate the physical (primary) energy demand and the physical emissions of each single greenhouse gas.

In the impact assessment the single energy inputs and emissions are aggregated to the primary energy demand and the global warming effects by applying the global warming potentials to the single GHG emissions.

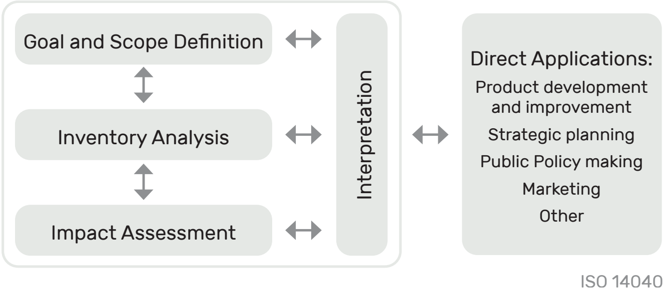

Figure 2 - Life Cycle Assessment framework according to ISO 14040

The LCA performed here is an ‘attributional LCA’, as an attributional life cycle assessment estimates what share of the global environmental burdens belongs to the transportation service and is based on average data. In contrast, a ‘consequential LCA’ gives an estimate of how the global environmental burdens are affected by the production and use of the product and ideally uses marginal data in many parts of the life cycle.

2.2. System Boundaries

For providing a transportation service, all processes must be analysed from raw material and resource extraction to the vehicle offering the transportation service. The elements and system boundaries of vehicle’s LCA include all technical systems using and converting primary energy and material resources to provide the transportation service and contributing to environmental effects.

In Figure 3 the simplified scheme of the process chain exemplary for a battery electric vehicle is shown covering the production, the operation and the end-of-life phase of the system:

- The production phase includes the production of the vehicle and the battery.
- The operation phase offers the transportation service by driving the vehicle, charging & fueling infrastructure, electricity grid, electricity and fuel production, spare and maintenance parts and ends with the extraction of primary energy in nature.
- The end-of-life phase includes the dismantling processes of the vehicle and sorting the materials for reuse, recycling and energy generation.

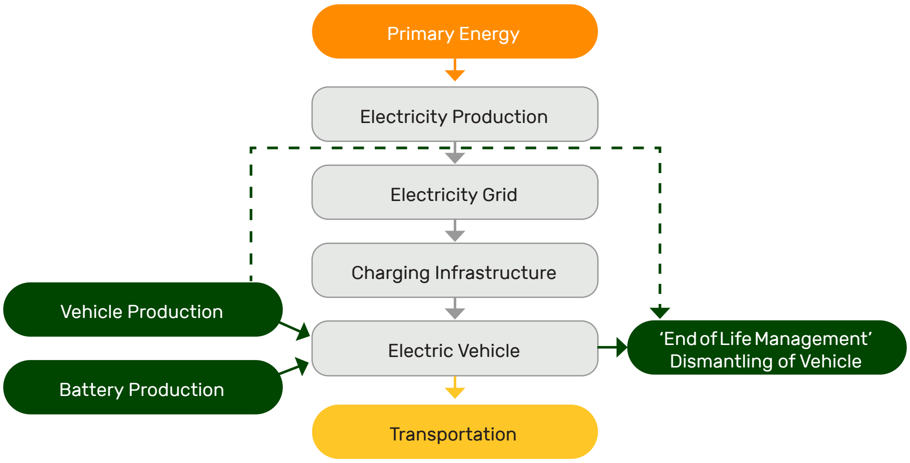

Figure 3 - Scope of life cycle assessment – example battery electric vehicle

Life cycle assessment of the three phases in the life cycle of a vehicle – production, operation (including fuel/energy supply) and end-of-life treatment – cumulates the environmental effects over the whole lifetime. In Figure 4 this is shown for three hypothetical vehicle types. The cumulated effects over the entire lifetime are then distributed to the transportation service provided in the operation phase (e.g. 240,000 km in 16 years) to get the specific effects per driven kilometre (e.g. g CO_2-eq./km). If the framework conditions are changing during the operation phase, e.g. changing electricity supply, the effects might be different for each year in the operation phase.

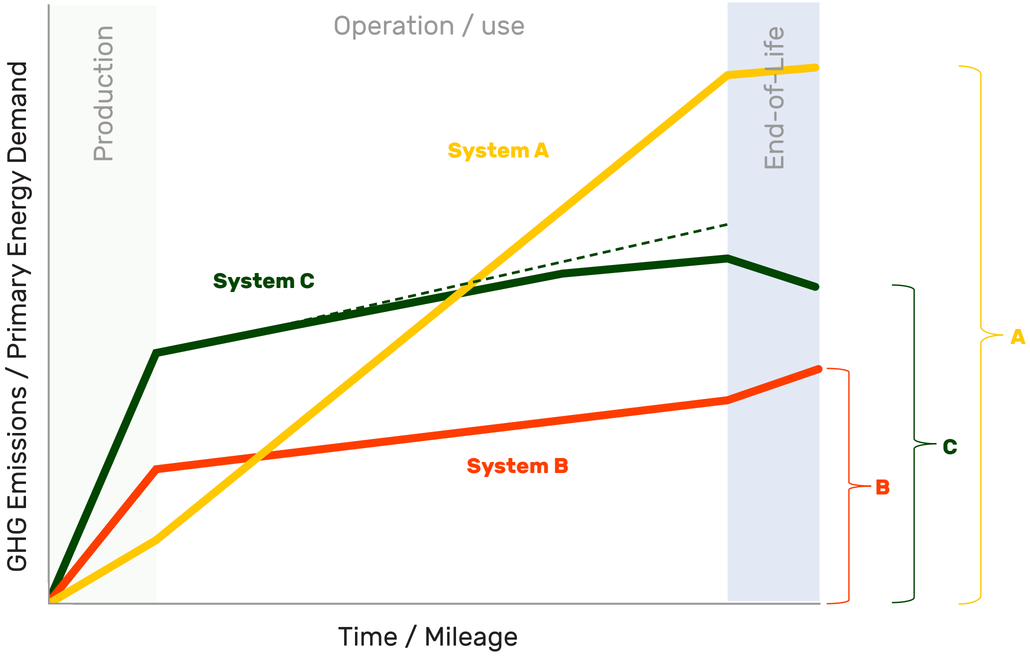

Figure 4 - The three phases in the life cycle of a vehicle – production, operation / use (including fuel/energy supply) and end-of-life treatment for 3 hypothetical vehicle types A, B and C

All GHG emissions and energy relevant processes to provide a transportation service with a passenger vehicle are considered in the process chain, in which possible co-products, e.g. animal feed from FAME production, district heat from electricity production, are also accounted for with their effects of substituting for other products and services.

As examples, in Figure 5 the process chain for a diesel B7 ICE vehicle and in Figure 6 the process chain for a battery electric vehicle are shown.

The schemes of the process chain show the most relevant processes in the LCA of a transportation system from main raw material in nature (on the top) to the provided transportation service (on the bottom).

The five most relevant process steps are:

1. Cultivation, collection or extraction of raw materials
2. Transportation of raw materials
3. Conversion of raw materials to transportation fuel and electricity, where other products might be co-produced, e.g. wind power plant, refinery, electrolysis
4. Distribution of transportation fuel/energy incl. filling/charging station and infrastructure
5. Vehicle using the transportation fuel.

The main inputs to the process steps are energy (e.g. electricity, fuels), auxiliary materials (e.g. fertilizer, chemicals) and materials for the production of the energy conversion and transportation facilities; e.g. the materials for the production of the vehicle also including the battery for BEV and the energy for manufacturing and assembling.

The main outputs of a process step are beside transportation fuels, GHG emissions and co-products (e.g. animal feed, chemicals, heat).

On the top of a process step the most important input into it (e.g. raw oil, hydrogen) is shown and an arrow links the process to the previous step in the process chain. On the bottom of the process step the most important output (e.g. diesel, electricity) is shown and an arrow links the process to the next step in the process chain.

On the left hand side, the input in terms of primary energy demand is shown, which is associated with the energy and material needed, and is calculated in the LCA.

On the right hand side, the output in terms of GHG emissions (covering CO_2, CH_4, and N_2O) is shown, which is associated with the energy and material needed, and is calculated in the LCA.

The GHG emissions cover:

- Direct emissions from fuel combustion in the process step
- Direct emissions from processing or losses (e.g. CH_4 from natural gas extraction, N_2O from fertilization)
- Indirect emissions from the supply of energy & materials and the production & end-of-life of the facilities for energy conversion and transportation.

In the Inventory Analysis of the LCA (see Figure 2) all physical mass and energy flows e.g. CO_2, N_2O, electricity are analysed or estimated in the process chains. In the Impact Assessment, the results of the inventory analysis of the process chains are assessed for the different impact categories, e.g. the single GHG emissions are added up using the global warming potential of the different gases to the global warming potential in CO_2-equivalents (see also chapter 2.6.).

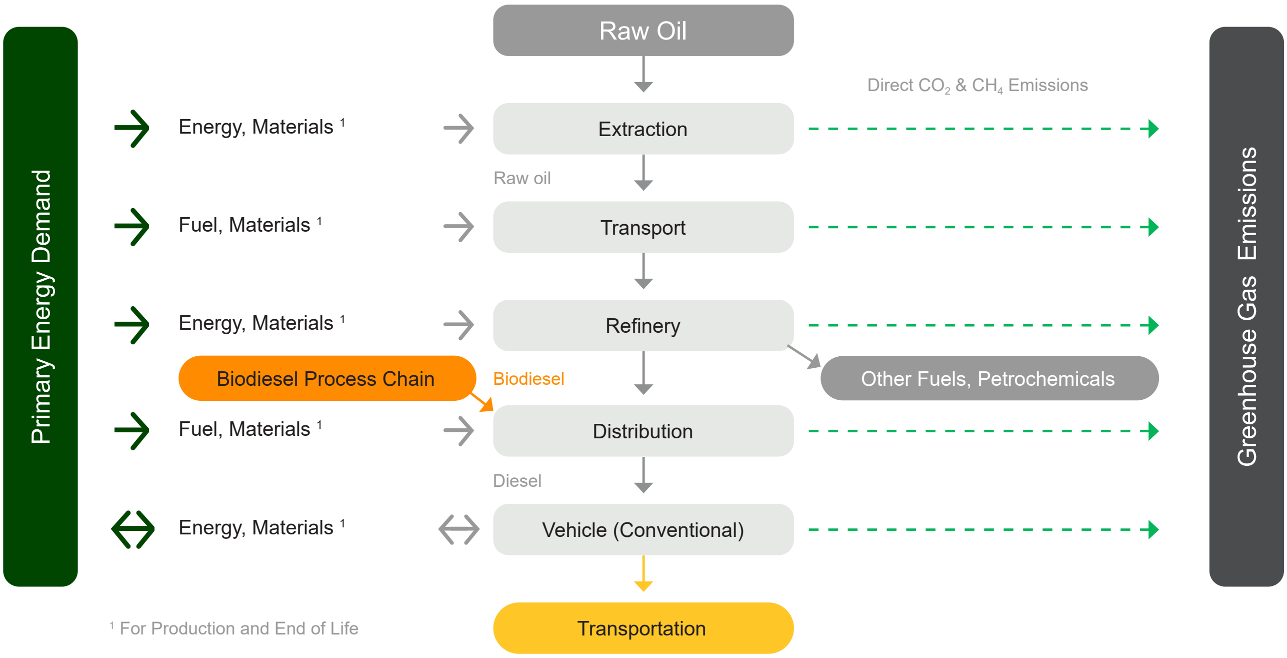

Figure 5 - Process chain for an internal combustion engine vehicle running on diesel B7

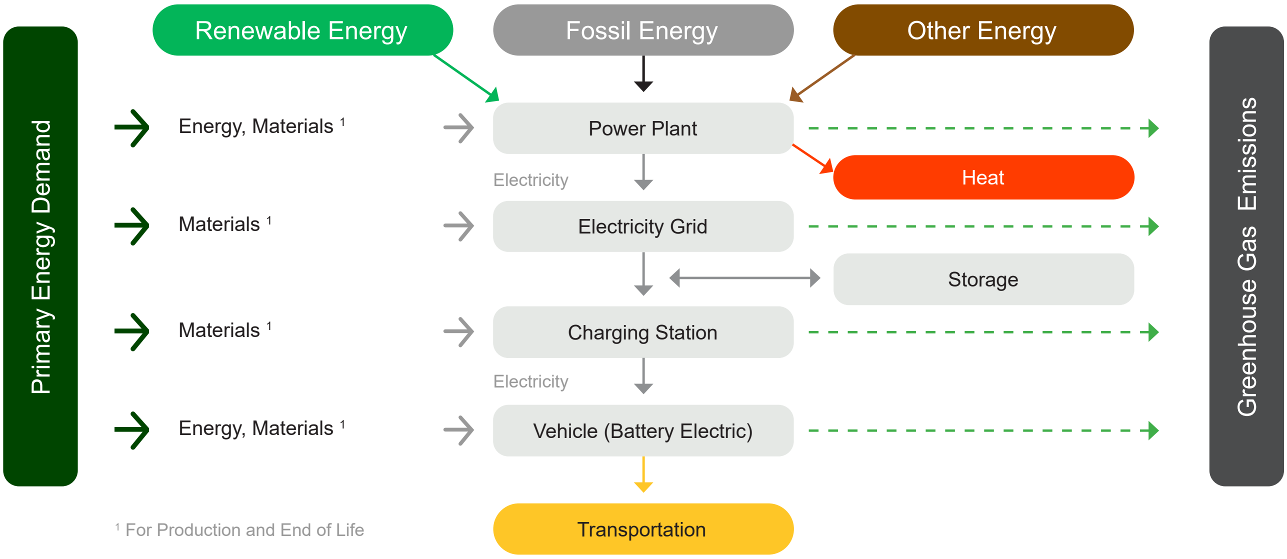

Figure 6 - Process chain for a battery electric vehicle using an electricity mix

Depending on the propulsion system and the energy carrier, the transportation systems have different GHG emissions and primary energy demand, which occur on different locations, at different phases and time in the life cycle. For example: an ICE vehicle using diesel has the highest CO_2 emissions from the stack of the vehicle operation, a biodiesel ICE vehicle has the highest N_2O emissions from nitrogen fertilization of the raw material cultivation in agriculture and a current battery electric vehicle using renewable electricity has the highest CO_2 emissions deriving from the battery production.

2.3. Functional Unit

In LCA the cumulated environmental effects over the lifetime are attributed to the functional unit, which is the service of a system that is provided. In this analysis the considered transportation systems provide a transportation service with passenger vehicles. That means that the cumulated environmental effects of a passenger vehicle are attributed to the functional unit of driving:

- 1 kilometre and
- Max. 240,000 km in the total lifetime in max. 16 years.

These functional units are also used to compare the different transportation systems:

- GHG emissions in g CO_2-eq./km and tonnes CO_2-eq./vehicle at the different stages in the life cycle, e.g. production, fuel/energy supply, operation and end-of-life
- Primary energy demand in kWh_{total}/km and MWh/vehicle with the %-share of renewable energy.

The functional units are split up in the following contributions:

- Vehicle production in absolute values (total, battery, fuel cell and H_2-tank)
- Fuel/energy supply per km for each year (1 to 16) separately
- Maintenance per kilometre
- Direct GHG emissions of ICE, HEV and PHEV vehicle operation per kilometre
- Vehicle end-of-life in absolute values.

The different possible driving ranges per filling or charging of an ICE, HEV, PHEV, BEV and FCV cannot be reflected in these functional units.

2.4. Allocation

An allocation of environmental effects in LCA is necessary, where a process produces more than one product, e.g. in an oil refinery: different energy carriers and raw materials for chemical industry, heat and electricity in a combined heat and power (CHP) plant, production of FAME with animal feed and glycerin as co-products.

As this LCA focuses on energy systems, wherever reasonable, an allocation for energy carriers as co-product is done based on the energy content (lower heating value) of the products (“energy allocation”). For all other co-products e.g. animal feed in the value chain of FAME and bio-ethanol a credit for the substituted feed is given. Also for the glycerin and fertilizer coproduced with FAME a credit for the substituted synthetic glycerin and synthetic fertilizer is given.

