Estimated Greenhouse Gas Emissions and Primary Energy Demand of Passenger Vehicles Tested in Green NCAP

Life Cycle Assessment Methodology and Data

green ncap

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

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CONTENTS

1.	**INTRODUCTION**	4
2.	**GOAL AND SCOPE**	5
3.	**METHODOLOGY OF LIFE CYCLE ASSESSMENT**	6
3.1.	**Definition Life Cycle Assessment (LCA)**	6
3.2.	**Environmental Effects**	6
3.3.	**System Boundaries**	7
3.4.	**Functional Unit**	9
3.5.	**Allocation**	9
3.6.	**Consideration for End of Life**	10
4.	**DATA**	11
4.1.	**Data Structure**	11
4.2.	**Foreground Data**	11
4.3.	**Background Data**	12
ANNEX I: MAIN DATA		15
ANNEX II: ABBREVIATIONS		23
ANNEX III: REFERENCES		24

1. INTRODUCTION

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.

Based on the methodology of “Life Cycle Assessment” (LCA) an LCA Expert Tool (Version 2.1) was developed at LIFE - Institute of Climate, Energy and Society at JOANNEUM RESEARCH in Austria. This LCA Expert tool, which is documented in a report and a handbook in 2022, estimates the greenhouse gas (GHG) emissions and the primary energy demand of 157 different transportation systems with passenger vehicles using different fuels, propulsion systems and state of technologies (2021, 2030 and 2050) in 40 countries.

2. GOAL AND SCOPE

In the present case, the LCA Expert Tool is used to assess the life cycle based GHG emissions and primary energy demand of the 61 vehicles tested in Green NCAP in the period 2019-2021 as a basis to provide relevant LCA information about these vehicles to consumers. At the same time, the 61 examples serve as an introduction to Green NCAP's LCA.

The considered 61 vehicles analysed for Green NCAP for the average situation in EU 28 (27 EU members states and UK) are:

1. Petrol E10 ICE: 22 vehicles
2. Diesel B7 ICE: 18 vehicles
3. Petrol E10 HEV: 4 vehicles
4. Diesel B7 HEV: 2 vehicles
5. CNG ICE: 2 vehicles
6. Petrol PHEV: 5 vehicles for average EU 28
7. BEV: 7 vehicles for average EU 28
8. HFCV: 1 vehicle for hydrogen from natural gas

(further details see Annex I)

3. METHODOLOGY OF LIFE CYCLE ASSESSMENT

3.1. 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. 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 consumption of different transportation systems can be identified and calculated.

To reflect the LCA definition all results are 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.

According to ISO 14040, a LCA consist of the 4 following phases, which are closely linked during the whole process of applying LCA methodology:

- 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.

The LCA performed here is an "attributional LCA", as an attributional life cycle assessment estimates what share of the global environmental burden 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.

3.2. Environmental Effects

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

As a 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 to 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 and 1 kg N_2O = 298 kg CO_2-eq.

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. 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, waste, residues.

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

3.3. System Boundaries

For providing a LCA on a transportation service, all processes must be analysed from raw material and resource extraction to the vehicle offering the transportation. 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.

The simplified process chain for a battery electric vehicle, for example, covers 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 & fuelling infrastructure, electricity grid, electricity production, spare and maintenance parts and ends with the extraction of primary energy and resources in nature.
- The end-of-life phase included the dismantling processes of the vehicle and sorting the materials for reuse, recycling and energy generation.

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. 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).

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 considered with their effects of substituting for other products and services.

In the Inventory Analysis of the LCA 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.

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 in an Asian country.

The schemes of the process chains 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 5 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/electricity, where other products might be co-produced
4. Distribution of transportation fuel/electricity incl. filling/charging station
5. Vehicle using the transportation fuel/electricity.

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 facilities; e.g. the materials for the production of the vehicle also including the battery for electric vehicles 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).

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 and materials and the production and end of life of the facilities.

