Master Thesis

# Life Cycle Assessment of the Hybrid Vehicle – Toyota Prius


by

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A thesis submitted in partial fulfillment of the requirements

for the degree of Mechanical Engineering

in the

Institut für Werkzeugmaschinen

und Fertigungstechnik

September 2013

# DECLARATION BY STUDENT

I hereby declare that the present Master thesis was conducted autonomously and without illegitimate help or counsel from third party using only the stated scientific resources and referenced literature.

Braunschweig, 27th September 2013

_______________________________________

(Tiago Mendes Henriques)

*I dedicate this thesis to*

*my family, parents and sister*

*for their constant support and unconditional love.*

*I love you all*

# KURZFASSUNG

Die Luftverschmutzung, die globale Erwärmung sowie die Verknappung der endlichen Ressourcen sind die größten Bedenken der vergangenen Jahrzehnte. Die Nachfrage nach jeglicher Mobilität steigt rapide. Dementsprechend bemüht ist die Automobilindustrie Lösungen für Mobilität unter dem Aspekt der Nachhaltigkeit und dem Umweltschutz anzubieten. Die Elektrifizierung hat sich hierbei als der beste Weg herausgestellt, um die Umweltprobleme sowie die Abhängigkeit von fossilen Brennstoffen zu lösen.

Diese Arbeit soll einen Einblick über die Umweltauswirkungen des Hybridfahrzeuges Toyota Prius geben. Hierbei findet eine Gliederung in vier verschiedene Lebensphasen statt. Im Anschluss bietet die Sachbilanz die Möglichkeit die Umweltauswirkungen mit verschiedenen Antriebsmöglichkeiten und Brennstoffen zu vergleichen.

Das Modell hat gezeigt, dass der Toyota Prius während der Nutzung einen hohen Einfluss auf das Treibhauspotenzial aufweist. Durch die Nutzung anderer Brennstoffe, wie beispielsweise Ethanol oder Methanol lassen sich die Auswirkungen am Treibhauspotenzial sowie der Verbrauch an abiotischen Ressourcen reduzieren. Vergleicht man die Elektromobilität mit der konventionellen, so ist festzustellen, dass diese Art der Mobilität die derzeit beste Möglichkeit zur Reduzierung der Umweltbelastungen bietet. Die Auswirkungen der Elektromobilität sind im hohen Maße abhängig von der Art des verwendeten Strommixes.

# ABSTRACT

Air pollution, global warming and shortage of crude oil are all the major concern of recent century. The demand for mobility is rising rapidly and the automotive industry has been striving over the last years to find measures to deal with this concern. Electrification has been seen as the most suitable way to mitigate the environmental problem and fossil fuel dependence.

This study intends to give an insight about the environmental impact of the hybrid vehicle, Toyota Prius considering all the life stages, and afterwards apply the life cycle inventory to assess other possible hybrid combinations by using different fuels to compare the environmental impact.

The hybrid Prius, has shown to have a considerable impact in the use phase, namely in the impact category, global warming. However, by using some another fuel solutions, for instance methanol or ethanol blended with biomass, the impacts can be reduced substantially such as, global warming and resources depletion of abiotic resources.

Compared with other technologies, the electric vehicle has revealed definitely to be the most suitable measure to mitigate the environmental impact, once its overall impact is lower than all the other technologies here mentioned. The impact of this technology has demonstrated to be highly dependent on the electricity mix.

# ACKNOWLEDGEMENTS

This is so far the largest challenge of my education and life. It has been very exciting to do something completely of my own and without distinct answers, but sometimes also very frustrating and difficult.

At the end all feelings are the gratitude, affection and attention of all the people who made this thesis possible and an unforgettable experience in my life. Therefore I would like to express my gratitude to everyone who has assisted and encouraged me during this work directly and indirectly

First and foremost I would like to express my gratitude to my supervisor Dipl.Wirtsch.-Ing. & Ingénieur diplômé Patricia Egede, for the chance to write the thesis at Institut für Werkzeugmaschinen und Fertigungstechnik and to make this project possible.

I am grateful to the Technische Universität Braunschweig for offer me the opportunity to study abroad.

My sincere thanks to my dear colleague Christoph Herms, for the patience and unyielding confidence kept me on track even when my own confidence waned.

Special thanks to the members of the IWF. They provided a friendly and cooperative atmosphere which helped me, giving me strength to continue.

I wish to thank everyone who gave me strengths to complete this thesis, specially my international friends for their great support. Without their continued efforts and support, I would have not been able to bring my work to a successful completion.

Finally, but definitely not the least I owe hugely to my dear parents and sister, for their sacrifices made throughout my academic life are simply ineffable. Their permanent love and confidence on me have encouraged me to go ahead in my study and career.

Once again I simply and humbly say thanks to you all.

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# ABBREVIATIONS

| Abbreviation | Description |
|---|---|
| AC | Alternating Current |
| AER | All Electric Range |
| AFV | Alternative Fuel Vehicle |
| BEV | Battery Electric Vehicle |
| BMS | Battery Management System |
| CD | Charge Depleting Mode |
| CS | Charge Sustaining Mode |
| CV | Conventional Vehicle |
| DC | Direct Current |
| DoH | Degree of Hybridization |
| eLCar | E – Mobility Life Cycle Assessment Recommendations |
| ELCD | European Reference Life Cycle Database |
| EM | Electric Motor |
| EMS | Environmental Management Standards |
| EoL | End – of – Life |
| EREV | Extend Range Electric Vehicles |
| EU | European Union |
| EP | Eutrophication |
| EV | Electric Vehicle |
| GHG | Greenhouse Gas |
| GWP | Global Warming Potential |
| HFVS | Hydrogen Fuel Cell Vehicle |
| ICE | Internal Combustion Engine |
| ICEV | Internal Combustion Vehicle |
| ifu | Institute für Umweltinformatik Hamburg Gmbh (ifu hamburg) |
| ILCD | Internal reference Life Cycle System |
| IM | Induction Motor |
| ISO | International Organizational for Standardization |
| IWF | Institute für Werkzeugmaschinen und Fertigungstechnik |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory Analysis |
| LCIA | Life Cycle Impact Assessment |
| NiMH | Nickel Metal – Hydride |
| PHEV | Plug – in – Hybrid Electric Vehicle |
| PM | Permanent Magnets |
| PTW | Pump – to – Wheel |
| RE | Renewable Energy |

| | |
|---|---|
| RES | Renewable Energy Sources |
| SOC | State of Charge |
| SRM | Switched Reluctance Motor |
| TTW | Tank – to – Wheels |
| TUBS | Technical Universität Braunschweig |
| WTP | Well – to – Pump |
| WTT | Well – to – Thank |
| WTW | Well – to – Wheels |
| ZEV | Zero Emissions - Vehicle |

# CHEMICAL ELEMENTS

| Abbreviation | Description |
|---|---|
| $CO_2$ | Carbon Dioxide |
| HC | Hydrocarbon |
| $SF_6$ | Sulfur Hexafluoride |
| $N_2O$ | Nitrous Oxide |
| $SF_6$ | Sulfur Hexafluoride |

# 1 *Introduction*

Surveys on transportation sector have shown the number of the cars on road has continued to grow. Considering that they use petroleum as the first choice, these vehicles not only reduce petroleum resources, but also release a significant amount of exhaust, which can cause global warming, harm the environment and impact human health. The European Union, has demonstrated the overall transportation is responsible for 30% of all fuel emissions in the EU[1]

Mostly all vehicles, at the present, rely on the combustion of hydrocarbons [2].

Considering that the combustion is never ideal, unburned HCs among others pollutants are released, presenting all of them toxicity for human health. These gases are responsible for trap the Sun's infra – red radiation reflected by the ground, thus retaining the energy in the atmosphere increasing this way, the temperature which will induce ecological damages such as "*El Niño*" and regularly causes tornados, inundations and dryness. This problem is aggravated especially in urban areas due high traffic densities.

In order to cope with this concern, a new term came up *Powertrain Electrification*, which ultimately seeks, some electrical components, in order to improve the efficiency of the vehicles as well as reduce that dependence of petroleum. The starting point to electrification, in automotive sector is named Hybridization. This term means the possibility to have two or more power sources, for instance, petroleum and electricity.

Some car manufacturers have already offered hybrid vehicles in their portfolio and several others are expected to follow within the next years. Parts of them have triumphed on the market such as Toyota and Honda. Furthermore, there are an increasing number of small car manufacturers trying to enter the market with electric cars[3].

The electric vehicle usually refers to cars that are using only an electric drive system with an electro-chemical battery for electricity storage. They have ecological advantages (zero emissions) superior efficiency their efficiency is by far, higher than conventional vehicles.

However their driving ranges are much lower than the ranges of conventional cars and refuelling is a slow process. Furthermore, their costs are still too high to address the market today.

[1] (2012)
[2] Chemical compound with molecules made up of carbon and hydrogen atoms fuels in order to deliver the energy necessary for their propulsion.
[3] (Ehsani, et al., 2007 pp. 719,720)

Hybrid cars, on the other hand do not face with the driving range and refuelling problems, having so the same driving range as the conventional vehicles. Besides, they are economically attractive (when compared to the EVs) apart from high fuel efficiency, high performance, and low emissions.

Therefore hybridization is an umbrella term that includes a variety of systems where the engine and the electric machines contribute to the propulsion of the car and there are also systems that are closely related to pure battery electric cars like plug in hybrid electric vehicles (PHEV).

All these propulsion technologies are associated with the development of vehicle powertrain electrification. However, the technical and economic potential of each technology and consequently their role in future remains uncertain.

The environmental impact of a car is a complex task. According to Volkswagen Company[4] the life of a car begins long before it first takes to the road, it means, that the LCA of a car is the sum of either cycles, the fuel cycle and the car cycle, or in other words, the LCA starts from the extraction of natural resources to produces the materials and ending with conversion of the energy stored in tank of the vehicle into a mechanical energy for vehicle's propulsion, and others purposes such as heating, cooling lighting and so on.

The first step of an LCA is to define the goal and the scope, wherein the intended application of the study, the data sources, and the system boundaries are described and the criteria for selecting input and output flows or process are specified. The following step consists in an inventory, which provides a collection of data and calculation or quantification of inputs and outputs over the entire life cycle stage. Afterwards collection of data is assessed of all relevant input and output flows in the third step, which is referred to impact analysis. The last step is the summary or the conclusion from the inventory and impact analysis.

These steps are outlined in International Organization for Standardization (ISO) standard (ISO 14040, 2006).

(Volkswagen AG Group Research, 2010) [4]

## 1.1 Objectives

This thesis will provide a closer view on the performance of electrified powertrain namely the Hybrid Vehicle Toyota Prius, regarding its Life Cycle Assessment, and the goal of this thesis is to analyse in detail the Life Cycle Assessment of the vehicle Toyota Prius considering all working principles of hybrid vehicles. In pursuit of this global objective, the thesis addresses the following questions:

- Review the theoretic background of Life Cycle Assessment of Hybrid Vehicles;
- Detailed modelling of all life cycle phases of the hybrid vehicle Toyota Prius with Umberto's software following the eLCAr guidelines;
- Assessment of the environmental impact using different fuels;
- Simplified comparison with a conventional and electrical vehicles.

**STRUCTURE OF THE THESIS**

***Chapter 2*** **–** Methodology of life cycle assessment, powertrain electrification;

***Chapter 3*** **–** Study Case of hybrid vehicle-Toyota Prius with Umberto;

***Chapter 4*** – Assessment of the environmental impact using different fuels

***Chapter 5*** – Comparison with conventional vehicles and electrical vehicle

***Chapter 6*** – Conclusion

***Appendix A*** – Technical specifications –Toyota

***Appendix B*** – Impact Categories – General Tables

***Appendix C*** – Alternative Fuels **–** Graphics

# 2 *Methodology*

This chapter aims to give a general overview about the Life Cycle Assessment and Powertrain Electrification.

## 2.1 Life Cycle Assessment

Environmentally conscious decision making requires information about environmental consequences of alternative products, processes or activities. Life cycle assessment (LCA) is a systematic tool to analyse and assess environmental impacts over the entire life cycle of product.

An LCA encompasses the assessment of impacts on the environment from the extraction of raw materials to the final disposal of waste, or in other words, addresses the environmental aspects and potential environmental impacts over the life cycle from raw materials extraction, manufacturing, product use, recycling to final disposal, identifying and quantifying the environmental impacts at each stage, as shown in the Figure 2.1.

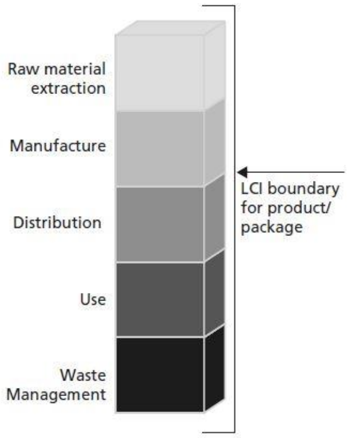


Figure 2.1 – Boundary of LCA[5]

However is important point out, that LCA is a decision supporting tool not a decision making, which means this tool should be used accompanied by other tools to identify impact areas, that will support sustainable development

Thus, it can be defined also as a tool that is responsible for carry out an integrated analysis of the environmental impact of products at all stages in their life cycle.

A major international initiative in this direction is the series of environmental management standards (EMS) proposed by the International Standards Organization, widely known as ISO 14000[6].

[5] (Lave, et al., 1995)

According to this norm, an LCA involves a *"Holistic"* approach or *"cradle – to – grave"* approach, which sets out a systematic procedure for compiling and examining the inputs and outputs of materials and energy and associated its environmental impacts throughout its entire life cycle[7].

Although conceptually simple and appealing, the formulation of an LCA is an inherently complex task with many possible pathways to reach the desire objectives, especially in the use phase, because it can be hard to predict how the consumer will use and ultimately dispose of the product. For this reason sometimes is performed an LCA only Cradle--to--gate approach which includes all the processes up to the product – use phase. Hence cradle – to – gate gives results more reliable and also provides information on which manufactures can act effectively.

In the Figure 2.2 is shown these different stages.

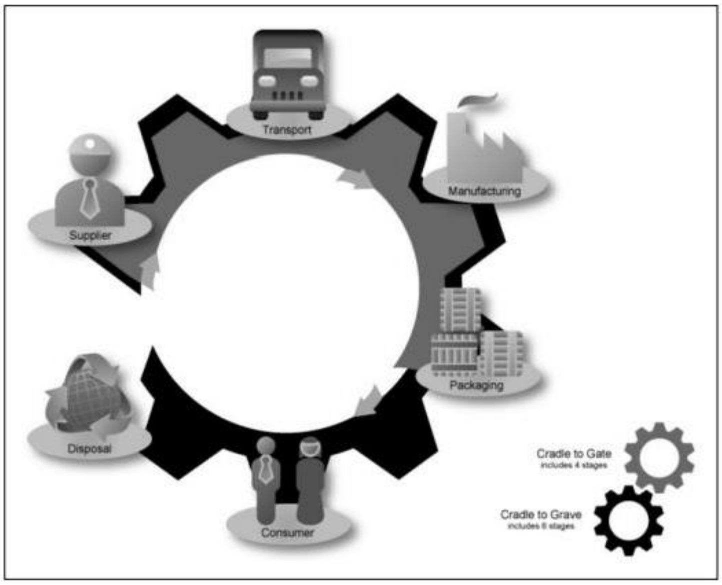


Figure 2.2 - Cradle - to- Grave versus Cradle - to Gate

The life cycle assessment of automotive technology is a complex task, because producing the fuel is only half of the process. Different vehicles have different efficiencies ratios, as well as different environmental impacts during their production, use and dismantling phase. Being so, the only way to assess all the process is to assess separately the fuel cycle and the vehicle cycle, as illustrated in the Figure 2.3 and the entire LCA is the sum of these two processes, also called Well--to--Wheels (WTW).