A special case of allocation appears, when an automotive battery is also used in a 2nd life for a stationary application (‘2nd stationary life’) as modelled here (see chapter 3.3.1.2.). In that case the GHG emissions and the primary energy demand from the battery production are allocated to the automotive and stationary use. The allocation is based on the share of total cumulated electricity stored in the 1st automotive life in the BEV and the 2nd stationary life. Here, the same amount of stored electricity in the automotive and stationary use is assumed.

2.5. Consideration For End-of-Life

The consideration of the environmental effects of the ‘end-of-life’ phase covers the following two aspects:

- GHG emissions and primary energy demand for collection, dismantling and recycling of vehicles to secondary material
- Credits for substitution of primary material by recovered secondary material.

The given credits for the secondary material recovered depend on the purity of the single materials or mix of materials. As the given credits are higher than the GHG emissions and primary energy demand of the recovery processes for most of the considered vehicles, the end-of-life phase might have negative GHG emissions and a negative primary energy demand.

The influence of the end-of-life GHG emissions and primary energy demand in the total lifetime of the vehicle is relatively small, compared to the production and operation phase. For this reason, the end-of-life is calculated for the year 2039 and is independent from the calculated vehicle lifetime. The calculated vehicle lifetime is a result of the user selected annual mileage and the maximum of 240,000 km and 16 years.

2.6. Environmental Effects

Based on the inventory data two impact categories are assessed:

1. Global warming and
2. Total primary energy demand.

Additionally, the most relevant aspects of land use change for the raw material production for biofuels on GHG emissions are described. Other environmental effects like emissions to air NO_x, SO_2, PM and their consequential impacts like acidification, ozone formation, and human toxicity are not considered[1].

2.6.1. Greenhouse Gas Emissions

The greenhouse gas emissions – carbon dioxide (CO_2), methane (CH_4) and nitrogen oxide/laughing gas (N_2O) – are considered.

As measure of the greenhouse effect of these gases the global warming potential (GWP) is used. This gives the contribution of the different gases to the possible global warming and is expressed in form of an equivalent amount of CO_2. The concept of global warming potential was developed to compare the contribution of the different gases to global warming. The global warming effect of a kilogram gas is expressed with a multiple (“equivalent factor”) of the effect of one kilogram carbon dioxide. With the equivalent factors for 100 years (GWP 100) the amount of the gases is calculated in amount of CO_2-equivalents (CO_2-eq.) [IPCC 2019]:

- 1 kg CO_2 = 1 kg CO_2-eq.
- 1 kg CH_4 = 34 kg CO_2-eq.
- 1 kg N_2O = 298 kg CO_2-eq.

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[1] The Clean Air Index in Green NCAP´s vehicle rating programme assesses the pollutants produced locally by a vehicle; see: www.greenncap.com

2.6.2. Land Use Change and Biofuels

Biofuels (and E-fuels) contain carbon and its combustion in an ICE creates about the same CO_2 emissions like petrol, diesel or CNG per energy unit.

The biogenic CO_2 emissions to the atmosphere from the combustion of biofuels are calculated to be zero, as the same amount was fixed before in the biomass by photosynthesis taking CO_2 from the atmosphere (CO_2 uptake = CO_2 from combustion).

This accounting system for biogenic CO_2 is used also in the national GHG accounting system following the IPCC guideline for national inventories in the energy sector. Changes and dynamics in the carbon stocks, e.g. the carbon which is stored in plants, litter and soil, in agriculture and forestry are considered in the CO_2 emissions or CO_2 uptake caused by Land Use Changes (LUC) for biomass used for biofuels.

Analysing CO_2 effects from land use change two different types of LUC are relevant (Figure 7):

- Direct Land Use Change (dLUC)
- Indirect Land Use Change (iLUC)

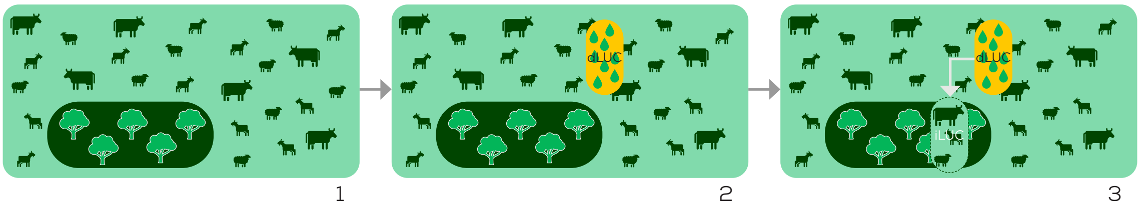

Figure 7 - Direct Land Use Change (dLUC) and Indirect Land Use Change (iLUC)

Direct Land Use Change (dLUC) occurs if for cultivation of energy crops a land use change takes place, e.g. from pasture to crop land. Direct effects can be calculated, e.g. change of carbon storage pools with the difference of carbon stocks from pasture and crop land per hectare. This initial effect, which occurs once, must be allocated to the biomass cultivated on the crop land, e.g. for biofuels.

Indirect Land Use Change (iLUC) occurs if existing crop land is now used for energy crops, which was used for other products before. The demand for these products remains and additional land is used causing land use change on global scale, e.g. conversion of natural forests into agricultural land. Indirect effects can be calculated after localization, which is difficult on a global level. The calculation of this initial effect is done one the difference of the carbon stock from forest and agricultural land. But on a physical level a direct allocation of these indirect effects to a specific agricultural crop, e.g. for biofuel or additional animal feed is not possible. The indirect effects are calculated by using economic models and methods. These models give broad ranges of possible iLUC effects of biomass cultivation for biofuels.

For the calculation of GHG emissions due to Land Use Change the European Commission uses the GLOBIOM-Modell - Global Biosphere Management Model ([Valin H. et al., 2015]; www.globiom.org). IIASA's Global Biosphere Management Model (GLOBIOM) is used to analyse the competition for land use between agriculture, forestry, and bioenergy, which are the main land-based production sectors. As such, the model can provide scientists and policymakers with the means to assess, on a global basis, the rational production of food, forest fiber, and bioenergy, all of which contribute to human welfare. In GLOBIOM no distinction between iLUC and dLUC is possible, as iLUC cannot be allocated to certain agricultural activities.

Exemplary in Figure 8 some results of possible LUC effects of biofuel from the GLOBIOM model are shown. The highest possible GHG emissions of LUC are calculated for FAME from palm oil with about 231 g CO_2-eq./MJ and from soy oil with about 150 g CO_2-eq./MJ, followed by FAME from rape seed oil with about 65 g CO_2-eq./MJ. The possible GHG emissions of bio-ethanol from maize, wheat and sugar beet due to LUC effects are with 14 to 34 g CO_2-eq./MJ significantly lower.

The main data for possible dLUC and iLUC effects on the GHG emissions are shown in Table 14 in ANNEX I: MAIN DATA.

The calculation in the Tool only includes possible CO_2 emissions from dLUC; as it was decided among the stakeholder involved.

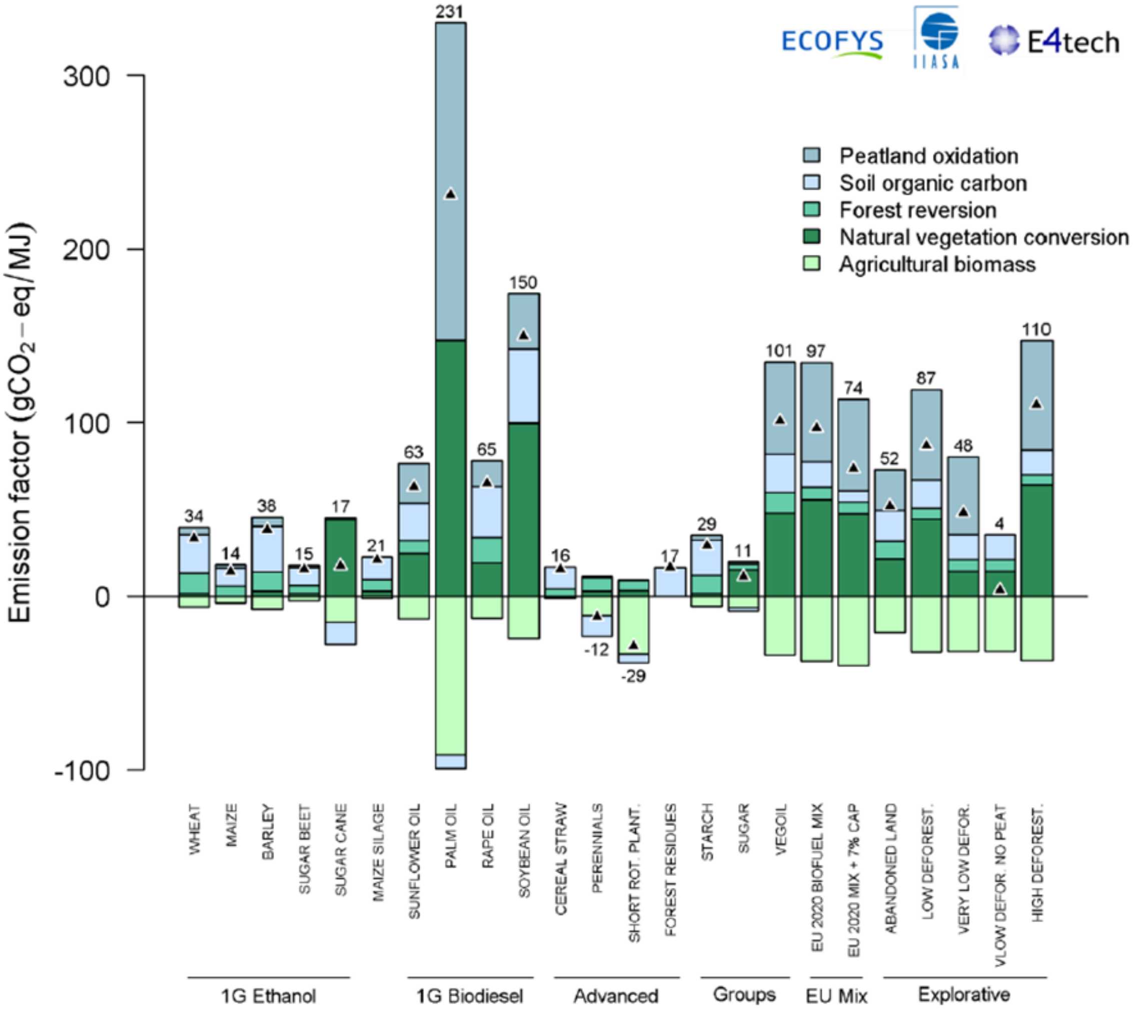

Figure 8 - Possible LUC effects on GHG emissions of biofuels [Valin H. et al., 2015]

Diesel B7 (7 vol.-% FAME) and petrol E10 (10 vol.-% EtOH) are used for ICE, HEV and PHEV, as biofuel blending is state of the art in Europe. Most of this biofuel used is produced in Europe with European feedstock, e.g. wheat, corn, rapeseed and waste cooking oil.

Based on the current legislation in Europe (RED-Renewable Energy Directive [EU 2018]) these biofuels fulfil relevant sustainability criteria e.g. minimum GHG reduction. The combustion of biofuels in ICE, HEV and PHEV is considered to be 'CO_2 neutral'. Therefore, the effect of CO_2 emissions of biofuel blending from ICE is less than 7% compared to pure diesel or petrol due to the lower volumetric heating value of biofuels.

The GHG emissions of biofuel production (e.g. N_2O emissions from agricultural cultivation) are calculated based on LCA incl. possible direct land use change. Indirect land use change effects are not considered as they are out of the scope of the LCA applied here. In other studies addressing land use, possible indirect land use change effects are analysed based on global economic models, e.g. EtOH 43 – 61 g CO_2/kWh and FAME 119 – 238 g CO_2/kWh [EU 2015] for single feedstocks, which might lead to additional CO_2 emissions in the life cycle of 25 – 65 g CO_2/km using pure biofuel with current feedstock mix; with E10 and B7 the effect is correspondingly much lower.

The European biofuel industry follows strict legislation and uses synergy effects (e.g. animal food production, starch products, glycerine). However, it shall be acknowledged that biofuel-production might conflict with food- and feedstock production globally, but these effects are difficult to quantify.

2.6.3. Primary Energy Demand

Based on the amount and type of final energy carriers e.g. fuels, electricity, the necessary amount of primary energy is calculated to supply the energy needed for the transportation systems. E.g. the electricity production in a coal power plant has an average annual efficiency of about 40%; that means that the primary energy demand to produce 1 kWh of electricity is 2.5 kWh of coal. For renewable electricity generation from wind, photovoltaics and hydro power the annual efficiency of the power plant is set per definition to 100%; that means that the primary energy demand to produce 1 kWh of electricity is 1 kWh of wind, solar or hydro power.

The following primary energy resources are considered:

- Fossil resources: coal, oil and gas,
- Renewable resources: hydro power, biomass, solar, wind
- Other resources e.g. nuclear[2], waste, residues.

The primary energy demand is calculated based on the lower heating values.

2.7. Description of Terms For Communication

For communication to a broader audience the most relevant terms are briefly described. The terms used are the following:

- Life Cycle Assessment (LCA) is a method to estimate the overall environmental effects of a vehicle in its total lifecycle, covering vehicle production, vehicle operation and end-of-life of the vehicle
- GHG emissions are given in CO_2-equivalent (CO_2-eq.) covering the sum of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) according to their contribution to global warming for a time horizon of 100 years (GWP 100). The unit is g CO_2-eq. per kilometre driven
- The Primary Energy Demand is the sum of all primary energy taken from nature to provide the transportation service covering coal, oil, natural gas, hydro, wind, solar and nuclear energy. The unit is kWh per kilometre driven
- The renewable share of primary energy demand covers hydro, wind, solar energy and biomass
- The GHG emissions and the primary energy demand are given in:
  - Total LCA and
  - Contributions in the three phases of the life cycle
    - Production
    - Operation and
    - End-of-life
- Production covers the production of the total vehicle (incl. battery, fuel cell, H_2-tank)
- Operation covers the operation of the vehicle with the supply of energy, the use of energy and maintenance
- End-of-life covers the recycling and waste treatment of used vehicles. As the recovered secondary material substitutes for primary material, the GHG emissions and the primary energy demand can be negative.

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[2] Except for the electricity mixes, the nuclear primary energy is included in the fossil primary energy due to the used data source.

3. DATA BASE

3.1. Data Structure

Basically, in the LCA data are used that represent adequately the technical, geographical and timely framework condition to fulfil the goal and the scope of the LCA based estimation of GHG emissions and primary energy demand. In this assessment and in the LCA Expert Tool, the different transportation systems are compared to each other. The most important aspect of the basic data is to reflect the main differences (e.g. fuel demand per km) between the systems and the states of technology, in order to to identify the most significant differences between the GHG emissions and the primary energy demand. The basic data are based on generic and global process chains, e.g. steel and aluminium.

So the main focus of the data collection and selection is on the main influences that effect the estimated overall GHG emissions and primary energy demand significantly.

By reflecting this, in the LCA two different types of data categories (see example Figure 9) are set up: the fore- and background data.

The foreground data, which have a significant influence on the total environmental effects considering the specific goal and scope, determine most of the differences between the considered vehicles and their technologies. The foreground data must be collected, assessed and documented explicitly in accordance to the goal and the scope of the LCA. The foreground data for this LCA are mainly the following vehicle data, received from the mobility clubs and Green NCAP:

- Propulsion system
- Type of fuel
- Fuel/energy demand
- Vehicle mass
- Battery capacity
- CH_4 and N_2O emissions from vehicles equipped with an ICE Vehicle (where available from Green NCAP testing) and the
- Average electricity mix for the considered countries and the EU27 mix.

The background data, which have a minor influence on the difference between the considered environmental effects of the compared vehicles, e.g. environmental effects of steel or petrol E10 supply, are taken and documented from adequate data bases, e.g. own JOANNEUM data, GEMIS 5.2 [GEMIS 2023], ecoinvent 3.4 [Ecoinvent 2019]. The background data are used referring to the goal of this LCA, where the Life Cycle Assessment is performed for generic global supply chains of vehicle production and energy supply in Europe between 2024 and 2039.

