`

CLEVER
Clean Vehicles Research: LCA and Policy Measures

LCA report

Boureima Fayçal-Siddikou
Wynen Vincent
Sergeant Nele
Rombaut Heijke
Messagie Maarten
Prof. Dr. ir. Van Mierlo Joeri

Vrije Universiteit Brussel
Department of Electrical Engineering and Energy Technology (ETEC)
Mobility and automotive technology research group (MOBI)

`

Table of contents

Table of tables

ACRONYMS, ABBREVIATIONS AND UNITS

ABS	Acrylonitrile Butadiene Styrene
Ag	Silver
Al_2O_3	Aluminum Oxide
BEV	Battery Electric Vehicle
BIOSES	BIOfuel Sustainable End uSe
BTL	Biomass-to-Liquid
$CaCl_2$	Calcium Chloride
CeO_2	Cerium Oxide
Cd	Cadmium
$CHCL_3$	Trichloromethane
CLEVER	Clean Vehicle Research: LCA and Policy Measures
CNG	Compressed natural Gas
CRT	Continuously Regenerated Trap
Cu O	Copper Onoxide
DfE	Design for Environment
ECE (UDC)	Urban Driving Cycle
EoL	End-of-Life
ETBE	Ethyl Tert-Butyl Ether
ETEC	Department of Electrotechnical Engineering and Energy Technology
EuroNcap:	European New Car Assessment Program
FCAI:	Federal Chamber of Automotive Industry of Australia
FCEV	Fuel Cell Engine Vehicle
FISITA:	International Federation of Automotive Engineering Societies
GJ	Giga Joule
HCl	Hydrogen Choride
HEV	Hybrid Electric Vehicle
HF	Hydrogen Fluoride
n.a	not available
NH_3	Ammonia
HNO_3	Nitric acid
kg	kilogram
ICEV	Internal Combustion Engine Vehicle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
Li-ion	Lithium-ion

LPG	Liquefied Petroleum Gas
LTDD	Life Time Driven Distance
m	meter
Mo	Molybdenum
MTBE	Methyl Tert-Butyl Ether
NEDC	New European Driving Cycle
NG	Natural Gas
NiMH	Nickel Metal Hydride
NiCd	Nickel Cadmium
Nm_3	Normal cubic meter
O_2	Oxygen
OVAM	Openbare Vlaamse Afvalstoffen Maatschappij – Public Flemish Waste Company
Pb	Lead
PGM	Platinum Group Metals
PM	Particulate Mater
ppm	parts per million
PVDF	Polyvinilidene Fluoride
RDC	Research, Development and Consulting
RME	Rape Methyl Ester
SCR	Selective Catalytic Reduction
SBR	Styrene Butadiene Rubber
SME	Soybean Methyl Ester
SMR	Steam reforming
SUV	Sports Utility Vehicle
SUBAT	SUStainable BATtery
tkm	ton-kilometer
TiO_2	Titanium Dioxide
TTW	Tank-to-Wheel
UCTE	Union for the co-ordination of transmission of electricity
VSP	Vehicle Simulation Program
VUB	Vrije Universiteit Brussel
WTT	Well-to-Tank
WTW	Well-to-Wheel
Zn	Zinc
ZrO_2	Zirconium Oxide

Introduction

The CLEVER project aims at fulfilling the following objectives:

- Create an objective image of the environmental impact of vehicles with conventional and alternative fuels and/or drive trains;
- Investigate which price instruments and other policy measures are possible to realize a sustainable vehicle choice;
- Examine the external costs and verify which barriers exist for the introduction of clean vehicle technologies on the Belgian market;
- Analyse the global environmental performances of the Belgian car fleet;
- Formulate recommendations for the Belgian government to stimulate the purchase and use of clean vehicles

For the environmental part of the CLEVER project, an LCA methodology has been used. To perform the LCA, an input and output data gathering process called Life Cycle Inventory (LCI) has been done. The LCI step provides information on all the inputs and outputs from and to the environment from all the unit processes involved in the product system with respect to the functional unit which is a lifetime driven distance of 230,500 km. In other words, the life cycle inventory is the compilation of all the needed materials, chemicals, energies and all the emissions related to the fulfillment of the functional unit. In the CLEVER project, a special data gathering strategy has been developed and executed for that issue. A literature review has been performed and a list of all the relevant European and Belgian projects (CONCAWE [1], ExternE [2], Libiofuels [3], PREMIA [4], SGS-INGENIEURE [5], SenterNovem [6], Camden LCA [7], VITO & 3E [8]…) was established. All the relevant data from those projects were analysed and centralized in a specific data gathering template.

When specific Belgian data are not available, average European data are considered.

As the CLEVER project aims at developing a per-model applicable LCA, the Belgian fleet has been classified into nine different categories (see chapter I). This categorization has enabled to adapt the Tank-to-Wheel emissions from the Ecoscore database to the different Belgian market segments. For the other life cycle phases, the Ecoinvent database has been used to calculate LCI of materials, manufacturing processes, energy production, fuel production and distribution for both conventional and alternative vehicles. Detailed LCI data of different battery technologies for hybrid electric (HEV) and battery electric vehicles (BEV) have been collected from the SUBAT project [9]. The use of supercapacitors in HEV has been included as well. Thanks to the OVAM study on the vehicles' end-of-life in Belgium, all the recycling and energy recovery rates per material with respect to the real efficiency of Belgian recycling plants were collected [10]..

Notice: For reminding the Ecoinvent Data v2.01 [11] is the reference LCI database of the CLEVER project. It contains about 4000 datasets of products and services covering energy, transport, building materials, wood, chemicals, electronics, mechanical engineering, paper and pulp, plastics, renewable fibers, metals, waste treatment and agricultural products. Each dataset contains all the resources and all the emissions (towards soil, air and water) linked to the production of the corresponding product or service. Thereby it is important to keep in mind that the information contained in all the tables of this report is just summarizing the main inputs (materials, energy and chemicals) for the production of the corresponding products or services. Unit processes, such as waste treatment, transport, industrial plants, etc. are taken into account even if they don’t appear explicitly in the tables (for convenience reasons). The complete Ecoinvent datasets have been checked and are used in the CLEVER LCA model.

I. Goal of the study

The Clever LCA study has been commissioned by the Belgian Science Policy (BELSPO) and its intended purpose is to perform a comparative assessment of different vehicles (conventional and alternative) in order to provide policy makers with outcomes which will allow them taking the appropriate measures to promote the purchase and the use of clean vehicles.

The assessment will cover the following aspects:

- Evaluate and compare the life cycle impact of different vehicles within a same vehicle category
- Evaluate the environmental benefit of replacing conventional vehicles by alternative ones.
- Evaluate the environmental impact of the life cycles of fuels (well-to-wheel) and vehicles (cradle-to grave).
- Integrate manufacturing and end-of-life phases in environmental vehicle assessments.

All the relevant parameters of the assessment (mass, fuel consumption, emissions…) will be modeled as a range of value instead of a single average value. This modeling system will allow taking into account the diversity of different situations by using statistical variables for environmental data.

II. Scope of the study

The LCA model includes all vehicle segments and technologies available in the Belgian fleet. The assessment describes the current situation of the Belgian fleet and compare the environmental impacts of vehicles with different conventional (diesel, petrol) and alternative fuels (LPG, CNG, alcohols, bio-fuels, biogas, hydrogen) and/or drive trains (internal combustion engines and battery, hybrid and fuel cell electric vehicles. The results include all the life cycle steps (production, transport, use phase, maintenance and end-of-life) of a vehicle in a Belgian context.

II.1 Functional unit

The functional unit is a quantified description of the performance of product systems, for use as a reference unit. It allows comparing two or several product systems on the basis of a common provided service. In this study, the functional unit will be defined in such a way that all the life cycle phases of vehicles will be taken into account in the analysis and in a Belgian context. To calculate the average lifetime of a Belgian vehicle, the variation from 2002 to 2006 of the ages of all the Belgian end-of-life vehicles treated in Belgian authorized recycling plants have been assessed by FEBELAUTO (Figure 1) [13] and an average lifespan of 13.7 years has been obtained. Next to the average lifespan, an annual mileage of 15000 km [12] vehicle has been into account. The multiplication of the average lifespan and the annual mileage gave a driven distance of 205,500 km. However, the Functional unit has been extended to 230,500 km because the statistics show an increase of both the lifespan and the annual mileage from 2007 [12], [13]. Additionally, a range of life time driven distance is defined in a Belgian context as a normal distribution function with a standard deviation of 70,074.52 and a geometric mean of 230500 (Functional unit) which will be the comparison basis of all the vehicles (see figure 2). Thereby, the effectively driven distance of the vehicles will range from approximately 50,000 km (e.g. total loss car) to 400,000 km (e.g. collection car) (Figure 2).This will allow assessing the relative contribution of the production phase to the overall environmental impact regarding the use phase. In order to take into account the needed number of vehicles to cover the F.U., the manufacturing step of vehicles is multiplied by the quotient of the F.U. over the effectively driven distance.

With such an approach, the average LCA results will always correspond to the F.U but al the alternative scenarios between the minimum and the maximum driven distances can be assessed without performing new LCA models

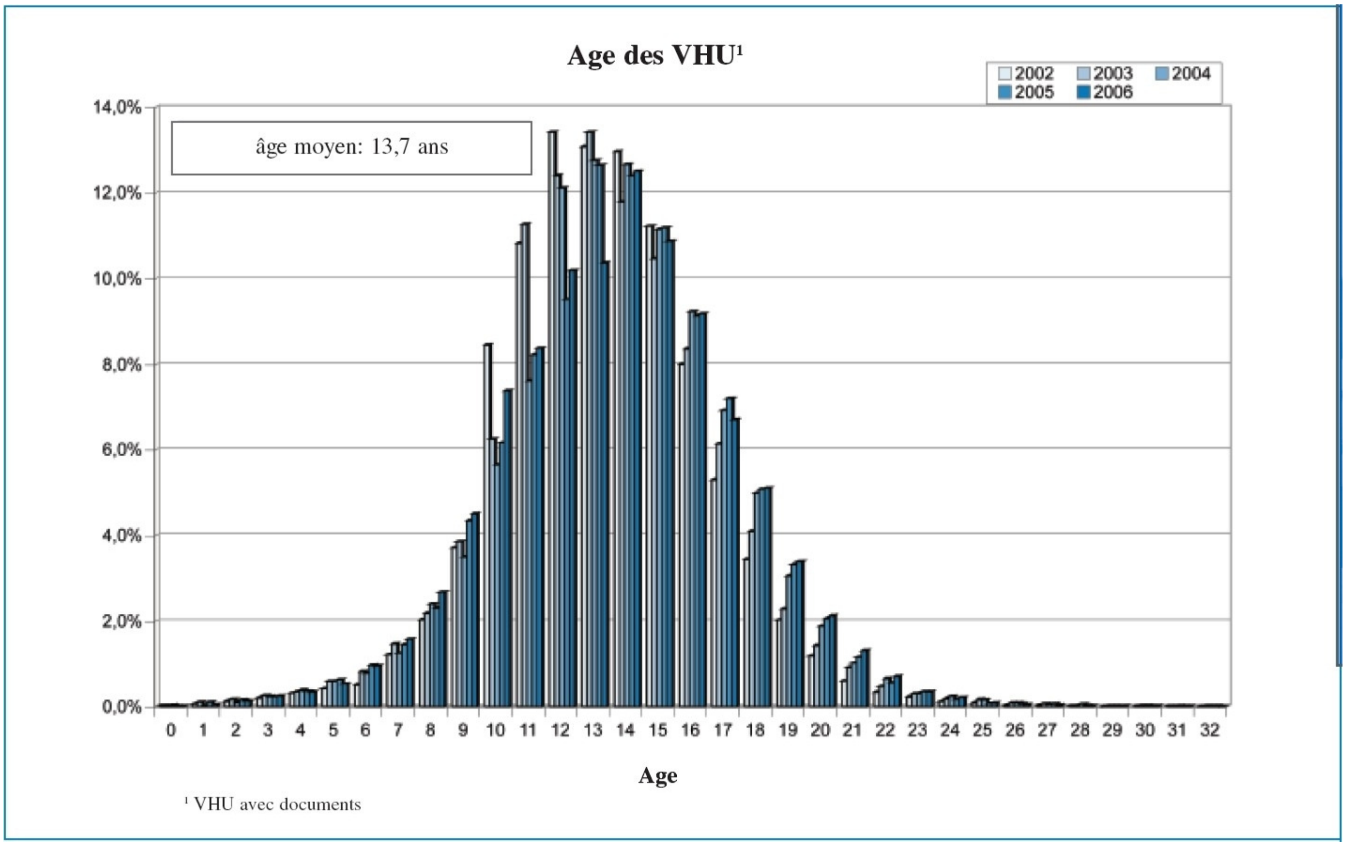

Figure 1: variation of the lifespan of Belgian end-of-life vehicles [13]

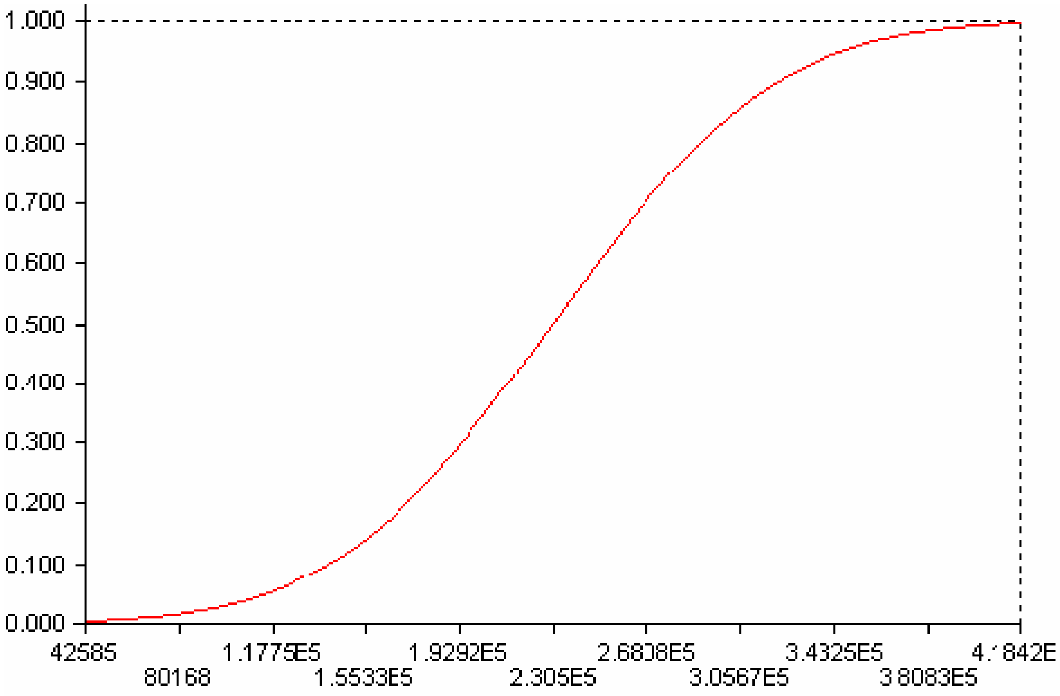

Figure 2: Distribution function of the life time driven distance

II.2 Data quality requirements

The LCA model includes all vehicle segments and technologies available in the Belgian fleet. The assessment describes the current situation of the Belgian fleet. Two main quality criteria have been chosen: the time period and the location. For the time period, dataset which are valid from year 2000 onward are used. Foe the location, a priority order has been defined: Belgian specific dataset are always preferred. When a Belgian dataset is not available a European one is used. And when both Belgian and European datasets are not available, a global one is then used. Close, to the time period and the location, datasets with mature and recent technology are preferred. However, for recent products such as second generation biofuels, pilot scale technologies are sometimes chosen. Details of all the ecoivent processes used in this study are summarised in Table 1 to Table 11. The time periods of datasets which do not fulfil the time criteria are put in red.

Whenever possible, the most recent Belgian data have been used. They are completed with European data when specific data for Belgium are not available. The raw material production, transport, manufacturing, use, maintenance and end-of-life of all the vehicles are taken into account. The vehicle specific data such as the segment, technology, fuel type, fuel consumption, euro standard, weight and direct emissions are retrieved from the Ecoscore database [14]. The Ecoscore database is a compilation of vehicle technical and environmental data mainly gathered from the Belgian Federal service in charge of vehicle registration (DIV) and the Belgian federation of automotive manufacturers and importers (FEBIAC). Direct emissions and fuel consumption are gathered from homologation data which are available for all road vehicles on the European market and giving the advantage of assessing all the vehicles on the same basis. Homologation data are measured according to the New European Driving Cycle (NEDC) [15]. It includes the regulated direct emissions, namely CO (carbon monoxide), NO_x (nitrogen oxides), HC (hydrocarbons) and PM_{10} (particulate matter), expressed in g/km. Close to these emissions, non regulated emissions such as CO_2 (carbon dioxide), SO_2 (sulphur dioxide), N_2O (nitrous oxide) and CH_4 (methane). CO_2 and SO_2 are calculated on the basis of the fuel consumption and the fuel characteristics. The N_2O and CH_4 direct emissions are specific to the vehicle technology [16].However, the testing conditions under NEDC does not include the additional fuel consumption of the cooling and the heating devices [17]. The considered weight for the vehicle is the ‘in running order’ mass including coolant, oils, fuel, spare wheels, tools and the driver (75 kg) [18].

For most vehicles, material production, energy, manufacturing, production plants, waste treatment and transport are derived from the version 2.01 of the ecoinvent database [11]. For ecoinvent multi-output processes, allocation factors are attributed to each input and output of unit processes [19]. The ecoinvent and the Ecoscore databases are considered to reflect the current Belgian situation.

Allocation criteria such as energy content, exergy, weight and unit price are used from the ecoinvent database according to the considered multi-output process. The CO_2 emissions of bio-fuels are allocated on the basis of their carbon balance (Centre of Life Cycle Inventory, 2009). In this study, ecoinvent default allocation is always used.

The transport, shredding and further separation processes of EoL vehicles are based on the state-of-the art of the Belgian recycling activities (OVAM, 2009). No explicit cut-off criteria have been defined. Whenever possible, all vehicle materials and life cycle steps have been taken into account.

Table 1: Datasets used to model the bodyshell of the different vehicles and the fuel production

Material/Process	Used Ecoinvent process	Location	Time Period
manufacturing of the body shell	passenger car, RER, [unit] (#1936)	Europe	2000
Belgian Electricity Supply mix	electricity mix, BE, [kWh] (#696)	Belgium	2004
natural gas produced in the Netherlands	natural gas, at production onshore, NL, [Nm3] (#1422)	The Netherlands	2000
natural gas produced in Norway	natural gas, at production offshore, NO, [Nm3] (#1416)	Norway	2000
natural gas produced in Algeria	natural gas, at production onshore, DZ, [Nm3] (#1419)	Algeria	[1]
natural gas produced in Russia	natural gas, at production onshore, RU, [Nm3] (#1421)	Russia	[1]
natural gas at Belgian consumer	natural gas, high pressure, at consumer, BE, [MJ] (#1321)	Belgium	2000
hydrogen produced by cracking	hydrogen, cracking, APME, at plant, RER, [kg] (#285)	Europe	1999-2001
normal Diesel	diesel, at regional storage, RER, [kg] (#1543)	Europe	2000
low sulphur Petrol	petrol, low-sulphur, at regional storage, RER, [kg] (#1567)	Europe	2000
unleaded Petrol	petrol, unleaded, at refinery, RER, [kg] (#1571)	Europe	2000
diesel	diesel, at refinery, RER, [kg] (#1541)	Europe	2000
low sulphur Diesel	diesel, low-sulphur, at regional storage, RER, [kg] (#1548)	Europe	2000
propane/Butane	propane/ butane, at refinery, RER, [kg] (#1576)	Europe	2000
ethanol from Rye	ethanol, 99.7% in H2O, from biomass, at distillation, RER, [kg] (#6544)	Europe	2002-2006
ethanol from Sugar cane	ethanol, 95% in H2O, from sugar cane, at fermentation plant, BR, [kg] (#6259)	Brazil	2000-2006
ethanol from Sugar beets	ethanol, 95% in H2O, from sugar beets, at fermentation plant, CH, [kg] (#6226)	Switzerland	2000-2004
ethanol from Grass	ethanol, 95% in H2O, from grass, at fermentation plant, CH, [kg] (#6223)	Switzerland	2000-2004
ethanol from wood	ethanol, 95% in H2O, from wood, at distillery, CH, [kg] (#6542)	Switzerland	1999-2006
BTL methanol	methanol, from synthetic gas, at plant, CH, [kg] (#6244)	Switzerland	1995-2004
rape methyl ester	rape methyl ester, at esterification plant, RER, [kg] (#6573)	Europe	1996-2003
soybean methyl ester	soybean methyl ester, production US, at service station, CH, [kg] (#6664)	U.S./Switzerland	2004-2008
vegetable oil methyl ester	vegetable oil methyl ester, at esterification plant, FR, [kg] (#6592)	France	1996-2003
biogas from biowaste	biogas, from biowaste, at storage, CH, [Nm3] (#6164)	Switzerland	1999-2004
methane from biogas	methane, 96 vol-%, from biogas, at purification, CH, [Nm3] (#6176)	Switzerland	2004-2005

---

[1] Modelled with mixture of data from different periods and different countries

Table 2: Datasets used to model the manufacturing of the assumed fuel cell

Material/Process	Used Ecoinvent process	Location	Time Period
trichloromethane	trichloromethane, at plant, RER, [kg] (#452)	Europe	1998-1999
hydrogen fluoride	hydrogen fluoride, at plant, GLO, [kg] (#283)	Global	1979-2006
oxygen	oxygen, liquid, at plant, RER, [kg] (#301)	Europe	1997-2001
white fuming nitric acid	nitric acid, 50% in H2O, at plant, RER, [kg] (#299)	Europe	1990-2001
platinum	platinum, at regional storage, RER, [kg] (#1133)	Europe	2002
carbon black	carbon black, at plant, GLO, [kg] (#261)	Global	2000
hydrogen chloride	hydrogen fluoride, at plant, GLO, [kg] (#283)	Global	1979-2006
nitric acid	nitric acid, 50% in H2O, at plant, RER, [kg] (#299)	Europe	1990-2001
ammonia	ammonia, liquid, at regional storehouse, RER, [kg] (#246)	Europe	2000
carbon fiber	Modelled with Ecoinvent unit processes and values from IDEMAT 2001		
oil cokes	heavy fuel oil, at refinery, RER, [kg] (#1550)	Europe	2000
oil pitch	heavy fuel oil, at refinery, RER, [kg] (#1550)	Europe	2000
phenol formaldehyde resin	phenolic resin, at plant, RER, [kg] (#1673)	Europe	2000
silicone rubber	silicone product, at plant, RER, [kg] (#324)	Europe	1997-2001
steel	steel, low-alloyed, at plant, RER, [kg] (#1154)	Europe	2000-2002
naphtha	naphtha, at refinery, CH, [kg] (#1563)	Switzerland	2000
electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004
steam	steam, for chemical processes, at plant, RER, [kg] (#1988)	Europe	1992-1995
fuel oil	heavy fuel oil, at refinery, RER, [kg] (#1550)	Europe	2000

Table 3: Datasets used to model the manufacturing of the NiCd battery

Material/Process	Used Ecoinvent process	Location	Time Period
Nickel	nickel, 99.5%, at plant, GLO, [kg] (#1121)	Global	1994-2003
Nickel Hydroxide	nickel, primary, from platinum group metal production, RU, [kg] (#1125)	Russia	1995-2002
Cadmium hydroxide	cadmium, primary, at plant, GLO, [kg] (#7163)	Global	2000-2005
Cobalt Hydroxide	cobalt, at plant, GLO, [kg] (#5836)	Global	2000
KOH	potassium hydroxide, at regional storage, RER, [kg] (#6122)	Europe	1998-2004
NAOH	sodium hydroxide, 50% in H2O, production mix, at plant, RER, [kg] (#336)	Europe	2000
Lithium hydroxide	lithium hydroxide, at plant, GLO, [kg] (#7222)	Global	2000-2006
H2O	tap water, at user, RER, [kg] (#2288)	Europe	2000
Polypropylene	polypropylene, granulate, at plant, RER, [kg] (#1834)	Europe	1999-2001
Steel	steel, low-alloyed, at plant, RER, [kg] (#1154)	Europe	2000-2002
Polyethylene	polyethylene, HDPE, granulate, at plant, RER, [kg] (#1829)	Europe	1999-2001
Assembly energy	electricity, medium voltage, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004

Table 4: Datasets used to model the manufacturing of the Li-ion battery

Material/Process	Used Ecoinvent process	Location	Time Period
Carbon	carbon black, at plant, GLO, [kg] (#261)	Global	2000
Lithium Metal (Co/Ni/Mn) oxide(LiMO2)	electrode, positive, LiMn2O4, at plant, GLO, [kg] (#7064)	Global	2002-2006
Polyvinilidene Fluoride PVDF	polyvinylidenchloride, granulate, at plant, RER, [kg] (#1844)	Europe	1994-2001
Styrene butadiene rubber (SBR)	synthetic rubber, at plant, RER, [kg] (#1847)	Europe	1995-2003
Propylene carbonate PC	solvents, organic, unspecified, at plant, GLO, [kg] (#443)	Global	2000
Ethylene carbonate EC	solvents, organic, unspecified, at plant, GLO, [kg] (#443)	Global	2000
Dimethyl carbonate DMC	solvents, organic, unspecified, at plant, GLO, [kg] (#443)	Global	2000
Lithium hexafluoro phosphate	modelled with unit processes from ecoinvent		
Other	polypropylene, granulate, at plant, RER, [kg] (#1834)	Europe	2000-2002
Aluminum	aluminium, production mix, at plant, RER, [kg] (#1056)	Europe	2002
Copper	copper, at regional storage, RER, [kg] (#1074)	Europe	1994-2003
Assembly energy	electricity, medium voltage, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004

Table 5: Dataset used to model the manufcaturing of the lead-acid battery

Material/Process	Used Ecoinvent process	Location	Time Period
Antimony	Antimony as ressource (direclty added as elementary flow)		
Arsenic	Arsenic as ressource (directly added as elementary flow)		
Copper	copper, at regional storage, RER, [kg] (#1074)	Europe	1994-2003
lead	lead, at regional storage, RER, [kg] (#1103)	Europe	2000-2005
oxygen	oxygen, liquid, at plant, RER, [kg] (#301)	Europe	1997-2001
Sulphuric acid	sulphuric acid, liquid, at plant, RER, [kg] (#350)	Europe	1990-2000
H2O	tap water, at user, RER, [kg] (#2288)	Europe	2000
Glass	flat glass, uncoated, at plant, RER, [kg] (#806)	Europe	1996-2001
Polyethylene	polyethylene, HDPE, granulate, at plant, RER, [kg] (#1829)	Europe	1999-2001
Polypropylene	polypropylene, granulate, at plant, RER, [kg] (#1834)	Europe	2000-2002
Assembly energy	electricity, medium voltage, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004

Table 6: Datasets used to model the manufacturing of the NiMH battery

Material/Process	Used Ecoinvent process	Location	Time Period
Nickel	nickel, 99.5%, at plant, GLO, [kg] (#1121)	Global	1994-2003
Rare earth	lanthanum oxide, at plant, CN, [kg] (#6944),	China	2000-2005
Rare earth	cerium concentrate, 60% cerium oxide, at plant, CN, [kg] (#6949)	China	2000-2005
Rare earth	praseodymium oxide, at plant, CN, [kg] (#6951)	China	2000-2005
Rare earth	neodymium oxide, at plant, CN, [kg] (#6950)	China	2000-2005
Nickel Hydroxide	nickel, primary, from platinum group metal production, RU, [kg] (#1125)	Russia	1995-2002
Cobalt	cobalt, at plant, GLO, [kg] (#5836)	Global	2000
KOH	potassium hydroxide, at regional storage, RER, [kg] (#6122)	Europe	1998-2004
NaOH	sodium hydroxide, 50% in H2O, production mix, at plant, RER, [kg] (#336)	Europe	2000
H2O	tap water, at user, RER, [kg] (#2288)	Europe	2000
Polypropylene	polypropylene, granulate, at plant, RER, [kg] (#1834)	Europe	1999-2001
Polyethylene	polyethylene, HDPE, granulate, at plant, RER, [kg] (#1829)	Europe	1999-2001
Copper	copper, at regional storage, RER, [kg] (#1074)	Europe	1994-2003
Other	polypropylene, granulate, at plant, RER, [kg] (#1834)	Europe	1999-2001
Steel	steel, low-alloyed, at plant, RER, [kg] (#1154)	Europe	2000-2002
Assembly energy	electricity, medium voltage, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004