The "*fuel cycle*" also known as, well – to – tank (WTT) or upstream stage. It incorporates the feedstock or fuel production/extraction and processing/conversion to final energy, until arrive

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[6] (Tibor, et al., 1996)
[77] (ISO 14040, 2006)

to the vehicle's tank. The second stage is related to the "*vehicle cycle*" also designed tank – to – wheel (TTW) or downstream stage. This stage, deals with vehicle operation itself[8][9].

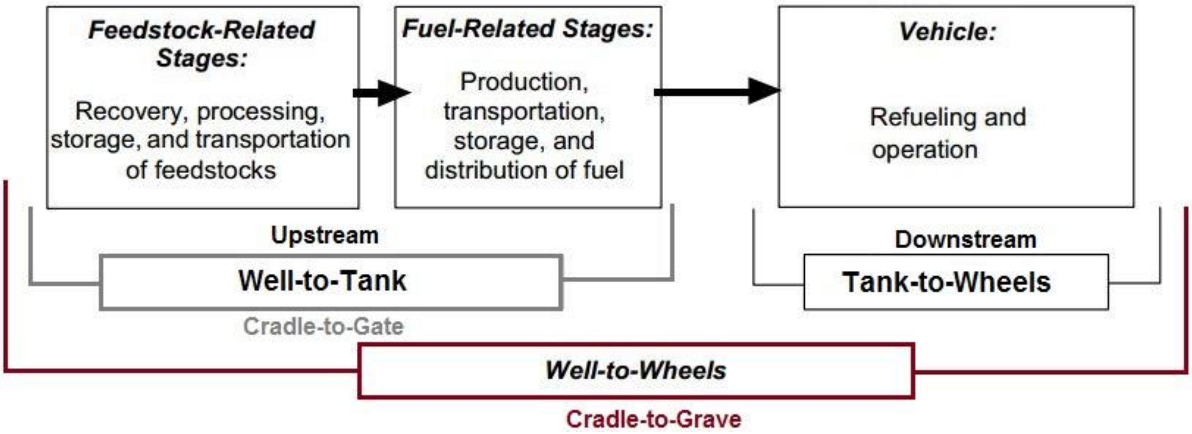


Figure 2.3 – Complete LCA: Well – to – Wheels

The targets presented on Directive 2000/53/EC[10] of the European Union End – of – Life Vehicle are envisaged from 1st of January of 2015 to increase 95% of reuse and recovery and 85% of reuse and recycling[11].

According to ISO 14000 the first step to be considered in an LCA, defines the goal and the scope of the study. The following step consists in an inventory, which provides a collection of data and calculation or quantification of inputs and outputs over the entire life cycle stage. After the inventory the data collection is assessed with all relevant input and output flows. The last step is the conclusion from the inventory and impact analysis, as shown in the Figure 2.4 provided by ISO 14040.

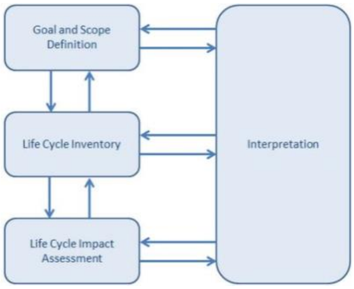


Figure 2.4 –Stages of an LCA (ISO 14040)

[8] (Faria, et al., 2012 p. 8)
[9] (Gao, et al., 2012 p. 607)
[10] This directive establishes quantified targets for the reuse and recycling and recovery of end of life vehicles including their components and materials, as well as spare and replacement parts, without prejudice to safety standards, air emissions and noise control
[11] (European Comission - Environment, 2013) – accessed May, 30 2013

### 2.1.1 Goal and Scope Definition

The goal is the first phase of an life cycle assessment. It contains some background of the study and defines why an LCA is being conducted, the reasons for carrying out the study and the intended audience (the report description shall be adequate to the audience, with technical or non-technical language), and identification who commissioned the LCA's study.

The scope describes in detail the methodological framework. It shall be clearly defined and consistent, as well as the goal, to assure the well boundaries of the system. It includes the following items:[12][13]

#### PRODUCT SYSTEM

The product system to be studied consists of a set of unit process that is linked to another by flows. Dividing the product system into its component unit processes helps in the identification of the inputs and outputs of the product system.

#### FUNCTION, FUNCTIONAL UNIT AND REFERENCE FLOW

Functional unit is used to provide a reference to which the inputs and outputs are related in a common basis (because sometimes happen different systems are being assessed), and afterwards the result of this quantification is the reference flow.

#### SYSTEM BOUNDARY

As the name stands for itself, defines the external interfaces of the product to be included in the system. Thus, this is important because ensure that all the processes are included in our system besides, all the relevant potential impacts on the environment are appropriately covered. In an ideal LCA the system boundaries will be set out all inputs and outputs are as elementary flows however, the compilation of such a broad data set requires vast resources.

#### IMPACT CATEGORIES

Every study of an LCA includes impacts on the surrounding environment. The most important impacts, are numerated below:

- Bio-diversity degradation
- Climate change
- Stratospheric ozone depletion
- Human toxicity
- Eco-toxicity

[12] (ISO 14041, 1998)
[13] (Duce, et al., 2013)

- Photo-oxidant formation
- Acidification
- Eutrophication

#### DATA QUALITY

Data quality is important because gives reliability to the study[14].

#### ALLOCATION

According to ISO 14041, is defined as the partition of inputs and outputs of a process to the product system under study.

### 2.1.2 Life Cycle Inventory

Usually is the most labour – intensive part of an LCA, because it involves data collection and calculation procedures and further how they will be organized, in order to quantify and qualify all the relevant inputs and outputs of the product system. As result of this step, all the inputs and outputs of the system are represented in flow diagram processes and normalised to the functional unit in order to avoid any double counting or also called overlap[15].

The resulting set of linear equations can be solved in order to determine all elementary interactions with the environment that are induced by any of the processes.

#### DATA COLLECTION

This step involves knowledge about each unit process in the different systems. It involves the quantitative and qualitative aspects inherent to the inputs and outputs, that are need to define the process starts and ends, as well as the function unit process[16].

#### DATA VALIDATION AND CALCULATION

After data collection, comes up the compilation and calculation procedures to generate the results of the inventory of the defined system for each unit process and for the defined functional unit of the product system. Afterwards, the data collected is checked using different methodologies for instances mass and energy balances, as well as the comparison with similar studies. Thereby, is an iterative process because normally requires a return to the data collection phase in an attempt to solve the data gap, or possibly requiring the researcher to revisit and adjust the goal, the scope or the system boundaries[17][18].

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[14] (ISO 14041, 1998)
[15] (ISO 14041, 1998)
[16] (ISO 14041, 1998)
[17] (Duce, et al., 2013)

### ALLOCATION

Allocation plays an important role in an LCA. Mathematically speaking is possible, in an ideal LCA link up the outputs to the inputs by a proportional linear relationship. However most of the industrial processes have multiple inputs, outputs and intermediate products. Therefore there is no linearity between the processes. For such cases is used allocation, otherwise for a single output would be attributed all the environmental impacts of the complex system[19][20][21].

### 2.1.3 Life Cycle Impact Assessment

According to ISO 14000, LCIA is the third phase of an LCA, and is aimed to evaluate the significance of the impact, as an indicator from an environmental perspective. The results are normally here shown at the level on human health, natural environmental and resources depletion, based on flows[22].

A classical LCIA includes at the first step, the characterization of the impact, after that they are sorted and assign to a specific impact categories. The final step consists in sum up all the impacts that are characterized into common equivalence units in order to get an overall impact category total[23].

Is important to notice that the results of LCIA should be seen as environmental impacts or as an important indicator instead of predictions of actual environmental effects[24][25]

### 2.1.4 Interpretation

Describes the final phase of an LCA, is a systematic procedure to identify, qualify, check and evaluate information from the results of the previous phases, and they are appraised, summarized and discussed as a basis for conclusions, in order to help decision-makers[26].

Moreover, this phase shall provide a readily understandable, credible and complete presentation of the results, in accordance with the goal and scope definition. Being so, is a helpful tool in decision-making, for example for information purposes, for improvements or for establishment of a new product system. Sometimes whenever LCI involves comparisons is necessary includes another activity for additional considerations[27]

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[18] (ISO 14041, 1998)
[19] (ISO 14040, 2006)
[20] (ISO 14050, 2009)
[21] (ISO 14041, 1998)
[22] (LC - Impact) accessed June 13, 2013
[23] (Duce, et al., 2013 pp. 120-130)
[24] (Duce, et al., 2013)
[25] (ISO 14042, 2000)
[26] (ISO 14043, 2000)
[27] (Duce, et al., 2013)

## 2.2 Powertrain Electrification

The increasing cost of fuels, climate change and environmental pollution have brought the great fear the society. Considering that the transportation sector plays a key role for emitters of pollutants and greenhouse gases. These concerns have stimulated namely the automotive industry which is doing special efforts in investments in R&D looking for new vehicle technologies. In order to cope with this concern, electrification of the conventional vehicles is the most promising put forwarded till now, which can lead significant improvements in vehicle performance, energy utilization efficiency, and polluting emissions[28][29].

Among several technologies, Electrical Vehicles (EVs) and Fuel – Cell – Vehicles (FCVs) are the only ones that have no emissions during their use phase, so-called *zero-emission vehicles* (ZEVs).

Another point that is worth noting is the electric motors achieve 85-90% of efficiency while a typical ICE efficiency is 28-30%[30] .

The main obstacle for EV has been the battery size, which limits travel range and consequently does not attract customers, up to now. The second option still not very attractive, due their high cost and low reliability.

Thereby, hybrid electric vehicle (HEV) presents the more appealing to customers due its high performance, high fuel efficiency, low emissions, the same travel range as conventional vehicle (CV) and its technologies and/or spare parts are markedly available. Being so, carmakers are betting in development and research in this field, for example two successful brands in the global market are Toyota and Honda[31]

The cost of the electric motors, power electronics and batteries as is well known increase with the increasing power output desired. In order to proceed toward the electrification after the HEVs technology come Plug-in Hybrid Electric Vehicles (PHEVs). They are similar to HEVs in configuration, but they use electricity from the grid to power a portion of their travel.

### ELECTRIC VEHICLE

The electric drivetrain consists mainly in three systems which are the electric motor (instead of conventional engine), energy store, and auxiliary system. The first one includes the vehicle controller, the power electronic converter, the mechanical transmission and the driving wheels. The second one comprises the energy source, the energy management unit and the

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[28] (Ehsani, et al., 2007)
[29] (Larminie, et al., 2003)
[30] (Faria, et al., 2012)
[31] (Ehsani, et al., 2007)

energy refuelling unit. The energy storages used nowadays, are mainly ultra-capacitors and flywheels. The advantages for ultra-capacitors over the batteries include long life cycles, high charge/discharge efficiency, high specific power, and wide range of operating temperatures. The drawbacks are low specific energy density and wide voltage variations which does not make possible to use ultra-capacitors alone as energy storage for EVs and HEVs. The flywheel is kind of energy supply unit that stores energy in mechanical form. It stores kinetic energy within a rotating wheel, as a disk made of composite materials. The aim of this device is to maximize the energy density, contributing to the increase of the energy stored on--board of the vehicle[32].

The auxiliary system contemplates power steering unit, hotel climate control unit, and supply unit[33].

Thereby this system allows the operation with zero emission vehicles (so – called ZEVs) at their point of use, assuming that the electricity produced came from renewable energies, as was mentioned above, is taken into account the system has virtually zero emissions.

Most new BEVs also use *regenerative braking*, which allows the electric motor to act as a generator in order to recover the energy that would normally be lost through heat dissipation and frictional losses as in ICEVs, improving so the energy efficiency and reduces brake wear.

Despite these benefits, they have higher efficiency by using an electric motor instead of Internal Combustion Engine (ICE) and quiet and smooth operation except from the tyres. All these factors contribute for an ideal vehicle for inner city and urban usage[34].

### HYBRID VEHICLES

HVs are seen by some researchers as a very promising near-term technology for improving fuel economy and reducing emissions.

This technology has two or more different power sources, such an internal combustion engine and an electric motor. They create the bridge between EVs and ICEs vehicles fusing the advantages of these two power sources, as well as, overcome some of their disadvantages.

The electricity is used only as an intermediate energy storage medium to improve the overall efficiency of the vehicle. Thus they do not need to be plugged in to recharge the battery because it is recharged automatically as the vehicle is being driven.

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[32] (Electric Power Institute)
[33] (Ehsani, et al., 2010)
[34] (Faria, et al., 2012)

As with EVs, most hybrids are endowed of regenerative braking which captures energy from braking to be put back into the battery, improving energy efficiency, fuel consumption and reduces brake wear as EVs do[35].

Despite enormous improvements in battery technology, the major limiting factor of HEVs remains in batteries due to their poor charge/discharge efficiency, short life cycles, and low current capabilities. In order to cope with these limitations, alternative energy storage units have been studied, as mentioned earlier[36].

### *Architecture*

The architecture of a hybrid vehicle is related with the connection between the components that define the energy flow (mechanical and electrical energy). Hence hybrid drive train has mainly three different types of architecture series, parallel and series-parallel[37][38].

#### *Series Hybrid System*

This architecture has two electric machines, a generator and an electric motor. This is called a series hybrid system because the power flows to the wheels is done in series as shown in the Figure 2.5

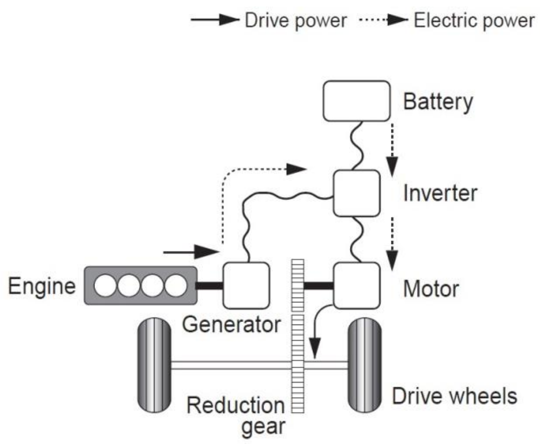


Figure 2.5 - Series Hybrid System Source : Toyota[39]

A series drivetrain architecture all the torque required to propel the vehicle is provided by an electric motor using the electricity from the battery.