In general, the use of different background data sources might lead to methodological inconsistencies (e.g. allocation, state of technology etc.) and to some extent might lead to arbitrary results. For this reason, priority is given in using the different databases. For the background data, JOANNEUM data sets are of highest priority and the missing data are added from GEMIS and from ecoinvent. All relevant data are explicitly documented in the following chapters.

Typical background data for the LCA are about:

- Electricity mix for auxiliary processes
- Production of materials for vehicles
- Auxiliary material and energy for processes
- Distribution infrastructure (e.g. electricity, hydrogen, liquid and gaseous fuels).

The background data are interpolated between 2020, 2030 and 2050, where necessary.

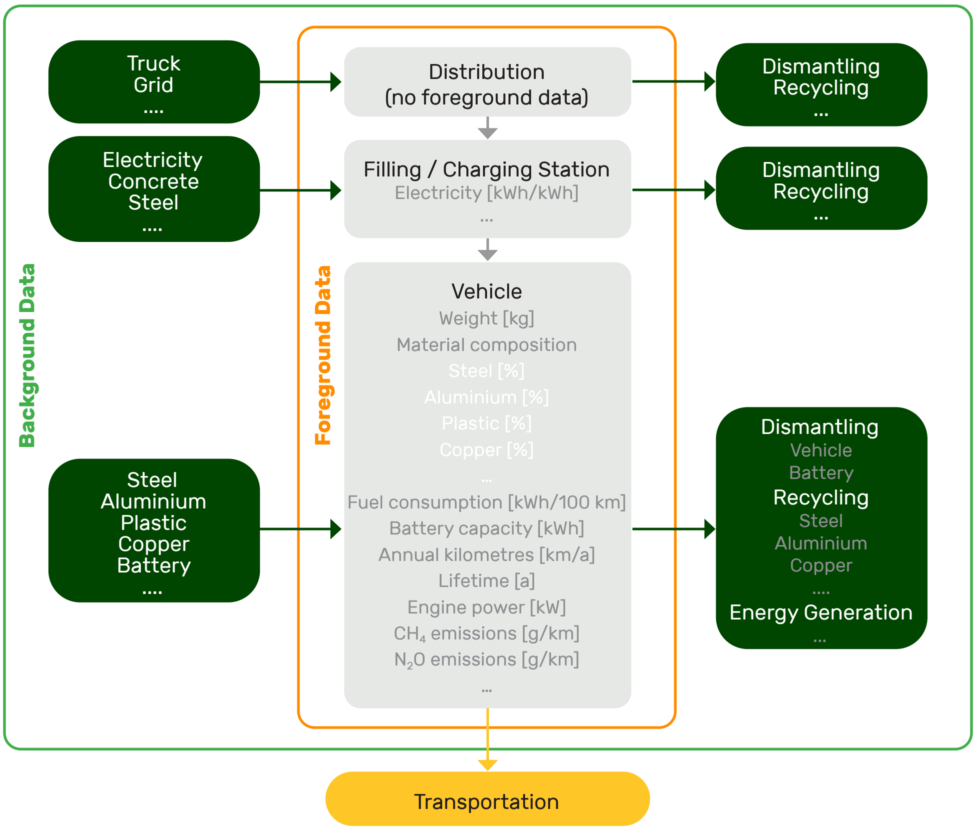


Figure 9 - Examples of foreground data ('Vehicle', 'Filling/charging station',) and background data ('Material and component production', 'Dismantling, recycling and energy generation')

In the initial state of the LCA it is not always entirely clear, which data are explicitly foreground data and which are the background data, e.g. charging infrastructure for electric vehicles, as this depends on the specific aim and goal of the LCA. This is also in accordance to the iteration processes according to ISO 14040 (see Figure 2). For this purpose also relevant inputs and clarification from the continuous stakeholder process, as well as requirements from the future usage of the Tool are used to finally set the foreground data explicitly.

All basic data are documented and integrated in the LCA Expert Tool v2.4 [Jungmeier et al. 2024], and the most relevant data are also given in this report. The foreground data and selected background data were discussed among the stakeholders.

3.2. Foreground Data

There are three groups of foreground data specified:

1. Specification of the vehicle
2. Resources and processes used to produce the energy carrier for the vehicle
3. Possible future developments.

3.2.1. Vehicle Specification

The foreground data for the specification of the vehicle are:

- Vehicle data
    - Mass
    - Annual kilometres [km/a]: defined by user with max 240,000 km in lifetime
    - Lifetime: maximum 16 years
    - Energy demand
    - CH_4 and N_2O emissions: if not available, default data are used [Jungmeier et al 2024]
- Battery and charging
    - Capacity [kWh]
    - Lifetime: same as vehicle based on stakeholder decision: max. 240,000 km
    - Charging losses [%]: 2% charging losses outside the vehicle are considered [Green NCAP 2022]
    - Location of battery production [%] (interpolated for 2024 based on [McKinsey 2024 and Schade 2022])
        - China: 78%
        - Europe: 14%
        - USA: 8%
    - End-of-life [%]
        - Material recycling: 97%
        - 2nd stationary life: 3%.

3.2.2. Biomass Resources

The foreground data for the biogenic resources to produce and supply the energy carrier for the vehicle are:

- Land use change (LUC) (Table 1 in ANNEX I: MAIN DATA), considers: sugar cane from pasture, soy beans from pasture, palm oil from tropical forest.
- Share of biofuel blending – biodiesel (FAME) in diesel: 7 vol.-%, bioethanol (EtOH) in petrol: 10 vol.-% in E10; 85 vol.-% in E85.
- Biomass mix (Table 2 in ANNEX I: MAIN DATA) ([JRC 2020], [IEA 2024], [OECD-FAO 2024] , [Rangaraju 2021] and [JOANNEUM RESEARCH 2024])
    - FAME – rape seed oil, cooking oil and animal fat, palm oil, soya oil
    - EtOH – wheat and maize, sugar beet, sugar cane, wood, straw.

3.2.3. Electricity Mix

For the European countries the national consumption electricity mix, its GHG emissions and primary energy demand were kindly provided by Ricardo [Ricardo 2023] solely for the use in Green NCAP LCA Projects. For the years 2020, 2030 and 2040. The values for 2050 were extrapolated. The data were supplied for two different scenarios:

- Baseline is based on REF2020 for EU countries (further updated also to include actual year 2020 data from Eurostat statistics on electricity production by fuel),
- Tech1.5 has been further updated for 2030 based on the MIX scenario from the Fit-for-55 package (see here: Policy scenarios for delivering the European Green Deal from modelling files for EU), with projections for 2040 based on the Tech1.5 scenario from the EU's Long-Term Strategy to reach a climate-neutral Europe by 2050.

However, most of the policy proposals for Fit-for-55 have now been formally adopted (status: Fit for 55 - The EU's plan for a green transition - Consilium (europa.eu)), which suggests that values closer to the MIX/Tech1.5 scenario present the 'current' policy expectation. Crucially, a couple of policies that are contributing to the future FF55 package for electricity have not yet been agreed on (e.g. 'The proposal for a revision of the Council directive on the taxation of energy products and electricity'). The limitation is given by the fact that the EU27+UK data is not perfectly consistent with the updated UK-only data. Therefore, conservatively an average of the two scenarios is reasonable to represent current policy in place (until new EC reference scenario becomes available).

For Germany, the GHG emissions in 2024 are not based on this electricity mix, as it was decided in the stakeholder consultations based on an explicit wish of the ADAC. The ADAC prefers using the published GHG emissions of the German electricity mix in 2024 by the Environmental Agency [Bundesanzeiger 2023].

Non-EU countries were calculated with the specified foreground data using LCA, using also the GHG emissions from upstream emission from IEA [IEA 2023 a].

The shares of the electricity mix of the different countries are shown in the Table 3 in ANNEX I: MAIN DATA. Between 2020, 2030 and 2050, the foreground data are interpolated for the 16 years of lifetime of the vehicles.

It is important to notice that in the calculations of the operation phase of the vehicle, the changes of the energy/electricity supply in the lifetime of the vehicle are considered.

3.3. Background Data

The background data cover all other data that are necessary to estimate the LCA based GHG emissions and the primary energy demand of the transportation systems with passenger vehicles. These data derive from different data bases (e.g. GEMIS 5.2, ecoinvent 3.4) and own data. In the following section the most relevant background data, which are necessary to assess and discuss the main results of the LCA, are shown.

The background data are grouped as follows:

- Vehicle covering production, operation, maintenance and end-of-life
- Supply of energy carriers to the vehicle also covering production of hydrogen, electricity supply and biofuels as well as their possible land use change effects.

3.3.1. Vehicle

3.3.1.1. Vehicle Production

The estimation of the vehicle material composition (except battery, see chapter 3.3.1.2 and Table 4 in ANNEX I: MAIN DATA) is mainly based on work from Graz University of Technology [Hausberger et al. 2018] and own work at JOANNEUM RESEARCH, especially on hydrogen storage tanks and electronics in vehicles [JOANNEUM RESEARCH 2024].

The energy demand for the basic vehicle manufacturing in a vehicle factory is estimated based on the VW Sustainability report [VW 2021]:

- Electricity: 1,060 kWh/vehicle
- Heat: 590 kWh/vehicle
- Natural gas: 420 kWh/vehicle.

The background data for vehicle production cover

- Share of material mix for vehicles (Table 4 in ANNEX I: MAIN DATA) and hydrogen fuel cell & tank production (Table 5 ANNEX I: MAIN DATA) to calculate the environmental effects of vehicle production. The H_2 pressure is 700 bar, the mass of the H_2-tank and-of-the fuel cell system is 276 kg.
- Materials (Table 6 in ANNEX I: MAIN DATA) and primary energy for vehicle production.

3.3.1.2. Battery Production

On the basis of a literature review on environmental life cycle impacts of automotive batteries, the calculation of GHG emissions from battery manufacturing is done with the JOANNEUM RESEARCH in-house “JR Battery LCA-Tool” [Aichberger et al. 2020a], [Pucker-Singer et al. 2021].

The main processes in the LCA of automotive batteries are (Figure 10):

- Raw material mining and refining
- Grade material production
- Battery system manufacturing
- Battery use
- Reuse
- Recycling and 2nd life (Reuse)
- Transports.

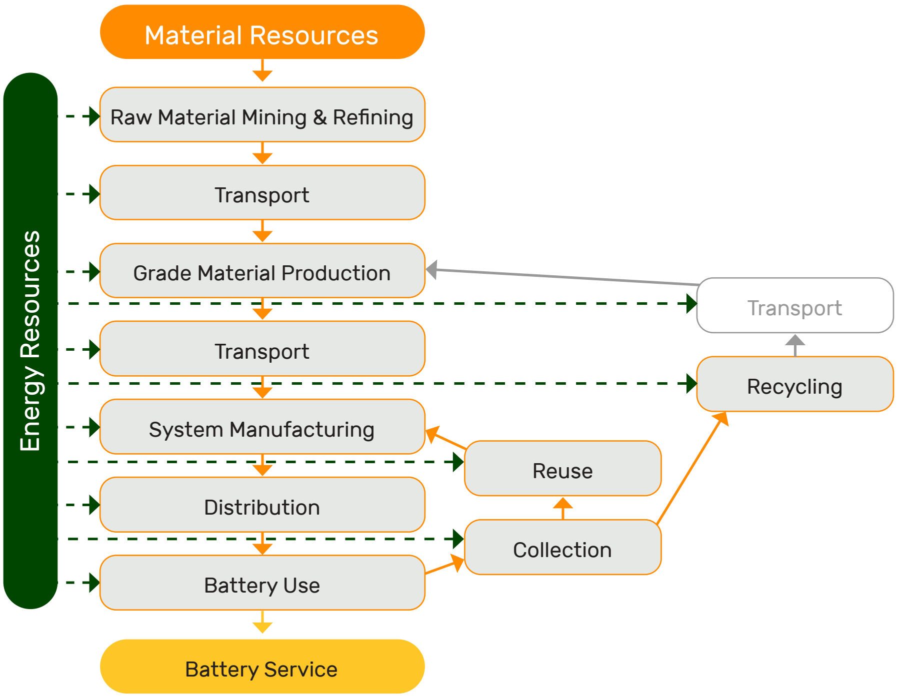


Figure 10 - System boundaries for automotive battery systems

The LCA for automotive battery system is calculated in the in-house battery LCA-Tool for the following two functional units

- Per kWh battery capacity, e.g. kg CO_2-eq./kWh
- Per km driven (assuming e.g. 57 kWh battery capacity and 240,000 km lifetime mileage), e.g. g CO_2-eq./km with a passenger vehicle

The modelling of the automotive battery system is done for the following seven main components Figure 11:

1. Cathode
2. Anode
3. Electrolyte
4. Separator
5. Module and battery packaging (pack, module and cell case)
6. Battery-Management-System (BMS)
7. Cooling (thermal) system.

The distribution of the mass to these components is shown in Figure 12.

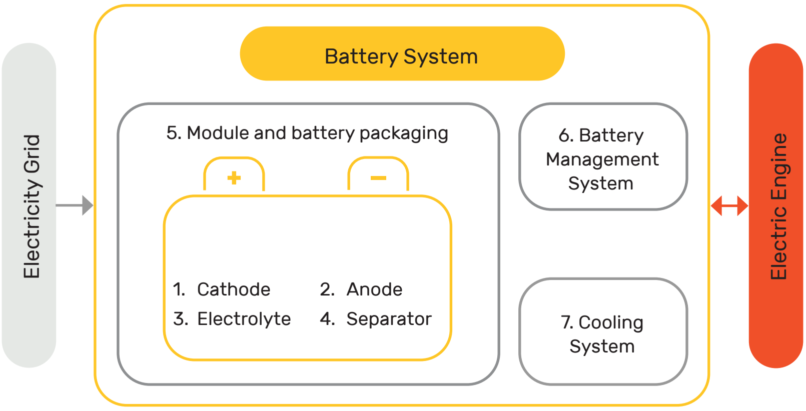


Figure 11 - Main components of the automotive battery system

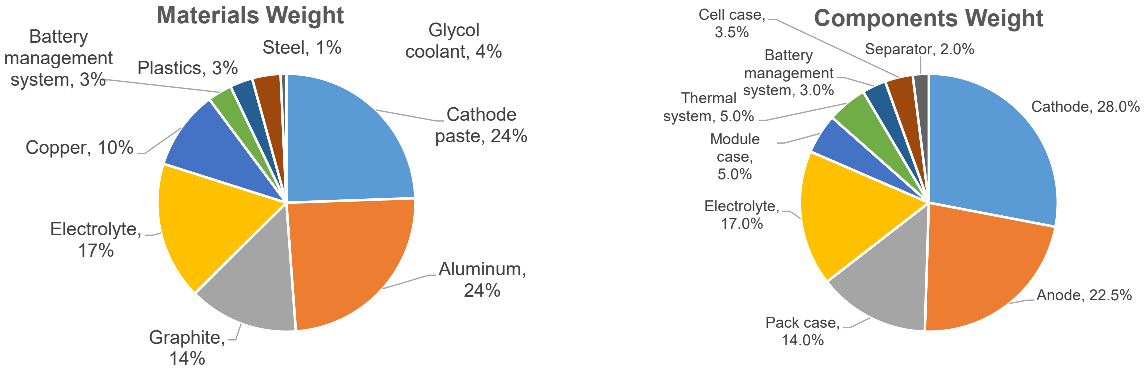


Figure 12 - Estimated average distribution of the mass of these components in the automotive battery system [JOANNEUM RESEARCH 2024]

The following main materials of the automotive battery system are considered in the LCA:

- Positive active material (incl. Lithium, Nickel and Cobalt)
- Aluminum
- Graphite
- Copper
- Lithium hexafluorophosphate (Electrolyte)
- Steel
- Polymer.