Table 7: Datasets used model the manufacturing of the hydrogen tank

Material/Process	Used Ecoinvent process	Location	Time Period
Polyeheytlene	polyethylene, HDPE, granulate, at plant, RER, [kg] (#1829)	Europe	1999-2001
Carbon fiber	Modelled with Ecoinvent unit processes and values from IDEMAT 2001		
Epoxy resin	epoxy resin, liquid, at plant, RER, [kg] (#1802)	Europe	1994-1995
Aluminum	aluminium, production mix, at plant, RER, [kg] (#1056)	Europe	2002
Stainless steel	chromium steel 18/8, at plant, RER, [kg] (#1072)	Europe	2000-2002
Electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004

Table 8: Datasets used to model the hydrometallurgical recycling process of the Li-ion battery

Material/Process	Used Ecoinvent process	Location	Time Period
reagent	chemicals inorganic, at plant, GLO, [kg] (#264)	Global	2000
electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004
industrial Water	tap water, at user, RER, [kg] (#2288)	RER	2000
sulphuric acid	sulphuric acid, liquid, at plant, RER, [kg] (#350)	Europe	1990-2000
lime	lime, hydrated, loose, at plant, CH, [kg] (#486)	Switzerland	2000-2002
cobalt	cobalt, at plant, GLO, [kg] (#5836)	Global	2000
lithium	lithium carbonate, at plant, GLO, [kg] (#7241)	Global	2000-2007
iron and steel	steel, electric, un- and low-alloyed, at plant, RER, [kg] (#1153)	Europe	2001
non ferrous metals	aluminium, production mix, at plant, RER, [kg] (#1056)	Europe	2002

Table 9: Datasets used to model the pyrometallurgical recycling process of the NiMH battery

Material/Process	Used Ecoinvent process	Location	Time Period
active carbon	carbon black, at plant, GLO, [kg] (#261)	Global	2000
electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004
natural gas and propane	propane/ butane, at refinery, RER, [kg] (#1576)	Europe	2000
process water	tap water, at user, RER, [kg] (#2288)	Europe	2000
nickel-cobalt-iron	steel, electric, un- and low-alloyed, at plant, RER, [kg] (#1153)	Europe	2001

Table 10: Datasets used to model the campine recycling process of lead-acid battery

Material/Process	Used Ecoinvent process	Location	Time Period
limestone	limestone, milled, loose, at plant, CH, [kg] (#468)	Switzerland	2000-2002
iron scrap	iron scrap, at plant, RER, [kg] (#1101)	Europe	2002
Sodium hydroxide	sodium hydroxide, 50% in H2O, production mix, at plant, RER, [kg] (#336)	Europe	2000
sodium nitrate	chemicals inorganic, at plant, GLO, [kg] (#264)	Global	2000
sulphur	secondary sulphur, at refinery, RER, [kg] (#318)	Europe	2000
iron chloride	iron (III) chloride, 40% in H2O, at plant, CH, [kg] (#292)	Switzerland	1995-2001
electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004
natural gas	natural gas, high pressure, at consumer, RER, [MJ] (#1320)	Europe	2000
coke	petroleum coke, at refinery, RER, [kg] (#1574)	Europe	2000
process water	tap water, at user, RER, [kg] (#2288)	Europe	2000
lead	lead, primary, at plant, GLO, [kg] (#10777)	Global	2000-2005
sulphuric acid	sulphuric acid, liquid, at plant, RER, [kg] (#350)	Europe	1990-2000

Table 11: Datasets used to model the pyrometallurgical recycling process of NiCd battery

Material/Process	Used Ecoinvent process	Location	Time Period
active carbon	carbon black, at plant, GLO, [kg] (#261)	Global	2000
electricity	electricity, medium voltage, production UCTE, at grid, UCTE, [kWh] (#664)	UCTE	1992-2004
propane/butane	propane/ butane, at refinery, RER, [kg] (#1576)	Europe	1980-2000
Process Water	tap water, at user, RER, [kg] (#2288)	Europe	2000
cadmium	cadmium, primary, at plant, GLO, [kg] (#7163)	Global	2000-2005
nickel-iron	steel, electric, un- and low-alloyed, at plant, RER, [kg] (#1153)	Europe	2001

II.3 Data uncertainties

In the Ecoinvent database, the inputs and outputs involved in a unit process are expressed with single values. According to how the inventory data have been measured or collected, different types of uncertainty may exist on these data. When the inputs and outputs are from a measurement campaign, the uncertainty is measured and expressed in quantitative term. Four types of uncertainty distributions are taken into account in the Ecoinvent software namely normal, lognormal, triangular and uniform distributions. However, lognormal distribution has been used for almost all the unit processes. The amounts of inputs and outputs involved in the different product or processes are expressed as the geometric mean of a lognormal distribution of data comprised between a minimum and a maximum. The uncertainty on the geometric mean is then expressed as the square of the standard deviation of the distribution within a confidence interval of 95%. When uncertainty information is not available for average data coming from one single source, a qualitative approach, **the pedigree matrix**, is used. Within this approach, uncertainty factors (Table 12) based on expert judgement are attributed to products, processes and pollutants. The uncertainty on the data sources are then assessed according to 7 parameters which are the reliability, the completeness, the temporal correlation, the geographical correlation, the technological correlation, the sample size, and the basic uncertainty factor (Table 13). The different parameters are ranked between 1 and 5 according to the default attributed uncertainty factors. The uncertainty on the data source is then calculated as the square of the standard deviation according to the following formula:

$$\delta^2 = \exp\sqrt{[\ln(u_1)]^2 + [\ln(u_2)]^2 + [\ln(u_3)]^2 + [\ln(u_3)]^2 + [\ln(u_3)]^2 + [\ln(u_4)]^2 + [\ln(u_5)]^2 + [\ln(u_6)]^2 + [\ln(u_b)]^2}$$

With:
U_1: uncertainty factor of reliability
U_2: uncertainty factor of completeness
U_3: uncertainty factor of temporal correlation
U_4: uncertainty factor of geographical correlation
U_5: uncertainty factor of other technological correlation
U_6: uncertainty factor of sample size
U_b: basic uncertainty factor

Table 12: basic uncertainty factors [20]

input/output	c	p	a	**Input/output group**	c	p	a
demand of : thermal energy , electricity, semi -finished products,							
	1.05	1.05	1.05	**Pollutants emitted to air**			
working material , waste treatment services transport services (tkm)				CO_2	1.05	1.1	
	2	2	2	SO_2	1.05		
infrastructure	3	3	3	NMVOC total	1.5		
ressources :				NO_x, N_2O	1.5		1.4
primary energy carriers, metals , salts,	1.05	1.05	1.05	CH_4, NH_2	1.5		1.2
land use, occupation	1.5	1.5	1.1	Individual hydrocarbons	1.5	1.2	
land use, trasnformation	2	2	1.2	PM>10	1.5	1.5	
Pollutants emitted to soil:				PM 10	2	2	
oil, hydrocarbon total		1.5		PM 2.5	3	3	
heavy metals		1.5	1.5	Polycyclic aromatic HC	3		
pesticides			1.2	CO, heavy metals	5		
				inorganic emissions, others		1.5	
				radionucleides		3	

p: process emissions, c: combustion emissions, a: agricultural emissions

Table 13: Default uncertainty factors applied with the pedigreed matrix [20

Indicator	1	2	3	4	5
Reliability	1.00	1.05	1.10	1.20	1.50
Completeness	1.00	1.02	1.05	1.10	1.20
Temporal correlation	1.00	1.03	1.10	1.20	1.50
Geographical correlation	1.00	1.01	1.02		1.10
Further technological correlation	1.00		1.20	1.50	2.00
Sample size	1.00	1.02	1.05	1.10	1.20

III. The CLEVER LCA tool

III.1 Range based modelling system

The different vehicle technologies are modeled in one single LCA tree (Figure 3). For each specific vehicle technology, the fuel consumption, the weight and the different emissions are written as statistical distributions. The data analysis methodology has allowed attributing to each range of data the most relevant distribution. A preliminary calculation has shown that the fuel consumption is the most important parameter of the model and it has almost a perfect correlation with the greenhouse effect which is one of the most important impact categories in LCA of vehicles. So it has been decided to write the distribution of all the other parameters (weight and emissions) in function of the distribution of the fuel consumption. As a consequence, when running the LCA model, all the parameters will vary in function of the variation of the fuel consumption instead of varying independently. This will create a dynamic model in which every change in one part of the model will influence the other parts allowing a permanent and automatic sensitivity analysis.

The range-based modeling system allows comparing two systems with simultaneously varying parameters. In fact, while comparing two different systems within an LCA, two types of variations could happen:

- Variation of the results due to the variation of the parameters which are common to the two systems
- Variation of the results due to the variation of parameters which are specific to one given system.

Thus, to achieve a real comparison of the two systems one should identify and assess the variability of system specific parameters which allow distinguishing the specificities of each system. Furthermore, this will allow situation specific evaluation of the system for their eco-friendliness.

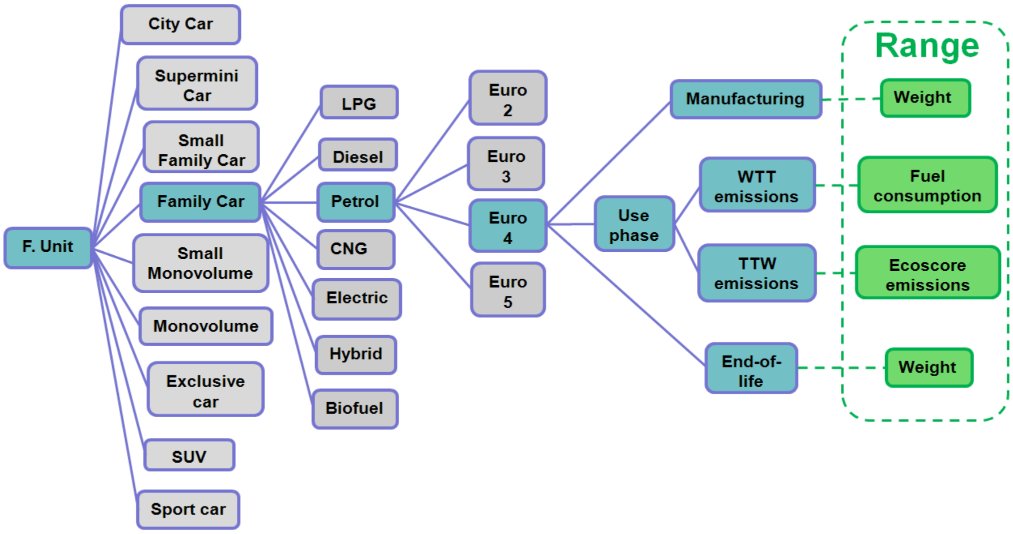

Figure 3: Range-based modelling system used in CLEVER.

III.2 Vehicle fleet segmentation

In contrast to several other vehicle LCA studies, the CLEVER project is developing an LCA methodology allowing per-model applicability instead of an average vehicle LCA. This methodology allows taking into account all the segments of the Belgian car market and producing LCA results per vehicle segments, technology, fuels and Euro emission standards.. Thus the authorities are able to take the right measure for promoting the right segment and the consumer getting the detailed information required for his/her vehicle choice.Several vehicle segmentation systems already exist. In this framework, the main issue is the choice of the segmentation parameters. For example, the FCAI (Federal Chamber of Automotive Industry of Australia) uses the displacement [21], while the EuroNCAP (European New Car Assessment Program) uses the vehicle's length [22]. The FISITA (International Federation of Automotive Engineering Societies) system seems to be the most exhaustive since it takes into account the displacement, the power and the weight [23]. The assessment of all those systems reveals that none of them exactly correspond to the Belgian market segments.

After several meetings and discussions, the CLEVER team decided to develop a new classification system based on the Ecoscore [14] and on the FEDERAUTO (The Belgian confederation of car traders and mechanics) approach [24], combining the weight and the length of the vehicles. The classification criteria come from the Ecosocore database [25]. The innovation of this proposal is the split-up of some vehicle categories of the Ecoscore database into two others, e.g. the 'small car' category in the Ecoscore database into 'city car' and 'supermini'. Indeed the cars of these two categories present large differences in terms of emissions.

Table 14: Vehicle segmentation in Belgium

Segments	Examples
superminis	Citroen C1, Peugeot 106, Smart FORTWO
city cars	Fiat Punto
small family cars	Ford Focus, Opel Astra, Honda Civic
family cars	Volvo V50, Toyota PRIUS,
small monovolumes	Ford Focus C-MAX, Opel Zafira,
monovolumes	Ford Galaxy, Peugeot 807
exclusive cars	Mercedes S-KLASSE, Lexus LS
sport cars	Porsche 911
SUV	Lexus RX, Mercedes M KLASSE

IV. Inventory and data Collection

IV.1. Manufacturing

Gathering all the inputs and outputs involved in the manufacturing of all the vehicles considered in this study is a challenging task. Because of confidentiality reasons, vehicle manufacturers do not publish the detailed material breakdown of their different vehicles.

To solve this problem and to avoid modeling several times the life cycle stages which are common to all the considered vehicles, a theoretical car has been modeled. The model of this car [13] includes the raw materials, the manufacturing processes and energy consumption (Table 15) and the transport by rail and truck.

This theoretical car will be used as a parameter to model the manufacturing and transport phases for all the vehicle categories according to the following equation:

$$Vehicle_{cat} = \frac{[\, w_{\min}, w_{\max} \,]}{w_{theoritical}} * theoretical \qquad (1.)$$

Where

Vehicle$_{\mathrm{cat}}$: Manufacturing and transport within a category

w_{min}: Minimum vehicle weight per category

w_{max}: Maximum vehicle weight per category

$w_{\mathrm{theoretical}}$: Weight of the theoretical car

theoritical: Theoretical car

Table 15: Manufacturing data of the theoretical vehicle [26]

	Uncertainty (Standard deviation 95%)	**Amount**	***Units***
Raw materials and chemicals			
reinforcing steel	1.20	891.00 E00	kg
steel low alloyed	1.20	99.00 E00	kg
aluminum	1.24	51.80 E00	kg
polyvinylchloride	1.24	16.00 E00	kg
zinc	1.24	5.89 E00	kg
chromium	1.24	2.40 E00	kg
nickel	1.24	1.40 E00	kg
palladium	1.24	3.00 E-04	kg
platinum	1.24	1.6 0 E-03	kg
sulphuric acid	1.24	8.00 E-01	kg
alkyd paint	1.24	4.16 E00	kg
polyethylene	1.24	102.00 E00	kg
synthetic rubber	1.24	44.10 E00	kg
flat glass	1.24	30.10 E0	kg
copper	1.24	10.10 E00	kg
polypropylene	1.24	49.00 E00	kg
total		1306.95 E00	kg
Manufacturing			
copper wire drawing	1. 20	10.10 E00	kg
steel sheet rolling	1. 20	541.00 E00	kg
steel section bar rolling	1. 20	203.00 E00	kg
electricity	1. 24	2140.00 E00	kWh
light fuel oil	1. 24	63.00 E00	MJ
heat, natural gas	1. 24	2220.00 E00	(MJ)
water	1. 24	3220.00 E00	kg

IV.2. Fuel Cell Electric Vehicles (FCEV)

Because of the use of special materials during the production of the fuel cell and the hydrogen tank of FCEV, the manufacturing data of this vehicle technology have been gathered and treated separately. The Honda FCX Clarity has been considered as a reference car for this technology. Material breakdown and energy consumption for the production of the fuel cell (Table 16) and the hydrogen tank (Table 17) have been gathered from [27]. The technical specifications of the Honda FCX Clarity [28] have been used to adapt the weight of the fuel cell, the tank, the electric motor and the controller. The material breakdown and the production processes of the theoretical car (Table 15) is considered for the body shell.

Carbon fiber which is a component of both the fuel cell and the hydrogen tank doesn't exist in the Ecoinvent database. To solve this problem, the LCI data of the carbon fiber (Table 18) has been imported from the IDEMAT 2001 database [29]

Table 16: Manufacturing data of the assumed fuel cell [27, 28]

Inputs	**Uncertainty (Standard deviation 95%)**	**Amount**	***Units***
trichloromethane	n.a	1.92	kg
hydrogen fluoride	n.a	0.65	kg
oxygen	n.a	0.09	kg
white fuming nitric acid	n.a	0.22	kg
platinum	n.a	0.09	kg
carbon black	n.a	0.09	kg
hydrogen chloride	n.a	0.29	kg
nitric acid	n.a	0.05	kg
ammonia	n.a	0.02	kg
carbon fiber	n.a	10.87	kg
oil cokes	n.a	26.14	kg
oil pitch	n.a	10.56	kg
phenol formaldehyde resin	n.a	7.12	kg
silicone rubber	n.a	1.81	kg
steel	n.a	16.17	kg
naphtha	n.a	13.10	kg
electricity	n.a	2338.60	kWh
steam	n.a	182.23	kg
fuel oil	n.a	2.73	kg

n.a: not available

Table 17: Manufacturing data of the assumed hydrogen tank [27, 28]

Inputs	**Uncertainty (Standard deviation 95%)**	n.a	***Units***
polyethylene	n.a	n.a	kg
carbon fibre	n.a	71.4	kg
epoxy resin	n.a	30.6	kg
aluminum	n.a	6	kg

stainless steel	n.a	9	kg
electricity	n.a	4.5	kWh

Table 18: Needed resources for the Manufacturing of 1 kg of carbon fibre [29]

Inputs	**Uncertainty (Standard deviation 95%)**	**Amount**	***Units***
bauxite	n.a	7.77E-01	kg
clay	n.a	1.11E-04	kg
coal	n.a	2.19E+00	kg
natural gas	n.a	2.06E+00	kg
crude oil	n.a	4.49E-01	kg
energy, unspecified	n.a	1.79E-01	MJ
energy from coal	n.a	5.55E-01	MJ
energy from hydro power	n.a	2.91E-01	MJ
energy from natural gas	n.a	1.24E+01	MJ
energy from oil	n.a	1.72E+02	MJ
energy from uranium	n.a	3.94E-02	MJ
iron ore	n.a	5.70E-04	kg
limestone	n.a	5.17E-05	kg
sodium chloride	n.a	5.18E-04	kg
uranium ore	n.a	7.97E-03	kg
water	n.a	7.86E-02	kg

IV.3. Exhaust after treatment systems

Different exhaust control technologies exist on the automotive market. We can cite for instance the TWC (Three Way Catalytic converter), the CRT (Continuously Regenerated Trap), the Urea technology, the PM filter, the urea-SCR (Selective Catalytic Reduction)… In the CLEVER project, a typical sedan-specific catalytic converter will be considered. The LCI will include all the materials of the converter (Table 19) and all the manufacturing processes. The included processes are the ceramic brick manufacturing, the ceramic brick firing, the ceramic brick coating with Platinum Group Metals (PGM), the steel manufacturing and the exhaust system manufacturing [30]. The other technologies are not modeled due to lack of data. However, the influence on the LCA results will be less since the raw materials' production and the manufacturing phase contribution to the overall impact vary between 6 to 8% according to our preliminary results and the exhaust after treatment system makes up a small share of the total weight of the vehicle. Additionally, it is important to mention that a catalytic converter can reduce simultaneously the emissions of different pollutants (Table 20) while the other technologies are specific to one or two pollutants.

Table 19: Manufacturing data of a sedan-specific catalytic converter exhaust system [30]

Inputs	**Uncertainty (Standard deviation 95%)**	**Amount**	***Units***
steel	n.a	25.20	kg
talc	n.a	1.40	kg
platinum, rhodium, palladium	n.a	6.50	g
Al_2O_3 (10%); CeO_2 (20%);ZrO_2 (70%)	n.a	0.20 kg	kg
textile	n.a	0.20	kg
plastics (not specified)	n.a	0.10	kg
coal	n.a	710.00	kg
crude oil	n.a	427.00	kg

natural gas	n.a	50.3	kg

The after treatment efficiency rates of the catalytic converter per pollutant (Table 20) will be used to compare the environmental impact of a car with catalytic converter and a car without catalytic converter.

Table 20: After treatment efficiency of the catalytic converter [31]

	Relative reduction (with catalyst) %
CO	-95
NO_x	-90
HC	-95
CH_4	-70
CO_2	+0.5
SO_2	+0.5

IV.4. Electricity

In this paragraph, it is important to mention the difference between the production mix and the supply mix. The production mix is electricity which is really produced in Belgium when the supply mix is the electricity supplied to the end user including electricity from Belgium and abroad In addition, the shares of the different types of electricity per type of feedstock are different for the production and the supply mixes. In the CLEVER project, the supply mix will be considered since the electricity will be used at the end user side. The life cycle inventory of the Belgian electricity supply mix includes the shares of electricity production per type of technology (Table 21). The production shares are based on the yearly average for 2004. The nuclear electricity production is considered to be the average of UCTE (Union for the Co-ordination of Transmission of Electricity) countries other than Switzerland, Germany and France, since Belgium is still importing nuclear electricity. The wind electricity is a European average. The remaining electricity technologies are specific to Belgium.

Table 21: Belgian electricity supply mix: of 1 kWh [32]

Electricity type	**Uncertainty (Standard deviation 95%)**	**Amount (kWh)**
hard coal	1.05	9.11 E-02
Oil	1.05	1.67 E-02
natural gas	1.05	2.14 E-01
industrial gas	1.05	2.33 E-02
hydropower	1.05	3.08 E-03
hydropower, at pumped storage	1.05	1.34 E-02
nuclear	1.05	4.66 E-01
wind	1.21	1.45 E-03
wood cogeneration	1.21	5.10 E-03
cogeneration with biogas engine	1.21	2.32 E-03
production mix France	1.05	7.96 E-02
production mix Luxembourg	1.05	2.47 E-02
production mix the Netherlands	1.05	4.71 E-02

IV.5. The Electrabel electricity mix (main Belgian electricity provider)

After a detailed assessment and comparison of parameters of the Ecoinvent power plants and the Electrabel ones, some differences have been noticed. In the Ecoinvent inventory model, the conversion emissions are expressed per type of burned feedstock while in the Electrabel approach the conversion emissions are expressed per type of power plant. Additionally, because of the progressive installation of filters on Electrabel's plant, the conversion emissions have been relatively lowered. Also, the feedstock combustion efficiencies appear to be higher than the Ecoinvent ones. For all these reasons, the WTT emissions of the Electrabel electricity have been recalculated with input from Electrabel and the Ecoinvent tool.

In order to produce Electrabel specific emissions, the production and the transport to Belgium of the different feed stocks have been adapted to the Electrabel situation. Furthermore, the benefit of the filter installation programme on the different power plants of Electrabel has been taken into account. The Ecoinvent European average efficiencies of the power plants are replaced by the Electrabel specific ones. The emissions induced by the conversion step are calculated with respect to the share of the different feedstocks per type of power plant and the contribution of the different power plants to the Electrabel production mix. Additionally the variation of the Electrabel production mix during day and night times (Table 22) has been taken into account. Network losses during the electricity distribution are also taken into account.

Table 22: Emissions induced by the production and the distribution of 1 Electrabel kWh [33]

	Day	Night	Average
g CO_2 fossil/kWh	226.35	191.61	207.27
mg CO fossil/kWh	70.46	59.64	64.51
mg CH_4 fossil/kWh	143.14	111.99	126.02
mg SO_2/kWh	210.19	165.00	185.35
mg NO_x/kWh	303.05	246.36	271.90
mg N_2O/kWh	1.65	1.36	1.49
mg PM/kWh	57.07	46.48	51.25
mg HC/kWh	10.10	2.61	2.95
mg NMVOC/kWh	22.87	18.90	20.68

IV.6. Oil and Natural gas

For natural gas and oil, their exploration and the production from their country of origin (Table 23 and Table 24) and the transport to Europe are considered. For most part of the suppliers, a multi-output process combining gas and oil production is considered. The energy consumption (Table 25 to Table 28) due to the drying, the liquefaction (for Algeria), and the transport of the natural gas to Europe by pipeline or freight ship is also taken into account. The well for the exploration and the production, the onshore/offshore plant, the use of chemicals (Table 25 to Table 28) and the use of water are included as well. The share of natural gas and oil per supplier (Table 23 and Table 24) as well as their transport to Europe are taken into account. However in the CLEVER LCA model, European diesel and petrol are considered because oil based fuels available in the refueling stations in Belgium are not necessarily produced in Belgium but somewhere in Europe. Additionally, the considered natural gas supplying countries of Belgium and their contribution to the Belgian mix considered in the ecoinvent database are sometimes different from the one mentioned in the Belgian statistics [34]. For this reason the LCA results of the CNG vehicle will be presented with respect to different natural gas scenario specifying the supplying country(ies).

Table 23: Belgian oil suppliers in 2007 [34]

Oil suppliers for Belgium	**Share (%)**
Near and Middle east	25.4
West Europe	11.8
Africa	4.20
East Europe	44.80
Norway	9.30
Latin America	4.4
Others	0.10

Table 24: Belgium natural gas suppliers in 2007 [34]

Natural gas suppliers for Belgium	**Belgian statistics 2006 (%)**
Near and Middle east	12.60
Africa	2.20
Russia	4.50
Norway	33.20
The Netherlands	39.60
United Kingdom	5.30
Trinidad and Tobago	0.4
Others	2.20

Table 25: Main input for the onshore production of 1 Nm^3 of natural gas in the Netherlands [35].

	Uncertainty (Standard deviation 95%)	**Amount**	***Units***
Chemicals	1.1069	1.02 E-06	kg
chemicals organic, at plant	1.1069	2.17 E-05	kg
ethylene glycol, at plant	1.1069	3.51 E-05	kg
methanol, at regional storage	1.1069	1.34 E-06	kg
chemicals inorganic, at plant	1.1069	1.02 E-06	kg
Energy			
sweet gas burned in gas turbine	1.2321	44.95 E-04	Nm3
diesel burned in engine	1.2321	79.92 E-04	MJ
electricity, medium voltage, at grid	1.2321	116.55 E-04	kWh
Production			
well for exploration and production	1.2321	1.20 E-06	m

Table 26: Main input for the offshore production of 1 Nm^3 of natural gas in Norway [35].

	Uncertainty (Standard deviation 95%)	**Amount**	***Units***
Chemicals			
chemicals organic, at plant	1.2423	1.39 E-04	kg
chemicals inorganic, at plant	1.2423	1.84 E-04	kg
Energy			
diesel, at regional storage	1.0714	1.44 E-04	kg
diesel, burned in engine	1.2152	479.37 E-04	MJ
sweet gas, burned in gas turbine	1.0714	12.98 E-03	Nm^3
natural gas, sweet, burned in flare	1.0714	28.67 E-04	Nm^3
drying, natural gas	1.0714	5954.25 E-04	Nm^3
Production			
well for exploration and production,	1.2152	2.18 E-06	m

Table 27: Main inputs for the onshore production of 1 Nm^3 of natural gas in Algeria [35].

	Uncertainty (Standard deviation 95%)	Amount	*Units*
Energy			
sweet gas, burned in gas turbine	1.24	0.01 E00	Nm^3
natural gas, sweet, burned in flare	1.24	0.25 E-02	Nm^3
drying, natural gas	1.4	1.00 E00	Nm^3
diesel, burned in engine	1.24	0.04 E00	MJ
Production			
well for exploration and production,	1.33	3.2 E-06	m

Table 28: Main inputs for the onshore production of 1 Nm3 of natural gas in Russia [35].