[35] (Toyota Motor Corporation, May 2003)
[36] (Ehsani, et al., 2010)
[37] (Ehsani, et al., 2010)
[38] (Toyota Motor Corporation, May 2003)
[39] (Toyota Motor Corporation, May 2003 p. 2)

The engine (ICE) size is specified for keeping the batteries charged. It will feed the generator which in turn will generate electricity to store in the battery, working as a series flow or also known as cascade structure. Thus the configuration has some disadvantages such as: is heavy due the bigger size of the electric motor, expensive, bulky, reason why is used in heavy vehicles, for example heavy commercial vehicles and buses, instead of passenger cars. The energy form the engine changes its form twice to reach its destination (mechanical from engine to electric through generator and then to mechanical again through traction motor) causing significant energy losses.

However due to the fact of there is no mechanical connection between the engine and the driven wheels allows the engine to operate predominately at steady state in its most efficient mode [40][41].

***Parallel Hybrid System***

Both powers flows from the engine and the electric motor drive the wheels in parallel way, as shown in the Figure 2.6.

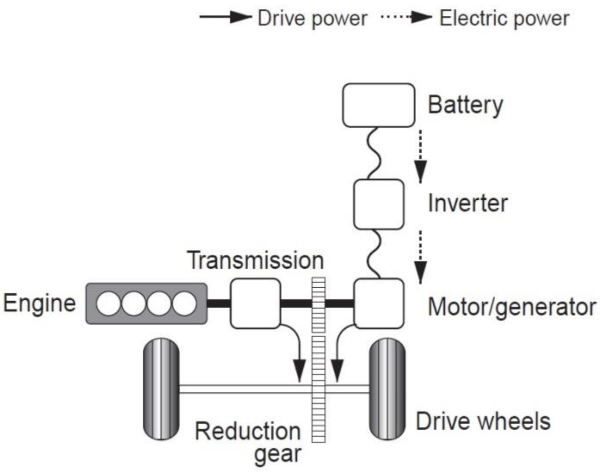


Figure 2.6 - Parallel Hybrid System Source: Toyota[42]

The engine and electric motor can directly supply their torque to the driven wheels through a mechanical coupling. This mechanical coupling may simply be a gearbox, pulley-belt unit or sprocket-chain unit, even a single axle. Thus either the battery or the engine may be used to propel the vehicle, or they may be used simultaneously when maximum power is required. Therefore there are no energy conversion occurred, thus, the losses are lesser. This configuration does not require generator which means that the system cannot drive the wheels from the electric motor while simultaneously charging the battery.

[40] (Ehsani, et al., 1997)
[41] (Ehsani, et al., 2010)
[42] (Toyota Motor Corporation, May 2003 p. 2)

By the fact of the power of the engine and motor are coupled together, the traction motor is smaller than series, thus this configuration is more compact.

In most applications, this architecture is more efficient and have only fewer components than the series architecture[43].

The main drawback lies in the mechanical coupling between the engine and the driven wheels, because the engine operating points cannot be fixed in a narrow speed region. Another disadvantage its complex structure and control. Due to its compact characteristics, parallel configuration is used by small vehicles. Most passenger cars employ this configuration, such as the Honda Insight, Honda Civic, Ford Escape, etc[44].

***Series-Parallel Hybrid System***

Series – Parallel Hybrid Drivetrain, or also called *Power – Split* combines the series and parallel system, in order to maximize the benefits of both systems reaching higher efficiency. However, it also needs an additional electric machine and a planetary unit, which makes the drivetrain somewhat complicated[45].

It has two motors, thus when necessary, the system drives the wheels while simultaneously generating electricity using a generator.

Due to this fact, this configuration offers high efficiency, because the engine power is split into two paths; one path is transferred to the drivetrain and the other to the generator.

This configuration is also endowed of a planetary gear (epicyclic). However it can be problematic due the speed ratios between the engine, the motors, and the wheels are fixed in relation to another. The planetary gear together with a motor generator plays a key role in this configuration, In this way, it becomes a simple gearbox with a fixed gear ratio. Another power (torque) source is the traction motor, which directly adds torque to the drive wheels.

When the generator/motor speed is negative or in others words in opposite direction of the torque, it operates in generating mode. But, on the other hand when the generator speed is positive, the generator/motor operates in motoring mode, adding power to the driven wheels.

This is the system used in the well – known Toyota Prius, see Figure 2.7.

[43] (Ehsani, et al., 1997)
[44] (Ehsani, et al., 2010)
[45] (Ehsani, et al., 2007)

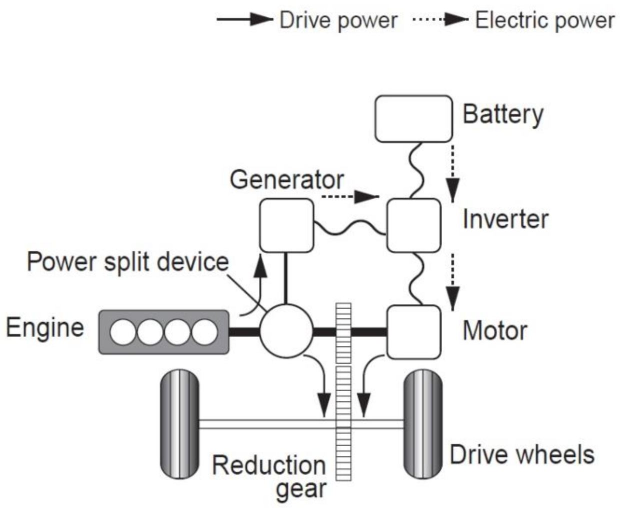


Figure 2.7 - Power Split System Source Toyota[46]

The power split is a planetary gear shown in figure above, as the name stand for itself this device splits power into two paths. The electric motor can power the car by itself, the engine can power the car by itself, or they can power the car together as parallel architecture. Another possible way can be the gasoline engine can operate independently of the vehicle speed, charging the batteries or providing power to the wheels as needed. Due the power split device allows the generator to start the engine, the car does not need a starter.

The generator is connected to the sun gear, and the engine (ICE) is connected to the planet carrier. The speed of the ring depends on all three components, thus they have to work together at all times, in order to control the output speed.

During the acceleration process, initially the electric motor and batteries provide all of the power to the wheels. By doing so, the ring gear starts to spin with the motor. Since the ring gear is spinning, the planets have to spin, which causes the sun gear and generator to spin. As the car accelerates, the generator spins at whatever speed it needs to in order for the engine to remain off.

Depending on the desired finality, each architecture present different features that may be considered. For example, if the main desired feature is simplicity, and costs thus the series architecture presents the optimal solution. On the other hand, the parallel may be a good choice, if the performance and costs are the most important features to be regarded. Finally if the drivability and performance are the desired features, then the series – parallel may be optimal[47].

[46] (Toyota Motor Corporation, May 2003 p. 2)
[47] (Pistoia, 2010)

As a remark, in both types of hybrid, the electric motor assists in acceleration, which allows for a smaller and more efficient internal combustion engine. In Figure 2.8 is presented the main features that a Hybrid Vehicle contains.

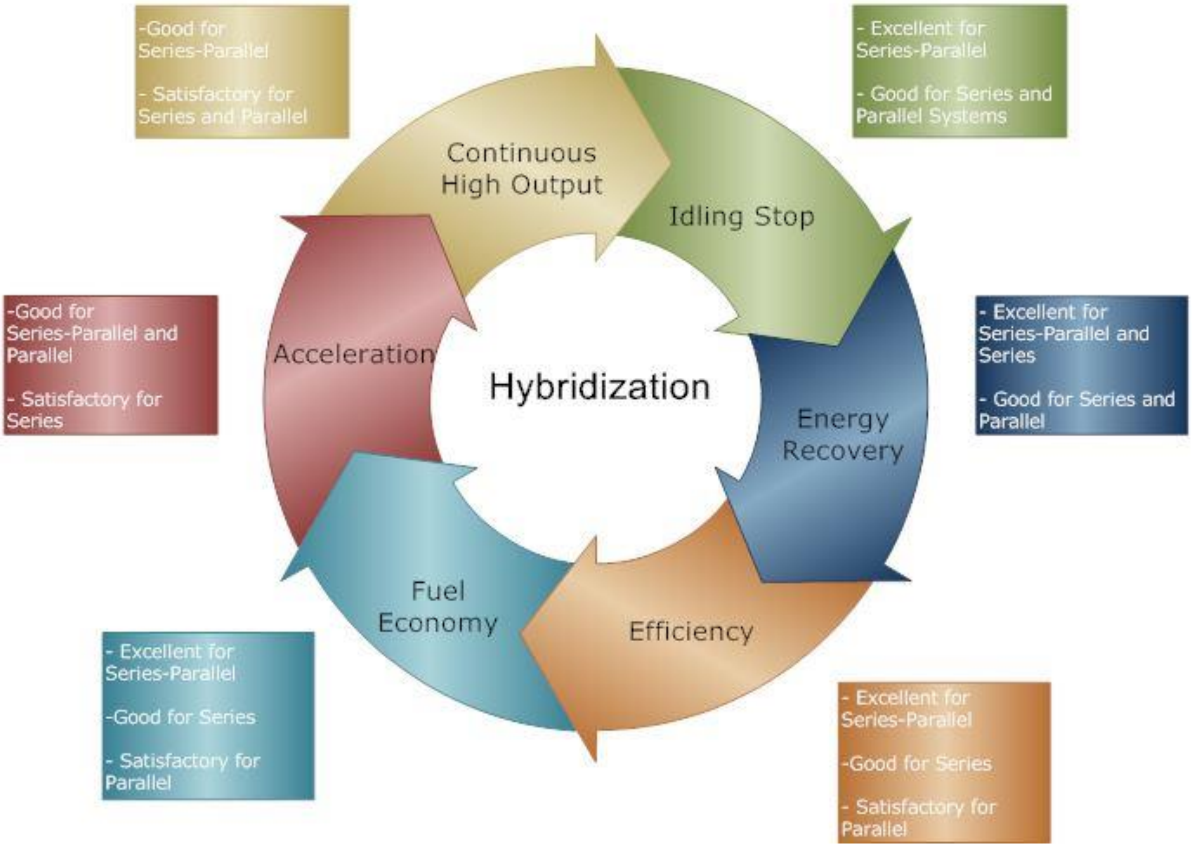


Figure 2.8 - Hybridization

With regard to *Energy Recovery* feature, series and series - parallel architecture are highly favourable due their generator, which allow them to drive the wheels while simultaneously generating electricity using a generator as mentioned earlier. In summary, the Series – Parallel architecture is up to now the solution that gathers the main features, being so, the most suitable solution having only the cost as drawback.

Concerning to the ratio of the engine and motor operation in hybrids vehicles, in series its engine generate all the energy used for the motor, thus they have the same amount of work. However, in parallel architecture the scenario is different, since the engine has the main power source, being used much more than the motor. For the Series – Parallel the power split (planetary gear) divides the power from the engine.

### *Degrees of Hybridization*

In order to reach the maximum performance, it is important to have the right combination of engine and electric motor ratio. Thus sizing the electric motor is a key point in a HEV to improve fuel economy. This ratio is defined as the hybridization factor (HF)[48][49][50].

To do so, all car manufactures and the experts of this sector are using the same criterion which is called degree of hybridization (DoH) (or also known hybridization factor HF) consists in the ratio of the power of the electric motor to the total power of the vehicle. It can be defined mathematically as follows:

$$DoH = \frac{P_{EM}}{P_{EM} + P_{ICE}} \qquad (1)$$

The term *Pem* describes the power of the electric propulsion motor and the *Pice*, is the power of the Internal Combustion Engine. DoH is 0 and 1 for conventional vehicles (CV) and all--electric vehicles (EV), respectively.

Therefore, on the basis of this criterion, the hybrid is classified according to:

### *Micro Hybrid*

The micro hybrid endowed with a small electric motor 3-5 kW (called integrated starter generator (ISG) coupled with a conventional internal engine, also known as Integrated Starter Generator (ISG) [51]. This system allows the turn off the ICE as soon as the car stops, and automatically switches it on at restarting process. This technology is called Stop\& Start, respectively. Another feature of this electric motor is the regenerative braking which makes possible recharge the battery (generally 12V) during vehicle deceleration and braking. Besides gives power supply to electrically driven accessories, including air-conditioning.

However is important to notice that the electric motor does not supply additional torque when the engine is running, due its small size. Thanks to the ISG, this hybrid can improve its fuel economy for city driving in the range 5 - 10%. This solution is adopted for many car makers such as Volkswagen blue motion, Fiat PUR $O_2$, Citroën C3, and so on.[52]

[48] (Lukic, et al., 2004 p. 386)
[49] (Albert, et al., 2004 p. 1256)
[50] (Baumann, et al., 2000 p. 59)
[51] (Chau, et al., 2007 p. 822)
[52] (Orecchin, et al., 2010)

### *Mild Hybrid*

Recently there are many carmakers adopting mild hybrids in order to intervene on emission and consumption reduction, and also because presents a reduced price when compared with full hybrids (due its careful construction) or all electric vehicles. The main difference between this solution and the micro hybrid lies in this case the electric system contributes significantly to the vehicle propulsion. Therefore the ISG is more powerful (typically 7 - 12 kW) and generally placed between the engine and the transmission.

This electric motor provides a supplementary torque to the engine when peak power is needed, for example to overtake or on uphill drives, extra power is temporarily delivered by the battery, reason why the engine is downsized. This additional motive power allows gains in fuel efficiency of the order of 10-15.

However, the traction with the electric motor by itself is not possible, except for launching step, so – called electric launch feature. It provides all other hybrid features, including idle stop and regenerative braking and power supply to electrically driven accessories, including air-conditioning. The battery voltage is typically 36-–144 V.

Honda Insight, Honda CR--Z, BMW active hybrid (7-series, the first mild hybrid of BMW) and Mercedes S400 are good examples of mild hybrids.[53][54]

### *Full Hybrid*

Engine downsizing is a well – known way of improving fuel consumption. The full hybrid as the name stands for itself is a full hybrid, which means it can offer all hybrid features mentioned so far, including obviously the downsized of the engine. Therefore a full hybrid vehicle allows starting and driving with the motor alone (electric mode) and thus zero emissions, is advantageous specially when driving at low speed or in congestion in urban areas.

However due the battery size the propulsion of the vehicle in a electric mode is possible only for short periods. The corresponding motor and battery ratings are typically 30–50 kW and 200–500 V, respectively.[55]

The Toyota Prius and Ford Escape are full hybrids. Instead of downsizing the engine, the motor can provide additional torque and hence better acceleration performance than a conventional vehicle with the same size engine. This full hybrid is sometimes termed the power hybrid.