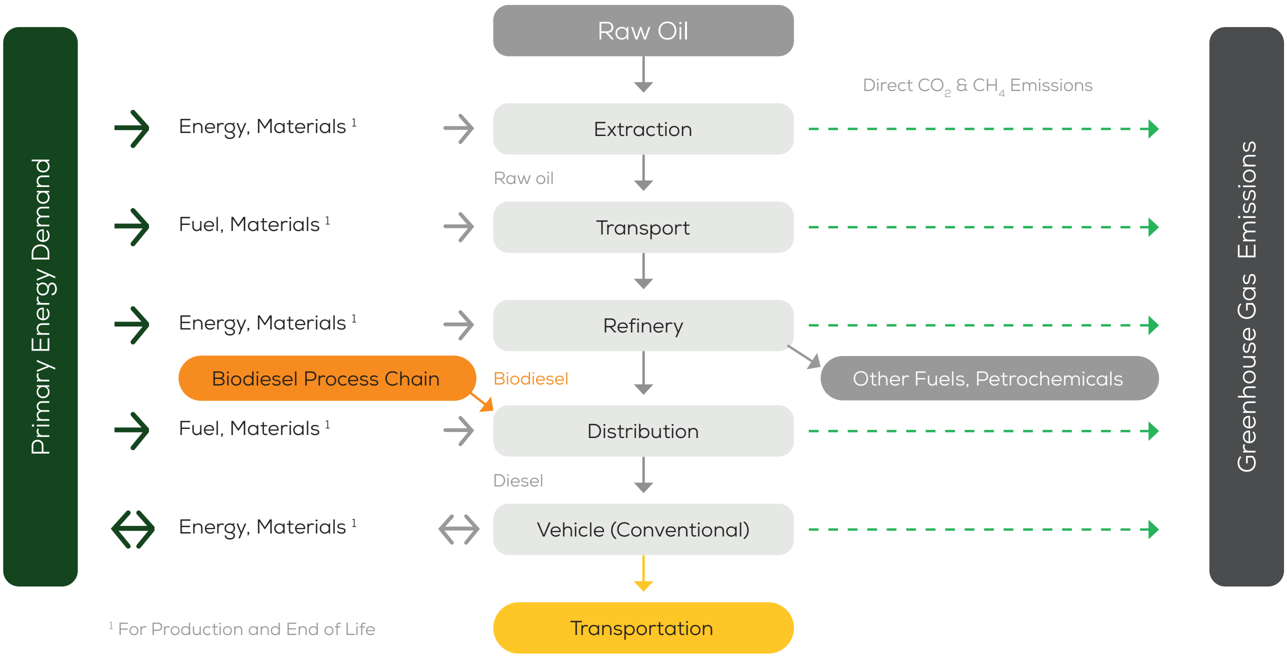


Figure 1 - Process chain for an internal combustion engine vehicle running on diesel B7