	Uncertainty (Standard deviation 95%)	Amount	*Units*
Energy			
sour gas, burned in gas turbine	1.24	0.2 E-2	Nm^3
sweet gas, burned in gas turbine	1.24	0.8 E-2	Nm^3
diesel, burned in engine	1.33	0.04 E00	MJ
natural gas, sweet, burned in flare	1.24	0.2 E-02	Nm^3
natural gas, sour, burned in flare	1.24	0.05 E-02	Nm^3
drying, natural gas	1.27	1.00 E00	Nm^3
sweetening, natural gas	1.27	0.2 E00	Nm^3
Production			
well for exploration and production	1.24	3.20 E-06	m

IV.7. Hydrogen

For the hydrogen production, no specific Belgian data were found. The main hydrogen production routes in Europe are steam methane reforming (SMR), partial oxidation (gasification) of heavy oil fractions, gasification of coke/coal, cracking of oil and water electrolysis. In this study, hydrogen production via steam reforming of natural gas is considered [36] since it accounts for more than 90 % of worldwide hydrogen production. The production of the natural gas, the electricity production, the construction and the decommissioning of the reforming plant and the construction of the natural gas pipeline are taken into account in the LCI (Table 29).

Additionnaly, hydrogen production data via fossil fuel cracking process have been gathered from the ecoinvent database (

Table 30) for sensitivity analysis purpose. These data are from the Eco-profiles of the European plastics industry (PlasticsEurop).

Table 29: WTT data of SMR hydrogen including the hydrogen production and the compression [36]

CO_2 (g/kg H2)	N_2O (g/kg H_2)	CH_4 (g/kg H_2)	CO (g/kgH_2)]	NOx (g/kgH_2)	NMHC (g/kg H_2)	SO_2 (g/kg H_2)	PM (g/kg H_2)
10620.6	0.04	59.8	5.7	12.3	16.8	9.5	2

Table 30: Needed resources to produce 1 kg of liquid hydrogen via fossil fuel cracking process [37]

Resources	**Uncertainty (Standard deviation 95%)**	**Amount**	***Units***
gas, natural, in ground	n.a	9.21E-01	Nm3
coal, hard, unspecified, in ground	n.a	4.88E-02	kg
coal, brown, in ground	n.a	2.80E-08	kg
uranium, in ground	n.a	2.62E-06	kg
barite, 15% in crude ore, in ground	n.a	3.01E-08	kg
aluminium, 24% in bauxite, 11% in crude ore, in ground	n.a	3.70E-07	kg
clay, bentonite, in ground	n.a	1.10E-04	kg
anhydrite, in ground	n.a	1.10E-05	kg
calcite, in ground	n.a	3.74E-04	kg
clay, unspecified, in ground	n.a	1.90E-10	kg
chromium, 25.5% in chromite, 11.6% in crude ore, in ground	n.a	3.70E-13	kg
copper, 0.99% in sulfide, Cu 0.36% and Mo 8.2E-3% in crude ore, in ground	n.a	9.97E-12	kg
dolomite, in ground	n.a	4.64E-06	kg
iron, 46% in ore, 25% in crude ore, in ground	n.a	3.78E-04	kg
feldspar, in ground	n.a	3.41E-16	kg
manganese, 35.7% in sedimentary deposit, 14.2% in crude ore, in ground	n.a	4.87E-07	kg
fluorspar, 92%, in ground	n.a	1.88E-07	kg
granite, in ground	n.a	1.64E-15	kg
gravel, in ground	n.a	1.39E-06	kg
cinnabar, in ground	n.a	8.40E-10	kg
magnesite, 60% in crude ore, in ground	n.a	5.42E-28	kg
nickel, 1.98% in silicates, 1.04% in crude ore, in ground	n.a	4.74E-13	kg
olivine, in ground	n.a	3.54E-06	kg
lead, 5.0% in sulfide, Pb 3.0%, Zn, Ag, Cd, In, in ground	n.a	1.83E-07	kg
Phosphorus, 18% in apatite, 12% in crude ore, in ground	n.a	1.24E-12	kg
sylvite, 25 % in sylvinite, in ground	n.a	4.45E-09	kg
TiO2, 95% in rutile, 0.40% in crude ore, in ground	n.a	3.82E-34	kg
sulfur, in ground	n.a	9.09E-05	kg
sand, unspecified, in ground	n.a	7.13E-05	kg
shale, in ground	n.a	3.11E-05	kg
sodium chloride, in ground	n.a	5.36E-04	kg
sodium nitrate, in ground	n.a	1.63E-27	kg
talc, in ground	n.a	3.93E-28	kg
zinc, 9.0% in sulfide, Zn 5.3%, Pb, Ag, Cd, In, in ground	n.a	6.67E-09	kg
peat, in ground	n.a	3.95E-04	kg
wood, unspecified, standing	n.a	4.04E-09	m3
energy, gross calorific value, in biomass	n.a	1.32E-01	MJ
energy, potential (in hydropower reservoir), converted	n.a	5.73E-02	MJ
water, unspecified natural origin	n.a	7.23E-04	m3
water, river	n.a	5.61E-04	m3
water, salt, ocean	n.a	7.85E-04	m3
water, well, in ground	n.a	9.01E-11	m3
water, cooling, unspecified natural origin	n.a	7.32E-02	m3

IV.8. Diesel and Petrol

For diesel and petrol production, all the processes on the refinery are taken into account except for the emissions from combustion facilities. It includes the waste water treatment, process emissions and direct discharges into rivers. Diesel and petrol are co-products of the multi-output process ‘crude oil, in refinery’ delivering petrol, unleaded petrol/diesel, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/butane, refinery gas, secondary sulphur and electricity. Major indicators like energy use have been estimated based on a survey in European refineries [38]. As the list of all the inputs (chemicals, water, washing agents, transport system, oil, energy, etc.) and all the waste treatment processes during the production of diesel and petrol is very large, only a list of the chemicals, energy and crude oil input are given in Table 31 and Table 32. However, all the input and output related to the diesel and petrol production are taken into account in the CLEVER LCA model. An additional energy use (6% of the energy use for diesel and petrol production in the refinery) has been estimated for the production of low sulphur diesel and petrol which should have less than 50 part-per-million (ppm) sulphur content.

Table 31: Main input of the production of 1 kg of normal diesel [38].

	Amount	**Uncertainty (Standard deviation 95%)**	***Units***
Chemicals			
calcium chloride	1.56 E-05	1.10	kg
hydrochloric acid	8.54 E-05	1.14	kg
nitrogen, liquid, at plant	7.91 E-04	1.14	kg
sodium hypochlorite, 15% in water,	4.80 E-05	1.34	kg
sulphuric acid	1.14 E-05	1.10	kg
ammonia	1.93 E-06	1.34	kg
lubricating oil	2.38 E-05	1.14	kg
chemicals organic	4.27 E-04	1.19	kg
washing agents			
zeolite	3.37 E-06	1.34	kg
soap	2.57 E-06	1.10	kg
Oil production			
crude oil	0.97 E00	1.07	kg
refinery gas, burned in flare	836.28 E-04	1.34	MJ
Energy			
electricity, medium voltage	245.23 E-04	1.10	kWh
refinery gas	1.98 E00	1.10	MJ
heavy fuel oil	0.68 E00	1.10	MJ
naphtha	0.038 E00	1.10	kg

Table 32: Main input for the production of 1 kg unleaded petrol [38].

	Amount	**Uncertainty (Standard deviation 95%)**	***Units***
Chemicals			
MTBE	4.93 E-03	1.09	kg
lubricating oil, at plant	2.37 E-05	1.14	kg
chemicals organic	1.82 E-04	1.19	kg
propylene glycol	1.97 E-05	1.26	kg
calcium chloride	1.55 E-05	1.1	kg
hydrochloric acid, 30% in water,	8.49 E-05	1.14	kg
nitrogen, liquid, at plant	7.86 E-04	1.14	kg
sodium hypochlorite, 15% in water,	4.77 E-05	1.34	kg
sulphuric acid	1.14 E-05	1.1	kg
ammonia	1.92 E-06	1.34	kg
chlorine	1.31 E-04	1.14	kg
Washing agents			
soap	2.56 E-06	1.1	kg
zeolite	1.76 E-05	1.34	kg
Oil production			
crude oil production	0.94 E00	1.07	kg
refinery gas, burned in flare	1496.21 E-04	1.34	MJ
Energy			
electricity, medium voltage,	553.57 E-04	1.1	kWh
refinery gas, burned in furnace	3.55 E00	1.09	MJ
heavy fuel oil	1.22 E00	1.09	MJ
naphtha	0.04 E00	1.1	kg

IV.9. LPG (Liquefied Petroleum Gas)

Liquefied petroleum gas (LPG) is a mixture of several hydrocarbons. The main constituents are propane, ethane and butane. It is produced directly during the extraction of natural gas and indirectly as a by-product of refining petroleum. One can convert 250 volumes of gas into one volume of liquid [39]. So 4 liters of LPG can be produced with one normal cubic meter of propane/butane. As the LCI of LPG doesn’t exist in the Ecoinvent database, the liquefaction, the distribution and the compression (in the refueling station) [40] processes of LPG have been combined with the production process of propane/butane (Table 33, Table 34 and Table 35). This assumption was validated by Niels Jungbluth from the Swiss Centre for Life Cycle inventories. The LCI includes all the processes on the refinery site (excluding the emissions from combustion facilities), the waste water treatment and direct discharges to rivers. As the complete list of all the inputs and outputs is very long, only the main input will be shown in table 16. However, the complete LCI is considered in the CLEVER LCA model. The composition of LPG might vary from one European country to another. However, 60% propane and 40% butane is the more common mixture rate in Europe [39]. In Belgium, the composition of the LPG is 50% propane and 50% butane [41]. LPG originates from crude oil refining (40%) and natural gas processing (60%) [42]

Table 33: Main input for the production of 1 kg of propane/butane [38].

	Amount	Uncertainty (Standard deviation 95%)	*Units*
Crude oil			
crude oil	9.64 E-01	1.07	kg
Chemicals			
sodium hydroxide, 50% in water	8.66 E-03	1.10	kg
calcium chloride	1.55 E-05	1.14	kg
hydrochloric acid, 30% in water	8.49 E-05	1.14	kg
nitrogen, liquid	7.86 E-04	1.34	kg
sodium hypochlorite, 15% in water	4.77 E-05	1.10	kg
sulphuric acid	1.14 E-05	1.34	kg
ammonia	1.92 E-06	1.14	kg
chlorine	6.83 E-06	1.14	kg
lubricating oil	2.37 E-05	1.19	kg
chemicals organic	1.8 2E-04	1.26	kg
propylene glycol	5.51 E-07	1.10	kg
Washing agents			
zeolite	1.09 E-05	1.34	kg
soap	2.56 E-06	1.10	kg
Energy			
electricity, medium voltage	4.92 E-02	1.10	kWh
refinery gas, burned in furnace	2.96 E00	1.10	MJ
heavy fuel oil, burned in refinery furnace	1.02 E00	1.10	MJ
naphtha, at regional storage	3.83 E-02	1.10	kg
refinery gas, burned in flare	1.25 E-01	1.34	MJ
water	1.45 E-02	1.10	kg

Table 34: Energy consumption during the liquefaction and the distribution of 1 GJ of LPG [40].

processes	**energy consumption (MJ/GJ of LPG)**
liquefaction	10
distribution	20
compression	10

Table 35: Main input for the production of 1liter of LPG [38, 40].

inputs	**amount**
propane/butane	0.55 kg
natural gas burned in gas motor	1.01 MJ

IV.10. CNG (Compressed Natural Gas)

Like LPG, CNG is not available in the Ecoinvent database. As the LCI of natural gas already exists in the Ecoinvent database, an assumption has been made to calculate the energy consumption due to the compression step. In the Well-to-Wheel study of the CONCAWE project [40], an energy consumption of 60MJ/GJ of CNG has been considered for the compression of CNG. The same assumption has been used in the CLEVER project to calculate the LCI of CNG. So, 1 GJ of natural gas and 60MJ of natural gas burned in a gas motor are needed to produce 1 GJ of CNG. The main inputs for the production of natural gas are described in the paragraph IV.

IV.11. Bio-fuels

After the acquisition of the second version (v2.0) of the Ecoinvent database, a complete and detailed well-to-tank assessment of bio-fuels has been performed. A detailed overview of the most important bio-fuels and their production stages has been made on the basis of the information contained in the Ecoinvent report entitled "Life Cycle Inventories of Bioenergy" [43] and the Ecoinvent website (www.ecoinvent.org). In general, three stages of production can be distinguished: feedstock production, conversion to fuel and distribution. Most of the time, the transport phase between the feedstock production and the conversion is included in the conversion stage. According to the type of feedstock, the bio-fuels have been classified into first and second generation bio-fuels. The first generation bio-fuels are produced from food crops such as sugar cane, sugar beet, corn, rye and wheat, while bio-fuels from the second generation are produced from the residual non-food part of crops and different types of waste such as waste cooking oil, whey, manure, etc. Three groups of bio-fuels have been assessed: the oil-based bio-fuels (fatty acid methyl ester or biodiesel), biogas, ethanol and methanol.

Typical bio-fuel production routes or pathways have been assessed. The most important ones are:

- Oil-based bio-fuels: feedstock production, solvent and cold-press oil extraction, esterification and distribution
- Biogas: feedstock production, gasification or digestion, purification and distribution
- Ethanol: feedstock production, fermentation, distillation and distribution
- Biomass to-Liquid (BTL) methanol (Fischer-Tropsch): synthetic gas from wood gasification, full-methanol steam reforming and distribution

The assessment takes into account the location (country or continent), farming machines and treatment, transport distances and conversion technologies. To produce the different blends of fuel, bio-fuels and fossil fuels are produced separately and mixed in the refueling stations. For this raison, WTT emissions of all the possible blends can be calculated by summing up the WTT emissions of the bio-fuel and the fossil fuel, multiplied by their corresponding share in the blend.

Beside Well-to-Tank data, some bio-fuels' Tank-to-Wheel (TTW) data will be included as well. The TTW data available in Ecoinvent v2.0 correspond to the 'small family car' category according to the classification made in the CLEVER project. It will cover the use phase of:

- E5 (5% ethanol, 95 % petrol),
- M100 (100 % methanol),
- Methane from biogas,
- Diesel with 5% Rape Methyl Ester (RME),
- Petrol with 4% ethyl tert-butyl ether (ETBE) and petrol with 15% ETBE.

Additionally, TTW emissions from the Volvo V50 FFV, the Saab 9.5 BioPower and the Citroen C4 have been provided by the BIOSES project.

A. Bio-ethanol

A1. First generation bio-ethanol

Within the category of first generation bio-fuels, two sugar based ethanols (sugar beet and sugar cane) and one starch based ethanols (rye) have been assessed. Four main steps of the production route of the bio-ethanols are assessed: the feedstock production, the fermentation, the distillation or dewatering and the distribution to the end-user

Ethanol from rye is one of the most produced bio-ethanol in Europe besides ethanol from sugar beet and wheat. For sugar beet ethanol, only a Swiss LCI is available. The LCI of wheat ethanol is not directly available in the Ecoinvent database, but the one of rye ethanol is enough since the conversion processes of wheat and rye ethanols are very similar. Ethanol from sugar cane produced in Brazil has been considered. Sugar cane ethanol represents about 52% of the world production in 2003 [43].

For the rye-based ethanol (Table 36), the cultivation of rye in Europe, including materials, energy use and infrastructure, is taken into account as well as the transport of the seed and its treatment (pre-cleaning, cleaning, eventually drying, chemical dressing and bag filling). The transport of rye grains to the distillery, the processing of rye grains to hydrated ethanol (95%) and the dehydratation of hydrated ethanol to anhydrous ethanol (99.7%) are also included.

Table 36: Main input for the production of 1 kg of rye ethanol [43].

	Amount	**Uncertainty (Standard deviation 95%)**	***Unit***
Feedstock			
rye grains conventional	3.34 E00	1.21	kg
Water			
water	4.18 E00	1.21	kg
Chemicals			
sulphuric acid	2.49 E-02	1.21	kg
soda	3.74 E-02	1.21	kg
ammonium sulphate	9.97 E-03	1.21	kg
diammonium phosphate	9.97 E-03	1.21	kg
Energy			
heat, natural gas, at industrial furnace	4.68 E00	1.21	MJ
electricity, medium voltage	1.47 E-01	1.21	kWh

For the sugar cane based ethanol (Table 38), the LCI covers cultivation of sugar cane in Brazil, including use of diesel, machines, fertilizers and pesticides, as well as the fermentation of sugar cane including materials, energy use and infrastructure. The dewatering of ethanol (95%) to increase the ethanol content to 99.7% has been taken into account as well. The supply (Table 37) of ethanol from Brazilian production plants to Europe has also been included.

Table 37: Ship transport of 1 kg of sugar cane ethanol from Brazil to Europe [43].

	Amount	**Uncertainty (Standard deviation 95%)**	***Unit***
transport, transoceanic tanker	9.72	2	tkm
transport, barge tanker	0.84	2	tkm

Table 38: Main inputs for the production of 1 kg of sugar cane ethanol [43].

	Amount	**Uncertainty (Standard deviation 95%)**	***Unit***
Feedstock			
sugar cane	1.49 E01	1.1249	kg
Chemicals			
sulphuric acid	1.08 E-02	1.1249	kg
ammonia	2.23 E-07	2.0809	kg
chlorine	8.93 E-06	2.0809	kg
sodium	1.12 E-04	2.0809	kg
chemicals organic	1.56 E-04	2.0809	kg
lubricating oil	2.09 E-03	2.0809	kg
Water			
water, decarbonised	2.14E-02	2.0809	kg

Energy			
Electricity from bagasse	8.36E-05	1.1150	kWh

For the sugar beet based ethanol (Table 39), the feedstock is produced in a Swiss context but it is still comparable to sugar beets produced in other European countries. The LCI includes the processes of soil cultivation, sowing, weed control, fertilisation, pest and pathogen control and harvest. The fermentation process including the materials, the infrastructure and the energy use is also taken into account. The extra energy consumption due to the dewatering process has been included as well.

Table 39: Main inputs for the production of 1 kg of sugar beet ethanol [43]

	Amount	**Uncertainty (Standard deviation 95%)**	***Unit***
Feedstock			
sugar beets at farm	7.55E+00	1.1249	kg
Chemicals			
sodium phosphate, at plant	5.73E-03	1.1249	kg
sodium sulphate, from natural sources, at plant	3.82E-03	1.1249	kg
sulphuric acid, liquid, at plant	2.87E-02	1.1249	kg
Energy			
heat, at cogeneration with biogas engine,	5.75E-01	1.1541	MJ
heat, natural gas, at industrial furnace	3.15E+00	1.1249	MJ
electricity, medium voltage, at grid	1.48E-01	1.1249	kWh
Water			
Water, cooling, unspecified natural origin	3.95E-07	1.1249	m3
tap water, at user	9.13E-01	1.1249	kg

A2. Second generation bio-ethanol

In the second generation category, ethanol from wood (Table 41) and grass (Table 40) are considered. The LCI of the grass ethanol covers the grass production and the fermentation including the infrastructures, the materials and the energy use. The LCI of the wood ethanol includes the transport of the wood from the forest and its processing to ethanol. Both the grass and wood ethanol are produced in a Swiss context. However they are the other European countries because the agricultural practices and the ethanol conversion technologies are comparable.

Table 40: Main inputs for the production of 1 kg of grass ethanol [43]

	Amount	**Uncertainty (Standard deviation 95%)**	***Unit***
Production			
grass from meadow intensive production	0.52	1.1249	kg
grass from natural meadow intensive production	0.99	1.1249	kg
grass from natural meadow extensive production	0.10	1.1249	kg
Energy			
heat, at cogeneration with biogas engine	15.38	1.1130	MJ
electricity, medium voltage	0.65	1.1130	kWh

Table 41: Main inputs for the production of 1 kg of wood ethanol [43]

	Amount	Uncertainty (Standard deviation 95%)	*Unit*
Feedstock			
wood chips, hardwood, at forest	1.61E-02	1.2229	m3
Chemicals			
maize starch, at plant	2.64E-02	1.2229	kg
Chemicals			
sulphuric acid, liquid, at plant	8.26E-02	1.2229	kg
ammonia, liquid, at regional storehouse	6.59E-02	1.2229	kg
magnesium sulphate, at plant	5.43E-04	1.2229	kg
calcium chloride, CaCl2, at regional storage	1.20E-03	1.2229	kg
chlorine, liquid, production mix, at plant	5.81E-06	1.3241	kg
sodium chloride, powder, at plant	7.26E-05	1.3241	kg
ammonium sulphate, as Nitrogen, at regional storehouse	1.18E-03	1.2229	kg
diammonium phosphate, as N, at regional storehouse	1.67E-03	1.2229	kg
chemicals organic, at plant	2.39E-04	1.2229	kg
lubricating oil, at plant	5.81E-05	1.3241	kg
urea, as Nitrogen, at regional storehouse	4.74E-04	1.3241	kg
Water			
tap water, at user	8.03E+00	1.2229	kg
water, decarbonised, at plant	1.39E-02	1.3241	kg

B. Methanol (Fischer-Tropsch)

Bio-methanol can be produced from ‘wood synthetic gas’ (Table 42) which is a gasified wood. The production process is a full-methanol steam reforming. The LCI of the methanol (Table 43) includes the production of synthetic gas from wood chips and the production of methanol derived from the synthetic gas. The extra hydrogen produced during the steam reforming is burned in the furnace of the plant. The processing energy as well as the use of catalysts is taken into account.

Table 42: Main input for the production of 1 kg of synthetic gas from wood [43].

	Amount	Uncertainty (Standard deviation 95%)	Units
Energy			
electricity, medium voltage	2.66 E-02	1.3279	kWh
Wood			
wood chips, mixed at forest	1.71 E-03	1.3120	m^3
wood chips, mixed, from industry,	5.88 E-04	1.3120	m^3
waste wood chips, mixed, from industry,	3.74 E-04	1.3120	m^3
Water			
tap water	0.14 E00	1.3960	kg
washing agents			
zeolite	20.80 E-04	1.3960	kg
Chemicals			
sodium hydroxide, 50% in water	82.80 E-05	1.3279	kg
sulphuric acid	32.90 E-04	1.3279	kg

Table 43: Main input for the production of 1 kg of methanol from synthetic gas [43].

	Amount	Uncertainty (Standard deviation 95%)	Unit
Chemicals			
aluminium oxide	2.40 E-04	2.1586	kg
copper oxide	9.00 E-05	2.1586	kg
Production			
synthetic gas	7.13 E00	1.5226	Nm^3
Energy			
electricity, medium voltage	0.28 E00	1.6512	kWh
Water			
water, deionised,	0.85 E00	1.5319	kg

C. Biodiesel

C1. First generation biodiesel

Two first generation biodiesels will be considered in the CLEVER project:

- Rape methyl ester (RME) which is the most developed biodiesel in Europe (2000 kilotons in 2004 [43])
- Soybean methyl ester (SME) produced in the US and imported to Europe.

The inventory of RME (Table 45) includes the processes of soil cultivation, sowing, weed control, fertilization, pest and pathogen control, harvest and drying of the grains, transport, oil extraction (Table 44) and the esterification processes. The machine infrastructure and sheds for machine sheltering are also included.

Table 44: Main input for the extraction of 1 kg of rape oil [43].

	Amount	Uncertainty (Standard deviation 95%)	Unit
Production			
rape seed	1.91 E00	1.0722	kg
Chemicals			
hexane	20.92 E-04	1.0913	kg
phosphoric acid, 85% in water	6.76 E-04	1.0913	kg
Energy			
electricity, medium voltage	81.41 E-03	1.0888	kWh
heat, natural gas, at industrial furnace	1.35 E00	1.0888	MJ

Table 45: Main inputs for the production of 1 kg of rape methyl ester [43].

	Amount	Uncertainty (Standard deviation 95%)	Unit
Production			
rape oil	0.89 E00	1.2090	kg
Chemicals			
phosphoric acid, 85% in water	39.98 E-04	1.0913	kg
potassium hydroxide	98.66 E-04	1.0913	kg
methanol	986.92 E-04	1.0722	kg
Energy			
electricity, medium voltage	367.45 E-04	1.0722	kWh
heat, natural gas, at industrial furnace	8025.42 E-04	1.0722	MJ
Water			
tap water	237.38 E-04	1.5642	kg

For the SME, the cultivation of soybeans in the US, the use of machines, fertilizers and pesticides, as well as the transport to the oil mill, the oil extraction (Table 46) and the esterification (Table 47) are included in the LCI. The transport of the final product from the US to Europe has been taken into account as well.

Table 46: Main inputs for the extraction of 1 kg of soybean oil [43].

	Amount	Uncertainty (Standard deviation 95%)	Unit
Production			
soybeans	1.83 E00	1.1130	kg
Water			
tap water	0.16 E00	1.1668	kg
Chemicals			
hexane	39.24 E-04	1.1668	kg
phosphoric acid, industrial grade	3.09 E-04	1.0752	kg
Energy			
electricity, medium voltage	75.77 E-03	1.1668	kWh
heat, at hard coal industrial furnace	0.15 E00	1.1668	MJ
heat, light fuel oil, at industrial furnace	565.96 E-04	1.1668	MJ
heat, natural gas, at industrial furnace	1.08 E00	1.1668	MJ

Table 47: Main inputs for the production of 1 kg of soybean methyl ester [43]

	Amount	Uncertainty (Standard deviation 95%)	Unit
Production			
soybean oil	0.95 E00	1.2093	kg
Chemicals			
hydrochloric acid, 30% in water	42.36 E-04	1.0913	kg
phosphoric acid,, 85% water	104.53 E-04	1.0913	kg
methanol	1045.64 E-04	1.0722	kg
Energy			
electricity, medium voltage	389.31 E-04	1.0722	kWh
heat, at hard coal industrial furnace	960.86 E-04	1.0722	MJ
heat, light fuel oil, at industrial furnace	374.13 E-04	1.0722	MJ
heat, natural gas, at industrial furnace	7167.91 E-04	1.0722	MJ
Water			
tap water	251.50 E-04	1.5642	kg

C2. Second generation biodiesel

The most developed second generation biodiesel in Europe is the waste cooking oil methyl ester (Table 48). Waste vegetable oil is collected and treated in dedicated plants in which all the impurities and water are removed. At the end of the process a treated vegetable oil consisting of 93.7% triglycerides and 6.7 % fatty acid methyl ester is obtained. The process refers to the catalyzed estherification of free fatty acids. The LCI covers the collection, the treatment, the conditioning, the storage and the treatment of the effluents.

Table 48: Main input for the production of 1 kg of waste cooking oil methyl ester [43].

	Amount	Uncertainty (Standard deviation 95%)	Unit
Energy			
electricity, medium voltage	508.0 4E-4	1.6211	kWh
heat, natural gas, at industrial furnace	0.77 E00	1.6211	MJ
Chemicals			
methanol	2.69 E-02	1.5955	kg
glycerin, from vegetable oil,	10.56 E-02	1.5955	kg
sulphuric acid	0.21 E-02	1.5955	kg

D. Biogas

Biogases are produced from miscellaneous substrates. The major production routes are fermentation of bio-waste, sewage sludge, whey, grass, liquid manure and co-fermentation of liquid manure and bio-waste. In all the cited biogases, only biogas from bio-waste is further upgraded to natural gas quality which can be used as a transportation fuel for natural gas vehicles [26], the other biogases are being used for heat and electricity co-generation. For the CLEVER project, biogas from bio-waste fermentation (Table 49) will be considered. Bio-waste contains biogenous household waste, garden waste and food waste.

The LCI covers the pre-treatment (including the disposal of contaminants), the digestion and post-composting of digested matter. The emissions to soil due to the use of presswater and digested matter as a fertilizer in agriculture are taken into account. The spreading of the fertilizer as well as the transport from the bio-waste plant to farms is also taken into account. The electricity consumption during the biogas upgrading (raw gas compression, H_2S removal, gas conditioning and methane enrichment of biogas) is included in the LCI as well. 1.5 Nm^3 of raw biogas is needed to produce 1 Nm^3 of methane with a purity of 96% and 0.5 kWh of electricity is used for this purification.

Table 49: Energy consumption for the production of 1Nm^3 of biogas from biowaste [43].

	Amount	**Uncertainty (Standard deviation 95%)**	**Unit**
Energy			
heat, natural gas, at boiler	1.08 E00	1.2335	MJ
electricity, low voltage	7.3 E-02	1.2335	kWh

IV.12. Battery Ellectric Vehicles, Fuel Cell Electric Vehicle and Hybrid Electric Vehicles

LCI data of batteries were collected from the SUBAT project [44] in which ETEC-VUB was involved. The LCI covers both Hybrid Electric Vehicles (HEV) and Battery Electric Vehicles (BEV). The material breakdown as well as the assembly energy of the different battery technologies is included. Manufacturing data of supercapacitors were provided by the Maxwell company which is a partner of the HyHEELS [45] project in which ETEC-VUB is involved as well.