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[53] (Orecchin, et al., 2010)
[54] (Chau, et al., 2007 pp. 821-822)
[55] (Chau, et al., 2007 pp. 821-822)

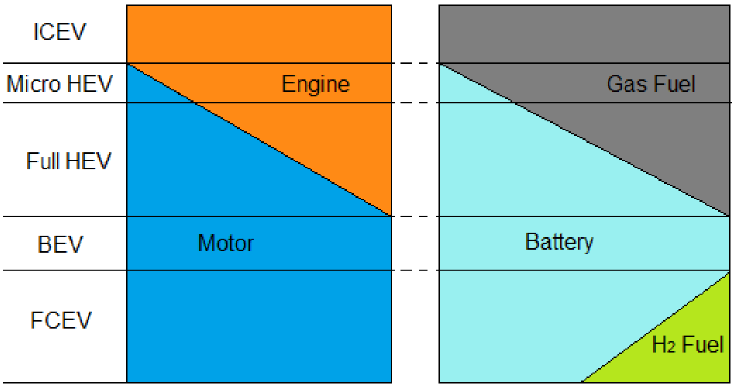


Figure 2.9 –Degree of Hybridization[56]

The Figure 2.9, aims to show how much is need each power source for different technologies.

### PLUG – IN HYBRID VEHICLES

Plug-in hybrid electric vehicles (PHEVs) combine operational aspects of both battery electric vehicles (BEVs) and hybrid electric vehicles (HEVs). Or in others words, PHEV is an HEV with the ability to recharge its energy storage system from the electricity grid to supply propulsive energy for the vehicle, therefore they have two different sources of energy available on board, the stored electrical energy from the grid and stored chemical energy in the form of fuel.

The components and vehicle architecture of PHEVs are similar to conventional hybrid-electric vehicles as mentioned earlier. Comparing to the fuel economy, they reduce $CO_2$ emissions by 25 % in the short term and as much as 50 % in the long term compared to the conventional hybrid.[57][58]

The primary difference between an HEVs and an PHEVs are the larger battery packs when compared to the HEVs. The size of the battery defines the vehicle's all electric range (AER). It can be defined as the total distance driven electrically from the beginning of a driving profile to the point at which the engine first turns on.  The nomenclature used by the carmakers, to show the sum of all miles (or km) driven with the engine off is given by $PEHV_{xx}$, where xx may be present either in miles or km. They can operate in two different modes, depending on state of charge (SOC) of the battery.[59]

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[56] (Chau, et al., 2007 p. 822)
[57] (Craigh, et al., 2008 p. 1185)
[58] (Duvall, et al., 2007 pp. 1-10)
[59] (Silva, et al., 2009 pp. 1636-1639)

When the battery is discharged until a minimum SOC is reached (normally 30 – 45%), depending on battery and powertrain configuration) is called charge depleting mode (CD), as operate EVs, or in others words the first mode is the Charge--depleting mode, where the battery discharges from its beginning state (e.g., 100% charged). Afterwards, the vehicle switches to sustaining mode (CS). When the vehicle reached this mode, both machines (ICE and EM) cooperate in the most efficient manner (operates like an HEV) and the vehicle remains in CS mode until the battery is plugged in again to recharge.

Generally the range for PHEVs is 20 - 40 miles (30 - 60km), thus the PHEV[40] can range 40 miles complete solely on electricity (is likely sometimes is necessary to take some power from the engine). Nevertheless due the increased battery weight when the PHEV is powered by the engine, the efficiency will decrease comparing with the HEV though part of this difference will be offset by the greater regenerative braking efficiency, and obviously by the capacity offered by the larger battery.[60]

PHEVs represent an important technical step toward increased fuel efficiency, decreased emissions, and greater energy independence due their efficiency, and if driven for relatively short distances, they could have zero emissions at the point of use. Because of that they are seen as one of the most promising means to improve the near-term sustainability of the transportation.

Plugging in reduces air pollution at the vehicle tail pipe, due its electric range, but on the other hand it may increase emissions at the power plant. This emissions at using phase are always linked up with the electrical efficiency and the fuel burned. For instance, recharging PHEVs with power generated by renewable energies, including wind and solar electricity, can potentially lead to low or zero PHEV emissions. The performance and impacts of PHEVs are always dependent on the conditions of use of the vehicle.[61]

The drawback of this technology is the demand for electricity is not constant over 24-hour cycle. The electric infrastructure at home, is so far, not prepared for to recharge the PEHVs simultaneously. Supposing 1 million plug-in charging their batteries from the public grid, would require almost 3.8 GW, assuming 8% of losses for distribution and 3 hours for recharging.[62][63]

[60] (Craigh, et al., 2008)
[61] (Helms, et al.)
[62] (Silva, et al., 2009 pp. 1636-1639)
[63] (Pistoia, 2010 pp. 193-210)

### HYDROGEN – FUEL – CELLS VEHICLES

Hydrogen Fuel Cell Vehicles (HFCVs) use fuel cells to generate electricity from hydrogen, without undergoing combustion. The electricity is either used to drive the vehicle or is stored in an energy storage device, such as battery pack or ultracapacitors. Since fuel cells generate electricity from isothermal chemical reaction, they do not burn fuel and therefore do not produce pollutants. The by-product of a hydrogen fuel cell is water. An HFCV provides quiet operation and more comfort for the ride.

Compared with EVs, the HFCV's have advantages of a longer driving range without a long battery charging time.

Hydrogen is the most abundant element on the planet, and it is the cleanest burning fuel on the basis of carbon atoms per fuel molecule. It also has the potential of producing only water when reacting with oxygen. A HEV with a hydrogen-fueled internal combustion (IC) engine has the potential of becoming a low-emission low-cost practical solution in the near future.

Hydrogen-fueled fuel cells are being considered as ideal candidates for future vehicles, due to their high efficiency and near-zero emission.

However, because their current high cost, low reliability, weight, bulky (due their low power density of the fuel cell system) and slow power response, these vehicles are still likely to be more of a far-term reality.[64]

### 2.2.1 Motors

The electric motor is the heart of every EV, HEV or PHEV.[65] Unlike an internal combustion engine (ICE), an electrical motor (EM) emits zero emissions, during its use phase. It is responsible for to convert the electric energy into mechanical energy to propel the vehicle, to enable regenerative braking and/or to generate electricity to charge the batteries on--board of the vehicle.

As noted earlier, EMs are inherently powerful, playing so, a key role in all kinds of vehicles studied up to now. Nowadays the most important characteristics of a motor for an EV or HEV are summarized as follows:[66]

- High instantaneous power and a high power density;
- High and fast torque at low speeds and high power at high speed;
- Constant-torque and power;

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[64] (He, et al., 2006)
[65] (Leitman, et al., 2009)
[66] (Zeraoulia, et al., 2006)

- High efficiency over wide speed range;
- Reliability and robustness;
- Price and its impact on the environment during the production (cradle – to – grave).

The most popular types of electric motors adopted by these vehicles are the induction motor (IM), the permanent magnet (PM) synchronous, and the switched reluctance motor (SRM).

### DC MOTOR

The direct current Motor Drives (DC) due them low reliability, higher need of maintenance (due commentators and brushes) and bulky construction are the main features, reasons why, they are not used in recent technologies.[67][68]

### AC MOTOR

The alternating current (AC) induction motor (IM) is quite mature, robustness, maintenance operation, high reliability and low cost are the main reasons to be part of EV, HEV and HFCV technologies. There are two types of induction motors, wound-rotor and squirrel cage motors. The first one presents high cost and maintenance, and lack robustness for this reason squirrel-cage is the elected to be part of EVs. Hereafter the squirrel cage will refer to induction motors.[69]

However these motors have some drawbacks such as high loss (especially copper losses), low efficiency, low power factor, and low inverter-usage factor, which is more serious for the high speed, large power motor. In order to cope with all these drawbacks there are on the market already technological solutions, to reduce improve their efficiency, namely control techniques. The direct competitor of this engine is the permanent magnet (PM) motor.[70]

### SYNCHRONOUS PERMANENT MAGNET (PM) BRUSHLESS MOTOR

The main design difference between these and induction motors is the presence of permanent magnets in the rotor that generate the second magnetic field. This allows the rotor to rotate at the same speed as the revolving magnetic field generated in the stator so – called "synchronous".

The permanent magnet AC brushless motors have magnets on the rotor, instead of windings on the rotor, due its higher efficiency they are widely used these days.

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[67] (Ehsani, et al., 2010 pp. 156-159)
[68] (Zeraoulia, et al., 2006)
[69] (Ehsani, et al., 2010 pp. 156-159)
[70] (Lee, et al., 205)

They have several advantages comparing with IM, for example overall weight and volume are significantly reduced (compactness), due its high – energy density magnets (rare – earth magnets), providing high torque with a small and light motor, high efficiency (as mentioned above) since they use PMs for excitations (there is no cooper losses in the windings of the rotor). They are easy for control (the control variables are easily accessible), for cooling (there is no current circulation in the rotor, thus the rotor does not heat up). Besides the have low maintenance, due the absence of brushes and low noise emissions since their commutation is electronic instead of mechanic.

Nevertheless these motors inherently have a short constant-power region due to their rather limited field weakening capability, they are expensive, since the magnets are rare and at last, they have the risk of demagnetization whenever undergo high temperatures.[71][72]

#### SWITCHED RELUCTANCE MOTOR (SRM)

SRMs are gaining much interest and are recognized to have a potential for HEV applications. They are attractive candidates because of its low cost, rugged structure, reliable converter topology, high efficiency over a wide speed range, and simplicity in control. It has no PM or winding on the rotor. The SRM has salient poles on both the stator and rotor. It has concentrated windings on the stator and no windings or PM on the rotor.

There are several configurations for SRM depending on the number and size of the rotor and stator poles. Due to its double saliency structure of the flux path for a phase winding varies with the rotor position. Comparing to synchronous (PM) mentioned above, these motors can operate with an extremely long constant-power range.[73]

The two problems associated with SR motors are the acoustic noise and torque ripple. The noise problems of SR motors are being addressed in various activities.

### 2.2.2 Batteries

The battery is used to power an electric motor. As is well known, the battery plays a key role in the future mobility. The battery is an electrochemical device responsible for converts the electrical energy into potential chemical energy during charging, and convert chemical energy into electric energy during discharging. It is composed of several cells stacked together. Each cell represents a unit that possesses all the chemical properties.

[71] (Ehsani, et al., 2010 pp. 156-159)
[72] (Zeraoulia, et al., 2006)
[73] (Zeraoulia, et al., 2006)

Due its price and weigh, on batteries the term optimize means downsize.[74]

The batteries are composed of three elements, two electrodes (positive and negative) connected by an ironically conductive material named electrolyte. When these electrodes are connected by an external device, the electrons flow from the more negative to the more positive potential. The task of the separator is preventing electronic contact, while enabling ionic transport, between the electrodes. Due all these many different compounds, its recycling process is not trivial. Diverse processes have been developed over the last years by several companies worldwide. The economic and environmental aspects of recycling obviously depend greatly on its components.

The battery represents the most expensive component in electric vehicles, due the amount of energy needed for achieve a sufficient range and a significant part of the components cost in hybrids, for instance in case of an PHEV, the battery cost can reach 50 - 80% of the total price.[75]

Its life cycle is hard to predict, as well as its number of cycles, because it depends on the usage profile. It is also worthwhile to point out that both utilization and rest time must be considered to assess the global lifetime, due to interactions between the active materials in both electrodes, positive (oxidizing) and negative (reducing). The electrolyte is never chemically stable (as should be ideally), thus slow reactions occur with the time, leading to capacity or power loss.

Up to now, several electrical energy storage and conversion devices have been considered for use in vehicle applications, in order to meet the prominent and diverse demand required by the automotive market. Therefore electric properties as well as the battery size, vary considerable with the vehicle type and size. Hence, each type of technology requires a different type of battery. As shown inFigure 2.10  the there are various types of batteries. It suggest, BEV-EV requires a larger amount of energy (high energy density [Wh/kg]), whereas HEV shall provide the maximum power (high power density [W/kg]). The Li-ion batteries can easily satisfy the HEV requirements, because the energy is much smaller than the requirements for EVs. Is also important to point out, the capacitors have a higher specific power than batteries however, their specific energy is lower.

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[74] (Pistoia, 2010 pp. 335-345)
[75] (Pistoia, 2010 pp. 19-60)

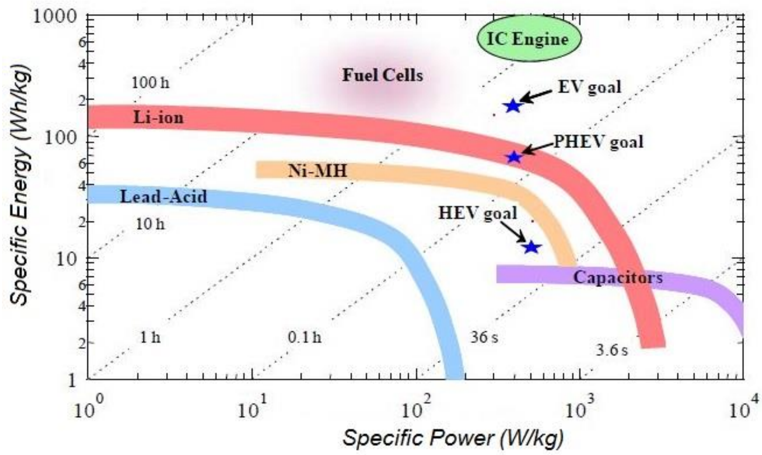


Figure 2.10 - Specific power density and specific energy[76]

Li – ion battery is the most promising candidate to use in vehicular applications.[77]

Several research have been made toward Li-ion batteries, not only because of its promising low cost in the future, compared to the Ni – MH but also due its higher power and energy, having so, all the potential to meet the requirements of a broader variety of vehicular application, namely for PHEVs and in a near future for HEVs and EVs. They are the most suitable existing technology for electric vehicles due their output high energy and power per unit of battery mass, allowing them to be lighter, which is the main aim of the electric powertrain.

During the charge, Li is removed from the cathode (positive electrode), transferred through the separator via the electrolyte and is inserted into the anode. The reverse occurs on discharge. The difference in voltage of the cathode and the voltage of the anode is the cell voltage. How quickly the Li is transferred from one electrode to the other or in other words how quickly the energy is removed is related to the power.

Furthermore these batteries allow to use different combinations of cathodes, anodes and electrolytes and depending on that combination, is found a new battery with different features (energy, power, life, safety, low temperature performance, etc.). Besides require little maintenance.[78]

One of those possible combinations is lithium manganese oxide $LiMn_2O_4$ is attractive for BEVs in many aspects, such as low cost, rather easy production process and, last but not least, thermal safety. In addition, manganese is abundant in nature.[79]

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[76] (Srinivasan, 2008)
[77] (Srinivasan, 2008)
[78] (Notter, et al., 2010)
[79] (Pistoia, 2010 pp. 405--428)

### EV'S BATTERIES

The battery represents one of the most expensive component, especially in electric vehicles, due their amount of energy needed for achieve a sufficient range. Considering that, the electric vehicle has only one power source which is electricity, thus as indicated earlier, EVs shall provide a big amount of energy, or in others words high energy density [Wh/kg].

However is important to notice that the car range is not proportional to the battery energy, because the energy consumption is due the battery weight excess. Due the large size, charging-time and the costs, its expansion and commercialization has been compromised up to now. Therefore battery leasing has been a feasible option to commercialise these vehicles.