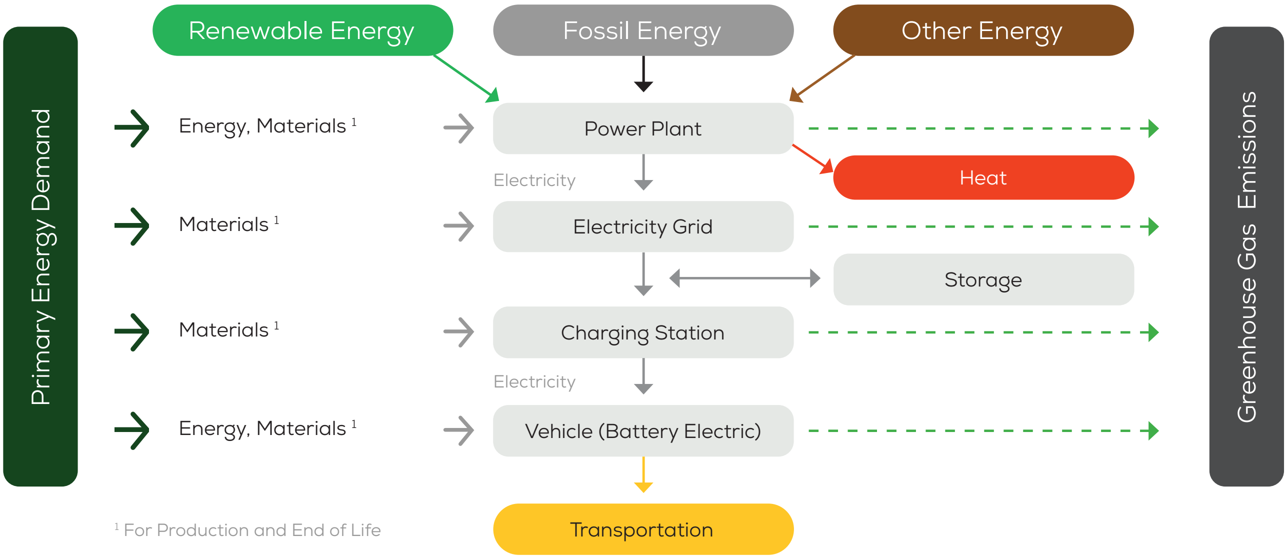


Figure 2 - Process chain for a battery electric vehicle using an electricity mix

3.4. 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
- Total of 240,000 km in the total lifetime of 16 years.

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

- GHG emissions in grams CO_2-eq/km and tons 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 consumption in kWhtotal/km and MWhtotal/vehicle with the %-share of fossil and renewable energy.

The functional units are also split up in fuel/energy supply, production, operation and end of life. The different possible driving ranges per filling or charging of an ICE, battery electric and fuel cell vehicle are not reflected in these functional units.

3.5. 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 glycerine 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 bioethanol a credit for the substituted feed is given. Also for the glycerine and fertilizer coproduced with FAME a credit for the substituted synthetic glycerine 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. 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.

3.6. 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 recovery processes, for most of the considered vehicles, the end-of-life phase has negative GHG emissions and a negative primary energy demand.

4. DATA

4.1. Data Structure

Basically, in the LCA, data sets are used that represent adequately the technical, geographical and timely framework conditions to fulfil the goal and the scope of the LCA based estimation of GHG emissions and primary energy demand. As in the LCA the different transportation systems using the 61 vehicles tested in Green NCAP are compared, the most important aspect of the basic data is, to reflect the most relevant differences (e.g. fuel consumption per km) between the systems and the states of technology to identify the most significant differences between the GHG emissions and the primary energy demand. 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 are set up: the fore- and background data.

The foreground data, which have a significant influence on the total environmental effects and determine most of the differences between the considered vehicles, must be collected, assessed and documented explicitly in accordance to the goal and the scope of this LCA. Examples for typical foreground data for the LCA are:

- Vehicle: e.g. mass, energy consumption, lifetime
- Type of biomass for biofuel
- Electricity source for electric vehicles.

The background data, which have a minor influence on the difference between the considered environmental effects of the compared transportation systems, e.g. environmental effects of steel, are taken and documented from adequate databases[1] , e.g. JOANNEUM RESEARCH, GEMIS 5.0 [GEMIS 2019], ecoinvent 3.4 [Ecoinvent 2019].

Typical background data for the LCA are on:

- Electricity mix for auxiliary processes
- Production of materials for vehicles
- Auxiliary material and energy for processes
- Distribution infrastructure.

All main data are documented in Annex I. It is important to notice that in the calculations of the operation phase of the vehicle, the changes of the energy/electricity supply (2021 – 2036) in the 16 years lifetime of the vehicle are considered.

4.2. Foreground Data

The foreground data for the specification of the vehicle are:

- Vehicle data:
  - Mass
  - Annual kilometres: 15,000 km/a
  - Lifetime: 16 years
  - Energy consumption (measured by Green NCAP under different conditions)
  - CH_4- and N_2O-emissions from ICE (measured by Green NCAP)

[1] 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. So here a priority was given in using the different data bases for the background data. The JOANNEUM RESEARCH data sets were of highest priority and the missing data were added from GEMIS [GEMIS 2019] and from ecoinvent [Ecoinvent 2019].

- Battery and charging (Table 1):
    - Capacity
    - Lifetime: same as vehicle based on Stakeholders’ decision
    - Share of slow and fast charging
    - Location of battery production: Asia, Europe, USA
    - End-of-life: material recycling and 2nd stationary life.