For the specific cases of BEV and FCEV, the Tesla Roadster and the Honda FCX Clarity have been respectively chosen. The ratio between the life time driven distance (230500 km) and the cycle life of the lithium-ion battery (100000 miles or 160934.4 km) [46] has been used to calculate the number of the needed batteries for the BEV. On the basis of this calculation, 1.43 batteries are used during the lifetime of the vehicle. The weight of the battery is approximately 408 kg (900 pounds) [46]. In the case of the FCEV, a lifespan of 5000 hours (typical value for fuel cells in automotive application) has been considered for the fuel cell. As a consequence, only one fuel cell stack is considered for the FCEV.

Inventory data of parts and components (body shell, tires, lead acid batteries…) which are common to all the vehicle technologies are collected and adapted as a parameter to each vehicle according to its specifications. Data for specific parts of specific vehicle technologies such as Nickel-Metal hydride (NIMH) batteries, Lithium-ion batteries (, fuel cells, hydrogen tanks…etc are gathered separately for the corresponding vehicles and included in the model. For each vehicle, common parts and specific parts are combined with respect to their weight percentages to model the manufacturing step.

For alternative vehicles such as BEV and FCEV, the LCI of the Golf A4 has been used to model only the body shell. Inventory data of specific parts of the cars such as hydrogen tanks and fuel cells (see paragraph IV.2) have been gathered from [27].

IV.13. Maintenance

As for the manufacturing phase, a theoretical maintenance (Table 50) process has been modeled. It will contain oil (Table 53) consumption, tires (Table 52), batteries for hybrid or electric vehicles and washing water during the lifespan of the vehicle. The theoretical maintenance process corresponds to a Golf A4 diesel which weighs 1181 kg and is used to fulfill the functional unit (230500 km). The calculations are based on the assumptions of the IMPRO-car project [47] and the Life Cycle Inventory for the Golf A4 [48]. The equation (1) used for the manufacturing phase will be used to extend that maintenance process to the other vehicles.

Close to the spare parts, the emitted particles from the abrasion of tire wear and break wear (Table 51) will also be taken into account [49]

Table 50: Theoretical maintenance process. [47, 48].

	Amount (230500 km)
tires	165.96 kg
lead-acid batteries	64.54 kg
oil	67.61 kg
washing water	12.29 m^3

Table 51: Non-exhaust emissions of passenger vehicle [49]

	PM 10-PM2.5	PM2.5
	g/km	g/km
tire wear emitted particles	0.0037	0.0027
brake wear emitted particles	0.0043	0.0031

Table 52: Material breakdown of a tire [47, 48]

Materials	**Weight%**
rubber	48.00
carbon black	22.00
steel	15.00
textile	5.00
zinc oxide	1.00
Sulphur	1.00
additives (xylene, benzene, phenol)	8.00

Table 53: Main inputs for the production of 1 kg of lubricant oil [38].

	Amount	**Uncertainty (Standard deviation 95%)**	**Unit**
Oil			
diesel	1.33	1.20	kg
Energy			
electricity, medium voltage	0.33	1.90	kWh
heat, natural gas, at industrial furnace	2.00	1.90	MJ

IV.14. End-of-life

End-of-life data have been provided by RDC-Environment, which has performed a study on end-of-life vehicles for the Flemish public waste management organization (OVAM). The global recycling rate of vehicles and consumption of resources during the recycling process have been included, as well as the range of recycling rates per type of material (Table 54). The efficiency of recycling processes and the real capacity of recycling plants were taken into account as well. As for the manufacturing and the maintenance phases, the end-of-life phase of the body shell has been modelled as a parameter which will be adapted to all the vehicles according to their weight. An energy consumption of 66kWh/ton [50] is considered for the shredding and the further separation processes. As batteries in end-of-life vehicles should be removed and treated separately during the depollution step of end-life vehicles, their treatment has been assessed separately. Different recycling processes have been considered according to the battery technology: Hydrometalurgical process for lithium ion technology (Table 55), pyrometalurgical for NiMH and NiCd technologies (Table 56 and Table 58)and the Campine process for Lead acid technology(Table 57) [51]. These processes are modelled within this study on an input/output basis with respect to the energy and chemical consumption at the input side and to the recycling efficiency per type of material at the output side. The recycling rates per type of materials of EoL vehicles are the ones from the OVAM/RDC study (Table 54). Non-recyclable chemicals are landfilled since most of them are not accepted in the incineration process. For supercapacitors, the aluminum, the ABS, the copper and the steel are considered to be recyclable. Since we have no energy consumption for the recycling of supercapacitors, the battery recycling process with the highest energy consumption has been considered for it (4.72 MJ/Kg).

Table 54: Recovery rates of end-of -life vehicle materials [10].

Material	**Average recycling rate (%)**	**Average energetic valorisation rate (%)**	**Total recovery rate (%)**
ferro-metals	99.82	0.00	99.82
aluminium	93.20	0.00	93.20
copper	88.53	0.00	88.53
zinc	93.49	0.00	93.49
lead	91.43	0.00	91.43
polypropylene	51.99	2.47	54.47
polyethylene	51.99	2.47	54.47
PMMA	3.00	29.49	32.49
ABS	49.27	4.95	54.21
PET	0.73	35.53	36.26
EPP	2.93	0.01	2.94
PP-EPDM	5.55	2.47	8.02
polyurethane	5.58	1.03	6.61
rubber	3.47	28.56	32.03
textile	6.19	2.10	8.29

Table 55: Hydrometallurgical recycling of Lithium Ion battery [51]

	Amount	***Unit***
Inputs		
EoL battey	1000	kg
reagent	25	kg
electricity	140	kWh
industrial water	0.72	m3
sulphuric acid	126	L
lime	116	kg
Recycling efficiency		
cobalt	1.00	
lithium	1.00	
iron and steel	0.75	
non ferrous metals	0.94	

Table 56: Pyrometallurgical recycling of NiMH battery [51]

	Amount	***Unit***
Inputs		
EoL battey	1000	kg
active carbon	1.67	kg
electricity	310	kWh
natural gas and propane	94.7	kg
process water	240	l
Recyccling efficiency		
nickel-cobalt-iron	0.73	

Table 57: Campine Lead acid battery recycling [51]

	Amount	***Unit***
Inputs		
EoL battery	1000	kg
limestone	5.8	kg
iron scrap	4.0	kg
sodium hydroxide	350	kg
sodium nitrate	0.4	kg
sulphur	0.9	kg
iron chloride	0.9	kg
slag	150	kg
electricity	35.2	kg
natural gas	16.2	kg
coke	20.0	kg
process water	770	kg
Recycling efficiency		
lead	1.00	
sulphuric acid for reuse	0.44	

Table 58: Pyrometallurgical recycling of NiCd battery [51]

	Amount	***Unit***
Inputs		
EoL battey	1000	kg
active carbon	1.67	kg
electricity	1545	kWh
propane/butane	170.6	kg
process water	240	kg
Recycling efficiency		
cadmium	0.90	
nickel-iron	0.95	

IV.15. Tank to Wheel (TTW) data

The Ecoscore database is the reference database for direct or Tank to-Wheel (TTW) emission data for the CLEVER project. It contains fuel/energy consumption and emission data resulting from the vehicle's homologation procedure. The average CO_2 emissions (g/km) as well as the HC, SO_2, NOx, CO, PM, CH_4, N_2O emissions (g/km) for each specific vehicle are contained in the Ecoscore database. The consumption of liquid fuels is expressed in l/100 km, of gases in m^3/100 km and of electric energy in kWh/km. As the emissions are measured with the New European Driving Cycle (NEDC) combining urban and extra-urban driving cycles, only average emissions and fuel consumption are available in the Ecoscore database. Therefore splitting up direct emissions into urban and extra-urban conditions is not possible. However, the CLEVER LCA model is developed to assess the environmental impact of both urban and extra-urban driving when the needed data will be available. The testing conditions under NEDC do not include the additional fuel consumption of the cooling and the heating devices (Chasserot M. 2007). The considered weight for the vehicle is the 'in running order' mass including coolant, oils, fuel, spare wheels, tools and the driver (75 kg).(Directive 92/21/EEC)

The Ecoscore database contains different vehicle technologies (petrol, diesel, battery electric, hybrid electric, and flexi-fuel) and different vehicle segment (see chapter I) of the Belgian fleet.

The modelling parameters of the life cycle of the different vehicles are extracted from the Ecoscore database. A data analysis was performed to extract these parameters from the raw data available in the Ecoscore database. Since the Belgian fleet includes a large variety of cars, the modelling parameters are not fixed values but ranges. In the model, all the possible variations of these parameters are taken into account, resulting in a variation of the considered impacts. When including the frequencies of these values, one can match a triangular or uniform distribution with the real distribution of the values. Figure 4 and Figure 5 give an example of this approach for a Euro 4 family car using petrol.

There are strong correlations between fuel consumption and vehicle weight, carbon dioxide and sulphur dioxide. These parameters can be described as a linear function of fuel consumption, multiplied with an 'error' distribution, expressing the difference between the linear equation and the real distribution of the parameter. For the other emissions (HC, NOx, CO, PM, CH4 and N2O), no satisfying correlation with fuel consumption was found. These emissions are modelled as a triangular or a uniform distribution, matching the reality as closely as possible.

The chosen distributions have an important impact on the overall result, preliminary conclusions of the data analysis are therefore interesting to discuss.

Fuel consumption, weight, CO_2 and SO_2 are highly dependent of the chosen segment. On the other side, the Euro standard does not influence these parameters. Impacts of manufacturing and well-to-tank emissions do not change by introducing newer Euro standards. Tank-to-wheel (TTW) emissions of CO_2 and SO_2 will also not change by introducing newer euro standards. On the other hand it is noticeable that the Euro standard influences highly the other regulated TTW emissions. The higher the Euro standard, the lower HC, NO_x, CO, PM, CH_4 and N_2O emissions are.

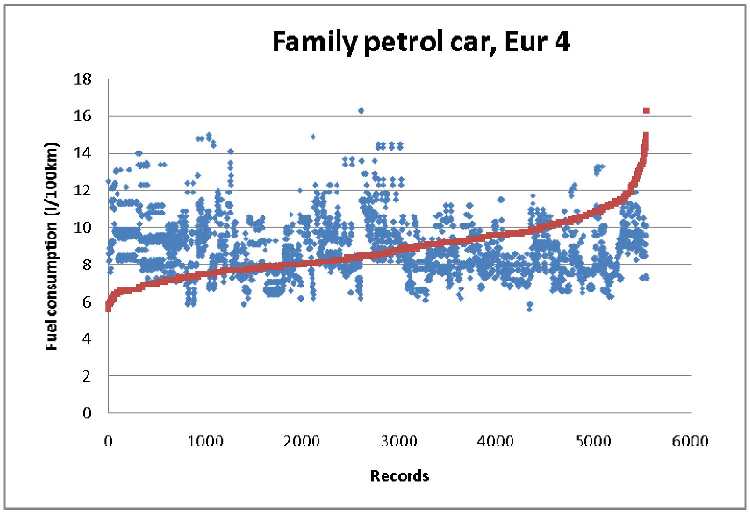

Figure 4: Range of the fuel consumption of the family petrol Euro 4 car

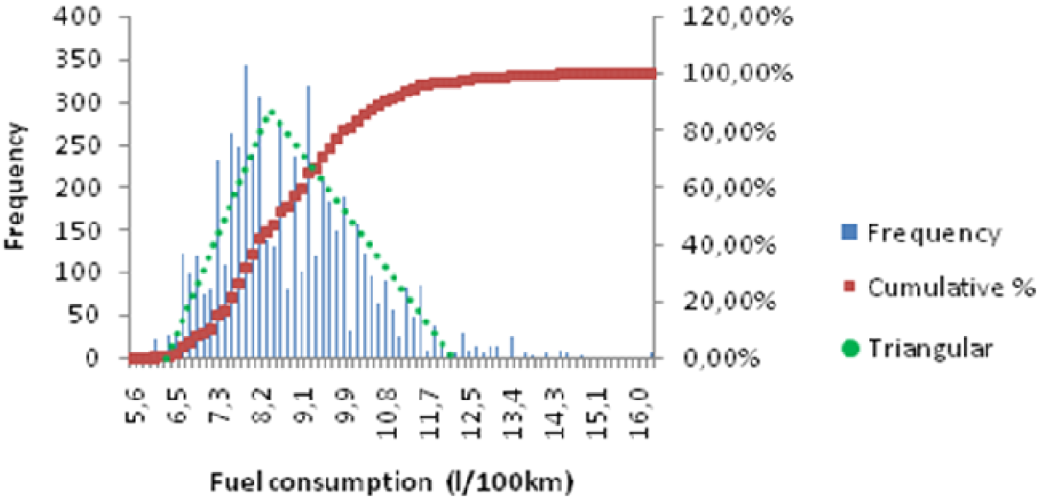

Figure 5: Distribution of the fuel consumption of the family petrol Euro 4 car

As heavy metal emissions are not available in the Ecoscore database, emission factors in terms of mg of substance per kg of burned fuel are gathered from the EMEP/CORINAIR emission inventory guidebook [49] for petrol and diesel cars (Table 59).

Next to the Ecoscore database, some bio-fuels' Tank-to-Wheel data (Table 60) available in Ecoinvent v2.0 have been collected as well. These emissions correspond to a range of vehicles with a weight between 1300 and 1500 kg [52]. This range of vehicles corresponds to the 'small family car' category according to the classification made in the CLEVER project. The use phases of E5 (petrol with 5% ethanol), methane from biogas, diesel with 5% RME, methanol, petrol with 4% ETBE and petrol with 15% ETBE are included. The emission measurements have been done with the New European Driving Cycle.

Furthermore, bio-fuel TTW emissions of the Volvo F50, the Saab 9.5 BioPower and the Citroen C4 have been provided by the BIOSES project (Table 61, Table 62and Table 63)

Table 59: heavy metal emissions of passenger car [49]

	mg/kg burned petrol	mg/kg burned diesel
cadmium	0.01	0.01
copper	1.70	1.70
chromium	0.05	0.05
nickel	0.07	0.07
selenium	0.01	0.01
zinc	1.00	1.00
lead	2.00E-03	1.10E-07
mercury	7.00E-05	2.00E-05
chromium IV	1.00E-04	1.00E-04

Note: 0.2% of the emitted chrome is emitted as Chromium (IV)

Table 60: TTW emissions of bio-fuel vehicles [43].

	Biomethane (g/km)	**E5 (g/km)**	**M100 (g/km)**	**B5 (g/km)**	**Petrol/ETBE15 (g/km)**	**Petrol/ETBE4 (g/km)**
CO fossil	0.00E00	8.75E-04	0.00E00	6.09E-04	7.22E-04	7.47E-04
CO bio	4.46E-01	2.95E-02	9.31E-01	2.86E-02	3.31E-02	8.63E-03
CO_2 fossil	0.00E00	189.00E00	0.00E00	166.00E00	177.00E00	183.00E00
CO_2 bio	172.00E00	6.36E00	177.00E00	7.80E00	8.09E00	2.12E00
CH_4 fossil	0.00E00	4.79E-03	0.00E00	3.37E-03	5.26E-03	5.44E-03
CH_4 bio	4.51E-02	1.61E-04	1.44E-03	1.58E-04	2.41E-04	6.29E-05
NOx	2.06E-02	5.84E-05	3.84E-02	5.05E-01	3.56E-02	3.56E-02
PM	6.67E-04	1.98E-03	0.00E00	3.16E-02	1.00E-01	1.00E-01
N_2O	8.66E-04	2.57E-03	2.60E-03	5.58E-03	1.33E-03	1.33E-03
SO_2	8.95E-04	5.99E-03	0.00E00	5.25E-03	5.13E-03	5.04E-03
NMVOC	1.05E-02	5.84E-02	5.18E-02	1.29E-01	9.33E-02	9.33E-02
Benzene	7.62E-04	1.88E-03	2.74E-03	1.80E-03	8.89E-03	8.89E-03
Toluene	5.25E-03	8.71E-03	5.56E-03	4.15E-04	7.68E-03	7.68E-03
Xylene	5.39E-03	9.31E-03	5.28E-04	1.04E-03	7.68E-03	7.68E-03

Table 61: TTW emissions of the Citroen C4 using different blends of diesel [53].

	Fuel consumption (l/100 km)	**CO_2 (g/km)**	**CO (g/km)**	**NO_x (g/km)**	**HC (g/km)**
diesel	5.79	152.4	3.4E-2	0.64	1.3 E-2
B5	6.03	159.1	2.8E-2	0.61	1.0 E-2
B10	5.94	156.0	2.3 E-2	0.58	1.0 E-2
B30	5.85	151.3	1.4 E-2	0.63	0.9 E-2
B100	6.07	149.7	1.2 E-2	0.71	1.6 E-2

Table 62: TTW emissioons of the Saab 9.5 BioPower using different blends of petrol [53]

	Fuel consumption (l/100 km)	**CO_2 (g/km)**	**CO (g/km)**	**NO_x (g/km)**	**HC (g/km)**
diesel	10.49	247.74	0.26	3.66E-03	5.36E-03
E5	10.43	240.78	0.31	2.85E-03	5.40E-03
E10	10.67	239.71	0.18	2.92E-03	4.48E-03
E30	10.44	222.11	0.08	2.84E-03	2.27E-03
E85	13.30	212.97	0.05	2.61E-03	2.15E-03

Table 63: TTW emissions of the Volvo F50 using different blends of petrol [53]

	Fuel consumption (l/100 km)	**CO_2 (g/km)**	**CO (g/km)**	**NO_x (g/km)**	**HC (g/km)**
Euro 95	7.40	175.63	0.21	17,33E-3	0.76E-3
E5	7.63	176.31	0.19	16.52E-3	0.69E-3
E10	7.93	178.07	0.21	20.02E-3	0.87E-3
E20	8.56	181.71	0.25	18.73E-3	0.99E-3
E85	12.16	192.90	0.15	18.73E-3	1.05E-3

Additionally, tailpipe emissions (Table 64) of two hydrogen vehicles have been collected from [54, 55]. It is important to mention that contrarily to the other vehicle technologies, the considered FCEV vehicle in this study is not yet homologated in Europe. Thus, an NEDC based fuel consumption is not available for this vehicle. So, an US EPA (Environmental Protection Agency) combined cycle based fuel economy of 60 miles (96.56 km) per kg has been considered for the FCEV (Honda 2010). The Honda FCX Clarity has a driving range of 240 miles (386.23 km).

Table 64: TTW emissions of 2 prototype hydrogen vehicles [54], [55]

Vehicle	Technology	storage	Fuel [kg H2/km]	NO_x [g/km]	CO [g/km]	CO_2 [g/km]	NMHC [g/km]
Ford P2000	H_2-ICEV	1,5 kg at 248 bar	4.40E-03	4.60E-01	5.10E-03	8.70E-01	4.70E-03
Honda FCX Clarity	FCEV	3.92 kg at 345 bar	1.04E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Air conditioning systems

According to [56], the use of an air conditioning system increases the vehicle's fuel consumption by 17.8 %, but this could vary according to the technology, the meteorological conditions and the driving style. For example the extra consumption due to the air conditioning ranges from 12 to 43% in an urban driving context according to the type of engine and the driving behavior. Additionally, the extra consumption due to the weight of the air conditioning system is about 8.2%.

IV.16 Conclusion

The LCI step of the CLEVER project has been performed thanks to a special data gathering strategy. A list of all the relevant data sources and projects has been made during a detailed literature review. Priority has been given to specific Belgian and European data. The Ecoinvent v2.0 and Ecoscore databases have been the main data sources. Raw material production, manufacturing, transport, fuel, energy, maintenance and Well-to-Wheel data are collected for conventional and alternative vehicles. However, some adaptations have been made to avoid repetition and to solve the problem with lack of data. Thus, for the manufacturing phase complete LCI data of the VW Golf have been used to model a theoretical car which is used as a parameter to model the other cars proportionately to their weight. For the emission control technologies, only LCI data of a sedan catalytic converter are obtained. It is also important to note that average Tank-to-Wheel data are considered instead of urban and extra-urban data since the direct emissions come from the New European Driving Cycle.

Finally, the gathering of direct emissions of bio-fuel cars has been completed by the emission measurement campaign which has been performed by the BIOSES project.

V. Life Cycle Impact Assessment

After the completion of the LCI, the different elementary flows that are linked to a product system need to be converted into environmental indicators. These indicators allow quantifying and comparing the potential environmental impacts of the different product systems. This step of the LCA is called Life Cycle Impact Assessment (LCIA). The LCIA has mandatory and optional elements. The mandatory elements include the selection of impact categories, the assignment of the elementary flows to the categories (classification) and the attribution of factors to each elementary flow according to its relative contribution to the category (Characterisation). The optional elements are the calculation of the magnitude of an impact category relative to reference information (normalization) and the grouping of the different impact indicators into a single score (weighting).[57]. However, weighting shall not be used for comparative LCA studies intended to be disclosed to the public [58].

As required by [58], LCIA category indicators and characterisation models based on international agreement should be used. In this perspective, the European commission via the

Joint Research Centre (JRC) has initiated the International Reference Life Cycle Data System (ILCD) in order to 'provide governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments' [59]. In the framework of the ILCD activities, an analysis of the existing LCIA methods has been performed [60]. In this analysis, the main existing methodologies are described regarding the documentation, the general principals, the consistency across a list of predefined impact categories and the interesting innovative aspects [60]. Finally, a list of preselected LCIA methods has been produced (Table 65). These preselected LCIA methods will be assessed in details by the ILCD team and a final list is expected for 2011.

Table 65: Pre-selection of characterisation models for further analysis [60]

	Climate change	Ozone depletion	Respiratory inorganics	Human toxicity[11]	Ionising radiation	Ecotoxicity	Ozone formation	Acidification	Terrest. Eutrophication	Aquatic Eutrophication.	Land use	Resource Consumption	Others
CML2002	o	o		M	o[12]	o	M	M	M	M	o	M	
Eco-indicator 99	E	E	E	o	o		E	E	E		E	E	
EDIP 2003/EDIP97[13]	o	M	o	M	o	M	M	M	M	M		M	Work environ. Road noise
EPS 2000	E	E	E	E	o	E	E	o	o	o	E	E	
Impact 2002+	o	o	E	M E	o	M E	E	M E		M E	o	E	
LIME	E	E	M	E		o	M E	M E	o	E	E	E	Indoor air
LUCAS	o	o		o		o	o	o	o	o	o	o	
MEEuP	o	o	M	M		M	M	M	M	M		water	
ReCiPe	M E	E	M E	M E	o	M E	M E	M E	o	M E	M E	E	
Swiss Ecoscarcity 07	o	o	o	o	M E	M	o	o	o	o	M E	water	Endocrine disruptors
TRACI	o	o	M	M		M	M	M	o	M		o	
Specific methods to be evaluated	Ecological footprint		14	USETox		USETox		Seppälä		Payet	Ecological footprint	deWulf et al.	Noise Müller Wenk
Specific methods of potential interest (not to be evaluated)				Watson (Bachmann)	Ecotoxicity of radiation (Laplace et al.)		EcoSense (Krewitt et al.)	EcoSense (Krewitt et al.)		Kärman & Jönsson	15		Meijer indoor air UNEP Indoor air (Bruzzi et al., 2007)

o: Available in the methodology, but not further investigated

M: Midpoint model available and further analysed

E: Endpoint model available and further analysed

In this study, it has been decided to use only LCIA methods preselected in the framework of the ILCD activities and which are relevant for the specific context of automotive LCA. The selected methods are:

- IPCC 2007 [61]
- Air acidification [62]
- Eutrophication [62]
- Mineral extraction [63]
- renewable and non renewable energy demand
- Respiratory effects (inorganics) [64]

As it can be noticed in Table 66 to Table 72, the most important and relevant elementary flows are considered in the selected impact calculation methods. Endpoint methods, excepted respiratory inorganics, have been used for all the selected impact categories.

For the specific cases of renewable and non renewable energy demand, the calculation method has been developed by RDC-ENVIRONMENT with inputs from themselves and from the Swiss Agency for the Environment, Forests and Landscape (BUWAL). The energy demand (Table 69 and Table 70) includes all the types of primary energy involved in a product system. It also includes the heating value of products, resources and materials.

The respiratory inorganics impact on human health (Table 71) is particularly interesting in this study because it includes particulates, carbon monoxide and nitrogen and sulphur based emissions. These emissions are among the pollutants allowing clear differenction between vehicle technologies and fuels.

The IPCC 2007 (100a) method has been extended to biogenic CO_2 and the CO_2 uptake from the air during the synthesis of the organic matter. A negative factor is attributed to the CO_2 uptake.

The air acidification (Table 67) and eutrophication (Table 68) calculation expressed respectively in kg SO_2eq/kg and kg PO_4eq/kg are from the CML 2001 methodology [62]. It includes mainly nitrogen, sulphur and phosphorus based emissions. These two methods allow performing a comprehensive assessment of the effect of the fertilizers for biofuels on one hand and assessing the impact of the use of products and resources containing sulphur (e.g. crude oil), phosphorus or nitrogen.

The mineral extraction damage (Table 72) expressed in MJ surplus/kg allows assessing the additional energy requirement for further mining of the mineral resources in the future due to the lower resource concentration. This method is particularly interesting for the manufacturing phase of vehicles in general and the manufacturing of specific components (battery, fuel cell, hydrogen tank…) in particular.

Table 66: IPCC 2007 (100a) including biogenic CO_2 and CO_2 uptake from the air [61]

Elementary flows	**Characterisation factor (kg CO_2 eq/kg)**
CFC 12 (CCl2F2)	10900
CFC 113 (CFCl2CFCl2)	6130
HFC 23 (CHF3)	14800
HCFC 21 (CHCl2F)	210
CFC 11 (CFCl3)	4750
Chloroform (CHCl3)	756

HFC 134a (CF3CH2F)	4470
Hexafluoroethane (C2F6, FC116)	12200
Halon 1211 (CF2ClBr)	1890
CFC 114 (CF2ClCF2Cl)	10000
Sulphur Hexafluoride (SF6)	22800
Halon 1301 (CF3Br)	7140
HCFC 22 (CHF2Cl)	1810
Methan (biomass)	25
Nitrous Oxide (N2O)	298
Methane (CH4)	25
Carbon Dioxide (CO2, biomass)	1
Carbon Dioxide (CO2, in air)	-1
Carbon Dioxide (CO2, fossil)	1
CFC 13 (CF3Cl)	14400
HCFC 124 (CHClFCF3)	609

Table 67: CML 2001 Air acidification [62]

Elementary flows	**Characterisation factor (kg SO_2eq/kg)**
Sulphuric Acid (H_2SO_4)	0.65
Hydrogen Sulphide (H_2S)	1.88
Hydrogen Fluoride (HF)	1.6
Ammonia (NH_3)	1.6
Hydrogen Chloride (HCl)	0.88
Nitrogen Oxides (NO_x as NO_2)	0.5
Sulphur Oxides (SO_x as SO_2)	1.2
Nitrogen Dioxide (NO_2)	0.5
Nitrogen Oxides (NO_x as NO_2)	0.5
Sulphur Dioxide (SO_2)	1.2
Hydrogen Sulphide (H_2S)	1.88

Table 68: CML 2001 eutrophication [62]

Elementary flows	**Characterisation factor (kg PO_4 eq/kg)**
ammonia	0,35
chemical oxygen demand	0,022
nitrogenous matter	0,42
nitrous oxide	0,27
phosphates	1.00
Phosphorus, total	3,06
phosphorus pentoxide	1,34
nitrate	0,10
nitrite	0,10
nitrogen	0,42
nitrogen dioxide	0,13
nitrogen monoxide	0,20
nitrogen oxides	0,13

▪

Table 69: Non renewable energy (BUWAL/RDC)

Elementary flows	**Characterisation factor**	***Unit***
Peat	25	MJeq/kg
Coal (in ground)	19	MJeq/kg
Oil (in ground)	45,6	MJeq/kg
Lignite (in ground)	9,5	MJeq/kg
Natural Gas (in ground)	48,1	MJeq/kg
Uranium (U, ore)	451000	MJeq/kg
Unspecified Fuel Energy	1	MJeq/MJ

Table 70: Renewable energy (BUWAL/RDC)

Elementary flows	**Characterisation factor**	***Unit***
Wood	20	MJeq/kg
Water Potential energy	1	MJeq/MJ
Non fossil Fuel Energy	1	MJeq/MJ
Solar energy	1	MJeq/MJ
Wind enery	1	MJeq/MJ
Geothermal energy	1	MJeq/MJ

Table 71: Impact 2002+ respiratory inorganics (endpoints) [64]

Elementary flows	**Normalised damage factors (Impact 2002+ point)**
Ammonia (NH3)	1.20E-02
Carbon Monoxide (CO)	1.03E-04
Nitrogen Dioxide (NO2)	1.25E-02
Nitrogen Oxides (NOx as NO2)	1.25E-02
Sulphur Oxides (SOx as SO2)	7.69E-03
Sulphur Dioxide (SO2)	7.69E-03
Particulates (PM 2.5)	9.86E-02
Carbon monoxide (biomass)	1.03E-04

Table 72: Eco-indicator 99 Hieratchist, Resources, Mineral extraction damage (midpoints) [63]

Elementary flows	**MJ surplus/kg**
Aluminum in bauxite	2.38
Chromium (Cr, ore)	0.9165
Copper (Cu, ore)	36.7
Iron (Fe, ore)	0.051
Lead (Pb, ore)	7.35
Manganese (Mn, ore)	0.313
Mercury (Hg, ore)	165.5
Molybdenum (Mo, ore)	41
Nickel (Ni, ore)	23.75
Tin (Sn, ore)	600
Zinc (Zn, ore)	4.09

VI. The RangeLCA software

The range-based modeling system possesses some innovative attributes which allow improving the reliability of the results. In statistical viewpoint, this approach employs the use of random variables instead of average values .Compared to a classic LCA tool; it allows assessing all the possible cases instead of one single case. The random values are modeled with parameters which include all the values between the extreme values by giving an occurrence probability to each data. According to the situation to be modeled different type of distribution functions can be chosen. One of the main assets of the RangeLCA software is the possibility to express a link between two life cycle steps by the prior links in such away that each variation or change in the previous steps will be automatically taken into account and all different situations will be included in one single model. Thus the sensitivity analysis of all the parameters will be systematically incorporated.