As indicated earlier, EVs shall provide big amount of energy. However is important to point out, the car range is not proportional to the battery energy, because the energy consumption is due the battery weight excess. Due the large size and the costs, its expansion and commercialization has been compromised up to now. Therefore battery leasing has been a feasible option to commercialise these vehicles.[80]

### HEV'S BATTERIES

The batteries required for HEVs vehicles ideally shall have high power density with much less emphasis on energy density. Over the last years enormous progress have been made using Li – ion batteries for HEV application. However three main barriers remain before their commercialization: cost, safety and low – temperature operation.

The cost of HEV batteries is mainly due their electrodes are more thin, which leads a bigger separator area (area of the separator: ~25% and the electrolyte~17%)[81].

At the present, the battery mostly used in HEVs is nickel metal--hydride (NiMH), made by PEVE.[82][83] This technology was proposed by Toyota since 1997, to be part of Prius model.[84]

Nickel – Metal – Hydride batteries are used mostly for HEVs. The primary advantage of this technology is its lifetime and safety, however on the other hand, has limitations in energy, power and its costs are not promising in the near future. As shows the Figure 2.10 these batteries are the most suitable to apply in HEVs, up to now. Compared to the lithium – ion batteries, energy capacity is lower and self-discharge is higher.

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[80] (Pistoia, 2010 pp. 335-345 )
[81] (Srinivasan, 2008)
[82] Primearth Electric Vehicle Energy Co., Ltd, is a Japanese supplier of the nickel metal--hydride (NiMH) battery packs for Toyota Motor Group (namely for Prius)
[83] (Primearth EV Energy Co, Ltd) accessed July 7, 2013
[84] (Pistoia, 2010 pp. 335-345)

The main problem for HEVs batteries lies into their poor charge/discharge efficiency, short life cycles, and low current capabilities. To alleviate these intrinsic limiting factors, other technologies are coming up, to overcome these limitations, for example ultracapacitors and Flywheels are seen as an alternative energy storage technology. The advantages of ultracapacitors over batteries include long life cycles, high charge/discharge efficiency, high specific power, and wide range of operating temperatures. However they have low specific energy and wide voltage variations as energy is taken out of or put into the device[85]. The Lithium batteries are expected to a very near future to integrate hybrid car.

### PHEV'S BATTERIES

In PHEVs case high power and enough energy to power the wheels are needed.

The battery required for a PHEV is as its structure, it means that its battery is sized in a middle term between EV and HEV. In other words the most important modification, compared to HEVs is the possibility to be charged directly from an external source, and obviously its size should be bigger in order to store more energy, to increase the electric driving range.

The key issue in the design of a plug-in hybrid-electric vehicle is the selection of the battery. The battery at first is recharged from a low state-of-charge (after deep discharges) more often than for the battery powered EV. As a result, the battery cycle life requirement for plug-in hybrids will be more demanding than for the pure [BEV]. A minimum of 2000-3000 cycles will be required. Hence, both in terms of power and cycle life, the plug-in hybrid application is more demanding for the battery than the EV application The cell size (Ah) of the PHEV battery will be smaller than for EVs because the energy stored will be lesser[86].

The poor properties of batteries compared to their requirements are the main limiting factor for the development of all types of electric vehicles in the last decades. However R\& D efforts have given some promising results up to now. For instance the hybrid Toyota Prius with its battery was achieved 10 years ago and was definitely well accepted by the market. Was an important started point to the car manufactures, start with power—electrification.

Summing up, lithium-ion battery represents, so far, the most promising solution for powertrain electrification due its features. The energy density of batteries has been increasing at the rate of ~5% per year over the last 15 years[87]. In addition its chemistry is not fixed having a wide variety, that can be used, each of which can change the characteristics of the system.

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[85] (Electric Power Institute)
[86] (Burke, 2007 pp. 806-820)
[87] (Srinivasan, 2008)

# 3 *Study Case of Hybrid Vehicle-Toyota Prius with Umberto*

In the following chapter at first, is presented a technical overview of the hybrid vehicle, Toyota Prius 2013, with the aim to step forward with all the information needed for all the consideration which will be made throughout the life cycle assessment. Right after, it will be described all the procedures taken into account, as well as all the assumptions made, to model the car, with different fuels using the Umberto and the Ecoinvent, to access the database. All the Life Cycle Assessment has been conducted in compliance with the family International Organization for Standardization ISO 14000.

## 3.1 Technical Overview of Toyota Prius 2013

Prius is a Latin word meaning to "*go before"* Since January 1997, Toyota has declared the started up *Toyota Eco Project* aiming two goals, tackle the reduction of $CO_2$ emissions and fuel saving with hybrid technology. Even though pioneer, this model was well accepted by the costumers, because was the first that seats four or five people, plus its luggage and by the fact of to be, one of the most economical and eco-friendly[88].

In 1998 Toyota Motor Corporation acquired ISO 14001 certification. After that, the company has been constantly monitoring its progress toward to achieve the environmental impact reduction targets[89].

The well – known *Hybrid Synergy Drive*, allows a remarkable fuel efficiency and the most incredible without compromise its performance. Thanks to this smart technology, this system controls to the switch between petrol and electric power or to combine both for achieve the maximum efficiency, which guarantees a high performance, less fuel consumption and less gases released into the air. Moreover, is smooth and extremely quiet whenever it runs only for electrical journeys[90].

The engine of Prius 2013, is an gasoline 1.8 – litre, and instead of the conventional Otto cycle, it uses the *Atkinson cycle* [91] which allows one of the most heat – efficiency and high – expansion ratio cycles. The difference between the petrol engines lies in its crankshaft design. It has a unique design, and thanks to that, the compression and the expansion are asymmetrical, thus the valves close late delaying compression. The expansion ratio is increased by reducing the volume of the combustion chamber and the chamber is evacuated only after the explosion force has sufficiently fallen. By doing so, the engine can extract all

[88] (Toyota Motor Corporation, May 2003 pp. 1, 2)
[89] (Toyota Eco - Vehicle), accessed on July 30, 2013
[90] (Hybrid Synergy Drive), accessed on August 1, 2013
[91] Thermodynamic Cycle that illustrates how the internal combustion engine works, is similar to well - known Otto-cycle.

the explosion energy, in a most efficiently way[92]. Therefore the engine requires 20% less energy to compress the mixture and with less energy needed from the compression and more energy produced from the expansion this type of engine is more productive and more fuel – efficient than another similar gasoline engine.

Nevertheless even more fuel efficient, is slightly less powerful than the conventional Otto cycle. However, it is supported by an electric motor controlled by the smart technology, already mentioned, which compensates the lack of power output requiring less fuel[93].

### 3.1.1 How does the Hybrid system work

The table below is intended give an brief overview of all the range of the car[94].

| Driving Conditions | Engine | Generator | Motor |
|---|---|---|---|
| At rest | 🔴 | 🔴 | 🔴 |
| Start - up | 🔴 | 🔴 | 🟢 |
| Normal Driving | 🟢 | 🔴 | 🟢 |
| Accelaration from start | 🟢 | 🟢 | 🔴 |
| Accelaration | 🟢 | 🟢 | 🟢 |
| Deceleration / Braking | 🔴 | 🔴 | 🟢 |
| Reverse | 🔴 | 🔴 | 🟢 |
| Stopping | 🔴 | 🔴 | 🔴 |

Figure 3.1- Work Stages

**DESCRIPTION OF THE STAGES:**

- ***At rest*** : the vehicle does not need any power source;
- ***Start – up***: as the name stands for itself, represents the start – up of the car, the motor is the only source for the car;
- ***Normal Driving***: is used in normal driving conditions, in this state the power split plays an important role, because divides the engine output between the wheels and the generator (MG1). The generator powers the electric motor MG2, which may assist the engine for propulsion required;
- ***Acceleration from Start***: it requires the engine to feed the generator, which will transfer the electric energy to the batteries where will be stored to later on be used by the motor;
- ***Acceleration***, both the engine and MG2 propel the vehicle;

[92] (Toyota Motor Corporation, May 2003 pp. 12 , 13)
[93] (Ebrahimi, 2013 pp. 1 - 3)
[94] (Toyota Motor Corporation, May 2003 pp. 10 - 13)

- ***Deceleration / Braking***: the engine is shut down and MG2 becomes a generator and is turned by the drive wheels and recharge the HV battery pack, which act as generator and recharges the battery;
- ***Reverse***: the engine is shut down and MG2 turns in the reverse direction as an electric motor whereas MG1 turns in the forward direction and just idles;
- ***Stopping***: the engine stops automatically, unless it is necessary to charge the battery and/or run the air – conditioning compressor. [95][96][97]

In order to supplement all this information is attached within the Appendix A  the Table 8.1 all the technical features related to the Prius, model of 2013, that were considered, to step forward with the modulation.

## 3.2 Life Cycle Assessment

### 3.2.1 Goal definition

As mentioned previously the number of cars on road has continued to grow. In order to reduce their environmental impact and to fulfil the targets established by European Union, the German federal government aims the market preparation to launch battery electric vehicles. Therefore is necessary to evaluate and analyse in detail whether the electrification of the powertrain complies their potential to reduce emissions and the consumption of the resources to aid the governmental project Fleets Go Green[98], and to the thirds parties involved.

The primary motivation for this study was the desire to assess the hybrid vehicle Toyota Prius 2013, and later on, compare it using different fuels.

The life cycle of automotive technology is defined here to include all the steps required to provide the fuel, to manufacture the car, to operate throughout its lifetime up to scrapping and recycling.

### 3.2.2 Scope

The scope of the assessment includes all the relevant processes according to ISO 14040. The modulation of the vehicle will be done with Umberto software.

#### Product System

The product system is the Hybrid Vehicle Toyota Prius.

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[95] (Toyota Motor Corporation, May 2003 p. 11)
[96] (Toyota Motor Coperation, 2013), accessed July 30, 2013
[97] (Toyota - Synergy Drive), accessed July 30, 2013
[98] http://www.fleets-go-green.de/de/home

The car was modelled in Umberto. The fact of the car are broken down into small parts is because the software is not able to process all the information in just one model, due its huge amount of database behind each process or each component. Thus, the way that the models are aggregated does not have any specific meaning.

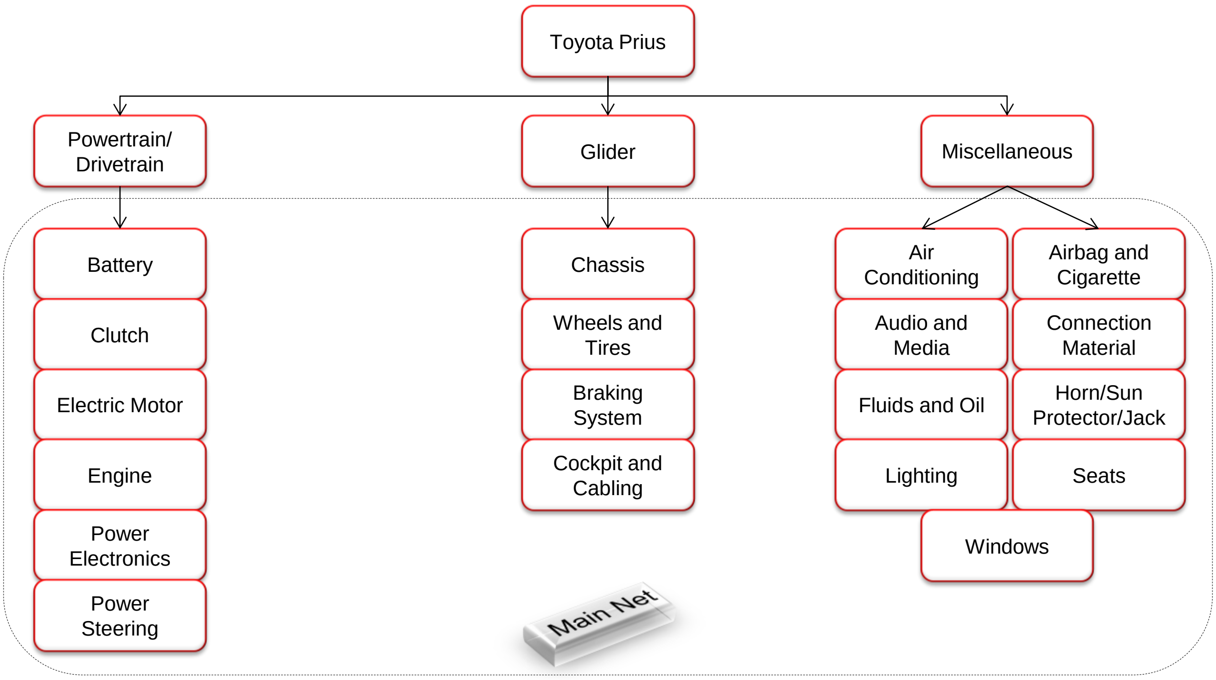


Figure 3.2 – Umberto Models – Main Net

The Figure 3.2 shows the number of models required to assembly the whole car. All study comprises nineteen models. Afterwards all these models will be joined so as to, study the impact of the whole entire car.

The second picture, Figure 3.3, shows the subnets. All these subnets are hidden processes from the correspondent main net (Figure 3.3) within its respective part. Their creation, allow faster calculations, avoids errors due its less complexity and is easier to understand the processes by the user and afterwards, whether necessary to change any process, is easier to find it.

All the assumptions from now on are all in agreement with this nomenclature.

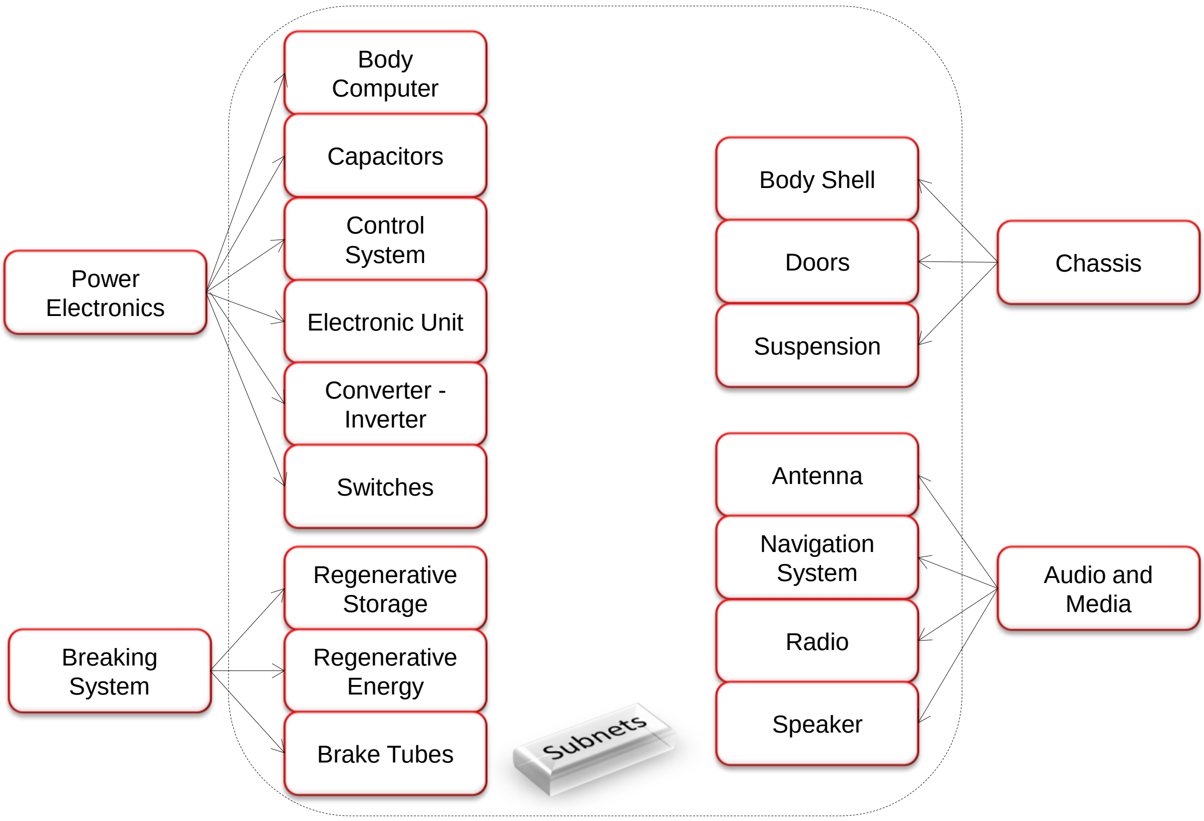


Figure 3.3 – Umberto Models – Subnets

### Functional Unit

According to the ISO 14041, the functional unit is used to provide a reference to which the inputs and outputs are referred in a common basis, to quantify the identified functions, of the product. Hence, in this study was defined as the kilometres that the car can be driven in whole its life, in a total of 200.000,00 kilometres.