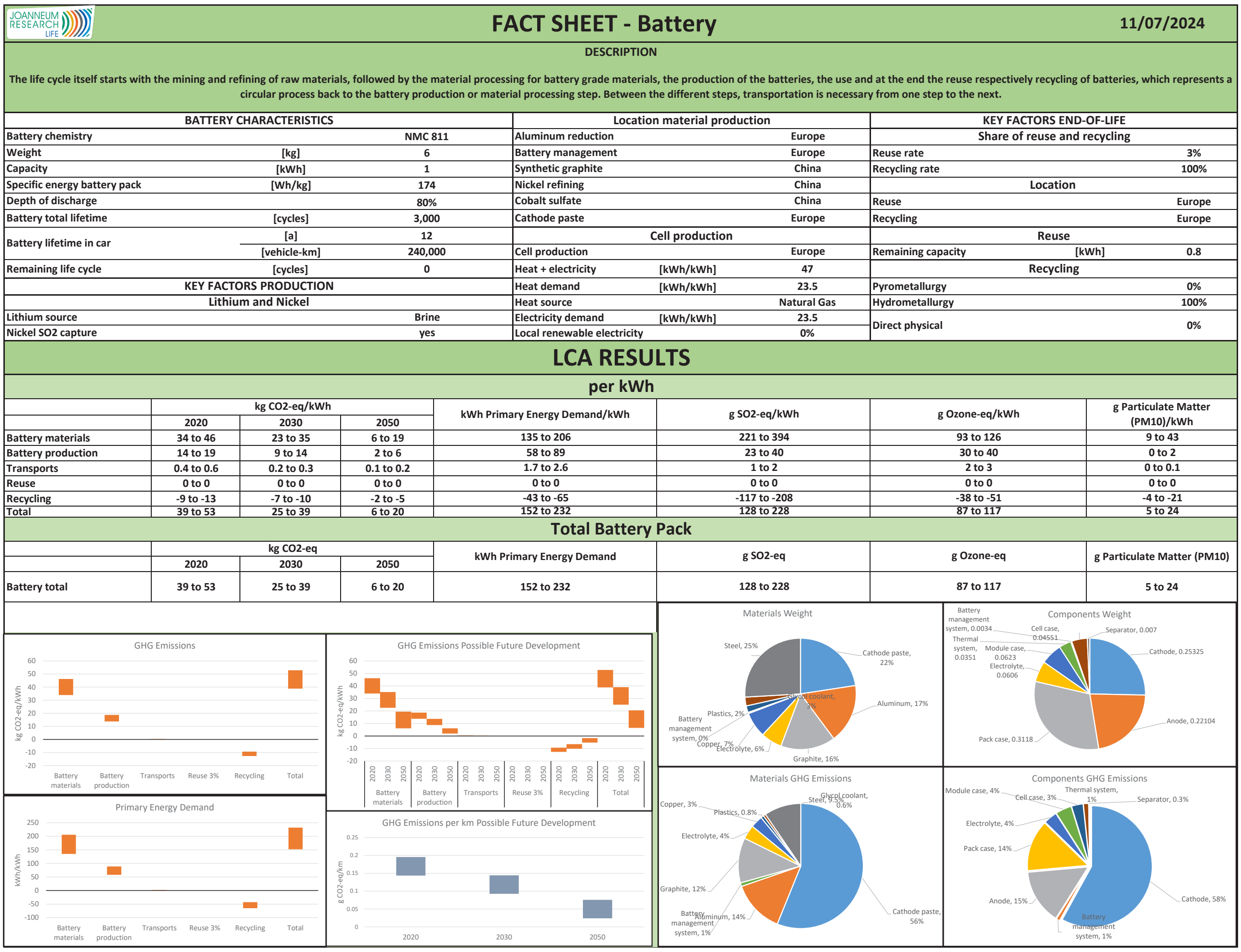
The LCA is done for batteries produced in Europe, USA and China separately, mainly based on the different electricity generation mix.

For the end-of-life phase of automotive batteries – material recycling or reuse as stationary application in a 2nd life – less data are available. The battery recycling is currently tested in pilot and demo plants as a combination of mechanical and pyro- and hydrometallurgical processes. For the LCA modelling the following assumptions are made:

- Dismantling of the battery module with use of aluminium and plastics
- Dismantling of the battery cells with use of copper and aluminium
- Dismantling of the cathode with use of aluminium and
- Hydrometallurgical recycling of cobalt and nickel.

In the following Figures (Figure 13, Figure 14 and Figure 15) the main inputs and results from the LCA of automotive batteries produced in Europe, USA and China for 2020, 2030 and 2050 are shown.

In Table 7 in ANNEX I: MAIN DATA the background data for batteries used in the tool are shown based on the LCA battery modelling for 2020, 2030 and 2050. The data used for the calculations are for 2022, which are based on the interpolation between 2020 and 2030. Data were derived from two main sources [McKinsey 2024] and [Schade, 2022]. It is expected that the European OEMs will further integrate the battery upstream value chain. Recycling activities are expected to take place in the countries where the vehicles are disposed.



FACT SHEET - Battery 11/07/2024

DESCRIPTION

The life cycle itself starts with the mining and refining of raw materials, followed by the material processing for battery grade materials, the production of the batteries, the use and at the end the reuse respectively recycling of batteries, which represents a circular process back to the battery production or material processing step. Between the different steps, transportation is necessary from one step to the next.

BATTERY CHARACTERISTICS		
Battery chemistry		NMC 811
Weight	[kg]	6
Capacity	[kWh]	1
Specific energy battery pack	[Wh/kg]	174
Depth of discharge		80%
Battery total lifetime	[cycles]	3,000
Battery lifetime in car	[a]	12
	[vehicle-km]	240,000
Remaining life cycle	[cycles]	0
KEY FACTORS PRODUCTION		
Lithium and Nickel		
Lithium source		Brine
Nickel SO2 capture		yes

Location material production		
Aluminum reduction		Europe
Battery management		Europe
Synthetic graphite		China
Nickel refining		China
Cobalt sulfate		China
Cathode paste		Europe
Cell production		
Cell production		Europe
Heat + electricity	[kWh/kWh]	47
Heat demand	[kWh/kWh]	23.5
Heat source		Natural Gas
Electricity demand	[kWh/kWh]	23.5
Local renewable electricity		0%

KEY FACTORS END-OF-LIFE		
Share of reuse and recycling		
Reuse rate		3%
Recycling rate		100%
Location		
Reuse		Europe
Recycling		Europe
Reuse		
Remaining capacity	[kWh]	0.8
Recycling		
Pyrometallurgy		0%
Hydrometallurgy		100%
Direct physical		0%

LCA RESULTS

per kWh

	kg CO2-eq/kWh			kWh Primary Energy Demand/kWh	g SO2-eq/kWh	g Ozone-eq/kWh	g Particulate Matter (PM10)/kWh
	2020	2030	2050				
Battery materials	34 to 46	23 to 35	6 to 19	135 to 206	221 to 394	93 to 126	9 to 43
Battery production	14 to 19	9 to 14	2 to 6	58 to 89	23 to 40	30 to 40	0 to 2
Transports	0.4 to 0.6	0.2 to 0.3	0.1 to 0.2	1.7 to 2.6	1 to 2	2 to 3	0 to 0.1
Reuse	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0
Recycling	-9 to -13	-7 to -10	-2 to -5	-43 to -65	-117 to -208	-38 to -51	-4 to -21
Total	39 to 53	25 to 39	6 to 20	152 to 232	128 to 228	87 to 117	5 to 24

Total Battery Pack

	kg CO2-eq			kWh Primary Energy Demand	g SO2-eq	g Ozone-eq	g Particulate Matter (PM10)
	2020	2030	2050				
Battery total	39 to 53	25 to 39	6 to 20	152 to 232	128 to 228	87 to 117	5 to 24

Figure 13 - LCA data and results of 'JR Battery LCA-Tool' for automotive batteries produced in Europe [JOANNEUM RESEARCH 2024]

FACT SHEET - Battery

11/07/2024

DESCRIPTION

The life cycle itself starts with the mining and refining of raw materials, followed by the material processing for battery grade materials, the production of the batteries, the use and at the end the reuse respectively recycling of batteries, which represents a circular process back to the battery production or material processing step. Between the different steps, transportation is necessary from one step to the next.

BATTERY CHARACTERISTICS		
Battery chemistry		NMC 811
Weight	[kg]	6
Capacity	[kWh]	1
Specific energy battery pack	[Wh/kg]	174
Depth of discharge		80%
Battery total lifetime	[cycles]	3,000
Battery lifetime in car	[a]	12
	[vehicle-km]	240,000
Remaining life cycle	[cycles]	0
KEY FACTORS PRODUCTION		
Lithium and Nickel		
Lithium source		Brine
Nickel SO2 capture		yes

Location material production		
Aluminum reduction		United States
Battery management		United States
Synthetic graphite		China
Nickel refining		China
Cobalt sulfate		China
Cathode paste		United States
Cell production		
Cell production		United States
Heat + electricity	[kWh/kWh]	47
Heat demand	[kWh/kWh]	23.5
Heat source		Natural Gas
Electricity demand	[kWh/kWh]	23.5
Local renewable electricity		0%

KEY FACTORS END-OF-LIFE		
Share of reuse and recycling		
Reuse rate		3%
Recycling rate		100%
Location		
Reuse		United States
Recycling		United States
Reuse		
Remaining capacity	[kWh]	0.8
Recycling		
Pyrometallurgy		0%
Hydrometallurgy		100%
Direct physical		0%

LCA RESULTS

per kWh

	kg CO2-eq/kWh			kWh Primary Energy Demand/kWh	g SO2-eq/kWh	g Ozone-eq/kWh	g Particulate Matter (PM10)/kWh
	2020	2030	2050				
Battery materials	37 to 49	25 to 37	8 to 20	149 to 213	230 to 397	99 to 130	9 to 43
Battery production	18 to 24	13 to 18	4 to 9	80 to 115	28 to 49	37 to 49	0 to 2
Transports	0.2 to 0.2	0.1 to 0.1	0 to 0.1	0.7 to 1	0 to 1	1 to 1	0 to 0
Reuse	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0
Recycling	-10 to -13	-7 to -10	-2 to -5	-44 to -64	-121 to -209	-40 to -53	-4 to -21
Total	46 to 60	31 to 45	9 to 23	185 to 265	138 to 238	97 to 127	5 to 24

Total Battery Pack

	kg CO2-eq			kWh Primary Energy Demand	g SO2-eq	g Ozone-eq	g Particulate Matter (PM10)
	2020	2030	2050				
Battery total	46 to 60	31 to 45	9 to 23	185 to 265	138 to 238	97 to 127	5 to 24

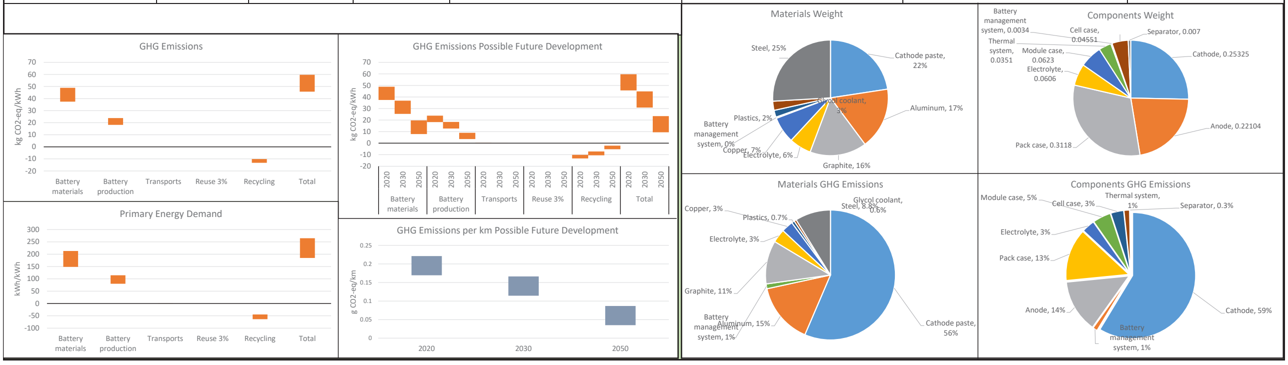
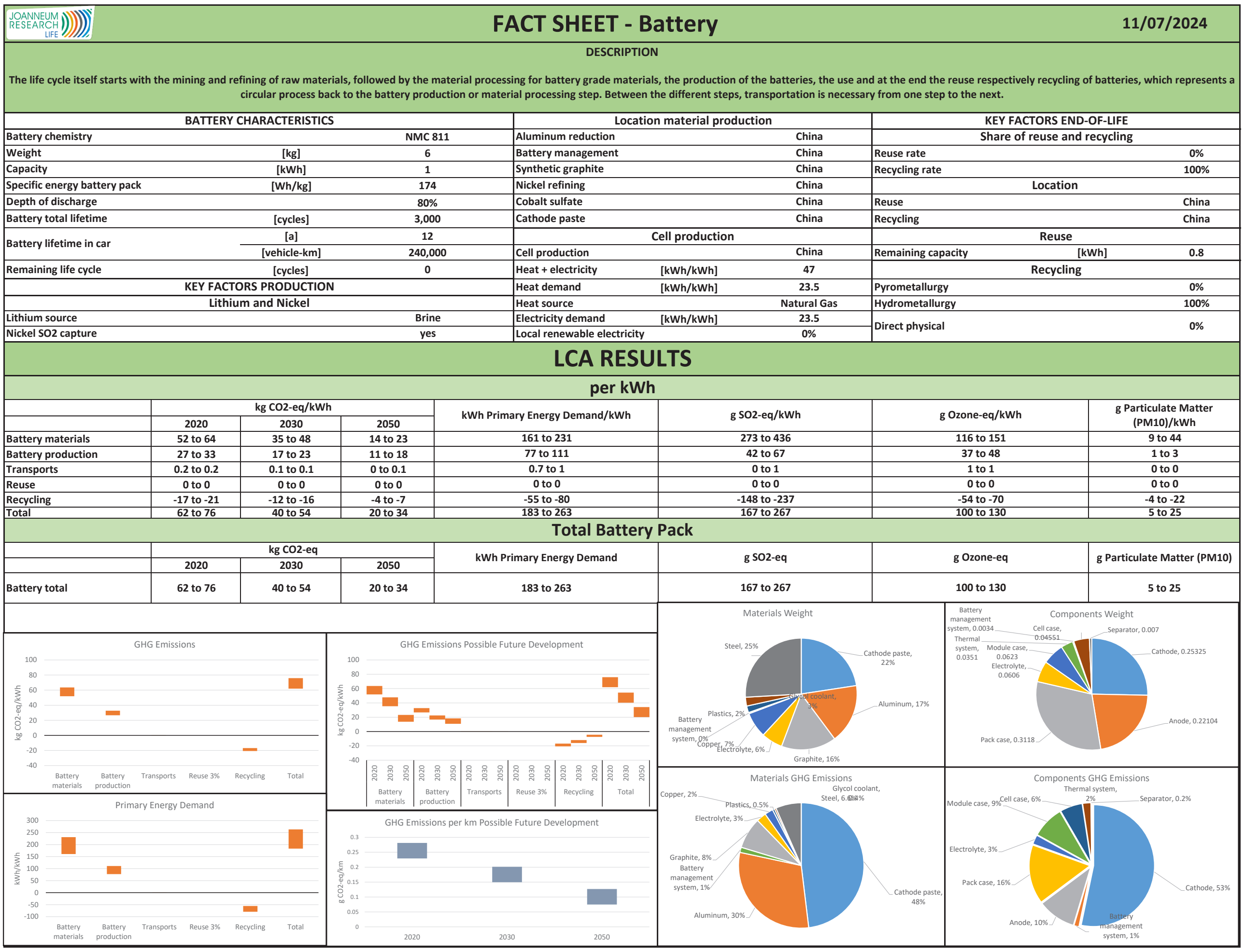


Figure 14 - LCA data and results of ‘JR Battery LCA-Tool’ for automotive batteries produced in USA [JOANNEUM RESEARCH 2024]



FACT SHEET - Battery 11/07/2024

DESCRIPTION

The life cycle itself starts with the mining and refining of raw materials, followed by the material processing for battery grade materials, the production of the batteries, the use and at the end the reuse respectively recycling of batteries, which represents a circular process back to the battery production or material processing step. Between the different steps, transportation is necessary from one step to the next.