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

- Land use change (LUC) (Table 2) considered for sugar cane and soybeans from pasture and palm oil from tropical forest
- Shares of biofuel blending are diesel B_7 – 7 vol.-% biodiesel (FAME) in diesel – and petrol E10 – 10 vol.-% of bioethanol (EtOH) in petrol.
- Biomass resources for biofuels (Table 3).

For the European electricity mix, the GHG emissions and primary energy demand were taken based on the EU Study commissioned by DG CLIMA 2020 [Hill et al. 2020]. In these LCA data, import and export of electricity as well as allocation due to coproduced heat in combined heat and power (CHP) plants are considered. The data for the electricity mix in EU28 (incl. UK) are shown in the Table 4. Between 2021, 2030 and 2050 the foreground data are interpolated.

4.3. 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.

The background data for vehicle production cover:

- Share of material mix for vehicles (Table 5) and fuel cell & tank production (Table 6) to calculate the environmental effects from vehicle production.
- Materials (Table 7) and primary energy demand for vehicle production.

On the basis of a recent literature review on environmental life cycle impacts of automotive batteries [Aichberger et al. 2020], the calculation of GHG emissions from battery manufacturing was 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 shown in Figure 3.

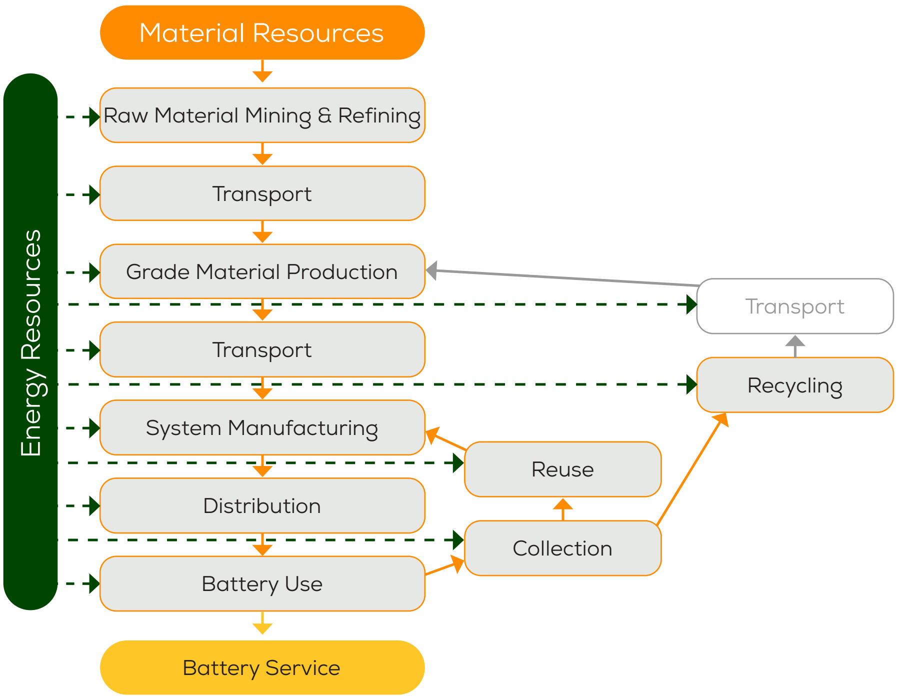
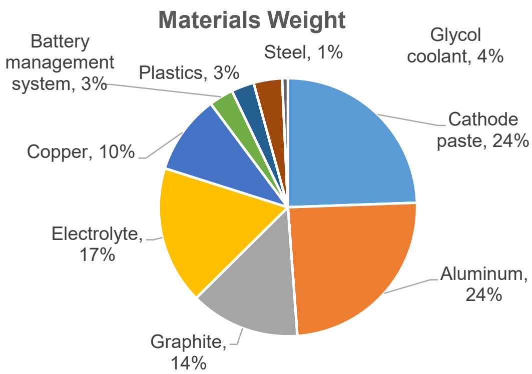


Figure 3 - System boundaries for automotive battery systems.