### System Boundary

The system boundary has to be included, to ensure that all the processes are included in the system in a way that all the relevant potential impacts on the environment are appropriately covered. The criteria used do define the system boundary are important for the degree of confidence in the results[99].

The system limits include the entire life of the car, and consists in four different stages. The figure shows all the boundaries of the system.

[99] (ISO 14040, 2006 p. 28)

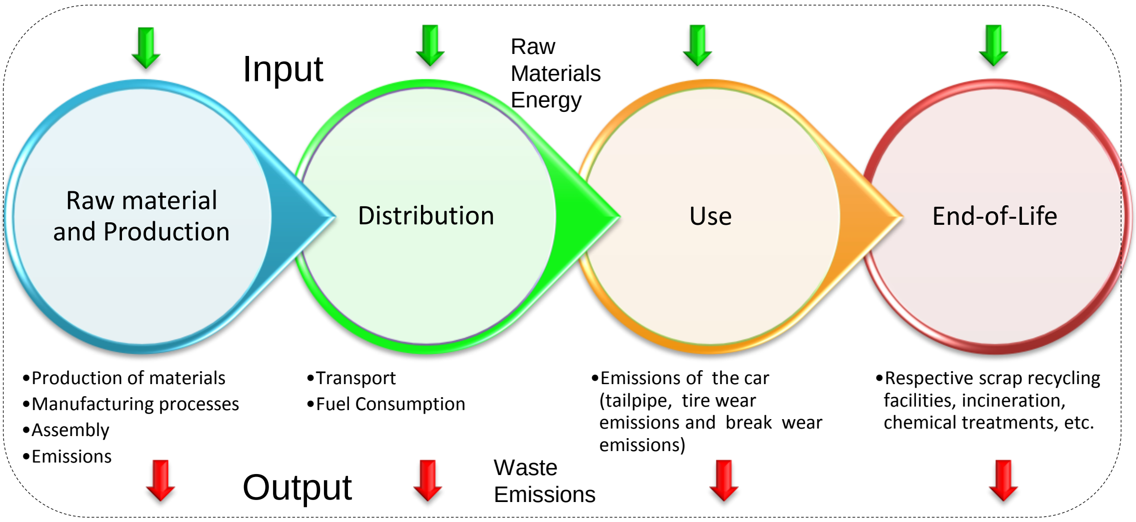


Figure 3.4 - System Boundary

Prius is built up in Japan, more precisely in Aichi. For this reason, all the assumption made from now on, namely for the production and distribution phase is related to Japan, whereas the use phase, as well as, the end of life, are assumed to be in Europe/Germany.

The acquisition of the raw materials is included within the scope of this study, and all upstream are considered.

***Production phase***

The production is the first stage, and encompasses the raw materials, as well as, their manufacturing processes associated, ending up with the final assembly. Is important to notice that is common in an LCA to split up into two different stages: Raw materials and Production where is included the manufacturing processes. However, to make it easier to the software and knowing that this fact does not change the final results, is assumed the mixing of these two phases.

***Distribution phase***

As regards the vehicle distribution, was necessary to calculate the distance between Aichi in Japan and Braunschweig in Germany, place where the car is supposed to be sold. To do so, was used the simple tool, *google Earth*, where it came up approximately the result of 22.000,00 Km of distance over the Pacific, Indian, and Atlantic Ocean. Once the car arrives to Germany, Bremerhaven, the car is carried by a truck about 250 km until Braunschweig.

### *Use phase*

During the use phase, considering that is an hybrid vehicle, it consumes petrol to power the wheels, and at the same the time recharges the hybrid batteries, which increases its overall efficiency. The consumption of fuel and subsequently the emissions released by the car, are considered to be in Europe.

The maintenance or reparations are out of the scope of this study.

### *End – of – Life*

The end of life is, as the name stands for itself, represents the last phase of the car, where will undergo for several dismantling processes, to recover all large metal scrap (e.g. steel, iron, aluminium, copper, zinc, etc.,), plastics and rubber as well as incineration and shredding residues, and afterwards these materials are sent to their respective scrap recycling facilities, while for example, the remaining electronics scrap is sent to a smelter facility[100] .

The end of life is also assumed to be made in Europe.

## IMPACT CATEGORIES

Every stage of an LCA, includes impacts on the surrounding environment. Each impact category has one substance as a reference, in order to quantify how much will be the impact.

For this study, were used two different methodologies, CML 2001 (Database created at the University of Leiden in Netherlands)[101] and TRACI (Tool for the Reduction and Assessment of Chemical and other Environmental Impacts) .[102]

These impact categories, should be in agreement with the scope and goal of the study, thus, the impact categories were chosen in agreement with the Institute of Machine Tools and Production Technology (IWF)[103] and because they are particularly important and generally used in the automotive sector.[104]

From the CML 2001, were elected six impact categories:

### *Acidification potential w/o LT (AP)*[105]

Includes the emission of acidifying substances (e.g., nitric acid and sulphuric acid), which have impacts on the soil, water, ecosystems, biological organisms and material (statues,

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[100] (Ecoinvent 3 Database, 2013)
[101] (Leiden University, 2013), accessed August 4, 2013
[102] (Bare, et al., 2012), accessed August 4, 2013
[103] (IWF)
[104] (Schmidt, 2004)
[105] The w/o is the nomenclature used to say With or Without and LT, Long Term

buildings, etc). The reference substance for this indicator is the sulphur dioxide $SO_2$, thus is measured in sulphur dioxide equivalents.

***Climate Change w/o LT,w/o LT (GWP)***

Is also known as Global Warming Potential (GWP) and is referenced for a period of 100 years. It is responsible for the emissions of the greenhouse gases, which increase the absorption of heat from solar radiation in the atmosphere and consequently increase the average global temperature. The reference substance for climate change is carbon dioxide $CO_2$, and is measured in carbon dioxide equivalent.

***Eutrophication potential w/o LT, generic w/o LT (EP)***

Also named *hypertrophication*, is an excessive input of nutrients into the water or soil, which can lead to change in the composition of flora and fauna. These nutrients are mainly nitrates and phosphates. The reference substance for this indicator is phosphate ($PO_4$) and is measured in phosphate equivalent.

***Photochemical oxidation w/o LT, high $NO_x$ w/o LT (POCP)***

Describes the formation of photo oxidants, which can be formed from hydrocarbons, such as, carbon monoxide (CO) and nitrogen oxides ($NO_x$), in conjunction with the sunlight. These photo oxidants are responsible for damage the human health, the functioning of ecosystems, in general. The reference substance is the ethylene, thus is measured in ethylene equivalent.

***Resources w/o LT, depletion of abiotic resources w/o LT***

Describes the exhaustion of raw materials within a region, or in another words can be defined as the decreasing of natural resources availability. Is an extremely important indicator to use in  sustainability and LCA methodologies. However is one of the most difficult issues to quantify while minimizing value choices and assumptions.

The reference substance for this indicator is antimony (Sb) and is measured in antimony equivalent.

The substances contributing for the human toxicity are numerous. In order to assess the respiratory effects, was taken from TRACI the following impact category:

***Human health, respiratory effects, average (PM 2.5)***

It encompasses the effects related to environmental pollution and deals with pollutants, for instance particulate matter (PM 2.5). This particulate matter is a small particle in the ambient air which has the ability to cause negative human effects namely respiratory illnesses and death. This indicator is expressed in particulate matter (PM) 2.5 equivalents, where the 2.5 represents the diameter of the particles in micrometres.[106][107]

### DATA QUALITY CRITERIA

The data quality is important because of the reliability of the study, as was mentioned in the previous chapter. The data base was given by the IWF, Braunschweig, Germany.

It consists in a excel data sheet, expressed in grams where all the raw materials, materials and manufacturing processes, are involved in a production of a generic electric vehicle. Therefore the data is not from Prius. This excel sheet has suffered some modifications and assumptions, in materials, manufacturing processes and weight of the parts. For instance the total weight for all the parts from the data sheet was approximately 600 kg (without battery), because is regarding to an electric vehicle.

In order to deal with this problem, and knowing the Prius has 1425 kg, (60 kg for the battery) was made an relation to the weight. It is important to be aware that all assumptions will probably make difference later on in the life cycle inventory analysis. However this was the only available source.

### ALLOCATION

The allocation is already included in database of the Ecoinvent 2.2 and Ecoinvent 3.

### TYPE OF CRITICAL REVIEW

This Life Cycle Assessment was conducted to complete my Master degree. The data here presented are not from Toyota, because of that this report is an internal document of the Institute of Machine Tools and Production Technology.

[106] (Stranddorf, et al., 2005)
[107] (Bakke, 2014 pp. 2-4)

### 3.2.3 Life Cycle Inventory Analysis

This phase is usually the most labour--intensive part of an LCA, because comprises all the data collection, as well as, the calculation procedures to quantify the relevant inputs and outputs[108]. All the data is processed with Umberto software.

#### DATA COLLECTION

The excel data sheet used, does not include all the data necessary to assess the Toyota Prius, for example:

- Energy need for the extraction of the raw materials (*)
- Emissions released during the extraction of raw materials (*)
- Amount of electricity needed for the assembly processes
- Emissions of the electricity used for the assembly processes (*)
- Emissions during the use phase (*)
- Energy and emissions for the end of life, regarding all the associated processes (*)
- Substitute tyres
- Data for Internal Conventional Engine (*)
- Adaptation of the Electric Motor and the Battery

The asterisk (*) means that all items presented above, are included in Ecoinvent 2.2 and Ecoinvent 3 database, and will be used to complement the data sheet with the permission of the IWF. In relation to those that are not marked with asterisk, is necessary to make some assumptions.

***Substitute tyres***

Was assumed the production for replacement of tyres (eleven times), multiplying their respective materials eleven times.

***Electric Motor***

The electric motor was necessary to change some of its composition of the raw materials from the generic data sheet. Were used permanent magnets (Neodymium), (approx. 2 kg) and removed copper approximately 7 kg (that was using for both winding rotor and stator).[109][110]

[108] (ISO 14040, 2006 p. 25)
[109] (Goodrich pp. 7 - 8)
[110] (Constantinides, 2010)

### *Battery NiMH*

The battery was the part that has suffered more modifications, because its composition and its weight. The battery of Prius is NiMH battery (nickel–metal hydride battery, abbreviated NiMH or Ni-MH)[111], as mentioned at beginning of this chapter, within the Toyota's technical specifications. Contrary to the electric motor, the materials of the battery differ per model, and there is no possible relation between them, due their electrodes, separator and so on.

According to these type of batteries, the separator is made out of Polypropylene micro porous membrane.[112] In order to build up a battery the weight of the battery from the excel data sheet was reduce in 80% (keeping the relation) in order to have the real value for the weight of the Prius battery (60 kg). Regarding to the materials, the lithium (8 kg) was replaced by nickel, zinc and hydrogen, as well as, the separator was modified to Polypropylene.

### *Internal Combustion Engine*

The ICE, was taken from Ecoinvent 3 "*Internal combustion engine production, passenger car, global*". It was set out the weight of 175 kg for the ICE. The dataset includes all raw materials and energy inputs required for its production.

In order to sum up, all the assumptions made so far, was built a pie graphic, Figure 3.5 where is possible to get an overview about all the materials used to produce the car, as well as the percentage of weight of each part. The materials "steel" dominates overall. Hence is mostly used for the chassis, suspension, motor and engine (heavier parts). In the second group are polymers, thermoplastics and aluminium, where the others parts have less percentage in its constitution.

The pie diagram of the Figure 3.6, shows the percentage of the weight of the powertrain, glider and the miscellaneous.