BATTERY CHARACTERISTICS		
Battery chemistry		NMC 811
Weight	[kg]	6
Capacity	[kWh]	1
Specific energy battery pack	[Wh/kg]	174
Depth of discharge		80%
Battery total lifetime	[cycles]	3,000
Battery lifetime in car	[a]	12
	[vehicle-km]	240,000
Remaining life cycle	[cycles]	0
KEY FACTORS PRODUCTION		
Lithium and Nickel		
Lithium source		Brine
Nickel SO2 capture		yes

Location material production		
Aluminum reduction		China
Battery management		China
Synthetic graphite		China
Nickel refining		China
Cobalt sulfate		China
Cathode paste		China
Cell production		
Cell production		China
Heat + electricity	[kWh/kWh]	47
Heat demand	[kWh/kWh]	23.5
Heat source		Natural Gas
Electricity demand	[kWh/kWh]	23.5
Local renewable electricity		0%

KEY FACTORS END-OF-LIFE		
Share of reuse and recycling		
Reuse rate		0%
Recycling rate		100%
Location		
Reuse		China
Recycling		China
Reuse		
Remaining capacity	[kWh]	0.8
Recycling		
Pyrometallurgy		0%
Hydrometallurgy		100%
Direct physical		0%

LCA RESULTS

per kWh

	kg CO2-eq/kWh			kWh Primary Energy Demand/kWh	g SO2-eq/kWh	g Ozone-eq/kWh	g Particulate Matter (PM10)/kWh
	2020	2030	2050				
Battery materials	52 to 64	35 to 48	14 to 23	161 to 231	273 to 436	116 to 151	9 to 44
Battery production	27 to 33	17 to 23	11 to 18	77 to 111	42 to 67	37 to 48	1 to 3
Transports	0.2 to 0.2	0.1 to 0.1	0 to 0.1	0.7 to 1	0 to 1	1 to 1	0 to 0
Reuse	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0	0 to 0
Recycling	-17 to -21	-12 to -16	-4 to -7	-55 to -80	-148 to -237	-54 to -70	-4 to -22
Total	62 to 76	40 to 54	20 to 34	183 to 263	167 to 267	100 to 130	5 to 25

Total Battery Pack

	kg CO2-eq			kWh Primary Energy Demand	g SO2-eq	g Ozone-eq	g Particulate Matter (PM10)
	2020	2030	2050				
Battery total	62 to 76	40 to 54	20 to 34	183 to 263	167 to 267	100 to 130	5 to 25

Figure 15 - LCA data and results of ‘JR Battery LCA-Tool’ for automotive batteries produced in China [JOANNEUM RESEARCH 2024]

3.3.1.3. Vehicle Operation

The energy consumption values for vehicle operation are provided by the stakeholders ADAC, ÖAMTC and Green NCAP. In cases where no CH_4 and N_2O emissions for HEV, ICE and PHEV are provided, the default data from the LCA Expert Tool 2.4 [Jungmeier et al 2024] are used.

3.3.1.4. Vehicle Maintenance

The environmental effects from the maintenance of the vehicle during operation are considered (Table 8 in ANNEX I: MAIN DATA), which are

- Tyres
- Spare/replacement parts (assumption: annually 0.5% of vehicle mass per year)
- Combustion engine motor oil for ICE, HEV and PHEV and
- Urea (diesel exhaust fluid) for diesel ICE.

Table 9 in ANNEX I: MAIN DATA shows the GHG emissions and PED relevant for maintenance.

3.3.1.5. Vehicle End-of-Life

For the environmental effects in the end-of-life phase of the vehicles the following issues are considered:

- The energy demand for recycling to recover the secondary material is assumed to be about 20% of the energy demand of the vehicle manufacturing
- A credit for the substitution of the materials: in average for all materials it is assumed that 1 t of secondary material substitutes for 0.15 t of primary material, e.g. for steel this is significantly higher and for electronics significantly lower
- The GHG emissions and primary energy demand of end-of-life are not depending on the year, they are estimated for the years between 2030 - 2035.

The end-of-life for batteries is calculated in much greater detail, directly sourced from the 'JR Battery LCA-Tool' [Aichberger et al. 2020] (see chapter 3.3.1.2.).

3.3.2. Supply of Fuels and Energy

3.3.2.1. Hydrogen Production

In Table 10 in ANNEX I: MAIN DATA the main data for hydrogen production via electrolysis and natural gas steam reforming are shown. The oxygen and heat from electrolysis are not used. The electricity demand for the compression from 30 bar to 800 bar and cooling of hydrogen is 2.7 kWh/kg H_2, which is based on the ionic compressor IC 90 of Linde Gas.

3.3.2.2. Biofuel Production

In Table 11 in ANNEX I: MAIN DATA the main data for vegetable oil production are given. The co-produced animal feed substitutes soy feed. In Table 12 in ANNEX I: MAIN DATA the main data for FAME (biodiesel) production are shown. The coproduced glycerin substitutes synthetically produced glycerin and the coproduced potassium substitutes for synthetic fertilizer. In Table 13 in ANNEX I: MAIN DATA the main data for bio-ethanol production are shown. The coproduced animal feed substitutes soy feed.

3.3.2.3. Land Use Change of Biofuels

The background data for land use change for biomass resources are shown in Table 14 in ANNEX I: MAIN DATA. The possible CO_2 emissions of iLUC are not considered in the analysis (see also chapter 2.6.2.), but for transport systems using biofuels an additional information on GHG emissions from iLUC is given in the Fact Sheet of LCA Tool 2.4 [Jungmeier et al. 2024].

3.3.2.4. Supply of Fuels and Electricity

The background data for the supply of energy carriers to the vehicle are:

- Heating values of fossil and biogenic resources (Table 15 in ANNEX I: MAIN DATA)
- Heating values of fuels (Table 16 in ANNEX I: MAIN DATA)
- Supply of fuels to the filling station (Table 17 and Table 18 in ANNEX I: MAIN DATA).
- Supply of electricity to the charging station incl. distribution (Table 19 and Table 20 in ANNEX I: MAIN DATA)[3], where 'electr. / RES EU' is 25% hydro, 50% wind and 25% PV
- Supply of hydrogen to the filling station (Table 21 in ANNEX I: MAIN DATA).

Newly added fuels are E85 and LPG.

---

[3] 'Nuclear' primary energy is included here under 'fossil' primary energy, based on the source used [Ricardo 2023]

The characteristics of LPG (80% Propane) are

- Heating value: 12.8 kWh/kg and 7.1 kWh/l
- CO_2 emissions from combustion: 237 g CO_2/kWh
- Supply of LPG is like petrol (GREET 2023))

The characteristics of E85 are

- Heating value: 6.29 kWh/l
- CO_2 emissions from combustion: 56 g CO_2/kWh
- Supply of E85 is a mixture of gasoline and EtOH based on energy content.

The charging losses (outside of the vehicle) for charging of BEV and PHEV are assumed with 2% [Green NCAP 2022].

These background data are calculated with the specified foreground data using LCA [JOANNEUM RESEARCH 2024], [Jungmeier et al. 2024].

4. MAIN FINDINGS AND CONCLUSIONS

The main findings of the environmental assessment using LCA applied on the about 30,000 different vehicles available on the European market are:

- The main differences between the vehicles are due to
    - The mass of the vehicle
    - The battery capacity
    - The energy demand per driven kilometre.
- The environmental effects of BEV and PHEV depend on the electricity mix of the considered country.
- The production of the battery has a significant influence on the GHG emissions and primary energy demand of the BEV and PHEV.
- The GHG emissions and primary energy demand of ICE are dominated by the operation of the vehicle.
- In general, the GHG emissions and primary energy savings from substituting for secondary materials at the end-of-life are quite small in the overall life cycle. However, due to the future recycling of batteries, BEV and PHEV are able to provide more secondary material than ICE.

ANNEX I: MAIN DATA

Table 1 Foreground data for land use change for biofuels

[JOANNEUM RESEARCH 2024]

Share of direct land use change (LUC) for biofuels	2021	2030	2050
Sugar cane (from pasture)	0%	0%	0%
Soja beans (from pasture)	0%	0%	0%
Palm oil (from trop. forest)	0%	0%	0%

Table 2 Foreground data for biomass mix for biofuels

[JRC 2020], [IEA 2024], [Rangaraju 2021] and [JOANNEUM RESEARCH 2024]

Country (EU27, CH, NO, UK)	2024	2030	2050
FAME			
Rape seed oil	35%	55%	55%
Used cooking oil	32%	32%	35%
Palm oil	27%	7%	4%
Soja oil	6%	6%	6%
HVO			
Rape seed oil	15%	15%	15%
Used cooking oil	38%	41%	43%
Palm oil	45%	42%	40%
Soja oil	2%	2%	2%
EtOH			
Wheat & maize	68%	60%	54%
Sugar beet	21%	21%	21%
Sugar cane	7%	6%	5%
Wood	2%	7%	10%
Straw	2%	7%	10%
FT-diesel			
Wood	50%	50%	50%
Straw	50%	50%	50%
CRG			
From fermentation			
Maize silage & manure	68%	61%	54%
Residues	32%	29%	26%
From gasification			
Wood	0%	5%	10%
Straw	0%	5%	10%

Table 3 Foreground data for electricity mixes 2024, 2030 and 2050

[Ricardo 2023], [Bundesanzeiger 2024] for Germany, [JOANNEUM RESEARCH 2024]

2024	Europe 27 EU27	Austria AT	Belgium BE	Bulgaria BG	Cyprus CY	Czech Republic CZ	Germany DE	Denmark DK	Estonia EE	Spain ES	Finland FI	France FR	Greece GR	Croatia HR	Hungary HU	Irland IE	Italy IT	Lithuania LT	Luxembourg LU	Latvia LV	Malta MT	Netherlands NL	Poland PL	Portugal PT	Romania RO	Sweden SE	Slovenia SI	Slovakia SK	Switzerland CH	Norway NO	United Kingdom UK
Coal	11.6%	0.9%	0.6%	27.3%	0.0%	31.4%	20.7%	8.0%	35.1%	1.4%	2.5%	0.6%	8.2%	5.5%	6.6%	1.8%	3.4%	0.8%	1.9%	0.0%	0.0%	4.6%	58.0%	3.0%	12.1%	0.6%	20.8%	4.0%	0.0%	0.1%	1.1%
Oil	0.7%	0.7%	0.3%	0.1%	52.6%	0.1%	0.7%	0.3%	0.2%	2.5%	0.3%	0.7%	5.4%	0.2%	0.3%	0.8%	2.1%	1.7%	0.0%	0.0%	1.7%	0.0%	0.7%	1.6%	0.0%	0.1%	0.1%	0.9%	0.0%	0.2%	0.2%
Natural gas	16.8%	11.4%	39.0%	9.4%	26.3%	7.9%	16.3%	3.1%	10.5%	19.0%	6.6%	4.7%	37.5%	19.4%	18.8%	40.9%	41.6%	25.2%	5.0%	34.5%	83.1%	47.6%	14.8%	21.1%	16.9%	0.5%	9.6%	11.2%	1.3%	0.4%	30.1%
Nuclear	22.1%	0.0%	23.2%	38.6%	0.0%	40.6%	6.8%	0.0%	0.0%	16.5%	36.4%	60.6%	0.0%	0.0%	54.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.9%	0.0%	0.0%	23.6%	28.8%	33.7%	58.2%	33.5%	0.0%	16.5%
Biomass	6.2%	6.0%	4.5%	3.7%	1.3%	5.7%	7.6%	16.4%	23.4%	2.3%	17.5%	1.6%	0.9%	6.6%	5.8%	3.8%	6.8%	13.4%	12.0%	13.9%	0.2%	3.9%	5.2%	6.2%	1.3%	7.2%	1.6%	5.3%	0.9%	0.0%	10.4%
Hydro	12.4%	58.1%	1.1%	9.5%	0.0%	4.0%	3.4%	0.1%	0.5%	12.0%	19.9%	12.2%	8.5%	45.1%	0.6%	3.0%	17.5%	14.6%	30.7%	39.8%	0.0%	0.0%	1.7%	26.5%	25.9%	42.5%	28.4%	15.6%	53.8%	77.3%	2.0%
Wind	21.6%	15.0%	22.8%	4.6%	5.2%	6.0%	28.4%	63.8%	26.8%	33.9%	15.7%	14.5%	25.5%	19.0%	2.8%	48.5%	10.7%	36.9%	21.7%	11.5%	0.1%	29.8%	16.1%	30.4%	14.4%	18.9%	1.2%	1.5%	0.5%	19.9%	35.4%
PV	8.3%	7.6%	7.8%	6.8%	14.6%	4.4%	11.8%	6.5%	2.7%	12.3%	0.7%	4.7%	14.0%	3.3%	10.4%	0.7%	15.3%	6.7%	27.5%	0.2%	14.9%	10.1%	3.5%	10.5%	5.9%	0.9%	4.6%	3.4%	4.9%	1.9%	4.4%
Waste	0.3%	0.3%	0.7%	0.0%	0.0%	0.1%	1.0%	2.0%	0.8%	0.2%	0.4%	0.3%	0.0%	1.1%	0.3%	0.6%	2.6%	0.8%	1.2%	0.0%	0.0%	1.1%	0.1%	0.8%	0.0%	0.6%	0.0%	0.1%	3.4%	0.1%	0.0%
Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	3.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.6%	0.1%	0.0%
SUM	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

2030	EU27	AT	BE	BG	CY	CZ	DE	DK	EE	ES	FI	FR	GR	HR	HU	IE	IT	LT	LU	LV	MT	NL	PL	PT	RO	SE	SI	SK	CH	NO	UK
Coal	6.7%	0.1%	0.0%	17.9%	0.0%	21.2%	16.3%	0.0%	29.8%	0.0%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	42.6%	0.0%	4.7%	0.0%	14.0%	0.0%	0.0%	0.0%	0.0%
Oil	0.2%	0.3%	0.0%	0.0%	0.0%	0.2%	0.5%	0.0%	0.0%	0.3%	0.2%	0.2%	0.6%	0.2%	0.0%	0.1%	0.8%	0.0%	0.0%	0.0%	0.0%	0.1%	0.1%	1.0%	0.0%	0.0%	0.0%	0.2%	0.0%	0.0%	0.0%
Natural gas	14.2%	3.9%	49.1%	14.6%	65.8%	3.9%	16.7%	0.8%	6.6%	7.1%	6.3%	1.2%	32.0%	9.7%	7.2%	26.7%	30.5%	13.8%	0.2%	31.9%	79.0%	25.7%	18.7%	2.5%	15.3%	0.6%	18.9%	7.4%	2.0%	0.6%	17.5%
Nuclear	16.8%	0.0%	0.0%	35.3%	0.0%	46.0%	0.0%	0.0%	0.0%	8.1%	40.3%	51.5%	0.0%	0.0%	66.9%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.2%	0.0%	0.0%	28.2%	27.1%	28.9%	65.1%	30.0%	0.0%	16.9%
Biomass	5.5%	6.1%	3.8%	3.1%	1.4%	4.8%	7.1%	14.9%	13.5%	2.5%	14.9%	2.1%	0.9%	5.5%	5.8%	2.3%	7.9%	18.6%	7.8%	12.2%	0.2%	1.6%	5.2%	5.7%	1.8%	9.1%	1.6%	4.7%	0.8%	0.0%	7.0%
Hydro	11.8%	51.5%	0.4%	11.5%	0.0%	3.6%	3.6%	0.0%	0.5%	10.6%	15.0%	11.8%	10.5%	47.6%	0.5%	1.7%	17.1%	6.0%	3.3%	31.3%	0.0%	0.1%	1.4%	27.8%	22.6%	39.9%	25.5%	13.9%	51.0%	56.1%	1.8%
Wind	31.7%	23.4%	35.4%	6.0%	5.5%	13.7%	36.6%	74.2%	45.8%	52.5%	21.9%	25.0%	34.9%	28.1%	4.2%	67.6%	16.6%	48.3%	30.7%	24.1%	0.2%	55.7%	25.2%	41.2%	17.3%	22.0%	2.8%	3.6%	1.0%	38.6%	52.1%
PV	12.7%	14.7%	10.9%	11.7%	27.3%	6.7%	16.2%	10.0%	3.7%	18.9%	1.2%	8.1%	21.2%	7.1%	15.3%	1.6%	24.9%	13.2%	57.9%	0.5%	20.7%	14.6%	6.8%	21.4%	10.0%	1.3%	8.3%	5.1%	8.0%	4.6%	4.6%
Waste	0.2%	0.0%	0.3%	0.0%	0.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	1.8%	0.1%	0.0%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.4%	0.0%	0.0%	0.0%	0.0%	3.1%	0.0%	0.0%
Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.1%	0.0%	0.0%
SUM	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