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. In Table 8 and Figure 4 the background data for batteries are shown.



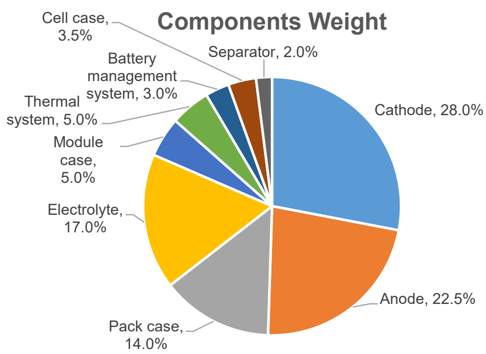


Figure 4 - Estimated average distribution of the weight of these components in the automotive battery system [JOANNEUM RESEARCH 2021]

The environmental effects from the maintenance of the vehicle operation are considered, which are tires, spare/replacement parts and engine oil for ICE, HEV and PHEV. Table 10 shows the GHG emissions and PED of the total lifetime mileage of a vehicle coming from the maintenance covering of tires, spare/replacement parts and engine oil.

For the environmental effects in the End-of-Life phase of the vehicles, the following two 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 was assumed that 1 t of secondary material substitutes 0.15 t of primary material, e.g. for steel this is significant higher and for electronics significant lower.

In Table 9 the main data for hydrogen production via electrolysis and natural gas steam reforming are shown. The oxygen and heat from electrolysis is not used.

In Table 11, Table 12 and Table 13 the main data for biofuel production are shown.

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

- Heating values of fuels (Table 14)
- Supply of fossil fuels (Table 15) and biofuels to the filling station (Table 16)
- Supply of electricity to the charging station (Table 17), where "electr. / RES EU" is 25% hydro, 50% wind and 25% PV.
- Supply of hydrogen to the filling station (Table 18)

These background data were calculated with the specified foreground data using LCA [JOANNEUM RESEARCH 2021, Jungmeier et al. 2019].

The background data for land use change for biomass resources are shown in Table 19. The possible CO_2-emissions of iLUC are not considered in the analysis.

ANNEX I: MAIN DATA

Table 1 Foreground data for battery production, charging and end-of-life (own assumptions and location of battery production

based on [Hill et al. 2020]

State of technology	2021
Location of battery production	
Asia	75%
Europe	6%
America	19%
End of life	
Recycling rate	97%
2nd stationary life	3%

Table 2 Foreground data for land use change for biofuels

own assumptions

Share of direct land use change (LUC) for biofuels	2021	2030	2050
Sugar cane (from pasture)	10%	10%	10%
Soja beans (from pasture)	10%	10%	10%
Palm oil (from trop. forest)	10%	10%	10%

Table 3 Foreground data for biomass mix for biofuels

JEC Well-To-Wheels report v5 [JRC 2020] and own assumptions

Country (EU 28)	2021	2030	2050
FAME			
Rape seed oil	53%	53%	53%
Used cooking oil	22%	22%	22%
Palm oil	20%	20%	20%
Soja oil	5%	5%	5%
EtOH			
Wheat&maize	68%	60%	54%
Sugar beet	21%	21%	21%
Sugar cane	7%	6%	5%
Wood	2%	7%	10%
Straw	2%	7%	10%

Table 4 Foreground data for EU28 (incl. UK) electricity mixes
[Hill et al. 2020]

	2020	2030	2050
Coal	21.3%	10.1%	0.8%
Oil	0.7%	0.6%	0.2%
Natural gas	17.3%	12.5%	11.2%
Nuclear	23.1%	18.3%	14.6%
Biomass	6.0%	9.1%	8.1%
Hydro	11.7%	10.7%	8.3%
Wind	15.3%	27.1%	42.6%
PV	4.6%	11.4%	13.4%
Waste	0.0%	0.0%	0.0%
Other	0.0%	0.2%	0.9%
SUM	100.0%	100.0%	100.0%

Table 5 Background data for material mix of vehicles (without battery and fuel cell)
based on [Hausberger et al. 2019] and [JOANNEUM RESEARCH 2021]

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	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Table 6 Background data for fuel cell and H_2 tank system
[JOANNEUM RESEARCH 2021]

	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%

The H_2 pressure is 700 bar, the weight of the H_2-tank and of the FC-system is 276 kg.