[111] (Toyota Motor Coperation, 2013 p. 17)
[112] (Arora, et al., 2004 pp. 4450-4452)

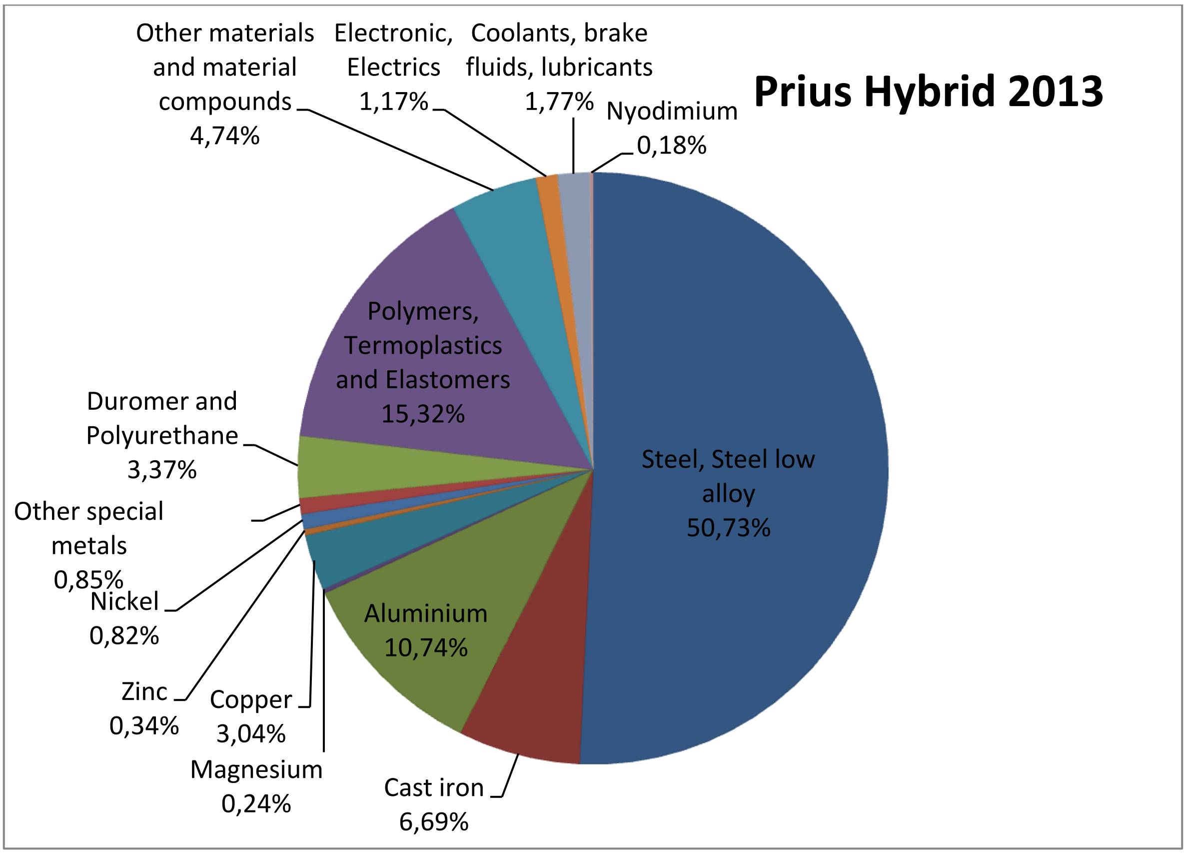


Figure 3.5 - Weight per parts of Toyota Prius

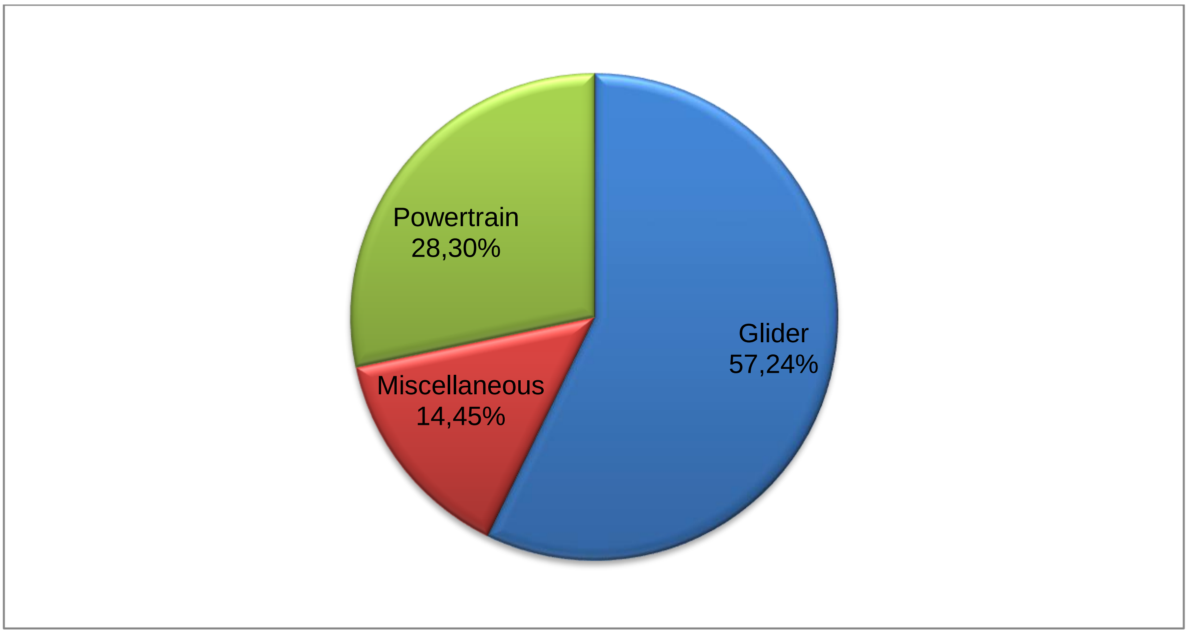


Figure 3.6 – Weight overall

The data collection is used to model the car in four different phases: Production, Distribution, Use and End – of—Life. The Figure 3.7 was drawn, with the purpose of providing information in order to easily understand what is necessary to take into account for all phases, as well as, the assumptions that have to be accounted for. From now on, all data collection is going to be introduced in Umberto's database.

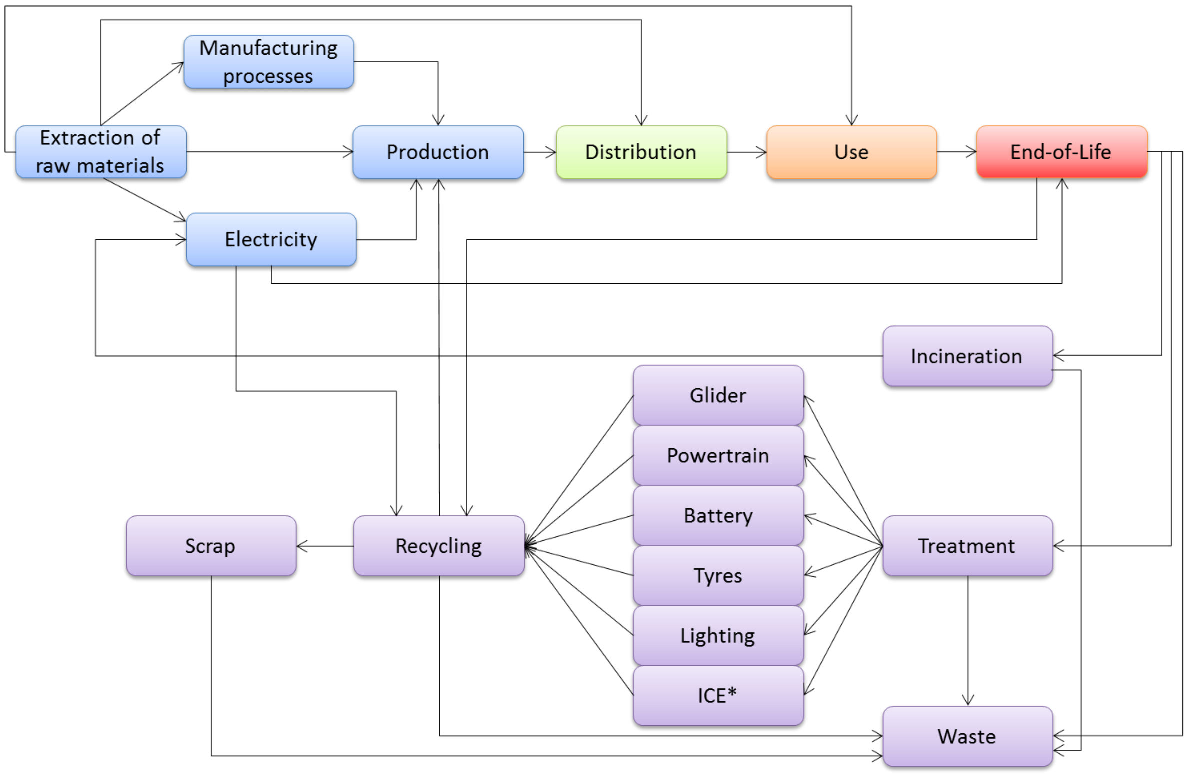


Figure 3.7 – Phase of Prius

### *Production*

The electricity, chosen for this process, is the "*electricity medium voltage, at grid*" in Japan. It includes the transmission network, and direct $SF_6$ emissions to the air. This process includes also the losses occurred during the transformation from high – voltage to medium voltage, as well as, the losses for the transportation.[113] However is important to notice, the amount of electricity was not given, therefore is necessary to make an assumption. According to the author [114] *Deluchi*, there is a standard reasonable value to quantify the amount of energy used for assembly processes, which is 3,8 MJ/kg. Therefore, multiplying the energy density per mass by the weight of the parts, is possible to find the energy needed for the assembly.

### *Distribution phase*

The transportation is broken down into two different carriers:

[113] (Ecoinvent 3 Database, 2013)
[114] (Stodolsky, et al., 1995 p. 9)

- Transport freight sea :

Is in Ecoinvent 3 database and the dataset represents the entire transport life cycle including the production, operation and maintenance of the transoceanic ship and the construction of the port.

- Transport freight, lorry 16 – 32 metric ton:

Is included in Ecoinvent 3 database and it refers to the entire transport life cycle, its production and maintenance, as well as the construction of road. The energy use and combustion emissions is included, as well.

All this database is related to be in Europe, Germany, and was chosen the truck more efficient (EURO 5)[115].

***Use phase***

To assess this phase is necessary to use the process "t*ransport, passenger car, medium size, petrol, EURO 5*", expressed in km. This process is used for the category "medium", because represents an engine size between 1.4 and 2.0 litres, and the average for the weight is estimated to be 1.600,00 kg[116].

Once the car size influences the amount of emissions to the air, caused by the burning of fuel is necessary to assess in a properly way. Considering that the Prius has a small consumption (3,9 L/100 km), would not be real to use this process for the Prius, because the results would be faked. However there is no database available within Ecoinvent for hybrid cars.

In order to prevent this big amount of emissions released during the use phase, and to make the scenario, as much real as possible, was created a formula, presented in equation (2) and (3) to adapt to this process, in order to obtain the final results with more accuracy during the use phase.

$$Distance = \frac{Mileage \times Weight\ Part}{Weight\ Prius} \times Relation \qquad (2)$$

$$Relation = \frac{Consumption\ Prius}{Consumption\ Average} \qquad (3)$$

115 Nomenclature used in Ecoinvent 2.2 and 3 to define the lowest emissions.
116 (Ecoinvent 3 Database, 2013)

The relation, is between Prius - 3,9 L/ 100 km and  7 L/100 km (value assumed in average for gasoline cars).

The  equation (2), aim to find the number of kilometres that the Prius  has to drive in its entire life, necessary to carry single parts ( e.g., battery, electric motor, chassis, etc.,) regarding its fuel efficiency comparing to the conventional vehicles.

***End-of-Life***

The end–of–life , does not present the most importance within the result of this study, reason why was taken some predefined processes from Ecoinvent database. The geography related to each treatment process is related to the global (GLO) and to Switzerland (CH).

The two following lists are for predefined processes and undefined processes, for the end of life respectively. Both of them, are from Ecoinvent database. Most of them are separated according to their respective model (see Figure 3.7 and Figure 3.2)

*First List:*

- Treatment of used glider for passenger car, GLO:

Expressed in kg, and the materialization of the glider includes 5 main fractions: scrap steel, scrap aluminium, scrap copper, scrap plastics and a shredding residue. The parts included within this process are, airbag and Cigarette, air condition, chassis, cockpit, breaking system, audio and media, horn/ sun protector / jack, seats and windows.

- Treatment of used powertrain for electric cars, GLO:

Expressed in kg, and includes the scrap of the steel, copper and aluminium is directly recovered from the components and afterwards is sent to their respective scrap, whereas the electronic scrap goes to smelter facilities. It is defined for electric motor, power electronics, clutch and power steering.

- Treatment of used Ni-metal hybrid battery, pyrometallurgical, GLO:

This treatment encompasses the energy, auxiliary consumption, waste production, emission (air and water), production and rough estimations of the efforts for the infrastructure and transportation.

- Treatment of used tyre, GLO:

Expressed in kg and represents the treatment of used tyre, by incineration of its two parts, rubber and steel scrap. The treatment of the rims and bearing units were done separately, without predefined processes).

- Treatment of used light commercial vehicle :

Expressed in kg and represents the treatment of use lighting within the vehicles

- Treatment of used internal combustion engine, GLO:

Expressed in kg, and it includes, the scrap steel, scrap Aluminium, scrap Copper, scrap plastics and the shredding residue.

*Second List*

- Treatment of waste, mineral oil hazardous waste incineration, CH:

Used for the end of life of the oil, used for the model Fluids and Oil.

- Treatment of spent antifreeze liquid, hazardous waste incineration, CH:

Used for the Air Conditioning, however is presented within the model of Fluids and Oil (see Figure 3.2) The inventory waste contains 100% Anti-Freeze liquid. It includes waste – specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning.

- Treatment of scrap steel, municipal incineration, CH:

Used for the model connection material, once, these are mostly made out of steel (bolt, screw, head screw, rivet, stud, etc.,) was assumed that its treatment only for the steel. It includes waste – specific air and water emissions from incineration, auxiliary material consumption for flue gas cleaning.

All these in information is available on Ecoinvent website database.

### DATA CALCULATION

After all the modulation, is necessary to select the phases and the impact categories mentioned within the scope, in order to step forward with the calculations. Due to the fact of all nineteen models, was not possible show within this report all of them, nevertheless the Figure 3.8 represents the model *Audio - Media* with all the phases included, to give an idea how the modulation was made (all the others look like similar).

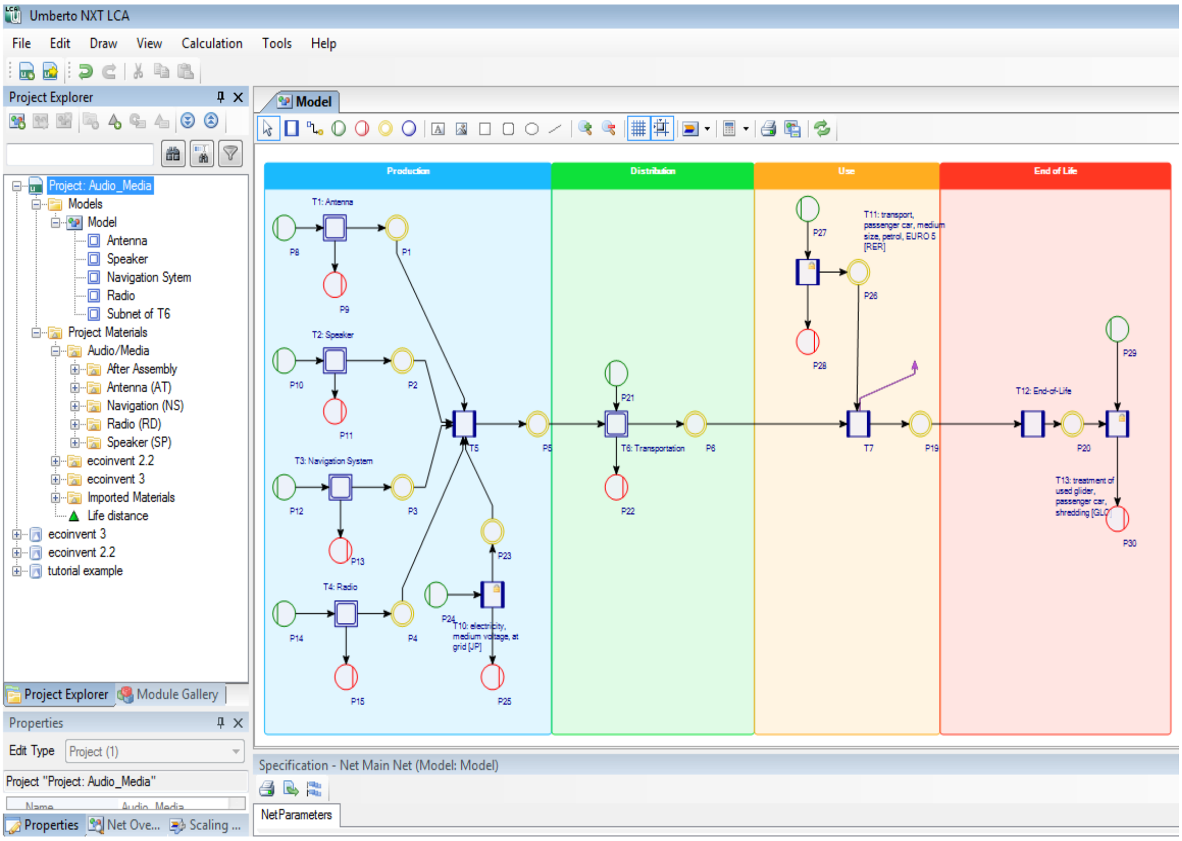


Figure 3.8 - Model - Audio/Media - Umberto

In this model is possible to identify the four phases, shown in painted rectangles. This window shows the main net where is included the all the phases, the production (Blue) where there are three subnets, *Antenna, Speaker, Navigation System and Radio* and the electricity needed to assembly all the parts. The processes in the subnets are hidden from the main net reason why is not possible to identify them. The phase green is the transport, which is also a subnet that has inside the transport freight with lorry and ship. The orange rectangle is the use phase, it encompasses the process of petrol refuelling during all its life and it has also the important functional unit, the purple arrow, which represents the life span the car of 200.000 km.