2050	Europe 27 EU27	Austria AT	Belgium BE	Bulgaria BG	Cyprus CY	Czech Republic CZ	Germany DE	Denmark DK	Estonia EE	Spain ES	Finland FI	France FR	Greece GR	Croatia HR	Hungary HU	Irland IE	Italy IT	Lithuania LT	Luxembourg LU	Latvia LV	Malta MT	Netherlands NL	Poland PL	Portugal PT	Romania RO	Sweden SE	Slovenia SI	Slovakia SK	Switzerland CH	Norway NO	United Kingdom UK
Coal	0.7%	0.0%	0.0%	0.2%	0.0%	2.9%	0.0%	0.0%	6.5%	0.0%	0.0%	0.0%	0.0%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	7.9%	0.0%	0.5%	0.0%	2.7%	0.0%	0.0%	0.0%	0.0%
Oil	0.1%	0.1%	0.0%	0.0%	0.2%	0.1%	0.1%	0.1%	0.0%	0.2%	0.1%	0.1%	0.2%	0.2%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.4%	0.0%	0.0%	0.0%	0.1%	0.0%	0.0%	0.0%
Natural gas	9.6%	2.9%	30.3%	13.3%	31.9%	11.0%	2.4%	4.0%	4.1%	3.6%	4.5%	1.5%	13.7%	8.5%	9.7%	14.3%	18.0%	6.8%	19.0%	14.2%	73.0%	17.2%	13.5%	1.0%	10.6%	2.9%	15.0%	6.2%	2.0%	0.3%	13.2%
Nuclear	14.6%	0.0%	0.0%	27.0%	0.0%	51.3%	0.0%	0.0%	0.0%	5.2%	42.5%	38.9%	0.0%	0.0%	49.8%	0.0%	0.0%	15.5%	0.0%	0.0%	0.0%	1.5%	18.4%	0.0%	20.8%	25.0%	24.1%	60.6%	30.0%	0.0%	23.1%
Biomass	8.3%	10.1%	10.5%	7.9%	3.0%	10.3%	4.5%	16.6%	10.3%	6.6%	18.8%	3.1%	2.5%	5.3%	10.3%	4.2%	13.8%	14.9%	9.5%	12.7%	4.5%	6.2%	9.1%	8.5%	5.8%	10.6%	6.8%	8.5%	1.2%	0.0%	4.1%
Hydro	9.6%	45.6%	0.5%	8.4%	0.0%	2.9%	2.7%	0.0%	0.7%	7.8%	13.8%	10.3%	8.3%	35.1%	0.9%	1.5%	12.5%	4.6%	2.9%	26.1%	0.0%	0.1%	1.5%	24.1%	16.8%	33.1%	21.4%	10.1%	50.0%	37.2%	1.3%
Wind	40.9%	24.9%	36.6%	26.2%	19.5%	10.6%	64.9%	73.3%	69.4%	48.5%	19.5%	35.5%	48.3%	29.9%	10.3%	74.8%	24.2%	40.0%	28.8%	42.9%	4.9%	62.2%	42.1%	51.0%	29.3%	27.3%	7.3%	8.3%	3.0%	59.1%	51.9%
PV	16.0%	16.4%	22.0%	16.7%	44.5%	10.8%	24.0%	5.9%	9.0%	28.1%	0.9%	10.1%	25.9%	19.0%	18.9%	5.2%	30.2%	18.1%	39.7%	4.1%	17.7%	12.1%	7.2%	14.9%	16.2%	1.1%	22.8%	6.2%	10.0%	3.5%	6.5%
Waste	0.3%	0.0%	0.1%	0.1%	1.0%	0.0%	0.9%	0.0%	0.0%	0.0%	0.0%	0.4%	1.0%	0.8%	0.0%	0.0%	1.1%	0.1%	0.0%	0.0%	0.0%	0.1%	0.1%	0.2%	0.1%	0.0%	0.0%	0.0%	1.3%	0.0%	0.0%
Other	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	2.5%	0.0%	0.0%
SUM	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 4 Background data for material mix of vehicles (without battery and fuel cell)

based on [Hausberger et al. 2018] and [JOANNEUM RESEARCH 2024]

Propulsion	**ICE**			**PHEV**			**BEV**	**HFC**
Fuel	Petrol & blending, bio-ethanol	Diesel & blending, biodiesel	CNG & blending, CRG	Petrol & electricity	Diesel & electricity	CNG & electricity	Electricity	Hydrogen (H_2)
Steel	50.4%	49.4%	52.1%	50.3%	49.4%	51.7%	44.6%	44.4%
Cast iron	8.0%	9.4%	7.9%	9.8%	11.1%	9.7%	5.4%	5.3%
Aluminium	10.6%	11.9%	10.5%	9.7%	10.9%	9.6%	16.1%	16.1%
Glas	2.4%	2.2%	2.3%	2.2%	2.0%	2.1%	2.4%	2.4%
Paint	0.4%	0.4%	0.4%	0.4%	0.3%	0.4%	0.4%	0.4%
Plastic	12.1%	11.0%	10.8%	11.0%	10.0%	10.1%	11.6%	12.0%
Rubber	3.9%	3.7%	3.9%	3.6%	3.4%	3.5%	4.0%	4.0%
Oil	0.8%	0.9%	0.8%	0.8%	0.9%	0.8%	0.4%	0.4%
Copper	2.3%	2.3%	2.3%	2.9%	2.9%	2.9%	3.7%	3.6%
Non ferrous metals	0.3%	0.4%	0.3%	1.1%	1.2%	1.1%	1.6%	1.6%
Electronic	4.9%	4.7%	4.9%	4.7%	4.4%	4.6%	5.7%	5.7%
Textiles	3.9%	3.7%	3.9%	3.6%	3.4%	3.5%	4.1%	4.0%
Carbon fiber	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
SUM	100%	100%	100%	100%	100%	100%	100%	100%

Table 5 Background data for hydrogen fuel cell (HFC) and H_2 tank system

[JOANNEUM RESEARCH 2024]

	Tank & HFC
Steel	19.6%
Aluminium	8.9%
Plastic	7.5%
Electronic	0.9%
Copper	5.3%
Graphit	6.2%
CFK	51.5%
SUM	100.0%

Table 6 Background data for materials for vehicle production

[JOANNEUM RESEARCH 2024]

Materials for vehicle production 2024	**GHG** [g CO_2-eq./kg]	**PED** [kWh/kg]	**PED_{fos}** [kWh/kg]
Steel	2,470	8.9	7.8
Cast iron	900	3.5	3.2
Aluminium	12,050	53.2	47.6
Glas	1,130	3.3	3.2
Paint	5,680	28.0	21.5
Plastic	3,610	8.6	7.8
Rubber	3,300	9.9	9.5
Oil	1,420	13.3	13.1
Copper	3,610	11.9	11.0
Non ferrous metals	7,670	30.3	26.3
Electronic	36,630	133.4	120.2
Textiles	24,250	75.2	69.2
Carbon fiber	18,940	90.2	83.1

Table 7 Background data for batteries interpolated for 2024 based on 2020 and 2030

[JOANNEUM RESEARCH 2024]

Li-Ion battery 2024	**Greenhouse Gas Emissions**				**Primary Energy Demand**				**Share**	**Energy density**
	CO_2 [kg/kWh]	**CH_4** [kg/kWh]	**N_2O** [kg/kWh]	**CO_2-eq.** [kg/kWh]	**Fossil** [kWh/kWh]	**Renew.** [kWh/kWh]	**Other** [kWh/kWh]	**Sum** [kWh/kWh]		[Wh/kg]
Production										
CN	77	0.131	0.003	77	249	4	2	255	78%	150
EU	50	0.115	0.002	50	198	11	7	216	14%	
US	57	0.124	0.002	57	231	10	6	247	8%	
MIX	**71**	**0.128**	**0.002**	**71**	**240**	**5**	**3**	**249**		
Recycling										
CN	-17	-0.016	-0.001	-17	-59	-1	0	-61	78%	
EU	-10	-0.007	0.000	-10	-40	-5	-4	-49	14%	
US	-11	-0.009	0.000	-11	-42	-4	-3	-49	8%	
MIX	**-15**	**-0.014**	**-0.001**	**-15**	**-55**	**-2**	**-1**	**-58**		
Total	**56**	**0.114**	**0.002**	**56**	**185**	**4**	**2**	**191**		

Table 8 Background data for operation

[HEV values represented by ICE]

Operation		**ICE**			**PHEV**		**BEV**	**HFC**
		Petrol	Diesel	CNG	Petrol & electricity	Diesel & electricity	Electricity	Hydrogen (H_2)
Tyres	[kg/KFZ a]	19.2	19.2	19.2	19.2	19.2	19.2	19.2
Engine oil	[kg/1000 km]	0.5	0.5	0.5	0.5	0.5		
Spare parts	[kg/KFZ a]	6.4	6.8	6.4	7.0	7.4	8.0	7.0
Urea	[kg/1000 km]		1.5			0.8		

Table 9 Background data for maintenance

[JOANNEUM RESEARCH 2024]

Maintenance	**GHG** [g CO_2-eq./kg]	**PED_{tot}** [kWh/kg]	**PED_{fos}** [kWh/kg]
Tyres	3,300	9.9	9.5
Engine oil production	1,417	13.3	13.1
Engine oil use	3,172		
Spare/replacement parts	5,038	19.7	17.6
Urea production	278	2.3	2.2
Urea use (CO_2 only)	250		

Table 10 Background data for hydrogen production via low temperature electrolysis (PEM or alkaline) and natural gas steam reforming

based on [JOANNEUM RESEARCH 2024] and [BioGrace 2015]

		Electrolyses	**Steam reforming**
Output			
H_2 30 bar	[MWh]	1	1
Input			
Electricity	[MWh]	1.43	
Natural gas	[t]		0.107

Table 11 Background data for vegetable oil production

based on [JOANNEUM RESEARCH 2024] and [BioGrace 2015]

		Rape seed	**Soy bean**	**Palm oil**
Output				
Vegetable oil	[MWh]	1	1	1
Animal feed	[t]	0.13	0.22	
Input				
Raw material	[t]	0.25	0.32	0.65
Electricity	[MWh]	11.10	33	0*
Heat	[MWh]	50	160	0*
Fuller's earth	[kg]	0.59	0.59	0.002
Phosphoric acid	[kg]	0.10	0.11	0.001
Hexane	[kg]	0.25	0.11	0

* Provided internally by CHP plant from processing residues

Table 12 Background data for FAME (biodiesel) production

based on [JOANNEUM RESEARCH 2024] and [BioGrace 2015]

		Amount
Output		
FAME	[MWh]	1.00
Glycerine	[kg]	10.00
Potassium (as fertilizer)	[kg]	0.64
Input		
Vegetable oil	[t]	0.10
Electricity	[kWh]	8.10
Heat	[kWh]	66.10
Methananol	[kg]	11.40
Potassium hydroxide	[kg]	1.00
Sulfuric acid	[kg]	1.00
Phosphoric acid	[kg]	0.30
NaOH	[kg]	0.70
Activated carbon	[kg]	0.10
N_2 (liquid)	[kg]	0.20

Table 13 Background data for bioethanol production

based on [JOANNEUM RESEARCH 2024], [BioGrace 2015]

		Wheat	**Maize (corn)**	**Sugar beet**	**Sugar cane**	**Wood**	**Straw**
Output							
Bio-ethanol	[MWh]	1.00	1.00	1.00	1.00	1.00	1.00
Animal feed (DDGS)	[kg]	131.00	121.00	78.00			
Input							
Raw material	[t]	0.42	0.55	1.62	1.97		0.63
Electricity	[kWh]	64.00	62.00	47.00			
Heat	[kWh]	450.00	436.00	614.00			
NaOH	[kg]	0.30	0.30	0.30			
Ammonia (25%)	[kg]	0.90	0.90	1.10		19.00	12.00
Sulfuric acid	[kg]	0.30	0.30	0.40		13.00	5.00
Urea	[kg]	0.10	0.10	0.10			
Molasses 880% (DM)	[kg]					9.00	6.00
Corn Steep Liquor (CSL)	[kg]					25.00	22.00
Diammoniahosphate $(NH_4)_2HPO_4$	[kg]					3.00	3.00

Table 14 Background data for direct and indirect land use change (LUC) for biomass resources

(based on [EU 2009] and [EU 2015])

iLUC*	**[g CO_2/MJ]**	**[g CO_2/kWh]**
Bio-ethanol (wheat, maize)	12	43
Bio-ethanol (sugar beet)	13	47
Bio-ethanol (sugar cane)	17	61
FAME/HVO (rape seeds)	33	119
FAME/HVO (soja beans)	55	198
FAME/HVO (palm oil)	66	238

dLUC*	**[kg CO_2/ha]**	**[g CO_2/kWh]**
Sugar cane (grassland)	2,576	
Soja beans (grassland)	2,825	
Palm oil (trop. forest)	28,441	
EtOH / sugar cane		68
FAME / palm oil		804
FAME / soja oil		330
HVO / palm oil		805
HVO / soja oil		331

* in brackets is the previouse use of the land

Table 15 Background data for lower heating values of fossil and biogenic resources

[JOANNEUM RESEARCH 2024]

Fossil Resources	[kWh/kg]	[g CO_2/kWh]
Coal	7.6	
Raw oil	11.1	
Natural gas		10.0

Biomass resourcees	[kWh/kg]	Water content
Wood	3.7	25%
Maize	2.8	35%
Wheat	3.9	14%
Sugar beet	0.8	73%
Rape seeds	6.8	9%
Soy beans	4.7	13%
Palm oil fruits	6.2	9%
Sugar cane	2.5	40%
Maize sillage	1.5	64%
Straw	3.9	14%
Waste cooking oil	10.3	0%
Bio-waste (DM)	2.2	69%
Manure (DM)	3.0	0%

Table 16 Background data for heating values of fuels

[JOANNEUM RESEARCH 2024] comparable to [EU 2018]

	[kWh/kg]	[kWh/l]	[kWh/Nm³]
Diesel	11.8	9.8	
Petrol	11.9	8.8	
CNG	13.9		10.0
Diesel B7		9.7	
Petrol E5		8.7	
Petrol E10		8.5	
FAME	10.3	9.1	
HVO	12.2	9.5	
FT-diesel	12.2	10.2	
EtOH	7.4	5.8	
CRG	13.9		10.0
H_2	33.3		
E-fuel FT-diesel	12.2	10.2	
E-fuel CRG	13.9		10.0
LPG	12.8	7.1	

Table 17 Background data for the supply of fossil fuels to the filling station

[JOANNEUM RESEARCH 2024]

Supply to filling station	g CO_2-eq/kWh															
Fuels	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Diesel	58.3	58.3	58.4	58.4	58.5	58.6	58.6	59.6	60.6	61.5	62.5	63.5	64.5	65.4	66.4	67.4
Diesel B7	63.9	63.9	63.8	63.7	63.6	63.5	63.4	64.3	65.1	66.0	66.8	67.7	68.5	69.4	70.3	71.1
Petrol	75.8	75.7	75.6	75.5	75.4	75.3	75.2	76.1	77.0	78.0	78.9	79.8	80.7	81.6	82.5	83.4
Petrol E5	80.8	80.5	80.2	79.9	79.7	79.4	79.1	79.8	80.6	81.4	82.2	83.0	83.8	84.5	85.3	86.1
Petrol E10	86.1	85.6	85.1	84.6	84.0	83.5	83.0	83.7	84.3	85.0	85.6	86.3	86.9	87.6	88.2	88.9
Petrol E85	194.5	189.6	184.6	179.7	174.7	169.8	164.8	162.8	160.7	158.6	156.6	154.5	152.5	150.4	148.3	146.3
CNG	40.7	40.8	41.0	41.2	41.3	41.5	41.7	42.5	43.3	44.2	45.0	45.8	46.6	47.5	48.3	49.1
CNG CRG5	44.1	44.2	44.2	44.3	44.3	44.4	44.4	45.2	45.9	46.7	47.4	48.2	48.9	49.6	50.4	51.1
LPG	75.8	75.7	75.6	75.5	75.4	75.3	75.2	76.1	77.0	78.0	78.9	79.8	80.7	81.6	82.5	83.4