Table 7 Materials for vehicle production
[JOANNEUM RESEARCH 2021], GEMIS 5.0 [GEMIS 2019], ecoinvent 3.4 [Ecoinvent 2019], [Hill et al. 2020]

Materials for vehicle production 2021	**GHG** [gCO_2eq/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	4,200	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

The energy demand for the vehicle manufacturing is estimated (based on [VW 2021]):

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

Table 8 Background data for batteries

[JOANNEUM RESEARCH 2021]

Li-Ion battery	**Greenhouse Gas Emissions**				**Primary Energy Demand**			
	CO_2 [kg/kWh]	**CH_4** [kg/kWh]	**N_2O** [kg/kWh]	**CO_2eq** [kg/kWh]	**Fossil** [kWh/kWh]	**Renew.** [kWh/kWh]	**Other** [kWh/kWh]	**Sum** [kWh/kWh]
Production								
CN	122	0.23	0.00	131	397	28	15	440
EU	67	0.18	0.00	74	259	66	62	387
US	81	0.20	0.00	88	325	43	58	426
Recycling								
CN	-22	-0.02	0.00	-23	-80	-3	0	-86
EU	-7	-0.01	0.00	-7	-31	-20	-10	-62
US	-10	-0.01	0.00	-10	-44	-16	-7	-68

Table 9 Data for hydrogen production via low temperature electrolysis (PEM or alkaline) and natural gas steam reforming

based on [JOANNEUM RESEARCH 2021, BioGrace 2015]

		Electrolyses	**Steam reforming**
Output			
H_2 30 bar	[MWh]	1	1
Input			
Electricity	[MWh]	1.43	
Natural gas	[t]		0.086

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.

Table 10 GHG emissions and primary energy demand from the maintenance in the whole lifetime of the vehicle (HEV like ICE)

Tires, oil, spare parts	**2021**			**2030**			**2050**		
	GHG [$kgCO_2eq$]	**PED** [kWh]	**PED_{fos}** [kWh]	**GHG** [$kgCO_2eq$]	**PED** [kWh]	**PED_{fos}** [kWh]	**GHG** [$kgCO_2eq$]	**PED** [kWh]	**PED_{fos}** [kWh]
Petrol ICE	1,880	6,070	5,700	1,850	6,040	5,590	1,830	6,010	5,510
Diesel ICE	1,870	6,070	5,700	1,840	6,040	5,590	1,820	6,010	5,510
CNG ICE	1,880	6,060	5,690	1,840	6,030	5,580	1,820	6,000	5,500
Petrol PHEV	1,900	6,150	5,770	1,870	6,120	5,660	1,850	6,090	5,580
Diesel PHEV	1,900	6,150	5,780	1,860	6,120	5,660	1,840	6,090	5,580
Electr. BEV	1,800	5,950	5,530	1,760	5,920	5,390	1,730	5,890	5,290
H_2 HFC	1,800	5,940	5,530	1,760	5,910	5,380	1,730	5,880	5,280

Assumption for spare parts: annually 0.5% of vehicle weight.

Table 11 Main data for vegetable oil production
based on [JOANNEUM RESEARCH 2021, 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 Main data for FAME (biodiesel) production
based on [JOANNEUM RESEARCH 2021, 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 Main data for bioethanol production

based on [JOANNEUM RESEARCH 2021, BioGrace 2015]

		Wheat	Maize (corn)	Sugar beet	Sugar cane	Wood	Straw
Output							
Bioethanol	[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 heating values of fuels

[JOANNEUM RESEARCH 2021] comparable to [EU 2018]

	[kWh/kg]	[kWh/l]	[kWh/Nm³]
Diesel	11.8	9.8	
Petrol	11.9	8.8	
CNG	15.4		10.0
Diesel B7		9.7	
Petrol E10		8.5	
FAME	10.3	9.1	
EtOH	7.4	5.8	
H_2	33.3		