Furthermore, the range-based modeling system allows comparing two systems with simultaneously varying parameters. In fact, while comparing two different systems within an LCA, two types of variations could happen: Variation of the results due to the variation of common parameters to the two systems and another variation of the results due to the variation of parameters which are specific to each system. Thus, to achieve a real comparison of the two systems one should identify and assess the variability of system specific parameters which allow distinguishing the specificities of each system. It produced results integrate a set of possible combinations for the various parameters and data in order to take into account possible synergy and compensation effects

VII. Results and discussion

The LCA results of this study should be interpreted with caution. The objective of this study is not to compare different technological options (hybrid, FCEV, BEV, ICE…) of one single vehicle but to compare different existing vehicle technologies of the Belgian fleet. More specifically, the compared vehicles do not have the same size or the same energy consumption but they are from the same market segment and are being used for the same purpose by the end-user. The comparison of different family car technologies shows that the climate impact is highly influenced by the vehicle technology, the type of fuel and the type of feedstock used to produce the fuel (Figure 6). One can notice in the Figure 6 that the sugar cane based E85 vehicle has the lowest greenhouse effect. This is due essentially to the benefit of the CO_2 uptake from the air during the production of the sugar cane. Additionally, the electricity used in the sugar cane fermentation plant is produced with the bagasse obtained after the crushing of the sugar cane. However this good score of the E85 highly depends on the feedstock type and e.g shifting from sugar cane to sugar beets will increase by more than three times the impact of the E85 vehicle (Figure 6). After the sugar cane based E85 vehicle, the BEV using the Belgian supply mix electricity has the lowest greenhouse effect. This good score of the BEV can be explained by the fact that 55% of the Belgian production mix electricity is nuclear and the fact that BEV is an exhaust emission free vehicle. Despite the low greenhouse effect of the BEV, the contribution of the lithium ion battery to the overall impact is still higher. However, a big share of the impact of the lithium battery is balanced by the benefit of the recycling. Like the BEV, the FCEV is also an exhaust emission free vehicle but it has a greenhouse effect higher than the BEV and comparable to the B100 (RME) one (Figure 6). The difference between the FCEV and the BEV is due essentially to the fact that the hydrogen is produced with natural gas when more than the half of the Belgian electricity is nuclear. Contrarily to the sugar cane based E85, the B100 (RME) production is almost greenhouse neutral. Indeed, the benefit of the CO_2 uptake from the air during the rape production is balanced by the effect of the intensive agricultural practices such as the fertilizing and the machinery.

Another interesting finding of this study is the good climate impact score of CNG vehicles in comparison to alternative vehicles such as hybrid and LPG. In fact, the natural gas production is less energy intensive and pollutes less than the production of petrol and propane/butane based LPG. Additionally, natural gas also has a good combustion efficiency. However, the benefit of fuel saving of hybrid cars (lower TTW impact) compared to ICE vehicles is clearly identified in the Figure 6. The relatively higher greenhouse effect of the LPG car can be explained by the fact that the LPG is modeled with propane/butane combined with a liquefaction process. The use of flare gas to produce LPG would reduce this impact. In general, for alternative vehicles such as FCEV and BEV the recycling of specific components such as the fuel cell or the lithium battery has a big environmental benefit. Furthermore the type of feedstock and the conversion technology for alternative fuels (bio-fuel, hydrogen…) have a strong influence on the GHE of the vehicles.

In order to have a deeper understanding of the results of this study, the LCA model has been run 1000 times with different values chosen randomly between the minimum and the maximum of all parameters modeled as a range. However extreme values corresponding to 2% of the iterations have been excluded. Thanks to this approach, the effect of the simultaneous variation of the vehicle weight, the energy consumption and the emissions has been assessed. No weight variation has been considered for specific cases (FCEV, BEV, E 85, CNG and B100) where only one vehicle is available. However, the errors on the measurements of the fuel consumption and the direct emissions have been included for these vehicles. As a consequence, vehicle technologies with large variety of brands and models (Petrol, Diesel, LPG and Hybrid) will have a wide spread of LCA results. With such an approach, stronger conclusions are drawn because the worst case of a given technology can be compared to the most favorable case of another one. For example, one can notice on the Figure 6 that the considered BEV powered with the Belgian electricity is not only better than the other fossil fuel vehicles in average but also better than the smallest fossil fuel vehicles of its segment. Thanks to this iterative approach, the overlaps between the different technologies are identified. On a policy perspective, the decision makers can use these kinds of results to determine for which groups of vehicles they can take the same policy measures or on the contrary to identify for which groups specific measures are necessary.

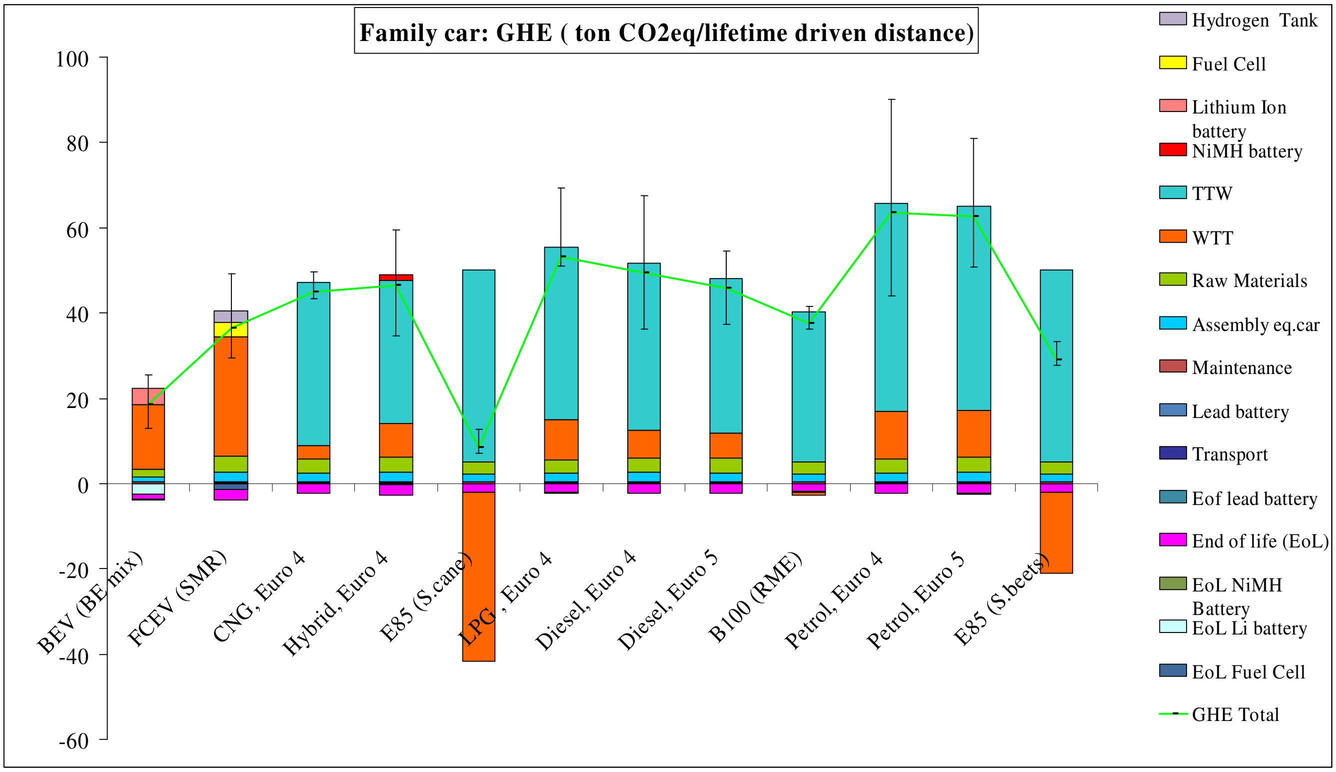

Figure 6: Comparative GHE assessment of family car technologies

On the Figure 7, different scenarios of BEV using different types of electricity have been compared to assess the influence of the electricity production technology on the LCA results of BEVs. The BEVs powered with windpower, hydropower or nuclear power appear to have very low greenhouse effect. They are followed by the scenarios of the Belgian mix electricity and the natural gas electricity which also have very low greenhouse effect in comparison to diesel and petrol vehicles. However, extreme scenarios in which BEVs are powered with oil or coal electricity appears to have climate impacts which are comparable to the ones of diesel cars. In average, the greenhouse effect of petrol cars is still higher than the one of BEVs powered with oil or coal electricity. Nevertheless, The error bars (Figure 7) show that small petrol cars within the family car segment can have greenhouse effect which is comparable to a BEV powered with coal or oil electricity.

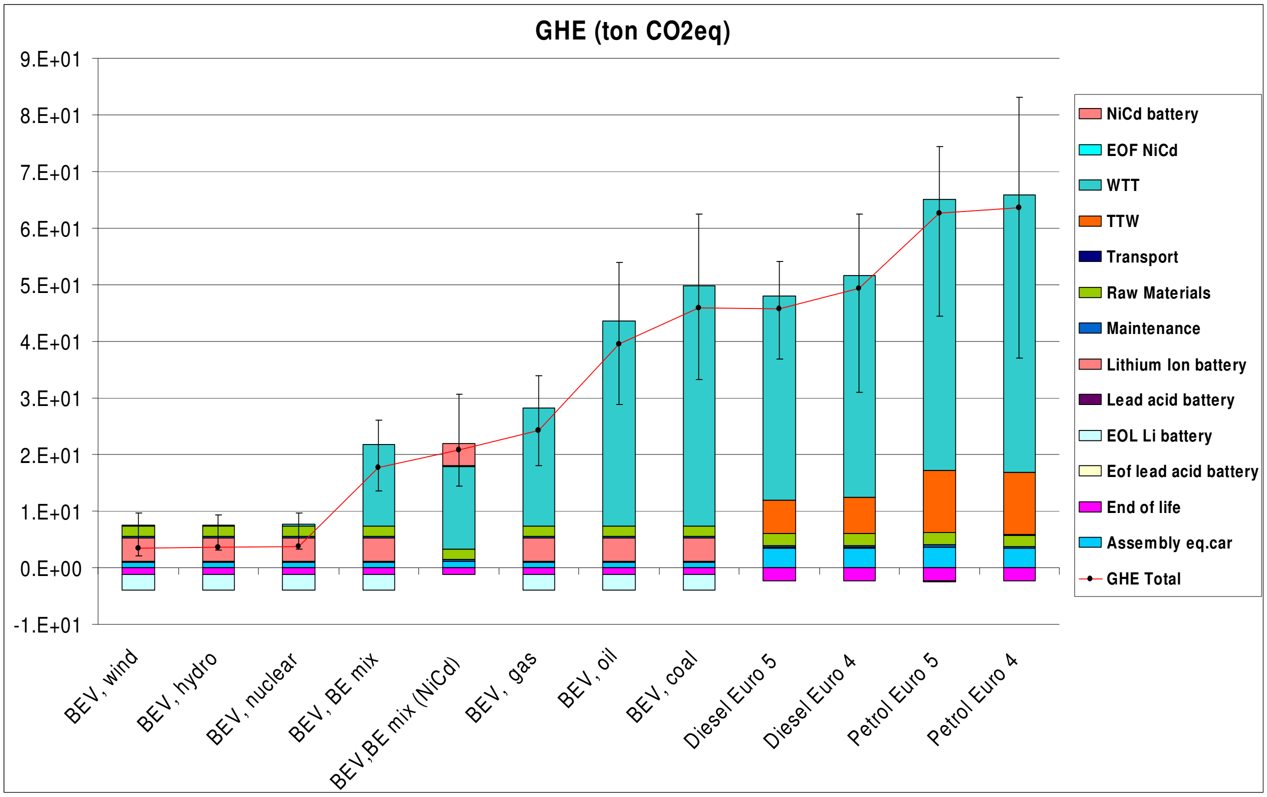

Figure 7: Sensitivity of the GHE impact of BEV to the type of electricity production

Close to the GHE, the respiratory effects of the different family car technologies have been compared (Figure 8). Contrarily to the GHE, the E85 sugar cane technology has the worst score for the respiratory effects (inorganics). This is due mainly to the burning of the sugar cane field before the harvest. The main pollutants emitted during the field burning are Carbone monoxide, methane and particles [65]. However, a regulation allowing a progressive shift from manual harvesting (with field burning) to automatic harvesting (without field burning) is being implemented in Sao Paolo by 2021 [66]. It is then followed by the RME vehicle. This high respiratory effect of the RME is due mainly to the emission of ammonia and nitrogen oxides which are directly linked to the use of nitrogen based mineral fertilizers. Additionally, the bio-diesel vehicle emits more nitrogen oxides than the corresponding diesel vehicle.

The best score in this impact category goes to the CNG vehicle. The production of the natural gas has relatively low emission for all the considered pollutants in this category. This is also true for the direct emissions of the CNG vehicle. The CNG technology is followed by the BEV. The FCEV has a respiratory effect lower than the ICE vehicles but slightly higher than the BEV. Without recycling of the fuel cell, the FCEV would have the worst score for this impact after the E85 and the RME vehicles.

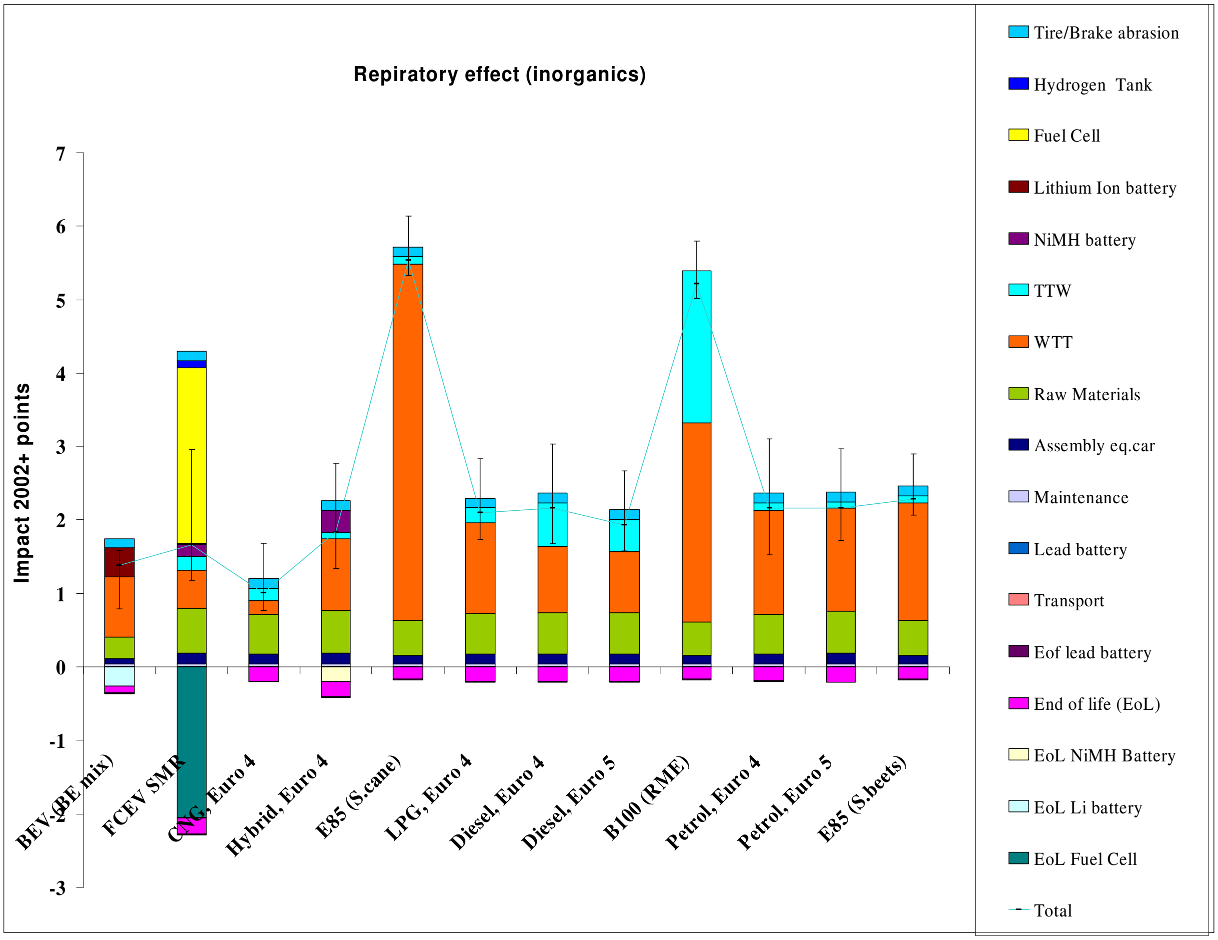

Figure 8: Respiratory effects of different family car technologies

After the overall vehicle technology comparison within the family car segment, a list of reference vehicles which are considered to be more representative of their respective segment has been made. The aim is to perform a fair comparison between equivalent vehicles because sometimes a limited number of vehicles with high weight or high fuel consumption can influence the average result of a full segment for a given technology. The individual comparison of the reference vehicle for GHE (Figure 9) gives the same ranking trend as in the Figure 6 for the different vehicle technologies. However, the Figure 9 shows that the differences between the different technologies, especially the difference between petrol and diesel, are smaller than in the overall comparison. Moreover, the Figure 9 shows that the segment also has a big influence on the LCA results. For example, a petrol family car will have a lower GHE than a hybrid SUV.

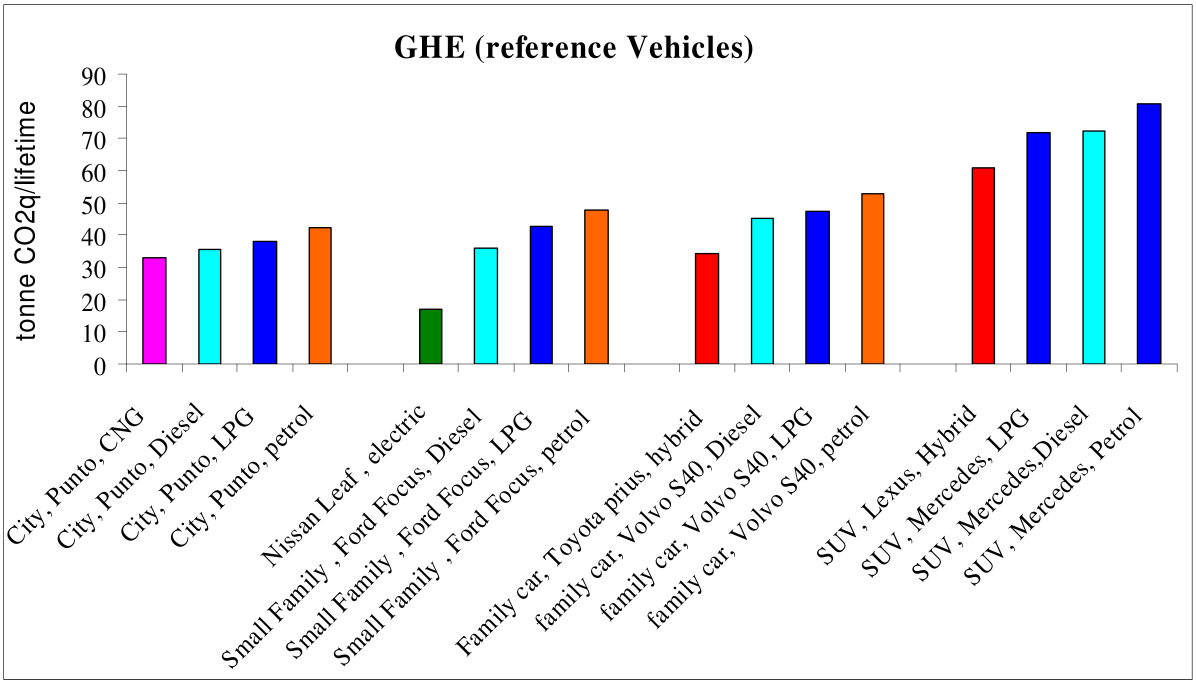

Figure 9: GHE of different comparable individual vehicle technologies and segments

VIII. Scientific validation of the Ecoscore approach

VIII.1 Introduction

The Vrije Universiteit Brussel, ULB and VITO have developed the Ecoscore methodology [14], a well-to-wheel environmental vehicle rating tool. This tool has been developed to apply in different policy measures for the Flemish government to promote the purchase and use of cleaner vehicles. Since this tool had to be transparent and easily applicable on a policy level, emission and fuel consumption data had to be available for all vehicles on the Belgian market. The LCA methodology however, requires an extensive set of emission data per vehicle, which is not always easy to retrieve. The more pragmatically Ecoscore tool is therefore based on a 'simplified' LCA methodology, where only the airborne well-to-wheel emissions are taken into account, but which allows the calculation of an environmental impact for each individual vehicle.

In this chapter, a comparison will be made between the Ecoscore and LCA results of different vehicle technologies and vehicles of different ages, to assess the influence of neglecting the impact of the manufacturing, maintenance and end-of-life phases of a vehicle and hence validate the Ecoscore approach.

VIII.2 Ecoscore methodology

The Ecoscore methodology has been developed with the aim to calculate the environmental impact for every individual vehicle and to compare different vehicle technologies in an objective way. Ecoscore is an environmental score, in which different damage effects are taken into account: climate change, air quality depletion (health impairing effects and effects on ecosystems) and noise pollution. The methodology is based on a well-to-wheel analysis, which means that besides tailpipe emissions, also the air pollution caused by the production and distribution of the fuel is taken into account. This allows a comparison of different vehicle fuels and technologies.

The Ecoscore methodology can be considered as a simplified LCA, since only the well-to-wheel environmental impact is considered, while the impacts of the production and end-of-life stages of the vehicle itself are neglected. The environmental evaluation of a vehicle through this methodology is being done according to a sequence of five steps, similar to those used in a standardised LCA: inventary, classification, characterisation, normalisation and weighting.

In the first step of the inventary, the direct (associated with the use of the vehicle) and indirect emissions (due to production and distribution of the fuel) associated with the vehicle are collected. Direct of tank-to-wheel emission and fuel consumption data are based on homologation data collected by Febiac and DIV (Federal service for vehicle registrations) and which can be consulted on www.ecoscore.be. Indirect or well-to-tank emission data have been obtained from the MEET 1995 study [67], complemented with Electrabel data for electricity production. In the calculation of the total impact of the vehicle, the exposition of the receptors is taken into account by giving the indirect emissions a smaller weight than the direct emissions (with an exception for greenhouse gases, since they have a global effect). Once the emissions have been calculated, their contribution to the different damage categories (climate change, air quality depletion and noise) are analysed in the classification and characterisation step. The contributions of the different greenhouse gases to global warming are calculated using global warming potentials (GWP), as defined by the Intergovernmental Panel on Climate Change (IPCC). External costs, based on the EU ExternE project [68], are used for the inventoried air quality depleting emissions. Noise pollution is expressed in dB(A), a decibel scale with A-weighting to take the sensitivity of human hearing into account. To quantify the relative severity of the evaluated damages of each damage category, a normalisation step based on a specific reference value is performed. The reference point is the damage associated with a theoretical passenger vehicle of which the emission levels correspond with the Euro 4 emission target levels for petrol vehicles, a CO_2 emission level of 120 g/km and a noise level of 70 dB(A). In a final step, the normalised damages are weighted before they can be added to become the “total environmental impact”. These weighting factors reflect policy priorities and decision maker’s opinions. An overview of the methodology is presented in . To obtain results situated between 0 (infinitely polluting) and 100 (emission free and silent vehicle), the total environmental impact (TI or Total Impact) is rescaled to the final Ecoscore indicator. The reference vehicle corresponds to an Ecoscore value of 70. The transformation is based on an exponential function, so it cannot deliver negative scores:

$$\text{Ecoscore} = 100*\exp(-0{,}00357*\text{TI})$$

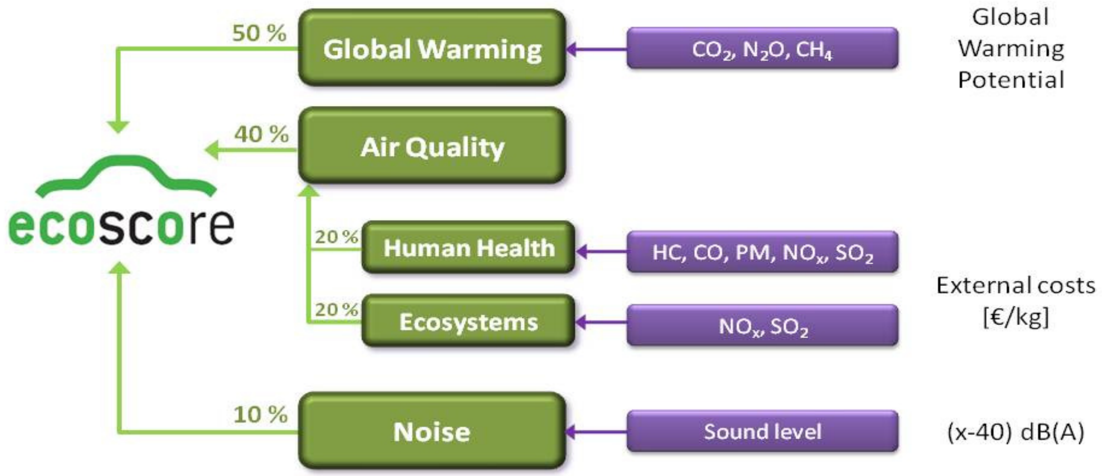

Figure 10: Overview of the Ecoscore methodology [14].

VIII.2 Vehicle selection

Three types of comparisons were made to validate the Ecoscore approach. For both petrol and diesel cars, the environmental performance was followed over the different Euro standards and hence vehicle ages. Another analysis includes the comparison of different vehicle technologies which are available on the market, all complying with the latest Euro 5 standard: petrol, diesel, LPG, CNG, petrol hybrid and BEV.

Based on the Ecoscore database of January 2010, a selection was made of comparable vehicles from different vehicle technologies (Table 73). The Volkswagen Golf was used as a reference model since it is available since Euro 2 and is still a popular car on the Belgian market. When no VW Golf model was available, comparable cars have been chosen from the database. For CNG the Opel Zafira was used, for BEV the Nissan Leaf and for the petrol hybrid the Toyota Prius. For these vehicles, the LCA results were calculated, making a distinction between the different life cycle phases, as well as the Total Impact. This was done for three impact categories: greenhouse effect, impact on human health and impact on ecosystems.