Supply to filling station	kWh fossil/kWh															
Fuels	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Diesel	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.19	1.19	1.19	1.20	1.20	1.20	1.21
Diesel B7	1.13	1.13	1.12	1.12	1.12	1.12	1.12	1.12	1.13	1.13	1.13	1.14	1.14	1.14	1.15	1.15
Petrol	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28
Petrol E5	1.24	1.24	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.23	1.24	1.24	1.24	1.25	1.25	1.25
Petrol E10	1.22	1.22	1.22	1.21	1.21	1.21	1.20	1.21	1.21	1.21	1.21	1.22	1.22	1.22	1.22	1.22
Petrol E85	0.88	0.86	0.84	0.82	0.80	0.77	0.75	0.74	0.73	0.72	0.71	0.71	0.70	0.69	0.68	0.67
CNG	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.16	1.16	1.16	1.16	1.16	1.16
CNG CRG5	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.12	1.12	1.12	1.12	1.12	1.12	1.12	1.13
LPG	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28

Supply to filling station	kWh renew./kWh															
Fuels	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Diesel	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Diesel B7	0.13	0.13	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
Petrol	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Petrol E5	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Petrol E10	0.13	0.13	0.13	0.13	0.13	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Petrol E85	1.48	1.49	1.50	1.51	1.52	1.52	1.53	1.54	1.54	1.54	1.55	1.55	1.55	1.56	1.56	1.57
CNG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CNG CRG5	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
LPG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Supply to filling station	kWh total/kWh															
Fuels	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039
Diesel	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.19	1.19	1.19	1.20	1.20	1.20	1.21	1.21
Diesel B7	1.25	1.25	1.25	1.24	1.24	1.23	1.23	1.23	1.24	1.24	1.24	1.24	1.25	1.25	1.25	1.25
Petrol	1.26	1.26	1.26	1.25	1.25	1.25	1.25	1.25	1.26	1.26	1.26	1.27	1.27	1.27	1.28	1.28
Petrol E5	1.31	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.31	1.31	1.31	1.32	1.32	1.32
Petrol E10	1.35	1.35	1.35	1.35	1.35	1.34	1.34	1.34	1.35	1.35	1.35	1.35	1.36	1.36	1.36	1.36
Petrol E85	2.37	2.36	2.35	2.33	2.32	2.30	2.29	2.28	2.28	2.27	2.27	2.26	2.26	2.25	2.24	2.24
CNG	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.16	1.16	1.16	1.16	1.16	1.16	1.17
CNG CRG5	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.19	1.19	1.19	1.19	1.19	1.19	1.19
LPG	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.16	1.16	1.16	1.16	1.16

Table 18 Background data for the supply of biofuels to the filling station [JOANNEUM RESEARCH 2024] for Europe without direct land use change

Supply to the filling station	**2024**			**2030**			**2050**		
Biofuels	**GHG** [g CO_2-eq./kWh]	**PED** [kWh/kWh]	**PED_{fos}** [kWh/kWh]	**GHG** [g CO_2-eq./kWh]	**PED** [kWh/kWh]	**PED_{fos}** [kWh/kWh]	**GHG** [g CO_2-eq./kWh]	**PED** [kWh/kWh]	**PED_{fos}** [kWh/kWh]
EtOH / wheat & maize	257	2.6	0.91	203	2.4	0.66	144	2.2	0.39
EtOH / sugar beet	292	2.4	1.12	224	2.3	0.80	149	2.1	0.46
EtOH / sugar cane	171	5.3	0.50	165	5.1	0.48	160	5.0	0.46
EtOH / wood	57	2.8	0.17	56	2.7	0.17	56	2.6	0.16
EtOH / straw	97	2.7	0.22	94	2.6	0.21	92	2.5	0.21
FAME / rape seed oil	215	2.2	0.47	199	2.1	0.41	189	2.1	0.37
FAME / waste cooking oil	16	1.1	0.13	8	1.0	0.09	0	1.0	0.05
FAME / palm oil	261	4.8	0.64	247	4.6	0.59	239	4.6	0.55
FAME / soja oil	64	1.9	0.39	49	1.8	0.33	35	1.8	0.27
HVO / rape seed oil	249	2.4	0.57	235	2.3	0.52	227	2.3	0.48
HVO / waste cooking oil	49	1.3	0.23	44	1.2	0.20	39	1.2	0.17
HVO / palm oil	296	5.0	0.74	282	4.8	0.69	278	4.8	0.67
HVO / soja oil	98	2.1	0.50	85	2.0	0.44	74	2.0	0.39
CRG / maize silage & manure	145	2.0	0.66	127	1.9	0.58	111	1.8	0.51
CRG / residues	61	1.7	0.26	54	1.6	0.23	46	1.5	0.20
CRG / wood	23	1.8	0.07	23	1.7	0.07	22	1.6	0.07
CRG / straw	55	1.8	0.12	53	1.7	0.11	51	1.7	0.11
FT-diesel / straw	85	2.2	0.21	82	2.1	0.20	79	2.1	0.19
FT-diesel / wood	47	2.2	0.16	46	2.1	0.15	44	2.0	0.14

Table 19 Background data for the supply of electricity to the charging station Part I [JOANNEUM RESEARCH 2022] based on [Ricardo 2023], [IEA 2023] and own calculations based on n electricity mix defined in foreground data[4]

Supply to charging station	**g CO_2-eq./kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Europe 27	295.1	280.5	265.9	251.3	236.7	222.1	207.5	200.9	194.4	187.8	181.2	174.6	168.0	161.5	154.9	148.3
Austria	133.3	121.6	110.0	98.3	86.7	75.0	63.3	62.4	61.4	60.4	59.5	58.5	57.6	56.6	55.6	54.7
Belgium	258.4	259.4	260.3	261.3	262.2	263.2	264.1	258.3	252.5	246.7	240.9	235.1	229.3	223.6	217.8	212.0
Bulgaria	509.1	490.6	472.0	453.5	434.9	416.3	397.8	382.4	367.0	351.6	336.2	320.8	305.4	290.0	274.6	259.1
Cyprus	599.2	560.2	521.1	482.0	443.0	403.9	364.9	355.3	345.8	336.3	326.7	317.2	307.6	298.1	288.6	279.0
Czech Republic	653.6	614.2	574.9	535.6	496.3	456.9	417.6	403.0	388.5	373.9	359.4	344.8	330.2	315.7	301.1	286.6
Germany	496.8	458.7	420.6	382.6	344.5	306.5	268.4	256.6	244.8	233.0	221.2	209.4	197.6	185.8	174.0	162.2
Denmark	226.6	197.4	168.3	139.1	110.0	80.8	51.7	50.4	49.2	47.9	46.6	45.4	44.1	42.9	41.6	40.3
Estonia	853.0	821.0	789.0	756.9	724.9	692.9	660.9	638.4	616.0	593.6	571.1	548.7	526.3	503.8	481.4	459.0
Spain	188.2	169.0	149.9	130.7	111.6	92.4	73.3	71.4	69.5	67.6	65.8	63.9	62.0	60.1	58.2	56.4
Finland	120.4	114.3	108.2	102.1	96.0	90.0	83.9	82.9	81.9	81.0	80.0	79.1	78.1	77.1	76.2	75.2
France	66.6	60.9	55.2	49.5	43.8	38.1	32.4	32.2	32.1	31.9	31.7	31.5	31.3	31.1	30.9	30.7
Greece	400.5	369.9	339.3	308.7	278.1	247.5	216.9	211.1	205.4	199.6	193.8	188.0	182.2	176.5	170.7	164.9
Croatia	220.6	199.3	178.0	156.7	135.4	114.1	92.8	92.4	92.0	91.6	91.2	90.8	90.4	90.0	89.6	89.2
Hungary	255.1	227.7	200.2	172.8	145.4	117.9	90.5	89.4	88.3	87.2	86.1	85.0	83.9	82.9	81.8	80.7
Irland	286.8	269.2	251.6	234.0	216.5	198.9	181.3	177.0	172.7	168.4	164.2	159.9	155.6	151.3	147.0	142.8
Italy	342.6	321.8	301.1	280.3	259.6	238.8	218.1	212.6	207.0	201.5	196.0	190.5	184.9	179.4	173.9	168.4
Lithuania	248.9	232.1	215.3	198.5	181.7	164.9	148.1	144.2	140.2	136.3	132.3	128.4	124.4	120.5	116.5	112.6
Luxembourg	210.7	198.7	186.7	174.7	162.7	150.7	138.7	135.7	132.8	129.8	126.8	123.8	120.8	117.8	114.8	111.8
Latvia	267.4	261.6	255.9	250.1	244.3	238.5	232.7	226.4	220.1	213.8	207.5	201.2	194.9	188.5	182.2	175.9
Malta	476.4	466.0	455.6	445.3	434.9	424.5	414.1	411.2	408.3	405.3	402.4	399.4	396.5	393.5	390.6	387.7
Netherlands	363.8	332.9	302.0	271.1	240.2	209.3	178.4	174.6	170.8	167.0	163.2	159.4	155.6	151.8	148.0	144.3
Poland	959.9	921.9	883.9	845.9	807.9	769.9	731.9	704.9	677.9	650.9	623.9	596.8	569.8	542.8	515.8	488.8
Portugal	215.2	190.1	164.9	139.8	114.6	89.5	64.4	63.0	61.7	60.4	59.1	57.7	56.4	55.1	53.8	52.4
Romania	326.4	304.3	282.2	260.1	238.0	215.9	193.8	188.5	183.1	177.8	172.5	167.1	161.8	156.4	151.1	145.7
Sweden	41.8	40.5	39.1	37.8	36.5	35.2	33.9	33.3	32.7	32.1	31.5	30.9	30.3	29.7	29.1	28.5
Slovenia	419.3	414.3	409.3	404.4	399.4	394.4	389.4	376.7	363.9	351.2	338.4	325.6	312.9	300.1	287.4	274.6
Slovakia	193.4	174.2	155.0	135.9	116.7	97.5	78.4	77.0	75.7	74.4	73.0	71.7	70.3	69.0	67.6	66.3
Switzerland	54.1	54.7	55.4	56.1	56.8	57.5	58.2	57.2	56.2	55.2	54.2	53.2	52.2	51.2	50.2	49.2
Norway	11.8	12.1	12.3	12.5	12.8	13.0	13.2	13.1	13.1	13.0	12.9	12.8	12.7	12.6	12.5	12.4
United Kingdom	231.7	214.6	197.5	180.4	163.3	146.2	129.1	126.5	123.9	121.2	118.6	116.0	113.4	110.7	108.1	105.5

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[4] For DE in 2023 the GHG emission are based on an official document of the Environmental Agency (Bundesanzeiger 2023).

Supply to charging station	**g CO_2-eq./kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Ren. electr.	29.6	29.4	29.1	28.9	28.6	28.4	28.2	27.9	27.7	27.5	27.3	27.0	26.8	26.6	26.4	26.1
Hydro	6.3	6.3	6.3	6.2	6.2	6.2	6.1	6.1	6.1	6.1	6.1	6.1	6.0	6.0	6.0	6.0
Wind	22.5	22.4	22.3	22.2	22.0	21.9	21.8	21.6	21.5	21.3	21.1	21.0	20.8	20.6	20.4	20.3
PV	67.1	66.4	65.7	65.0	64.3	63.6	62.8	62.3	61.8	61.2	60.7	60.1	59.6	59.1	58.5	58.0
Nuclear energy	18.6	18.4	18.2	18.0	17.8	17.6	17.4	17.3	17.2	17.1	17.0	16.9	16.8	16.7	16.6	16.5
Natural gas	633.4	628.4	623.3	618.2	613.1	608.1	603.0	599.1	595.1	591.2	587.2	583.3	579.3	575.4	571.4	567.5

Supply to charging station	**kWh fossil/kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Europe 27	1.69	1.62	1.55	1.48	1.42	1.35	1.28	1.26	1.23	1.20	1.18	1.15	1.12	1.10	1.07	1.04
Austria	0.57	0.53	0.49	0.45	0.41	0.37	0.33	0.33	0.32	0.32	0.32	0.31	0.31	0.30	0.30	0.30
Belgium	1.77	1.67	1.58	1.48	1.38	1.28	1.18	1.16	1.13	1.11	1.09	1.07	1.04	1.02	1.00	0.98
Bulgaria	2.68	2.63	2.58	2.53	2.48	2.43	2.37	2.32	2.26	2.21	2.15	2.10	2.04	1.99	1.93	1.88
Cyprus	2.16	2.04	1.92	1.80	1.68	1.56	1.44	1.41	1.38	1.34	1.31	1.28	1.24	1.21	1.18	1.15
Czech Republic	3.15	3.07	2.99	2.91	2.83	2.75	2.67	2.63	2.59	2.55	2.51	2.46	2.42	2.38	2.34	2.30
Germany	1.23	1.16	1.09	1.02	0.95	0.88	0.81	0.77	0.74	0.70	0.66	0.63	0.59	0.55	0.52	0.48
Denmark	0.95	0.84	0.73	0.62	0.51	0.40	0.29	0.29	0.28	0.28	0.27	0.27	0.27	0.26	0.26	0.26
Estonia	2.52	2.41	2.31	2.21	2.11	2.01	1.90	1.85	1.79	1.74	1.68	1.63	1.57	1.51	1.46	1.40
Spain	1.43	1.32	1.22	1.11	1.00	0.90	0.79	0.78	0.76	0.74	0.73	0.71	0.69	0.68	0.66	0.65
Finland	1.57	1.57	1.57	1.57	1.57	1.57	1.57	1.56	1.54	1.53	1.51	1.50	1.49	1.47	1.46	1.44
France	2.34	2.27	2.20	2.13	2.06	1.99	1.92	1.89	1.86	1.83	1.80	1.77	1.74	1.71	1.68	1.65
Greece	1.49	1.40	1.31	1.22	1.13	1.04	0.95	0.94	0.92	0.90	0.88	0.86	0.84	0.82	0.80	0.78
Croatia	1.05	0.98	0.92	0.86	0.79	0.73	0.66	0.66	0.65	0.64	0.63	0.62	0.61	0.60	0.60	0.59
Hungary	2.50	2.48	2.46	2.44	2.41	2.39	2.37	2.33	2.30	2.26	2.22	2.19	2.15	2.12	2.08	2.04
Irland	1.20	1.13	1.06	0.98	0.91	0.84	0.77	0.75	0.74	0.72	0.70	0.68	0.67	0.65	0.63	0.62
Italy	1.56	1.49	1.41	1.34	1.27	1.19	1.12	1.09	1.07	1.04	1.01	0.99	0.96	0.93	0.91	0.88
Lithuania	1.27	1.18	1.09	1.01	0.92	0.83	0.75	0.74	0.74	0.74	0.73	0.73	0.73	0.73	0.72	0.72
Luxembourg	1.22	1.16	1.11	1.05	1.00	0.94	0.89	0.87	0.86	0.85	0.84	0.82	0.81	0.80	0.79	0.77
Latvia	1.10	1.07	1.04	1.02	0.99	0.96	0.93	0.91	0.89	0.86	0.84	0.82	0.79	0.77	0.75	0.72
Malta	1.90	1.86	1.82	1.78	1.74	1.70	1.66	1.65	1.64	1.63	1.62	1.61	1.60	1.58	1.57	1.56
Netherlands	1.55	1.43	1.31	1.19	1.07	0.95	0.83	0.81	0.80	0.78	0.77	0.75	0.73	0.72	0.70	0.69
Poland	2.55	2.45	2.36	2.27	2.18	2.09	2.00	1.96	1.91	1.87	1.83	1.78	1.74	1.69	1.65	1.61