Table 15 Background data for the supply of fossil fuels to the filling station

[JOANNEUM RESEARCH 2021]

Supply of fossil fuels	2021			2030			2050		
	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]
Diesel / raw oil	58.1	1.18	1.18	58.6	1.18	1.18	78.1	1.25	1.25
Petrol / raw oil	76.2	1.26	1.26	75.3	1.25	1.25	93.4	1.31	1.31
CNG / natural gas	39.6	1.15	1.14	41.3	1.15	1.15	57.8	1.18	1.18

Table 16 Background data for the supply of biofuels to the filling station
[JOANNEUM RESEARCH 2021]

Supply of biofuels	2021			2030			2050		
	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]
EtOH / wheat & maize	267	2.6	0.93	206.0	2.4	0.66	145	2.2	0.39
EtOH / sugar beet	300	2.4	1.10	227.0	2.3	0.81	150	2.1	0.45
EtOH / sugar cane	171	5.3	0.50	165.0	5.1	0.48	160	5.0	0.46
EtOH / wood	57	2.8	0.17	56.0	2.7	0.17	56	2.6	0.16
EtOH / straw	97	2.7	0.22	94.0	2.6	0.21	92	2.5	0.21
FAME / rape seed oil	218	2.2	0.48	200.0	2.1	0.41	189	2.1	0.36
FAME / waste cooking oil	17	1.1	0.13	8.7	1.0	0.09	0.43	1.0	0.05
FAME / palm oil	262	4.8	0.64	247.0	4.6	0.59	239	4.6	0.55
FAME / soja oil	66	1.9	0.40	49.0	1.8	0.33	35	1.8	0.27

Table 17 Background data for the supply of electricity to the charging station
[JOANNEUM RESEARCH 2021] based on electricity mix defined in foreground data

Supply of electricity to the charging station	2021			2030			2050		
	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]
Electr. / RES EU	31	1.1	0.03	28	1.1	0.03	24	1.1	0.02
Electr. / EU28	439	2.6	2.00	254	2.2	1.32	97	1.6	0.72

RES EU mix: 25% hydro, 50% wind and 25% PV

Table 18 Background data for the supply of hydrogen to the filling station
[JOANNEUM RESEARCH 2021]

Supply of hydrogen	2021			2030			2050		
	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]	GHG [gCO_2eq/kWh]	PED [kWh/kWh]	PED_{fos} [kWh/kWh]
H_2 / natural gas	388.0	1.90	1.80	355.0	1.80	1.70	330.0	1.60	1.50
H_2 / EU RES	50.1	1.74	0.05	44.2	1.66	0.04	35.8	1.59	0.04

Table 19 Background data for direct and indirect land use change (LUC) for biomass resources based on [EU 2009, EU 2015]

iLUC*	[gCO_2/MJ]	[gCO_2/kWh]
Bioethanol (wheat, maize)	12	43
Bioethanol (sugar beet)	13	47
Bioethanol (sugar cane)	17	61
FAME/HVO (rape seeds)	33	119
FAME/HVO (soja beans)	55	198
FAME/HVO (palm oil)	66	238

dLUC*	[kgCO_2/ha]
Sugar cane (grassland)	2,576
Soja beans(grassland)	2,825
Palm oil (trop. forest)	28,441
	[gCO_2/kWh]
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

ANNEX II: ABBREVIATIONS

CNG	Compressed natural gas
CO_2	Carbon dioxide
CH_4	Methane
CHP	Combined heat and power (plant)
dLUC	Direct land use change
EtOH	(Bio)Ethanol
FAME	Fatty acid methyl esther (biodiesel)
GHG	Greenhouse gas emissions
H_2	Hydrogen
HEV	Hybrid electric vehicle
HFCV	Hydrogen fuel cell vehicle
HFC	Hydrogen fuel cell
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	Nitrogen oxide
PED	Primary Energy Demand
PHEV	Plug-in Hybrid Electric Vehicle
PV	Photovoltaics

ANNEX III: REFERENCES

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