Table 73: Selected vehicles with their fuel consumption, emissions, Ecoscore and Total Impact (TI).

Fuel/ Technology	Euro standard	Car model	Fuel consumption [l/100km]	CO_2 [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	SO_2 [g/km]	PM [g/km]	N_2O [g/km]	CH_4 [g/km]	Ecoscore	TI
Petrol	Euro 1	Chrysler Stratus	8,2	196	2,720	0,530	0,440	0,00124	0	0,027	0,020	48,93	200,42
	Euro 2	Volkswagen Golf	8,9	213	2,200	0,275	0,225	0,00134	0	0,013	0,020	52,36	181,39
	Euro 3	Volkswagen Golf	9,0	215	2,300	0,200	0,150	0,00136	0	0,005	0,020	54,02	172,66
	Euro 4	Volkswagen Golf	8,1	194	1,000	0,100	0,080	0,00122	0	0,005	0,020	58,90	148,34
	Euro 5	Volkswagen Golf	6,2	144	0,286	0,028	0,045	0,00094	0	0,005	0,020	67,05	112,05
Diesel	Euro 1	Jeep Cherokee	9,5	251	2,720	0,100	0,870	0,00162	0,14	0,002	0,010	20,96	438,12
	Euro 2	Volkswagen Golf	6,2	164	1,000	0,070	0,630	0,00105	0,08	0,005	0,010	36,81	280,22
	Euro 3	Volkswagen Golf	5,4	143	0,640	0,060	0,500	0,00092	0,05	0,008	0,010	46,68	213,62
	Euro 4	Volkswagen Golf	5,2	137	0,129	0,013	0,237	0,00088	0,02	0,008	0,010	60,50	140,96
	Euro 5	Volkswagen Golf	4,9	128	0,245	0,040	0,136	0,00083	0,001	0,008	0,010	70,22	99,10
LPG	Euro 5	Volkswagen Golf	7,1	169	0,330	0,032	0,012	0,00117	0	0,005	0,020	71,19	95,29
CNG	Euro 5	Opel Zafira	7,8	139	0,215	0,065	0,022	0	0	0,005	0,124	73,56	86,10
Hybrid	Euro 5	Toyota Prius	3,9	89	0,258	0,058	0,006	0,00059	0	0,005	0,020	77,40	71,81
BEV	Euro 5	Nissan Leaf	0,15 kWh/km	0	0,000	0,000	0,000	0	0	0	0,000	85,96	42,42

VIII.3 Comparison of Total Impact (Ecoscore) and LCA results

In the following figures, a comparison is made between Total Impact and LCA results for three impact categories: greenhouse effect, impact on human health and impact on ecosystems.

Figure 11 shows the results of this comparison for petrol cars of different ages according to the Euro standard. For the three assessed impact categories, the same trend is seen for TI as for LCA. The impact on human health and ecosystems decreases with the age of the petrol car, if assessed with LCA or TI. For greenhouse effect, the Euro 2 and Euro 3 petrol car have a higher impact than Euro 1, 4 and 5 due to the higher TTW emissions of these cars, which is directly related to the higher fuel consumption and hence CO_2 emissions of these vehicles (see Table 73). Since their regulated emissions (CO, NOx, HC) decrease according to the emission standards, their impact on human health and ecosystems is lower than for the Euro 1 petrol car. Between these different vehicles, the impact due to manufacture, maintenance and end-of-life remains almost constant. The differences are almost entirely due to the well-to-wheel emissions of the vehicle.

Figure 12 gives a similar comparison as was shown in Figure 11, but this time for diesel cars of different ages. Again the LCA and TI results display the same trend between the different cars. The impact on greenhouse effect, health and ecosystems decreases towards more recent cars. This can be almost entirely assigned to the well-to-wheel emissions, since the contribution of the manufacture, maintenance and end-of-life phases remains quite stable over time.

The last set of graphs (Figure 13) gives a comparison between different vehicle technologies/fuels, all complying with the Euro 5 emission standard. The impact on greenhouse effect is the lowest for the BEV, followed by the hybrid vehicle. The same ranking of vehicle technologies results from the LCA and TI analysis. The WTT and TTW phases are the largest contributors for this impact category. For the impact on human health and ecosystems, the other life cycle phases play a more important role, especially for the alternative vehicle technologies. The larger impact of the manufacturing phase for the CNG car is due to the higher weight of this car compared to the VW Golf. The larger impact on health and ecosystems of the manufacturing and end-of-life of the hybrid and BEV are due to the impact of the battery of these cars. This change in the contribution of the different life cycle phases has created some changes in the relative position of the vehicles, especially for human health. The CNG car has the lowest impact (TI and LCA) on human health due to the very low WTW emissions. Also for the impact on ecosystems, the CNG car has the lowest impact, together with the BEV.

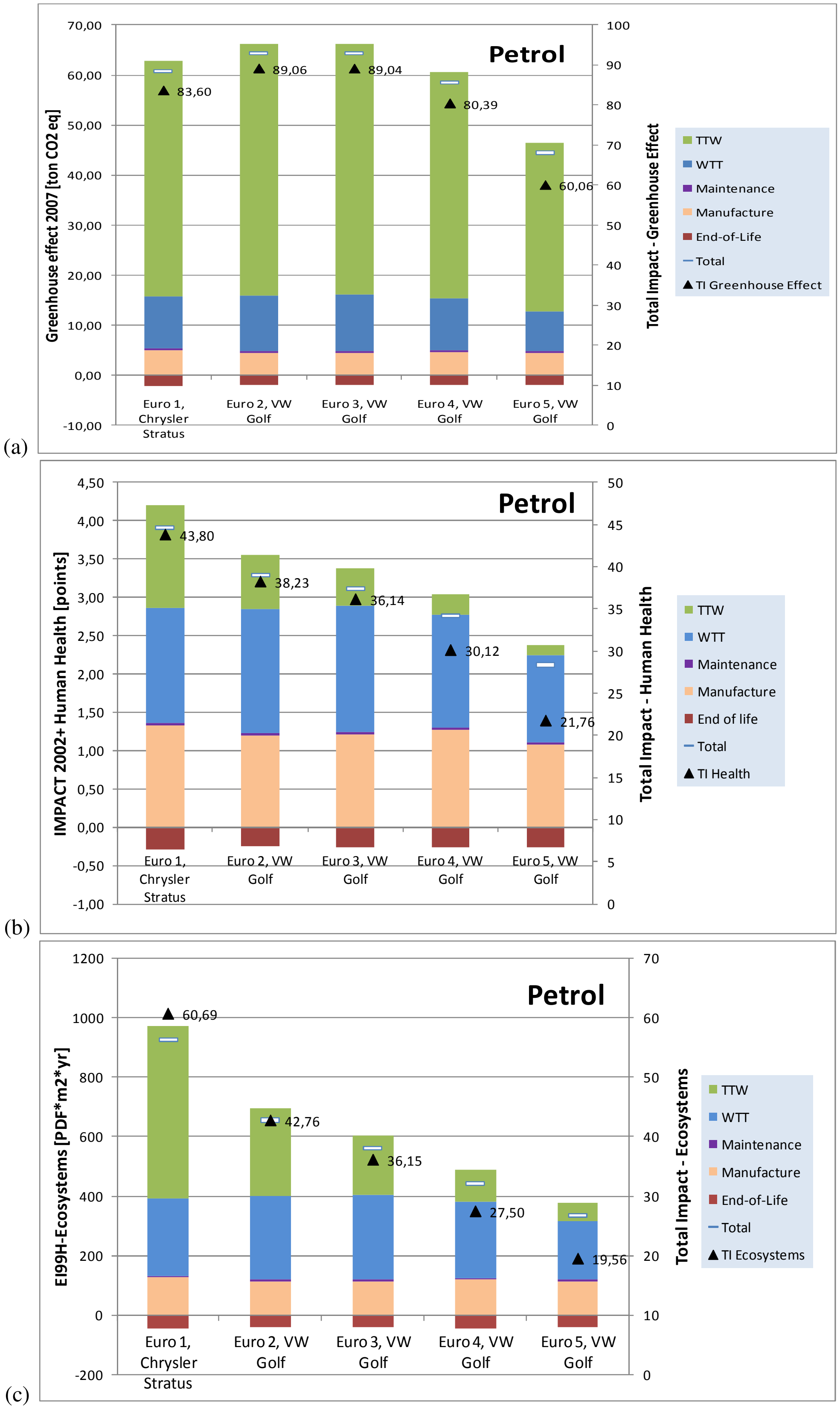

Figure 11: LCA and Total Impact results of a selection of petrol cars of different ages (Euro standards) for greenhouse effect (a), impact on human health (b) and impact on ecosystems (c). Total Impact results are indicated with a black triangle, total LCA results with a white horizontal line.

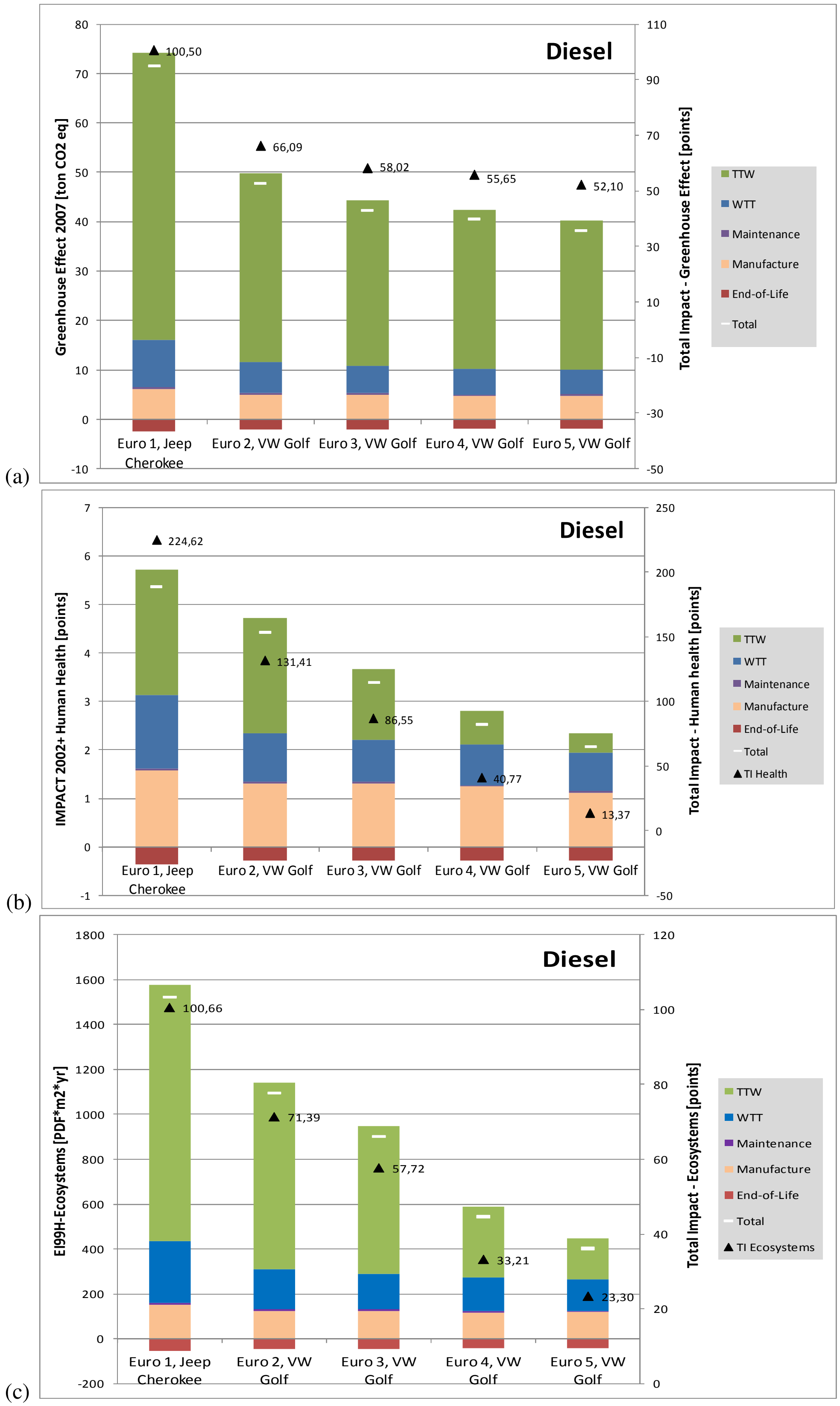

Figure 12: LCA and Total Impact results of a selection of diesel cars of different ages (Euro standards) for greenhouse effect (a), impact on human health (b) and impact on ecosystems (c). Total Impact results are indicated with a black triangle, total LCA results with a white horizontal line.

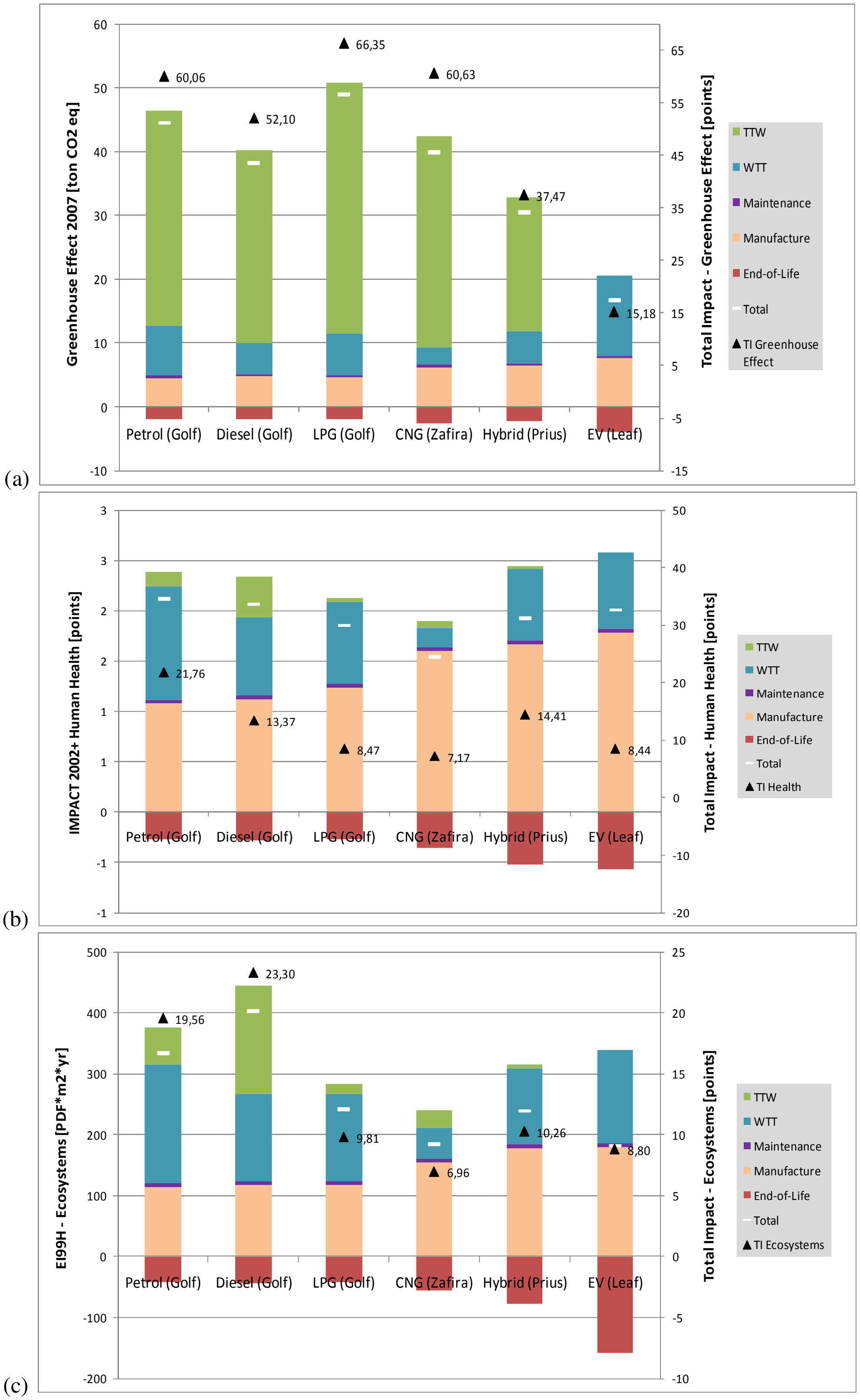

Figure 13: LCA and Total Impact results of a selection of different vehicle technologies for greenhouse effect (a), impact on human health (b) and impact on ecosystems (c). Total Impact results are indicated with a black triangle, total LCA results with a white horizontal line.

IX. Optimal time for replacement

IX.1 Introduction

The energy consumption and the exhaust emissions of new vehicles have decreased considerably the last years, driven by European emission standards, technological exhaust treatment improvements and efficient engine technologies. These technological transitions towards a more sustainable transportation system are encouraged by two main drivers: the availability of energy sources (political and economical dependence on oil producing countries and the depletion of the reserve base of fossil fuels) and the negative environmental aspects of the current transport system [69].

A persistent transition towards a more sustainable transportation sector will involve a mixture of several options such as: encouraging modal shifts (walking, cycling, public transport), cleaner vehicle technologies, changing driving behaviour, and controlling the need for motorized transportation [14].

A way to improve the environmental impact of the transport sector is by replacing old inefficient vehicles by newer ones. A passenger car in Belgium has a **lifetime driven distance (LTDD)** of 230,500 km, which corresponds to 13.7 years [13]. To cover this distance, a smaller impact on the environment could be obtained by replacing this car before its lifetime with an environmentally friendlier car. Vehicle replacement is normally driven by economic concerns. This chapter gives insights in how to introduce environmental aspects in automobile replacement policies. These policies aim at accelerating the adoption of cleaner vehicles by taking old vehicles out of the fleet, while supporting the vehicle industry. A scrappage policy must take the whole life cycle of a vehicle into account. Scrapping an old vehicle and manufacturing a new one creates additional environmental impacts which must be taken into consideration. Results of a Life Cycle Assessment (LCA) will be used to check how the Belgian fleet can evolve towards a greener composition.

IX.2 Methodology

Life Cycle Assessment is a cradle-to-grave approach to determine the total environmental impact of a product during its life cycle. It includes the extraction of raw materials, manufacturing, transportation, use and disposal. Since the 90s, LCA is a standardized methodology [57], [58]. It consists of four phases: goal definition and scoping, inventory analysis, impact assessment and interpretation.

The **goal** of this study is to adapt the vehicle fleet to a more ecological composition, in function of the LCA results. This analysis will be based on the comparison of the well-to-wheel emissions with the cradle-to-grave (manufacturing, dismantling, recycling and waste treatment) emissions for vehicles with different ages, Euro standards and technologies. Optimizing vehicle’s LTDD causes an LCA challenge, combining two contradictory environmental engineering concepts. Letting a vehicle have a longer use phase avoids specific impacts during manufacturing, such as mineral extraction damage and energy usage. Product life extension is a well known DfE (design for environment) strategy [70], [71]. To expand the LTDD the focus will lie on durability and maintenance. In this case the policy advise would be to replace the old vehicle as late as possible.

Conversely, replacement of an old vehicle with a new, more efficient one, can lower the impacts introduced during the use phase. Depending on the level of benefit, the policy advise would be to replace the old car as soon as possible. In this case, the focus will lie on the development of cleaner vehicle technologies [72].

The optimal time to replace a car depends highly on the market availability of cleaner vehicles. If an optimization, is to tackle greenhouse gases and there is no car on the market which consumes considerately less fuel, there is no reason to replace the old vehicle. Moreover, the CO_2 emissions introduced during scrapping an old car and manufacturing a new one would increase the overall impact on global warming.
To calculate in this case the optimal time of replacement [72] developed a methodology which takes future developments of cleaner vehicles into account. Today there are cleaner, energy efficient vehicle technologies available [73]. In this chapter it is discussed what can be done to optimize the environmental impact of a vehicle today. To differentiate between vehicle technologies it is investigated how long it takes a new car to have an environmental return on investment. If we replace an old car today, how fast are we going to feel the benefits? This period is the environmental breakeven point, the driven distance (or time) at which the investment of launching a new vehicle starts to have an environmental benefit.

The **scope** of the study is the Belgian family car fleet. A selection was made of comparable vehicles with different vehicle technologies (Table 74. LCA seeks to compare the impacts of different products throughout their lifetime. A **functional unit** is used to have a comparable analysis. The chosen functional unit is the use of a passenger car in Belgium over a lifetime driven distance of 230,500 km corresponding to a vehicle lifespan of 13.7 years [13], [74]. In this assessment, Ecoinvent [11] default **allocation** criteria such as energy content, exergy, weight and unit price are always used for the background system.
Different environmental impacts are considered in this assessment: acidification [62], eutrophication [62], mineral extraction [63], energy [75], greenhouse effect [61] and respiratory effects of inorganics [64]. For each specific impact calculation method, only the pollutants involved in the method are taken into account with respect to the characterization factor attributed to each pollutant. Of course other impacts will have different results, but the aim is to develop a theoretical framework to deal with the environmental breakeven point.

IX.3 Inventory

In this study, detailed environmental impacts of the different vehicle technologies are assessed for the small family car segment. A selection was made of comparable vehicles with different vehicle technologies (Table 74). The Volkswagen Golf was used as a reference model as it is available since Euro 2 and is still a popular car on the Belgian market. When no VW Golf model was available, comparable cars have been chosen from the database. For the CNG technology, the Opel Zafira was used, for BEV the Nissan Leaf and for petrol hybrid the Toyota Prius. The Nissan Leaf is considered to have a Lithium battery of 300kg. The Toyota Prius has a NiMH battery of 56kg.
A far-reaching life cycle inventory step has been elaborated covering all the inputs and outputs from and to the environment from all the unit processes involved in the product system. No explicit cut-off criteria have been defined. Whenever possible, all vehicle materials and life cycle steps have been taken into account. The inventory is, in other words, a broad list of all the needed materials, chemicals, energies and all the emissions related to the fulfilment of the functional unit. The life cycle inventory, which was created in the framework of the ‘CLEVER’ project, covers all the life cycle phases of conventional and alternative vehicles [76]. It includes

the extraction of raw materials, the manufacturing of components, the assembly, the use phase (on a well-to-wheel basis) and the end-of-life treatment. When specific Belgian data are not available, average European data are considered.

Manufacturing

The LCI data of the 'Golf A4, 1,4l Otto' [48] used in the ecoinvent database [26] have been adapted to model the manufacturing phase of all vehicles with respect to their specific weights. For the hybrid and BEV, the LCI of the Golf A4 has been used to model only the body shell. Detailed LCI data of different battery technologies for hybrid electric (HEV) and battery electric vehicles (BEV) have been collected from the SUBAT project [77]. The manufacturing phase considered in this assessment contains material production, component production, assembly and transportation to the end-users.

Use phase

The use phase of the vehicles is split up into Well-to-Tank (WTT) and Tank-to-Wheel (TTW). The WTT part covers the production and the distribution of the fuel while the TTW phase covers the use of this fuel by the vehicle. Data concerning petrol, diesel and the Belgian electricity supply mix are gathered from the Ecoinvent database [11]. At the TTW side, the major part of the data is from the Ecoscore database [14]. It includes technology, weight, fuel consumption and homologation emissions of all the registered vehicles in Belgium.

Beside the homologation data, heavy metal emissions and non-exhaust particle emissions [49] are added to the TTW model. Table 74 gives an overview of the tailpipe emissions, fuel consumption and weight of the different vehicle technologies. The maintenance phase is modelled as a part of the use phase to calculate the environmental breakeven point. This phase includes the tyres, the washing water and the lead-acid battery and has been modelled with inputs from the LCI of the Golf A4 combined with assumptions from the IMPRO-CAR project [47].

Table 74: Overview of the tailpipe emissions, fuel consumption and weight.

Fuel/ Technology	Euro standard	Fuel consumption [l/100km]	CO_2 [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	SO_2 [g/km]	PM [g/km]	N_2O [g/km]	CH_4 [g/km]	Weight [kg]
Petrol	Euro 2	8.9	213	2.200	0.275	0.225	0.00134	0	0.013	0.020	1197
Petrol	Euro 5	6.2	144	0.286	0.028	0.045	0.00094	0	0.005	0.020	1215
Diesel	Euro 2	6.2	164	1.000	0.070	0.630	0.00105	0.08	0.005	0.010	1333
Diesel	Euro 5	4.9	128	0.245	0.040	0.136	0.00083	0.001	0.008	0.010	1264
LPG	Euro 5	7.1	169	0.330	0.032	0.012	0.00117	0	0.005	0.020	1247
CNG	Euro 5	7.8	139	0.215	0.065	0.022	0	0	0.005	0.124	1660
Hybrid	Euro 5	3.9	89	0.258	0.058	0.006	0.00059	0	0.005	0.020	1370
BEV	Euro 5	0,15 kWh/km	0	0.000	0.000	0.000	0	0	0	0.000	1587

End-of-life phase

An end-of-life scenario including the transport to the recycling plant, depollution, shredding and the sorting has been defined in this study. As specified in the EU directive for EoL vehicles (2000/53/EC), batteries are removed during the depollution step and treated separately. For the specific case of NiMH and lithium batteries, a pyrometallurgical process has been used to recover nickel and lithium oxides [51]. Specific rates of material and energy recovery per type of material which were collected in the framework of the OVAM survey on Belgian recycling plants, are used [10]. The OVAM survey data reflect the state-of-the-art in Belgium. The recycling efficiency and the recycling process' energy consumption are taken into account in the model.

IX.4 Results

Environmental breakeven point

The overall LCA results for a full lifetime driven distance of 230,500 km is given in Table 75 for the different considered impact categories: acidification, eutrophication, mineral extraction, energy, greenhouse effect and respiratory effects of inorganics. In Table 76, Table 77 and Table 78 this data are subdivided in different life phases (manufacturing, usage, end-of-life treatment) these tables are used to calculate the environmental breakeven point with equation 3. The results are divided in the different life phases and the results of the use phase are given per km.

Table 75: Overview of total life cycle impact of the considered vehicle technologies

TOTAL	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Acidification [g SO_2 eq.]	1.82E+05	1.20E+05	2.06E+05	1.11E+05	5.68E+04	9.31E+04	9.56E+04	7.93E+04
Eutrophication [g PO_4 eq.]	1.93E+04	1.05E+04	2.83E+04	1.21E+04	4.65E+03	8.07E+03	7.35E+03	7.49E+03
Mineral extraction damage [MJ]	2.02E+03	2.02E+03	2.20E+03	2.08E+03	2.69E+03	2.05E+03	2.35E+03	2.75E+03
Energy [MJ]	9.63E+05	6.95E+05	7.36E+05	5.95E+05	9.12E+05	5.98E+05	4.99E+05	5.26E+05
Greenhouse effect [g CO_2 eq.]	6.43E+07	4.45E+07	4.77E+07	3.82E+07	3.98E+07	4.89E+07	3.04E+07	1.67E+07
Respiratory effects [points]	2.69E+00	1.57E+00	3.33E+00	1.54E+00	9.40E-01	1.34E+00	1.36E+00	1.09E+00

Figure 14: Overview of the impact on climate change for the different vehicle technologies, after a full lifetime of 230,500kmFigure 15: Cumulative burden on climate change for the different vehicle technologies give a detailed overview of the impact on climate change for the different vehicle technologies, after a full lifetime of 230,500km (13.7 years). Figure 14: Overview of the impact on climate change for the different vehicle technologies, after a full lifetime of 230,500km shows the division of the LCA results into the different life phases. The use phase is divided in a well-to-tank (WTT), tank-to-wheel (TTW) and maintenance step. The petrol Euro 2 vehicle has the largest impact on the greenhouse effect. The petrol vehicle has the highest fuel consumption, which explains the high WTT and TTW emissions. Thanks to the hybridization of the drive train, the hybrid vehicle manages to decrease fuel consumption and accordingly the impact on the greenhouse effect. As a consequence, the hybrid vehicle has the lowest impact of all internal combustion engine vehicles, considered in this assessment. The BEV has overall the lowest impact on the greenhouse effect. Figure 15: Cumulative burden on climate change for the different vehicle technologies gives an insight in the cumulative environmental burden of a specific vehicle. The first impact at zero driven distance is due to the manufacturing process. During the usage of a vehicle the cumulative environmental burden grows per kilometre. The negative values are avoided impacts due to the recovery of materials in the end-of-life (EoL) recycling step.