Supply to charging station	**kWh fossil/kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Portugal	0.98	0.89	0.80	0.71	0.62	0.53	0.44	0.44	0.43	0.42	0.41	0.40	0.40	0.39	0.38	0.37
Romania	1.89	1.86	1.83	1.81	1.78	1.75	1.72	1.69	1.66	1.63	1.60	1.57	1.54	1.51	1.48	1.45
Sweden	1.24	1.22	1.20	1.17	1.15	1.13	1.11	1.10	1.09	1.08	1.07	1.07	1.06	1.05	1.04	1.03
Slovenia	2.27	2.25	2.23	2.21	2.19	2.18	2.16	2.11	2.06	2.01	1.96	1.91	1.86	1.81	1.76	1.72
Slovakia	2.54	2.52	2.50	2.48	2.46	2.44	2.42	2.39	2.37	2.34	2.31	2.29	2.26	2.24	2.21	2.18
Switzerland	1.20	1.18	1.17	1.15	1.13	1.11	1.09	1.08	1.07	1.07	1.06	1.05	1.04	1.03	1.02	1.02
Norway	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02
United Kingdom	1.35	1.27	1.20	1.12	1.04	0.97	0.89	0.88	0.87	0.87	0.86	0.85	0.84	0.83	0.82	0.82
Ren. electr.	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Hydro	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Wind	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
PV	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Nuclear energy	3.18	3.18	3.18	3.18	3.18	3.17	3.17	3.15	3.14	3.12	3.10	3.08	3.07	3.05	3.03	3.01
Natural gas	2.51	2.49	2.47	2.45	2.43	2.41	2.39	2.37	2.36	2.34	2.33	2.31	2.29	2.28	2.26	2.24

Table 20 Background data for the supply of electricity to the charging station Part II [JOANNEUM RESEARCH 2024] based on [Ricardo 2023], [IEA 2023] and own calculations based on electricity mix defined in foreground data[5]

Supply to charging station	**kWh renew./kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Europe 27	0.67	0.68	0.70	0.72	0.74	0.76	0.78	0.78	0.79	0.79	0.79	0.80	0.80	0.80	0.81	0.81
Austria	1.03	1.05	1.07	1.09	1.11	1.13	1.15	1.14	1.14	1.13	1.13	1.12	1.11	1.11	1.10	1.10
Belgium	0.55	0.57	0.59	0.61	0.63	0.65	0.66	0.67	0.68	0.68	0.69	0.70	0.70	0.71	0.71	0.72
Bulgaria	0.35	0.36	0.37	0.39	0.40	0.41	0.42	0.43	0.45	0.46	0.48	0.49	0.51	0.52	0.54	0.55
Cyprus	0.24	0.27	0.29	0.31	0.33	0.35	0.38	0.39	0.41	0.42	0.43	0.45	0.46	0.48	0.49	0.51
Czech Republic	0.34	0.35	0.36	0.38	0.39	0.40	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.43	0.43	0.43
Germany	0.90	0.91	0.92	0.92	0.93	0.94	0.95	0.96	0.97	0.99	1.00	1.01	1.02	1.03	1.05	1.06
Denmark	1.20	1.23	1.25	1.27	1.30	1.32	1.34	1.34	1.33	1.32	1.32	1.31	1.30	1.30	1.29	1.28
Estonia	1.18	1.17	1.16	1.15	1.14	1.13	1.12	1.11	1.11	1.11	1.10	1.10	1.09	1.09	1.08	1.08
Spain	0.70	0.75	0.79	0.84	0.88	0.92	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.98	0.98	0.98
Finland	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
France	0.40	0.42	0.45	0.47	0.50	0.52	0.55	0.55	0.56	0.56	0.56	0.57	0.57	0.58	0.58	0.58
Greece	0.55	0.58	0.61	0.64	0.68	0.71	0.74	0.74	0.75	0.76	0.76	0.77	0.78	0.78	0.79	0.80
Croatia	0.90	0.93	0.96	1.00	1.03	1.06	1.10	1.09	1.08	1.08	1.07	1.06	1.05	1.05	1.04	1.03
Hungary	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.50	0.51	0.51	0.51	0.51	0.52	0.52	0.52	0.53
Irland	0.68	0.70	0.73	0.75	0.78	0.81	0.83	0.83	0.84	0.84	0.84	0.85	0.85	0.85	0.85	0.86
Italy	0.69	0.73	0.76	0.79	0.83	0.86	0.89	0.90	0.90	0.90	0.91	0.91	0.91	0.92	0.92	0.92
Lithuania	0.93	0.98	1.02	1.06	1.10	1.14	1.19	1.18	1.17	1.17	1.16	1.15	1.15	1.14	1.13	1.13
Luxembourg	0.88	0.89	0.91	0.92	0.93	0.94	0.96	0.95	0.95	0.94	0.94	0.94	0.93	0.93	0.92	0.92
Latvia	1.01	1.02	1.03	1.04	1.05	1.06	1.07	1.07	1.07	1.07	1.07	1.06	1.06	1.06	1.06	1.06
Malta	0.22	0.23	0.24	0.26	0.27	0.28	0.29	0.29	0.30	0.30	0.30	0.31	0.31	0.31	0.32	0.32
Netherlands	0.57	0.60	0.64	0.68	0.71	0.75	0.79	0.79	0.79	0.80	0.80	0.81	0.81	0.81	0.82	0.82
Poland	0.38	0.40	0.42	0.45	0.47	0.49	0.51	0.52	0.53	0.54	0.55	0.56	0.57	0.58	0.59	0.60
Portugal	0.91	0.95	0.98	1.02	1.06	1.10	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.13	1.12	1.12
Romania	0.56	0.57	0.58	0.59	0.60	0.61	0.62	0.62	0.63	0.64	0.65	0.65	0.66	0.67	0.68	0.68
Sweden	0.93	0.93	0.94	0.95	0.96	0.97	0.98	0.98	0.97	0.97	0.96	0.96	0.95	0.95	0.94	0.94
Slovenia	0.42	0.42	0.43	0.43	0.44	0.44	0.45	0.46	0.47	0.48	0.49	0.50	0.51	0.52	0.53	0.54
Slovakia	0.37	0.37	0.38	0.38	0.38	0.38	0.38	0.39	0.39	0.39	0.40	0.40	0.41	0.41	0.41	0.42
Switzerland	0.90	0.94	0.99	1.03	1.07	1.11	1.15	1.14	1.13	1.12	1.11	1.10	1.09	1.08	1.07	1.06
Norway	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
United Kingdom	0.82	0.85	0.89	0.92	0.95	0.99	1.02	1.02	1.01	1.01	1.01	1.00	1.00	0.99	0.99	0.99

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[5] For DE in 2023 the GHG emission are based on an official document of the Environmental Agency (Bundesanzeiger 2023).

Supply to charging station	**kWh renew./kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Ren. electr.	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Hydro	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Wind	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
PV	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nuclear energy	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural gas	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05

Supply to charging station	**kWh total/kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Europe 27	2.37	2.32	2.27	2.23	2.18	2.13	2.08	2.06	2.03	2.01	1.99	1.96	1.94	1.91	1.89	1.87
Austria	1.60	1.58	1.56	1.54	1.52	1.50	1.48	1.48	1.47	1.46	1.45	1.44	1.43	1.42	1.41	1.40
Belgium	2.35	2.26	2.18	2.10	2.02	1.94	1.86	1.84	1.82	1.81	1.79	1.77	1.76	1.74	1.72	1.71
Bulgaria	3.07	3.03	2.99	2.95	2.91	2.86	2.82	2.78	2.74	2.70	2.66	2.62	2.58	2.54	2.50	2.46
Cyprus	2.43	2.33	2.23	2.13	2.03	1.94	1.84	1.82	1.80	1.78	1.76	1.74	1.72	1.70	1.68	1.66
Czech Republic	3.52	3.46	3.39	3.32	3.25	3.19	3.12	3.08	3.04	3.00	2.96	2.92	2.88	2.84	2.80	2.76
Germany	2.13	2.07	2.01	1.94	1.88	1.82	1.76	1.74	1.71	1.69	1.66	1.64	1.61	1.59	1.56	1.54
Denmark	2.16	2.08	1.99	1.90	1.81	1.72	1.64	1.63	1.62	1.61	1.59	1.58	1.57	1.56	1.55	1.54
Estonia	3.72	3.61	3.50	3.39	3.27	3.16	3.05	2.99	2.93	2.86	2.80	2.74	2.68	2.62	2.56	2.50
Spain	2.15	2.08	2.02	1.96	1.90	1.83	1.77	1.75	1.74	1.72	1.71	1.69	1.68	1.66	1.65	1.63
Finland	2.54	2.53	2.52	2.51	2.50	2.48	2.47	2.46	2.45	2.43	2.42	2.40	2.39	2.38	2.36	2.35
France	2.77	2.72	2.68	2.63	2.59	2.54	2.49	2.47	2.44	2.41	2.39	2.36	2.33	2.30	2.28	2.25
Greece	2.06	2.00	1.94	1.88	1.82	1.76	1.70	1.69	1.68	1.67	1.65	1.64	1.63	1.61	1.60	1.59
Croatia	1.96	1.93	1.90	1.86	1.83	1.80	1.77	1.75	1.74	1.72	1.71	1.69	1.67	1.66	1.64	1.63
Hungary	2.97	2.96	2.95	2.94	2.92	2.91	2.90	2.86	2.83	2.80	2.76	2.73	2.70	2.66	2.63	2.60
Irland	1.89	1.84	1.80	1.75	1.70	1.66	1.61	1.60	1.58	1.57	1.55	1.54	1.52	1.51	1.50	1.48
Italy	2.27	2.23	2.19	2.15	2.11	2.07	2.03	2.00	1.98	1.96	1.93	1.91	1.89	1.86	1.84	1.81
Lithuania	2.22	2.17	2.13	2.08	2.03	1.99	1.94	1.93	1.92	1.91	1.90	1.89	1.88	1.87	1.86	1.86
Luxembourg	2.11	2.07	2.03	1.98	1.94	1.90	1.85	1.84	1.82	1.80	1.79	1.77	1.75	1.74	1.72	1.70
Latvia	2.12	2.10	2.08	2.07	2.05	2.03	2.01	1.99	1.97	1.94	1.92	1.89	1.87	1.84	1.82	1.80
Malta	2.15	2.12	2.09	2.06	2.03	2.00	1.97	1.96	1.96	1.95	1.94	1.93	1.93	1.92	1.91	1.90
Netherlands	2.14	2.05	1.97	1.88	1.80	1.71	1.63	1.61	1.60	1.59	1.58	1.56	1.55	1.54	1.53	1.51
Poland	2.96	2.89	2.82	2.75	2.68	2.61	2.54	2.50	2.47	2.43	2.40	2.36	2.33	2.29	2.26	2.22

Supply to charging station	**kWh total/kWh**															
Electricity	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
Portugal	1.90	1.85	1.80	1.74	1.69	1.64	1.58	1.57	1.56	1.55	1.55	1.54	1.53	1.52	1.51	1.50
Romania	2.47	2.45	2.43	2.42	2.40	2.38	2.36	2.33	2.31	2.29	2.26	2.24	2.22	2.19	2.17	2.15
Sweden	2.18	2.17	2.15	2.14	2.13	2.11	2.10	2.09	2.08	2.06	2.05	2.04	2.02	2.01	2.00	1.99
Slovenia	2.71	2.70	2.68	2.67	2.66	2.65	2.63	2.59	2.55	2.52	2.48	2.44	2.40	2.36	2.32	2.28
Slovakia	2.95	2.93	2.91	2.89	2.87	2.85	2.83	2.81	2.79	2.76	2.74	2.72	2.70	2.67	2.65	2.63
Switzerland	2.11	2.13	2.15	2.17	2.19	2.22	2.24	2.22	2.20	2.18	2.17	2.15	2.13	2.11	2.10	2.08
Norway	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
United Kingdom	2.19	2.14	2.10	2.05	2.01	1.97	1.92	1.91	1.90	1.89	1.87	1.86	1.85	1.84	1.82	1.81
Ren. electr.	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
Hydro	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06	1.06
Wind	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07	1.07
PV	1.12	1.12	1.12	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Nuclear energy	3.19	3.18	3.18	3.18	3.18	3.18	3.17	3.16	3.14	3.12	3.10	3.09	3.07	3.05	3.03	3.01
Natural gas	2.51	2.49	2.47	2.45	2.43	2.41	2.39	2.38	2.36	2.34	2.33	2.31	2.29	2.28	2.26	2.24

Table 21 Background data for the supply of hydrogen to the filling station

[JOANNEUM RESEARCH 2024]

Supply to filling station	**g CO_2-eq./kWh**															
Hydrogen	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
H_2 natural gas	360.5	359.0	357.4	355.8	354.3	352.7	351.2	351.1	351.0	350.9	350.8	350.7	350.7	350.6	350.5	350.4
H_2 ee	46.8	46.4	45.9	45.5	45.1	44.6	44.2	43.8	43.4	42.9	42.5	42.1	41.7	41.3	40.8	40.4
H_2 hydro	10.8	10.7	10.6	10.6	10.5	10.4	10.4	10.3	10.3	10.2	10.2	10.1	10.1	10.1	10.0	10.0
H_2 wind	36.0	35.8	35.5	35.2	35.0	34.7	34.4	34.1	33.8	33.5	33.2	32.8	32.5	32.2	31.9	31.6
H_2 PV	104.3	103.2	102.1	100.9	99.8	98.7	97.5	96.5	95.5	94.6	93.6	92.6	91.6	90.6	89.6	88.6

Supply to filling station	kWh fossil/kWh															
Hydrogen	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
H_2 natural gas	1.74	1.73	1.71	1.70	1.69	1.67	1.66	1.65	1.65	1.65	1.64	1.64	1.63	1.63	1.62	1.62
H_2 ren.	0.05	0.05	0.05	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
H_2 hydro	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
H_2 wind	0.04	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
H_2 PV	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09	0.09

Supply to filling station	kWh renew./kWh															
Hydrogen	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
H_2 natural gas	0.10	0.10	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11
H_2 ren.	1.66	1.65	1.64	1.64	1.63	1.62	1.61	1.61	1.61	1.60	1.60	1.60	1.60	1.59	1.59	1.59
H_2 hydro	1.66	1.65	1.64	1.64	1.63	1.62	1.61	1.61	1.61	1.60	1.60	1.60	1.60	1.59	1.59	1.59
H_2 wind	1.66	1.65	1.64	1.64	1.63	1.62	1.61	1.61	1.61	1.60	1.60	1.60	1.60	1.59	1.59	1.59
H_2 PV	1.66	1.65	1.64	1.64	1.63	1.62	1.61	1.61	1.61	1.60	1.60	1.60	1.60	1.59	1.59	1.59

Supply to filling station	kWh total/kWh															
Hydrogen	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**	**2036**	**2037**	**2038**	**2039**
H_2 natural gas	1.85	1.84	1.82	1.81	1.80	1.78	1.77	1.77	1.76	1.76	1.75	1.75	1.74	1.74	1.73	1.73
H_2 ren.	1.71	1.70	1.69	1.68	1.68	1.67	1.66	1.66	1.65	1.65	1.65	1.64	1.64	1.63	1.63	1.63
H_2 hydro	1.67	1.66	1.66	1.65	1.64	1.63	1.63	1.62	1.62	1.62	1.61	1.61	1.61	1.60	1.60	1.60
H_2 wind	1.70	1.69	1.68	1.67	1.66	1.66	1.65	1.65	1.64	1.64	1.64	1.63	1.63	1.62	1.62	1.62
H_2 PV	1.76	1.76	1.75	1.74	1.73	1.72	1.71	1.71	1.71	1.70	1.70	1.69	1.69	1.68	1.68	1.68

ANNEX II: ABBREVIATIONS

BEV	Battery Electric Vehicle
bioCO_2	Biogenic CO_2 from flue gas (12 - 15 vol.-%) of biomass combustion
CO_2air	Capture of CO_2 from air (0.04 vol.-%)
CNG	Compressed natural gas
CO_2	Carbon dioxide
CH_4	Methane
CHP	Combined heat and power (plant)
CRG	Compressed renewable gas
dLUC	Direct land use change
E-fuel	Synthetic fuel, produced with electricity (Power-to-fuel) and CO_2 from air or sustainable biomass
EtOH	(Bio)Ethanol
FAME	Fatty acid methyl ester (biodiesel)
FT-diesel	Fischer-Tropsch diesel
GHG	Greenhouse gas emissions
H_2	Hydrogen
HEV	Hybrid electric vehicle
HFCV	Hydrogen fuel cell vehicle
HFC	Hydrogen fuel cell
HVO	Hydrated vegetable oil
Hydro	Hydro power
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
iLUC	Indirect land use change
LCA	Life Cycle Assessment
LUC	Land use change
N_2O	Nitrous oxide (laughing gas)
PED	Primary energy demand
PHEV	Plug-In hybrid electric vehicle
PV	Photovoltaics

ANNEX III: REFERENCES

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