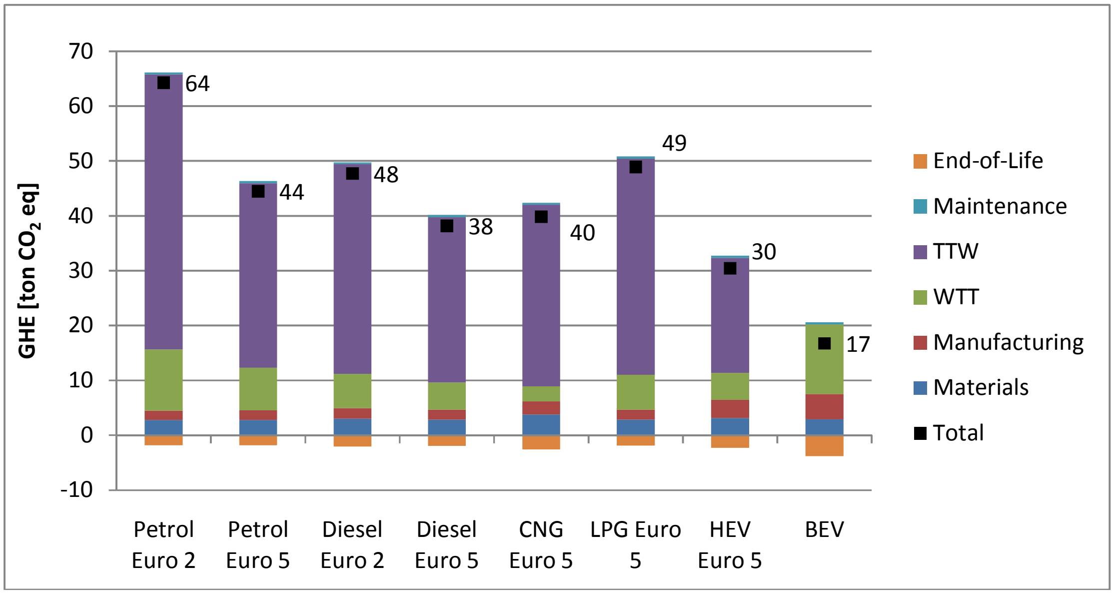

Figure 14: Overview of the impact on climate change for the different vehicle technologies, after a full lifetime of 230,500km

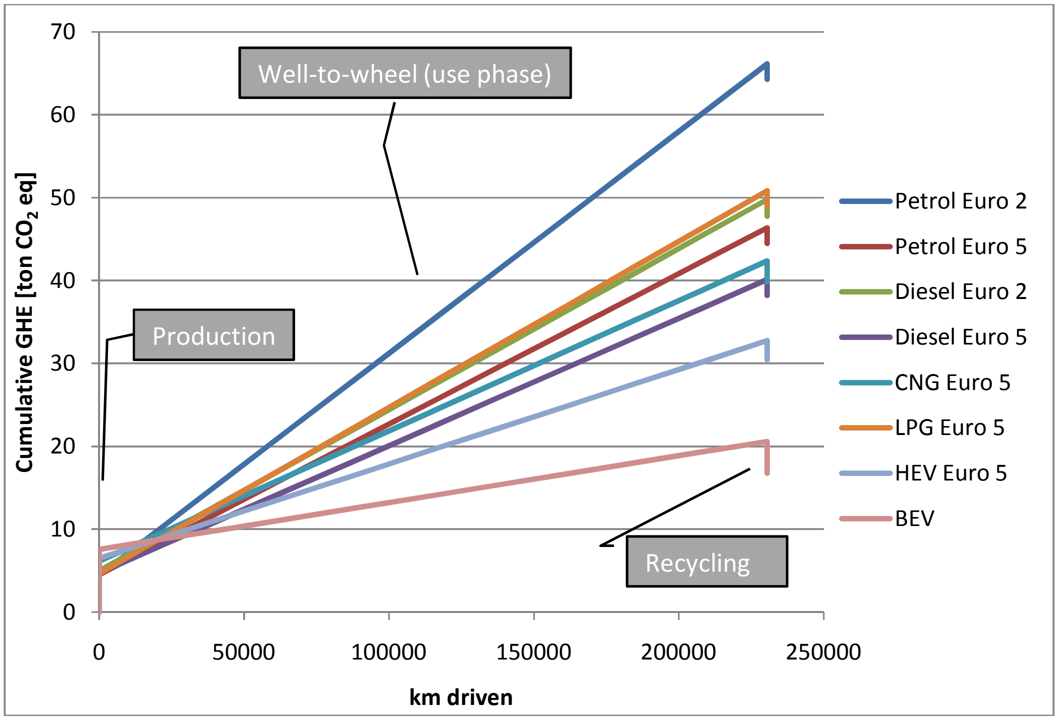

Figure 15: Cumulative burden on climate change for the different vehicle technologies

The **environmental breakeven point** is introduced as the driven distance (or time) at which the investment producing a new vehicle starts to have an environmental benefit. The environmental breakeven point (D_b) will be dissimilar for each pair of cars and is shown in Figure 16: Environmental breakeven point of the replacement of a vehicle.. Each impact category will also give a different set of environmental breakeven points.

Figure 16: Environmental breakeven point of the replacement of a vehicle. shows four choices when dealing with the replacement of a car, the environmental burden is shown in function of

the time. At time zero the decision is made to replace the car or not. Line 1 (black) shows the cumulative environmental burden of the decision to keep on using the old vehicle, at the end of its lifetime it will be recycled. The old car was already manufactured, so the impacts during manufacturing are not changed by the decision. Therefore, the cumulative environmental burden of line 1 is only function of the maintenance and the well-to-wheel emissions. Line 2 represents the replacement with a cleaner vehicle, at distance D_b the environmental benefit of replacing the old vehicle starts. The offset of the environmental burden is due to the impact during manufacturing of the new vehicle, taking the end-of-life treatment and its negative (or avoided) impacts into account of the old vehicle. In situation 3 the benefit of use phase of the new vehicle is not big enough to have an environmental return on investment in an appropriate time frame. In situation 4 the impact of the manufacturing is too big to be compensated by the use phase, this is especially true when investigating impacts like mineral extraction damage.
The manufacturing of the old car is not allocated to the environmental burden of this car, as it is not influenced by the replacement decision. The transport, shredding and further separation processes the old vehicle are allocated to decision 2, 3 and 4. The End-of-Life (EoL) treatment is based on the state-of-the-art of the Belgian recycling activities [10].

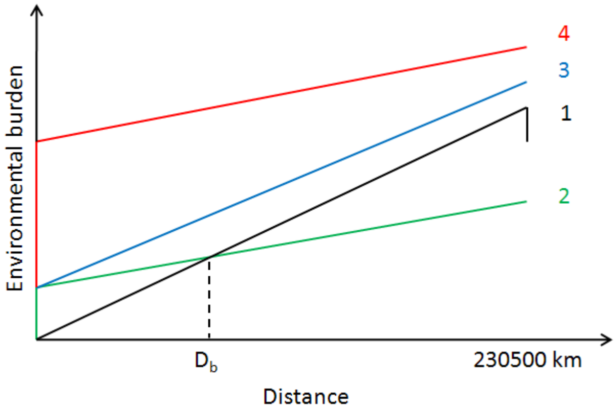

Figure 16: Environmental breakeven point of the replacement of a vehicle.

The environmental breakeven point distance (D_b), described in Figure 16: Environmental breakeven point of the replacement of a vehicle., can be calculated by expressing that the impact ($I_{\text{no replacement, Db}}$) of decision 1 (no replacement) is the same as decision 2 (replacement after D_b km) and solving it for D_b.
The environmental burden for the “no replacement” scenario at distance D_b is given by equation 1.

$$I_{no\ replacement,Db} = D_b \cdot i_{Use\ vehicle\ 1} \qquad (1)$$

The environmental burden for the “replacement” scenario at distance D_b is given by equation 2.

$$I_{replacement,Db} = I_{Man.\,vehicle\ 2} + D_b \cdot i_{Use\ vehicle\ 2} + I_{EoL\ vehicle\ 1} \qquad (2)$$

With:

$I_{\text{no replacement, Db}}$	the impact for the scenario “no replacement” after D_b km”
$I_{\text{replacement, Db}}$	the impact for the scenario “replacement” after D_b km

D_b	environmental breakeven point, expressed in km
$i_{\text{Use, vehicle j}}$	the impact per km on the use phase (Well-to-wheel and maintenance) of vehicle j
$I_{\text{Man, vehicle j}}$	the impact of the manufacturing phase of vehicle j
$I_{\text{EoL, vehicle j}}$	the impact of the End-of-life treatment phase of vehicle j

The environmental breakeven point can be calculated with equation 3.

$$D_b = \frac{I_{\text{Man, vehicle 2}} + I_{\text{EoL, vehicle 1}}}{i_{\text{Use, vehicle 1}} - i_{\text{Use, vehicle 2}}} \, km \tag{3}$$

In Table 76: Overview of the different environmental impacts of the manufacturing phase, Table 77: Overview of the different environmental impacts of the use phaseand Table 78: Overview of the different environmental impacts of the End-of-Life treatment these data are subdivided in different life phases (manufacturing, usage, EoL treatment). These tables are used to calculate the environmental breakeven point with equation 3. The results of the use phase are given per km.

Table 76: Overview of the different environmental impacts of the manufacturing phase

Manufacturing ($I_{\text{Man, vehicle j}}$)	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Acidification [g SO_2 eq.]	4.28E+04	4.34E+04	4.75E+04	4.51E+04	5.89E+04	4.45E+04	7.77E+04	6.71E+04
Eutrophication [g PO4 eq.]	2.95E+03	2.99E+03	3.28E+03	3.11E+03	4.07E+03	3.07E+03	3.98E+03	6.07E+03
Mineral extraction [MJ]	2.14E+03	2.17E+03	2.38E+03	2.26E+03	2.94E+03	2.23E+03	2.84E+03	2.47E+03
Energy [MJ]	1.03E+05	1.05E+05	1.15E+05	1.09E+05	1.43E+05	1.08E+05	1.47E+05	2.05E+05
Greenhouse effect [g CO_2 eq.]	4.46E+06	4.53E+06	4.96E+06	4.71E+06	6.16E+06	4.64E+06	6.48E+06	7.56E+06
Respiratory effects [points]	5.61E-01	5.69E-01	6.23E-01	5.91E-01	7.73E-01	5.84E-01	9.41E-01	8.93E-01

Table 77: Overview of the different environmental impacts of the use phase

Use phase per km ($i_{\text{Use, vehicle j}}$)	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Acidification [g SO_2 eq.]	6.56E-01	3.81E-01	7.44E-01	3.37E-01	5.89E-02	2.63E-01	2.27E-01	1.86E-01
Eutrophication [g PO_4 eq.]	7.66E-02	3.79E-02	1.15E-01	4.49E-02	1.01E-02	2.74E-02	2.17E-02	1.44E-02
Mineral extraction damage [MJ]	5.71E-04	4.60E-04	4.13E-04	3.70E-04	3.15E-04	3.67E-04	3.66E-04	3.00E-03
Energy [MJ]	3.91E+00	2.74E+00	2.89E+00	2.29E+00	3.58E+00	2.31E+00	1.74E+00	1.72E+00
Greenhouse effect [g CO_2 eq.]	2.68E+02	1.81E+02	1.94E+02	1.54E+02	1.57E+02	2.00E+02	1.14E+02	5.65E+01
Respiratory effects [points]	9.96E-06	5.05E-06	1.25E-05	4.89E-06	1.70E-06	4.03E-06	3.53E-06	3.18E-06

Table 78: Overview of the different environmental impacts of the End-of-Life treatment

End-of-life ($I_{\text{EoL, vehicle j}}$)	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Acidification [g SO_2 eq.]	-1.15E+04	-1.17E+04	-1.27E+04	-1.21E+04	-1.57E+04	-1.20E+04	-3.45E+04	-3.06E+04
Eutrophication [g PO4 eq.]	-1.26E+03	-1.28E+03	-1.41E+03	-1.33E+03	-1.75E+03	-1.32E+03	-1.63E+03	-1.89E+03

Mineral extraction damage [MJ]	-2.53E+02	-2.56E+02	-2.73E+02	-2.63E+02	-3.20E+02	-2.60E+02	-5.81E+02	-4.08E+02
Energy [MJ]	-4.05E+04	-4.11E+04	-4.50E+04	-4.27E+04	-5.59E+04	-4.21E+04	-4.96E+04	-7.65E+04
Greenhouse effect [g CO_2 eq.]	-1.84E+06	-1.87E+06	-2.05E+06	-1.94E+06	-2.54E+06	-1.92E+06	-2.29E+06	-3.84E+06
Respiratory effects [points]	-1.65E-01	-1.67E-01	-1.82E-01	-1.73E-01	-2.25E-01	-1.71E-01	-3.89E-01	-5.40E-01

The environmental breakeven point (D_b) for climate change is calculated and presented in Figure 17: Environmental breakeven points for climate change.. The lines represent the 'old' vehicles that are replaced by the new vehicle. The squares represent the environmental breakeven points. This is where the cumulative impact of the new vehicle crosses the line representing the old vehicle. As the BEV has the lowest impact on climate change, no other vehicle has a breakeven point with the cumulative line of the BEV, in the figure this is represented by the green line without squares. When replacing a petrol Euro 2 vehicle (grey line) the benefit of the replacement on GHE is obtained after only 5000 kilometres for all types of vehicles. The replacement of the petrol EURO2 vehicle with a Diesel Euro 5 vehicle has the earliest benefit, followed by the BEV and the HEV. This is due to the extra impact of the production of the battery of a BEV. However, after 5000 kilometres, the BEV (green square) reaches already his breakeven point with the Diesel Euro 5 vehicle (brown line).

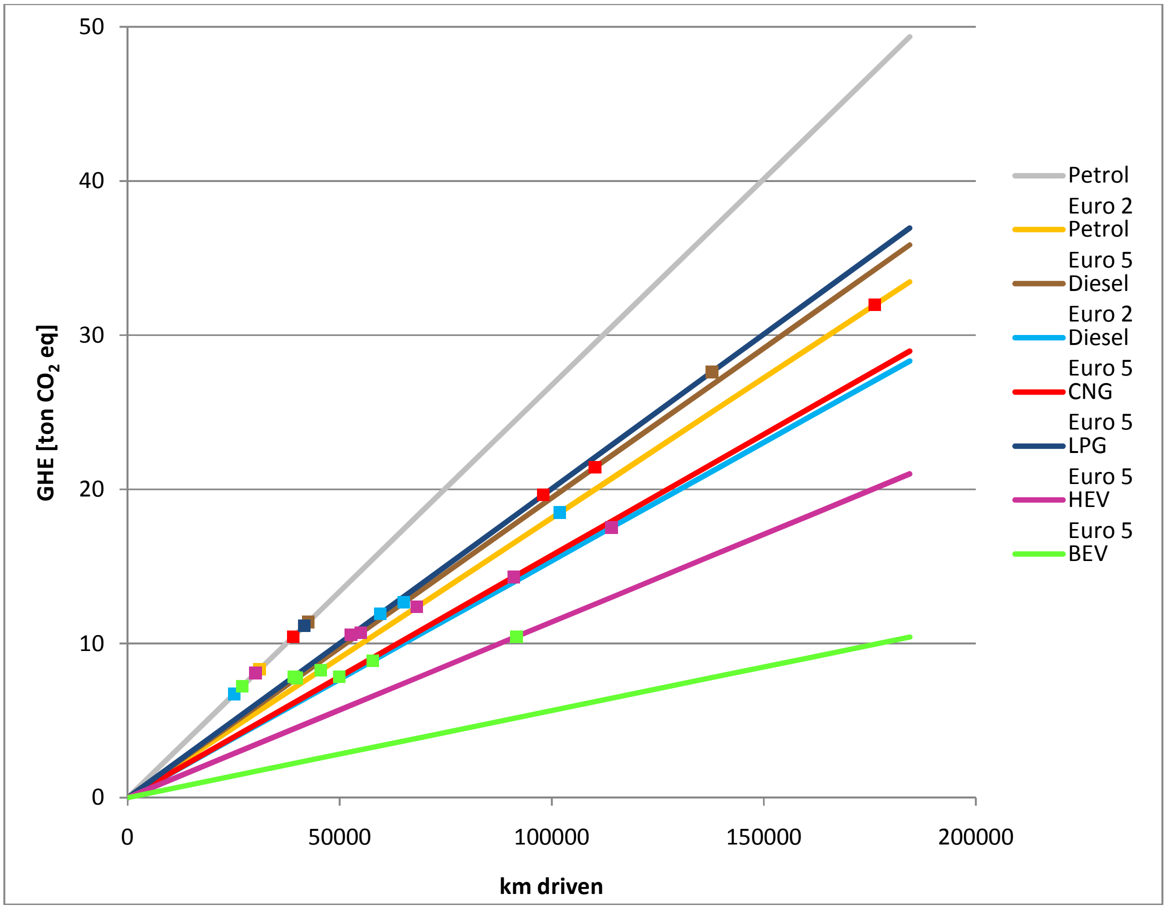

Figure 17: Environmental breakeven points for climate change.

The detailed information of the breakeven points for climate change are given in Table 79. The environmental breakeven points are given for the replacement of a vehicle in column i with vehicle in row j. Only positive values are withheld. Values higher than the total lifetime driven distance (230,500 km) are not in bold, since a higher value means that the replacement will have no positive effect during the vehicles' lifetime. For instance, in column 4 the breakeven points for replacing a diesel Euro 2 vehicle with another vehicle technology are given. Replacing a diesel Euro 2 vehicle with a diesel Euro 5 vehicle will have a benefit on the GHE after 65,151 kilometres.

Each impact category will also give a different set of environmental breakeven points, all impact categories and their corresponding sets of breakeven points are given in Table 79: Environmental breakeven point for the greenhouse effect when replacing a vehicle in column i with vehicle in row j and Table 84: Environmental breakeven point for mineral extraction damage when replacing a vehicle in column i with vehicle in row j.

Table 79: Environmental breakeven point for the greenhouse effect when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Petrol Euro 2	-	-	-	-	-	-	-	-
Petrol Euro 5	**31,150**	-	**191,292**	-	-	**137,740**	-	-
Diesel Euro 2	**42,587**	-	-	-	-	508,445	-	-
Diesel Euro 5	**25,123**	**101,888**	**65,151**	-	621,813	**59,607**	-	-
CNG Euro 4	**39,083**	**176,170**	**110,228**	-	-	**98,011**	-	-
LPG Euro 4	**41,674**	-	-	-	-	-	-	-
HEV Euro 5	**30,158**	**68,201**	**55,011**	**114,109**	**91,035**	**52,715**	-	-
BEV	**27,074**	**45,512**	**39,943**	**57,784**	**49,823**	**39,189**	**91,723**	-

Table 80: Environmental breakeven point for acidification when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Petrol Euro 2	-	-	340,354	-	-	-	-	-
Petrol Euro 5	**116,111**	-	**84,512**	-	-	-	-	-
Diesel Euro 2	-	-	-	-	-	-	-	-
Diesel Euro 5	**105,203**	748,727	**79,429**	-	-	-	-	-
CNG Euro 4	**79,321**	**146,435**	**67,323**	**168,411**	-	**230,052**	**145,039**	**223,010**
LPG Euro 4	**83,971**	277,467	**66,038**	439,597	-	-	-	-
HEV Euro 5	**154,384**	428,783	**125,660**	599,945	-	1,846,966	-	-
BEV	**118,131**	283,313	**97,274**	364,292	-	714,586	785,335	-

Table 81: Environmental breakeven point for eutrophication when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Petrol Euro 2	-	-	**40,348**	-	-	-	-	-
Petrol Euro 5	**44,720**	-	**20,634**	237,445	-	-	-	-
Diesel Euro 2	-	-	-	-	-	-	-	-
Diesel Euro 5	**58,349**	-	**24,401**	-	-	-	-	-
CNG Euro 4	**42,268**	**100,246**	**25,482**	**78,678**	-	**159,180**	**209,852**	510,963
LPG Euro 4	**36,734**	**169,876**	**19,040**	**99,178**	-	-	-	-
HEV Euro 5	**49,453**	**166,163**	**27,618**	**113,933**	-	467,370	-	-
BEV	**77,295**	**203,170**	**46,466**	**155,074**	-	364,283	602,813	-

Table 82: Environmental breakeven point for energy when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 5	LPG Euro 5	HEV Euro 5	BEV
Petrol Euro 2	-	-	-	-	-	-	-	-
Petrol Euro 5	**55,242**	-	**398,045**	-	**58,531**	-	-	-
Diesel Euro 2	**73,334**	-	-	-	**85,991**	-	-	-
Diesel Euro 5	**42,642**	**153,657**	**108,052**	-	**41,562**	3,912,627	-	-
CNG Euro 4	311,664	-	-	-	-	-	-	-
LPG Euro 4	**42,190**	**156,428**	**108,744**	-	**40,977**	-	-	-
HEV Euro 5	**49,172**	**106,293**	**88,880**	**188,732**	**49,588**	**184,042**	-	-
BEV	**75,344**	**161,543**	**137,264**	**284,150**	**80,402**	276,830	8,175,660	-

Table 83: Environmental breakeven point for respiratory effects when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 4	LPG Euro 4	HEV Euro 5	BEV
Petrol Euro 2	-	-	**146,643**	-	-	-	-	-
Petrol Euro 5	**82,389**	-	**51,635**	-	-	-	-	-
Diesel Euro 2	-	-	-	-	-	-	-	-
Diesel Euro 5	**84,202**	2,643,539	**53,482**	-	-	-	-	-
CNG Euro 4	**73,634**	**180,869**	**54,468**	**187,981**	-	258,582	**210,341**	**157,340**
LPG Euro 4	**70,654**	**407,547**	**47,153**	476,083	-	-	-	-
HEV Euro 5	**120,642**	**508,012**	**84,130**	563,224	-	1,538,163	-	-
BEV	**107,495**	**388,539**	**75,960**	421,328	-	852,869	1,456,648	-

Table 84: Environmental breakeven point for mineral extraction damage when replacing a vehicle in column i with vehicle in row j illustrates the environmental breakeven points for the mineral extraction damage. It is clear that the replacement of a vehicle never has a positive effect on this impact category, as the manufacturing of a new vehicle will introduces mineral depletion. Letting a vehicle have a longer use phase avoids this specific impact.

Table 84: Environmental breakeven point for mineral extraction damage when replacing a vehicle in column i with vehicle in row j

km	Petrol Euro 2	Petrol Euro 5	Diesel Euro 2	Diesel Euro 5	CNG Euro 4	LPG Euro 4	HEV Euro 5	BEV
Petrol Euro 2	-	-	-	-	-	-	-	715,583
Petrol Euro 5	17,347,463	-	-	-	-	-	-	696,522
Diesel Euro 2	13,453,860	45,025,263	-	-	-	-	-	762,254
Diesel Euro 5	9,961,716	22,115,730	45,702,721	-	-	-	-	704,541
CNG Euro 4	10,478,971	18,436,577	27,089,235	48,688,107	-	51,078,645	46,069,104	943,665
LPG Euro 4	9,695,172	21,202,544	42,558,825	779,247,902	-	-	-	692,763
HEV Euro 5	12,622,405	27,412,255	54,392,402	681,426,815	-	2,046,808,704	-	925,299
BEV	-	-	-	-	-	-	-	-

Last distance for replacement

Another interesting point in time to calculate is the 'Last distance for replacement', point D_L in Figure 18: Last distance for replacement. D_L is defined as the last possible distance to replace the old vehicle (red line) with a new vehicle (blue line), without polluting more than in the case of no replacement. This can be seen as the average lifespan of a Belgian vehicle minus the breakeven point (D_b). This approach is only applicable if it is considered that the lifespan of the particular vehicle is the same as the average lifespan. Beyond D_L it is not interesting anymore to replace the old vehicle because the environmental benefit will be beyond the considered lifespan. The larger the difference in environmental performance between the old vehicle (polluter) and its successor (cleaner vehicle) the closer D_L can lie to the lifespan. This means one can wait longer to replace the old vehicle, while still having a positive environmental impact after 13.7 (230,500 km) years. D_L can be calculated with equation 4.

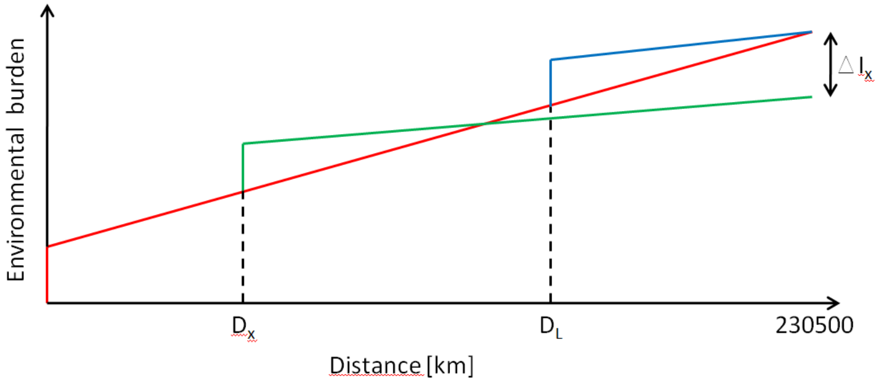

Figure 18: Last distance for replacement

$$D_L = 230{,}500km - D_b \tag{4}$$

The total environmental burden after a lifetime driven distance of 230,500 km for the replacement of an old vehicle (vehicle 1) at distance D_x by a newer vehicle (vehicle 2) is given by equation 5.

$$I_{total,Dx} = I_{Man.\ vehicle\ 1} + D_x \cdot i_{Use\ vehicle\ 1} + I_{EoL\ vehicle\ 1} + I_{Man.\ vehicle\ 2} + (230{,}500 - D_x) \cdot i_{Use\ vehicle\ 2} + I_{EoL\ vehicle\ 2} \tag{5}$$

The environmental benefit of replacing an old vehicle at distance D_x is given by ΔI_{Dx}. This is represented in Figure 18: Last distance for replacement by the difference between the environmental impact of the old vehicle (red line compared to the replacement scenario (green line). The environmental benefit can be calculated with equation 6.

$$\Delta I_{Dx} = I_{Man.\ vehicle\ 1} + 230{,}500 \cdot i_{Use\ vehicle\ 1} + I_{EoL\ vehicle\ 1} - I_{total,\mathrm{Dx}} \tag{6}$$

With:

$I_{\text{total, Dx}}$	the total life cycle impact of the decision of replacing a vehicle after D_x km
D_x	distance x, when the replacement is executed
$i_{\text{Use, vehicle j}}$	the impact per km on the use phase (Well-to-wheel and maintenance) of vehicle j
$I_{\text{Man, vehicle j}}$	the impact of the manufacturing phase of vehicle j
$I_{\text{EoL, vehicle j}}$	the impact of the End-of-life treatment phase of vehicle j
ΔI_{Dx}	environmental benefit of replacing a vehicle at distance D_x, compared to no replacement.

X. Applicability of the methodology for other transport modes

Transport is the cause of large quantities of pollutants in the atmosphere, and these have direct and indirect effects on environmental receptors (people, materials, agriculture, ecosystems and climate, etc.). VMM (Vlaamse Milieu Maatschappij) gives an overview in Figure 19: Emissions of different transport systems in Flanders [of the main pollutants introduced by motorized transportation in Flanders [78]. The emission levels are divided in different transportation modes: rail, water, air and road transport.

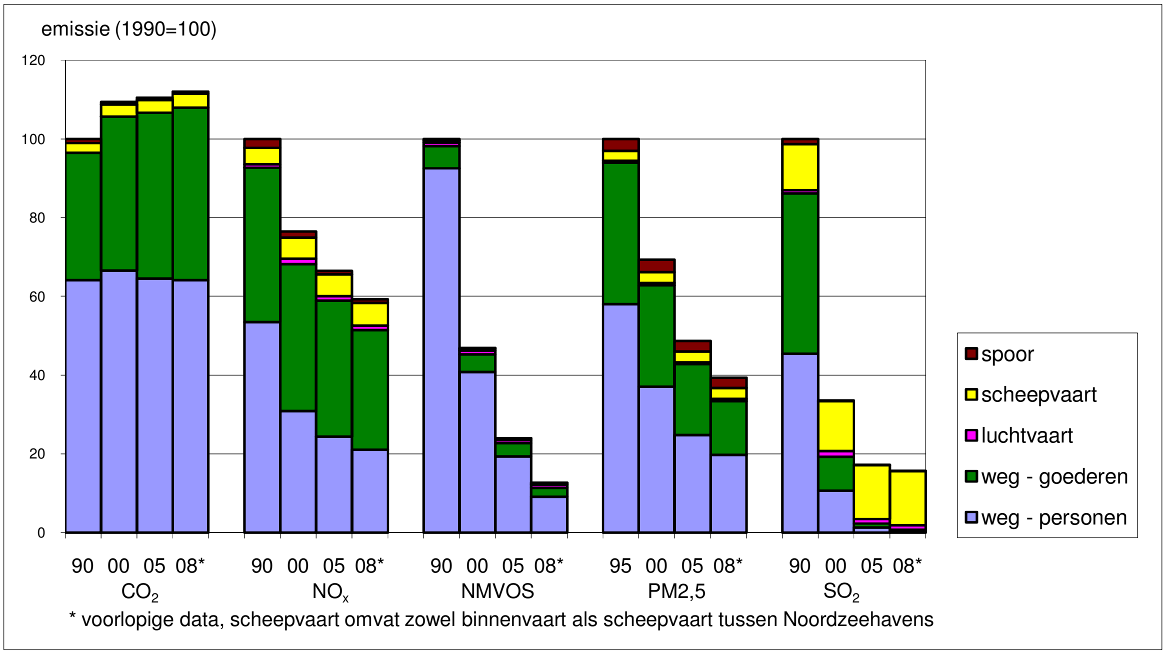

Figure 19: Emissions of different transport systems in Flanders [78]

In order to make transportation more sustainable different possible options are available: controlling the need for motorised travel (land use planning), making travel safer (driving behaviour), technical innovation and encouraging modal shifts (walking, bicycle, public transport). Among these options, technical innovation on vehicles plays a key positive role and is investigated in the CLEVER project. However, modal shifts can also play an important role to lower the environmental burden. In the CLEVER project it is not the aim to expand the model to all transport modes, but only to list the most important adaptations needed to enable such an expansion.

The environmental assessment can be expanded to other modes for passenger transport. Based on the environmental impact rating of e.g. public transport (trams, buses, trains, etc.) the public awareness of the beneficial effect of these transport modes as well as a behavioural shift can be enhanced. On the other hand policy makers might be interested in comparing freight transport by lorries with the ones by train, boat or plane.

LCA is the only efficient tool to compare the complete environmental burden of different products. It can be used to compare different transport modes. The main difference between transportation modes is the inventory part.

Before dealing with the data gathering it is clear that a first distinction has to be made based on the primary service that is delivered by the considered transportation system. A distinction between passenger and freight transportation is needed, because this will influence the Functional Unit. The Functional Unit is a quantified description of the performance of product systems, for use as a reference unit. It allows comparing two or several product systems on the basis of a common provided service. In the Clever framework, the functional unit is defined as driving with a passenger vehicle for a full Life Time Driven Distance (LTDD) of 230,500 km.

When comparing different transport modes for passengers, this LTDD is not solely applicable anymore as Functional Unit. When comparing different passenger transport modes (car, train, air plane, bus metro, tram) it is necessary to take the occupancy into account. The Functional unit should be written passenger kilometres (p.km). For freight transport the Functional Unit should include the weight of the goods that are transported (ton.km).

Since the methodology defined in the CLEVER project also includes background processes, such as the production of fuel (petrol, diesel, electricity, …) and materials (steel, copper, plastics, …) and their respective emissions the methodology can be extended to other transport modes.

When the BOM (Bill-of-Material) is available for the considered vehicles (e.g. train, urban busses) the cradle-to-grave emissions (related directly and indirectly to vehicle production and end-of-life processing of the vehicle) can be modelled in the same way as a passenger car.

The Well-to-Tank (WTT) part is already available from the inventory made in the CLEVER project, but must be completed with the specific energy usage and tailpipe emissions from the Tank-to-Wheel part of the use phase of a vehicle.

For the impact calculation itself it is suggested to use the same impact categories as in the CLEVER report. Retained classes are acidification, eutrophication, greenhouse gases, chemical toxicity indicators, depletion of the ozone layer, consumption of renewable and non-renewable energy and depletion of minerals.

XI. Main conclusions of the LCA

Comparing the environmental impact of conventional vehicles (diesel, petrol) has already shown to be a difficult exercise. Diesel cars for example are more fuel efficient and emit less greenhouse gases than petrol cars, but on the other hand emit more particulate matter and NO_x, which have a strong impact on human health. Many environmental rating tools exist which are able to give an environmental score to different vehicle technologies, but which provide different results due to the many methodologies and weighting parameters that can be used. The Ecoscore methodology is an example of such a rating tool, which is based on a well-to-wheel approach, implying that both tailpipe and indirect emissions due to the fuel or electricity production and distribution are taken into account.

The comparison becomes even more complex with the introduction of so-called ‘alternative’ fuels and drive trains (LPG, CNG, HEV, BEV, FCEV, biofuels, hydrogen). To make a fair comparison of all these fuels and technologies, not only the well-to-wheel emissions should be considered, but also the emissions due to the production, maintenance and end-of-life phase of the vehicle. In electric vehicles for instance, large batteries or a fuel cell are used, which are not present in conventional ICE vehicles and which can have a significant environmental impact.

To take all these life cycle phases and emissions into account, a Life Cycle Assessment (LCA) has been performed on a wide range of vehicles which are available on the Belgian market. LCA is an ISO-certificated methodology, which is generally used to compare products or services on a comparable basis. In the CLEVER project, an LCA methodology has been developed with a per-model applicability instead of an average vehicle LCA. This allows taking into account all segments of the Belgian passenger car market (family car, SUV, city car, etc.) and producing LCA results per vehicle technology and category. These vehicles were compared on the basis of the same provided service to the user, which has been defined as the use of a passenger car in Belgium during 13, 7 years and a lifetime driven distance of 230.500 km.

Because of the large variety of environmental impact categories, it is almost impossible and sometimes misleading to claim that a vehicle is better than the others from all viewpoints. In this project, a list of relevant environmental impact categories has been made in order to have a good appreciation of the environmental score of conventional and alternative vehicles. The impact calculation methods used in this project are: the IPCC 2007 Greenhouse Effect, The respiratory effect from Impact 2002+, air acidification and eutrophication from 'Centrum voor Milieukunde Leiden' (CML), the mineral extraction damage from Eco-indicator and the consumption of renewable and non-renewable energy.

When dealing with climate impact, conventional vehicles have the highest impact. On average, diesel vehicles always score better than petrol vehicles but the sensitivity analysis reveals a strong overlap between these two technologies. BEV powered with the Belgian supply mix electricity, with the exception of the sugar cane based E85 vehicle, has a lower greenhouse effect than all the registered family cars in Belgium. However, extreme scenarios, where electricity produced from 100% coal or oil is considered, give higher eutrophication and acidification impacts to the BEV. Moreover, the climate benefit of the use of nuclear and renewable electricity in BEV as well as the maintaining of this benefit when the energy consumption increases has been demonstrated.

In general, biofuels have lower CO_2 emissions due to the CO_2 uptake during the photosynthesis of the organic matter. However, this benefit of the CO_2 uptake can be balanced by N_2O emissions deriving from nitrogen contained in fertilizers. So the type of feedstock used to produce biofuels and the agricultural practices have a strong influence on the climate impact of biofuels. Contrarily to climate impact, first generation bio-fuels have a bad respiratory effect (Sugar cane ethanol and RME) and bad acidification (RME) scores because of nitrogen-based emissions (NH_3 and NO_x) and/or sometimes PM emissions. However, a vehicle using sugar beet ethanol will have a respiratory effect and an acidification impact which are comparable to conventional cars. Again, the type of feedstock used to produce the biofuel is the main influencing parameter of its environmental score. Close to the feedstock type, the agricultural practices also influence the environmental score of biofuel vehicles. For example, the respiratory effect score of sugar cane ethanol can be highly improved by avoiding burning the sugar cane before the harvest. This is why the development and production of second generation biofuels need to be encouraged. It is important to notice that petrol and diesel vehicles are better than respectively ethanol and biodiesel vehicles for respiratory effects (inorganics). For the acidification impact, petrol and ethanol vehicles are comparable while diesel vehicles are clearly better than RME vehicles.

The use of mineral resources is also a key issue in the manufacturing, the use and the maintenance of vehicles. For this impact category, the size of a vehicle and the use of specific components requiring specific materials are the influencing parameters. Hybrid vehicles and FCEV will have a higher impact for this indicator because of the use of specific and rare materials to produce components like the NiMH battery, fuel cell and hydrogen tank. The BEV has slightly lower mineral resource damage but the contribution of the battery is still high. Another finding for this indicator is the high contribution of the transport and distribution of the electricity used to power the BEV. This is essentially due to the use of copper in the electric cables. It is important to mention that an increase of the size of a BEV will quickly increase its mineral extraction damage. The RME vehicle has an impact higher than petrol and diesel and comparable to hybrid and FCEV. This is mainly due to the use of mineral fertilizers during the rape production. Petrol, diesel and ethanol vehicles have comparable results and have the best scores after BEV and CNG.

This study has also revealed how important recycling is especially for heavy and precious metals contained in specific components such as batteries and fuel cells (FCEV, Hybrid, BEV…).

For the different impact categories considered in this study, the impacts of LPG technology are comparable to diesel. However, better environmental scores are possible for LPG by using for example flare gas instead butane/propane from oil refinery to produce LPG.

FCEV are more interesting than petrol and diesel vehicles for greenhouse effect, respiratory effect and acidification. This is mainly due to the fact that the FCEV is a TTW emission-free (except water vapour) vehicle and the fact that the hydrogen is produced with natural gas via steam methane reforming. In fact natural gas has a very low acidification impact and respiratory effect. However, the steam reforming process used to produce the hydrogen is energy intensive. As a consequence, the FCEV has a bigger WTT greenhouse effect despite its interesting overall greenhouse score. The above mentioned environmental benefits of a FCEV are only applicable when producing hydrogen from methane. Producing hydrogen through electrolysis has a high environmental impact due to the energy intensity of this reforming step.

Another interesting finding of this study is that CNG vehicles appear to be an interesting alternative for conventional vehicles. It has a low climate impact (comparable to hybrid technology) and the best score for respiratory effects and acidification. It also has the lowest mineral extraction damage after BEV. However CNG is produced with a fossil fuel. So, CNG vehicles will become more interesting with the development of the biomethane sector.

Finally, it appears in this study that the vehicle segment has a strong influence on the LCA results. In general, the bigger the segment (e.g. from supermini to large family car), the worse the environmental score. Additionally, when comparing the results for the different vehicle segments, the trends between the different vehicle technologies remain the same.

The results of the LCA were compared with the results of the Ecoscore methodology (calculated as Total Impact) for different vehicle technologies and different ages within the same technology. Since the Ecoscore has to be calculated for all available vehicles, it is limited by the fact that only the emissions due to the well-to-wheel phases of the vehicle are readily available and can be used as a basis to calculate their environmental impact. The LCA methodology on the other hand, is not limited by these restrictions and offers the possibility to show very detailed results and this for a large range of impact categories. Therefore LCA can give a more profound image of the actual environmental impact of a vehicle.

Taking into account these considerations, the Ecoscore methodology has proven to be a good approach to estimate a vehicle's environmental impact, since the ranking of vehicles regarding their environmental performance will not be altered between both assessment methodologies. The influence of neglecting the impact of the manufacturing, maintenance and end-of-life phases has shown to be very small, especially for the conventional vehicle technologies (petrol, diesel, LPG). For hybrid and battery electric vehicles, the manufacturing and end-of-life of the battery also plays an important role, which is mainly displayed in the impact on human health and ecosystems. However, since the impact on global warming counts for 50 % in the final Ecoscore, these differences will play a smaller role and still lead to the same ranking of the vehicle technologies as in the LCA results for greenhouse effect.

This proves that the well-to-wheel approach used in the Ecoscore methodology is a solid basis for the environmental assessment of different vehicle technologies. The LCA methodology is an ideal tool to go deeper into these results and provide a thorough insight into the different impacts of a vehicle.

The environmental breakeven point is introduced as the driven distance (or time) at which the investment of launching a new vehicle starts to have an environmental benefit. The environmental breakeven point will be dissimilar for each pair of cars. A methodology and data is provided to calculate the environmental breakeven point for different types of vehicle technologies and impact categories. The included impact categories are: acidification, eutrophication, mineral extraction, energy, greenhouse effect and respiratory effects of inorganics.

The considered electric vehicle has the lowest impact on climate change and consequently it can replace every considered car when dealing with this impact category and have a positive effect after a distance ranging from 27,000 km (when replacing a Petrol Euro 2 vehicle) to 91,000 km (when replacing a fuel efficient hybrid Euro 5 vehicle). It is clear that in this situation the environmental breakeven point falls in the Life Time Driven Distance of 230,500 km (average life time of a vehicle in Belgium). Hybrid vehicles can replace all other technologies (except BEV) and still have a positive influence before the end-of-life.

Each impact category will give a different set of environmental breakeven points. The CNG vehicle has the best performance when dealing with respiratory effects. Nonetheless, the environmental breakeven point is mostly to far away in time to really provide an environmental benefit when replacing an old vehicle. This is especially true when trying to replace cleaner vehicle technologies such as LPG, hybrid and electric vehicles. Old Diesel Euro 2 vehicles, do not have a particulate filter. Due to their high PM and NO_x emissions, it is always beneficial to replace such a vehicle with another vehicle technology.

When introducing automobile replacement policies in order to accelerate the adoption of cleaner vehicles by taking old vehicles out of the fleet, one must bear in mind that such a scrappage policy is focussing on reducing environmental impacts introduced during the use phase. The policy advise would be to replace the old vehicle as soon as possible with a cleaner vehicle technology in order to maximise the environmental benefits.

Conversely, letting a vehicle have a longer use phase avoids specific impacts during manufacturing, such as mineral extraction damage. It is clear that the replacement of a vehicle cannot have a positive effect on this impact category, as the manufacturing of a new vehicle will always introduces mineral usage and depletion. Letting a vehicle have a longer use phase avoids this specific impact. To expand the LTDD the focus will lie on durability and maintenance. In this case the policy advise would be to replace the old vehicle as late as possible.

The 'Last distance for replacement', is introduced and defined as the last possible distance to replace an old vehicle with a new vehicle, without polluting more than in the case of no replacement. This can be seen as the average lifespan of a Belgian vehicle minus the breakeven point. Beyond the 'Last distance for replacement' it is not interesting anymore to replace the old vehicle because the environmental benefit will not take place in the considered lifespan. Finally, the environmental benefit of replacing an old vehicle at a certain moment during its lifecycle is being defined by the difference between the environmental impact of the old vehicle compared to the replacement scenario.

References

---

[1] EUCAR/JRC/CONCAWE, Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, 2006.

[2] European Commission, Directorate-General for Research/IER University of Stuttgart, Extern E-Externality of Energy, 2005.

[3] De Ruyck J., Lavric D., Bram S., Navak A., Jossart J-M., Remacle M-S., Palmers G., Dooms G., Hamelinck C., Liquid Bio-fuels in Belgium in a global Bio-energy context, January 2005.

[4] European Comission, PREMIA: Measures for the promotion of bio-fuels, May 2007.

[5] SGS-Ingenieure,Okologischer vergleich voor rapsöl mit RME und Stellungnahme, October 2001.

[6] SenterNovem, Particpative LCA on Bio-fuels, Report 2 GAVE-05.08, 2005.

[7] Lane B., Life Cycle Assessment of vehicle fuels and technologies, March 2006.

[8] VITO & 3E, Biobrandstoffen in Vlaanderen, February 2006.

[9] SUBAT, « Sustainable batteries », project funded by the European Commission http://www.battery-electric.com/documents.php , 2004

[10] OVAM, IBGE/BIM, OWD en RDC Environment, Validation of the recycling rates of end-of life vehicles, June 2008.

[11] Swiss Centre for Life Cycle, ecoinvent Data V2.01, CD-ROM, ISBN 3-905594-38-2, Dubendorf, 2007

[12] http://statbel.fgov.be/fr/statistiques/chiffres/circulation_et_transport/circulation/distances/index.jsp, visited on July 22, 2010

[13] FEBELAUTO, rapport annuel 2006.

[14] Timmermans J-M. Matheys J., Van Mierli J., Lataire P., Environmental rating of vehicles with different fuels and drive trains: a univocal and applicable methodology, European journal of transport and infrastructure research, 6(4), pp. 313-334, 2006

[15] The European Parliament and the Council of the European Union, Directive 98/69/EC relating to measures to be taken against air pollution by emissions from motor vehicles, 1998.

[16] Sergeant N. 1, Boureima F.-S., Matheys J., Timmermans J.-M. & Van Mierlo J., An environmental analysis of FCEV and H2-ICE vehicles using the Ecoscore methodology, World Electric Vehicle Journal Vol. 3, ISSN 2032-6653, 2009

[17] Chasserot M., Integrated approach to mobile air conditioning testing and labeling, European Commission's Public Consultation: reaching the 130 g/km objective through vehicle technology, July 2007

[18] Council of the European Communities, Directive 92/21/EEC on Masses and dimensions of motor vehicles of category M1, March 1992

[19] Frischknecht R., Jungbluth N., Althaus H-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G. and Spielmann M., The ecoinvent Database: Overview and methodological framework, International Journal of LCA, 2004

[20] Frischknecht R., Niels Jungbluth N., Althaus H-J., Doka G., Dones R., Heck T., Hellweg S., Hischier R., Nemecek T., Rebitzer G.; Spielmann M.; Wernet G.,Overview and methodology, ecoinvent report No.1; 2007

[21] http://www.fcai.com.au/, Visited on 09 September ,2008

[22] www.euroncap.com visited on July 25, 2007

[23] www.fisita.com, Visited on September 9, 2008

[24] Reniers J., FEDERAUTO Magazine, Aout/September 2007

[25] www.ecoscore.be, visited on 3rd Jully 2010

[26] Spielmann M., Bauer C., Dones R., Tuchschmid M., Ecoinvent report no 14 : Transport services, Data V2.0, Villigen and Uster, December 2007.

[27] Kudoh Y., Nansai K., Kondo Y., Tahara K., Life Cycel CO2 emissions of FCEV, BRV and GV in actual use, EVS 23 proceedings, Anaheim, 2007

[28] http://automobiles.honda.com/fcx-clarity/specifications.aspx, visited on March 9, 2009

[29] Product ecology consultants, SimaPro 7.1.8, 2008, The Netherlands

[30] Strauss k., Brent A. C., Hietkamp S., Characterization and Normalization factors for life cycle impact assessment –Mined Abiotic Resources Categories in South Africa-The manufacturing of catalytic converter exhaust system as a case study, International journal of LCA , November 2006

[31] Amatayakul W, Ramnäs O, Life cycle assessment of a catalytic converter for passenger cars , Journal of Cleaner Production , September 2001

[32] Dones R., Bauer C., Bolliger R., Burger B., Roder A., Faist-Emmenegger M., Frischnecht R, Jungbluth N., Tuchschmid M., Ecoinvent report No 5: Life cycle inventories of energy systems: results for current systems in switzerland and other UCTE countries, Villigen and Uster, December 2007.

[33] Boureima F., Sergeant N., Messagie M., Wynen V., Well-to-Wheel analysis of new vehicle technologies for future vehicle markets, Study performed by ETEC for Electrabel, Confidential, December 2009

[34] http://economie.fgov.be/energy/energy_statistics/Statistics_fr_005.htm , visited on 29 July 2008

[35] Faist-Emmenegger M., Heck T, Jungbluth N., Tuchschmid M.,Ecoinvent report No 6 : Erdgas, Data V2.0, Villingen ,December 2007.

[36] Prieur A., Favreau D., Vinot S., Well-to-Tank technology pathways and carbon balance, Deliverable 4.3, Roads2hycom project, January 2009

[37] Althaus H.-J., Chudacoff M., Hischier R., Jungbluth N., Osses M., Primas A.,Helleweg S., Ecoinvent report No 8, Life cyle invsntories of chemicals,Dubendorf, December 2007

[38] Jungbluth N,, Ecoinvent report No 6, Part 4, Erdoel, Data V2.0, Uster, 2007

[39] www.wikipedia.org , visited on 31 July 2008

[40] CONCAWE, EUCAR, JRC, 2007, Well-to-Wheels analysis of future automotive fuels and power trains in the European context", Well-to-Wheels Report, version 2c

[41] http://wps.com/LPG/WVU-review.html , visited on 5 August 5 2008

[42] AEGPL-Europe, Automotive LPG-Autogas: A competitive alternative fuel for improving air quality, 2004

[43] Niels Jungbluth N., Faist-Emmenegger M ,Dinkel F., Doka G., Chudacoff M., Dauriat A.,Spielmann M., Sutter J., Kljun N., Keller M., Schleiss k., Ecoinvent report No.17: Life Cycle Inventories of Bioenergy, Uster , December 2007

[44] Van Den Bossche P., Vergels F., Van Mierlo J., Matheys J., Van Autenboer W., SUBAT: an assessment of sustainable battery technology, Journal of power sources, Volume 162. Issue 2, November 2006

[45] HyHeels – Hybrid High Energy Electrical Storage, EC 6th Framework Programme, , coordinated by Siemens VDO Automotive and 11 partners.

[46] Teslamotors, http://www.teslamotors.com/blog2/?p=39, accessed on September 16, 2010

[47] Nemry F., Leduc G., Mongelli I.,Uihlen A., Environmental Improvement of Passenger cars(IMPRO-car), JRC-European Comission, 2008

[48] Schweimer G. W, Levin M., Life Cycle Inventory for the Golf A4, 2000

[49] European Environment Agency, CORINAIR: the Core Inventory of Air Emission in Europe, Atmospheric Emission Inventory Guidebook, December 2006

[50] Hischier R., Ecoinvent report no 18, part V: Disposal of electronic and electric equipment, Swiss centre for life cycle inventories, St-Gallen, 2007

[51] Fisher k:, Wallén E:, Laenen P-P; Collins M.; Battery Waste Management Life Cycle Assessment; final report for publication; commissioned by the UK department for environment, food and rural affairs (Defra), October 2006

[52] Michael S, Hans-Jörg A, Can a prolonged use of passenger reduced environmental burdens?, Journal of Cleaner Production, 2007

[53] Biofuel Sustainable End Uses (BIOSES), funded by the Belgian science policy in the framework of science for sustainable development (SSD), 2007-2010

[54] Szwabowski S J., Hashemi S., Stockhausen W F., Natkin R J., Reams l., Kabat D M., Potts C., ' Ford Hydrogen Engine Powered P2000 Vehicle' SAE technical paper series, Ford Motor Co., World Congress, Detroit Michigan, 2002

[55] http://automobiles.honda.com/fcx-clarity/specifications.aspx , visited on September 10, 2008

[56] IBGE-BIM/Guignard Aude, Timmermans Jean Marc, « Coûts financiers directs et indirects engenders par l'installation de systèmes d'air climatisé dans les voitures particulières », february 2005

[57] International; Standardisation Organisation, Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006), Geneva, 2006

[58] International; Standardisation Organisation, Environmental management - Life cycle assessment - Requirements and Guidelines (ISO 14044:2006), Geneva, 2006

[59] European Commission, Joint Research Centre, ILCD Handbook, International Reference Lifce Cycle Data System,: General Guide for Life Cycle Assessment-Detailed Guidance, Ispra, 2010

[60] European Commission, Joint Research Centre, ILCD Handbook, International Reference Lifce Cycle Data System,: Analysis of Existing Environmental Impact Assessment Methodologies for Use in Life Cycle Assessment , Ispra, 2010

[61] IPCC Fourth Assessment Report. Climate Change 2007. The Physical Science Basis. http://www.ipcc.ch/ipccreports/ar4-wg1.htm

---

[62] Guinée J. B., Gorrée M., Heijungs R., Huppes G., Kleijn R., de Koning A., van Oers L., Wegener Sleeswijk A., Suh S., Udo de Haes H. A., de Bruijn H., van Duin R., Huijbregts M. A. J., Lindeijer E., Roorda A. A. H., Weidema B. P., Life cycle assessment; An operational guide to the ISO standards; Parts 1 and 2. Ministry of Housing, Spatial Planning and Environment (VROM) and Centre of Environmental Science (CML), Den Haag and Leiden, The Netherlands, retrieved from:http://www.leidenuniv.nl/cml/ssp/projects/lca2/lca2.html.

[63] Goedkoop M. Spriensma R. (1999a) The Eco-indicator 99: A damage oriented method for life cycle impact assessment. PRé Consultants, Amersfoort, 1999

[64] Jolliet O., Margni M., Charles R., Humbert S., Payet J., Rebitzer G., Rosenbaum R., IMPACT 2002+: A New Life Cycle Impact Assessment Methodology, International Journal of Life Cycle Assessment, 8(6), pp.324-330, 2003

[65] Moreira J. R., Sugarcane for energy, recent results and progress in Brazil, Energy for sustainable development, 200

[66] Estado Sao Paolo, Lei 11241/02 | Lei nº 11.241, de 19 de setembro de 2002 de São Paulo, Dispõe sobre a eliminação gradativa da queima da palha da cana-de-açúcar e dá providências correlatas, 2002.

[67] European Commission (1999). Methodolgy for calculating transport emissions and energy consumption (MEET). Transport research, Fourth Framework Programme, Strategic Research, DG VII – 99, Luxembourg.

[68] ExternE project (1997). Externalities of Energy, fol. 2 – Methodology. A report produced for the European Commission, DG XII, Luxembourg.

[69] Van Mierlo J. & Macharis C. (2005). Goederen- en Personenvervoer: Vooruitzichten en Breekpunten, (Freight and passenger transport: prospects and breaking points), Garant, ISBN 90-441-4908-7, 579p

[70] Keoleian G., Menerey D. (1993). Life Cycle Design Guidance Manual: Environmental Requirements and The Product System; U.S. Government Printing Office: Washington, DC, EPA600-R-92-226.

[71] Stahel, W. R. (1994). In The Greening of Industrial Ecosystems; Allenby, B. R., Richards, D. J., Eds.; NationalAcademyPress: Washington, DC, pp 178-190.

[72] Kim H. C., Keoleian G., Grande D., Bean J. (2003). Life cycle optimization of automobile replacement: model and application, Environ. Sci. Technol. 5407-5413.

[73] Messagie M., Boureima F., Sergeant N., Matheys J., Turcksin L., Macharis C. and Van Mierlo J. (2010). ‘Life Cycle Assessment of conventional and alternative small passenger vehicles in Belgium’, IEEE VPPC 2010, Vehicle Power and Propulsion Conference, Lille, France, 1-3 September 2010.

[74] FPS Economy (2010). http://statbel.fgov.be/fr/statistiques/chiffres/circulation_et_transport/circulation/distances/index.jsp, accessed on July 22, 2010

[75] VDI. (1997), "Cumulative Energy Demand - Terms, Definitions, Methods of Calculation." VDI-Richtlinien 46000.

[76] Van Mierlo J., Boureima F., Sergeant N., Wynen V. , Messagie M.,Govaerts L., Denys T., Vanderschaeghe M.,Macharis C., Turcksin L., Hecq W., Englert M.,Lecrombs F.,Klopfert F.,De Caevel B., De Vos M. Clean Vehicle Research: LCA and policy measures (Clever), Final report Phase two. Brussels, Belgium: Belspo: 'http://www.belspo.be/belspo/ssd/science/Reports/CLEVER_Finalreport_phaseI_ML.pdf', 2011.

[77] Matheys J., Timmermans J., Van Mierlo J., Meyer S., Van Den Bossche P., Comparison of the environmental impact of 5 electric vehicle battery technolgies using LCA., International Journal of sustainable manufacturing, pp 318-329, ISBN-ISSN: 1742-7223, 2009.

[78] VMM (2007). Milieurapport Vlaanderen MIRA. Achtergronddocument sector transport.