The last phase is the end-of-life (red colour) with its respective treatment.

The calculation is all made by Umberto, after that the results from nineteen models were exported to an excel sheet where all data is joined by order of impact category phase with the purpose of join all the parts to come up with the final result.

### 3.2.4 Life Cycle Impact Assessment

The outcome of an LCIA phase is the collection of indicator results of different impact categories and is aimed to evaluate the significance of potential environmental impact categories[117], as well as to provide information for the life cycle interpretation. The selections of the impact categories, as well as, their respective indicators were already defined in the scope of this study. All the tables, not present here are attached in Appendix B.

#### CATEGORY INDICATORS AND CLASSIFICATION

Within the scope, were elected the impact categories with a general overview about all of them. However to assess the data gathered from the Life cycle inventory is necessary to characterize their category, affects, scale and the resultant indicator for each category. To do so, was built up the table down.

| | Acidification potential | Climate Change | Eutrophication Potential | Photochemical Oxidation | Depletion of Abiotic Resources | Respiratory effects |
|---|---|---|---|---|---|---|
| Abbreviation | AP | GWP | NP | POCP | ADF | |
| Characterization | CML 2001 | CML 2001 | CML 2001 | CML 2001 | CML 2001 | TRACI |
| Indicator | kg SO2 Eq/ kg Emiss. | kg CO2 Eq/kg Emiss. | kg PO4 Eq/ kg Emiss. | kg ethylene equivalents/kg emission | kg antimony Eq/kg extraction | kg of PM2.5-Eq |
| Affects | soil, ecosystems and materials (buildings) | ecosystem and human health | air, water and soil | human health, ecosystems and crops | extraction of minerals and fossil fuels | Human health |
| Scale | Continental | Global | Continental | Continental | Global | Continental |

Table 3.1 - Category indicators and classification

The Table 3.1 - Category indicators and classification, characterize all the impact categories, and all the data required[118].

All these characterization is need, because it helps to assess, quantify the impacts, validity and degree of accuracy[119].

[117] (ISO 14042, 2000 p. 10)
[118] (Goedkoop, et al., 2008 pp. 129-135)
[119] (ISO 14042, 2000 pp. 3-11)

## CALCULATION OF CATEGORY INDICATORS RESULTS, CHARACTERIZATION

The presentation of the calculation involves the conversion of LCI results to a common units and the aggregation of the results in their respective impact category that aims the numerical result, for each different indicator.

The results are presented in the Table 3.2 where is possible to observe for each model its respective impact. All the tables were made in excel sheets, and the values inside are highlighted with different colors aiming to quantify the values in order to give visual perception to make their analysis, easier and fast.

| Part/Component (Model) | AP [ kg SO2-Eq] | GWP [kg CO2-Eq] | EP [kg PO4-Eq] | POCP [kg ethylene-Eq] | ADP [kg antimony-Eq] | PM 2.5 [kg PM2.5-Eq] |
|---|---|---|---|---|---|---|
| 1 - Air Conditiong | 1,2370 | 367,1621 | 0,2098 | 0,0951 | 2,4557 | 0,3151 |
| 2 - Airbag / Cigarrete | 1,3749 | 331,1044 | 0,3409 | 0,1013 | 2,3146 | 0,3596 |
| 3 - Audio / Media | 4,7628 | 989,8120 | 0,9516 | 0,1946 | 7,4616 | 1,0075 |
| 4 - Battery | 29,1208 | 2.113,6944 | 1,8482 | 1,4523 | 14,5460 | 6,4031 |
| 5 - Breaking System | 13,6855 | 3.649,1762 | 1,5771 | 1,1824 | 22,6147 | 3,6443 |
| 6 - Chassis | 42,8100 | 15.195,4711 | 5,7146 | 3,9128 | 96,1790 | 11,4309 |
| 7 - Clutch | 1,1613 | 707,2414 | 0,1736 | 0,1052 | 2,2185 | 0,3051 |
| 8 - Cockpit / Cabling | 2,5936 | 859,4012 | 0,4328 | 0,2194 | 5,8656 | 0,6484 |
| 9 - Connection Material | 2,4697 | 761,6155 | 0,3396 | 0,2317 | 5,2004 | 0,7207 |
| 10 - Electric Motor | 17,1767 | 7.265,2353 | 2,7282 | 1,5051 | 29,1050 | 5,0131 |
| 11 - Fluids and Oil | 2,5119 | 922,6251 | 0,3060 | 0,2842 | 5,8519 | 0,6291 |
| 12 - Horn / Sun Protector / Jack | 0,4587 | 151,5978 | 0,0632 | 0,0422 | 1,0729 | 0,1201 |
| 13 - Engine | 25,6763 | 6.358,1790 | 3,6707 | 2,0224 | 42,6014 | 6,6392 |
| 14 - Lighting | 1,8019 | 702,9126 | 1,2123 | 0,1475 | 3,8337 | 0,4285 |
| 15 - Power Electronics | 22,7492 | 1.352,5671 | 1,3388 | 1,0537 | 9,4000 | 5,4046 |
| 16 - Power Steering | 5,1529 | 2.711,6604 | 0,7505 | 0,4513 | 10,0430 | 1,4884 |
| 17 - Seats | 6,0120 | 1.973,7541 | 0,7984 | 0,8398 | 13,9999 | 1,5197 |
| 18 - Wheels and Tyres | 15,7849 | 5.403,7669 | 1,9447 | 1,3906 | 37,2489 | 4,2248 |
| 19 - Windows | 7,1730 | 2.327,5750 | 0,9600 | 0,6176 | 15,6723 | 1,8062 |
| Total | 203,7132 | 54.144,5515 | 25,3611 | 15,8493 | 327,6851 | 52,1085 |

Table 3.2 – Impacts Category

The result in general was already predicted, especially for the chassis due its weight (includes body shell, suspension and doors see Figure 3.3 – Umberto Models – Subnets) and number of processes. It will be analysed deeply only the most important models, such the chassis, battery, engine, motor breaking system and power electronics, among others depending on the impact category because of their bigger impact on the environment.

It is also important to emphasize, that the weight is one of the most important factors, not only for the transportation but because of the electricity needed for the assembly process, as was mentioned before.

### *Global Warming Potential*

The model of the chassis is one of the heavier and biggest models, for instance it includes, the total of 198 processes only within the production phase.

In the graphic of theFigure 3.9, is possible to see that the transportation is the main factor responsible for this high value.

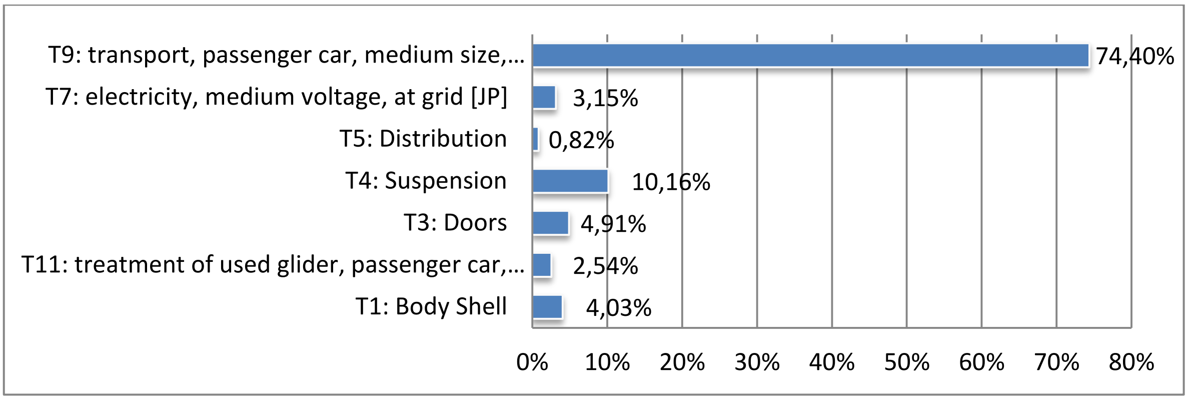


Figure 3.9 Chassis model – Climate Change

The suspension has a contribution of 10%, according to graphic of the Thanks to the software Umberto, is possible to have a deep analysis within every subnet, being so possible to find out, which are the materials, process or processes responsible for induce the impact. Therefore in the suspension, was possible to determine the magnesium - alloy, AZ91, die casting at the plant is responsible process for that. The magnesium is widely used in automotive industry because it provides a light weighting. However this alkaline uses sulphur hexafluoride $SF_6$ as cover gas to prevent the rapid and hazardous oxidation of the molten magnesium. This gas is one of the most extremely powerful and persistent greenhouse gas with a 100-year global warming potential[120].

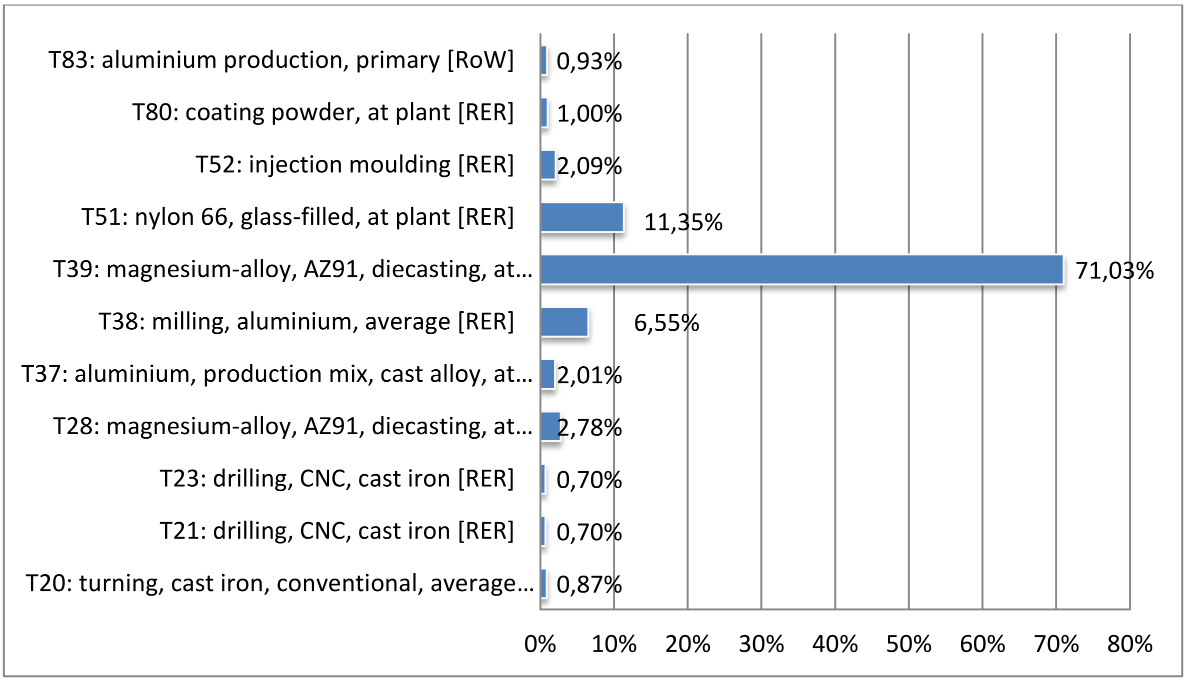


Figure 3.10 – Subnet Suspension – Climate Change

120 (Bartos, et al., 2007)

The electric motor of Prius is a synchronous permanent magnets (PM) motor, where the magnets are made out of *Neodymium*, which is a Rare Earth Metal. However it uses only two kilograms of these magnets, because is a small electric motor, supported by the engine.

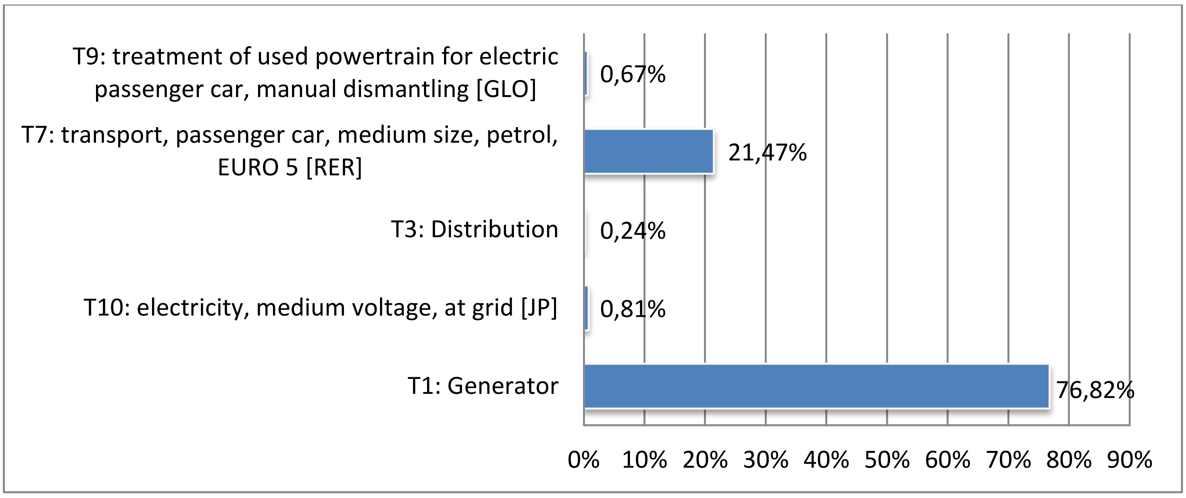


Figure 3.11 - Electric Motor - Climate Change

The Figure 3.11 identifies the generator has the most harmful part for the environment. The reason for that is the aluminium as well as their respective manufacturing processes, which has a considerable impact, as in the chassis.

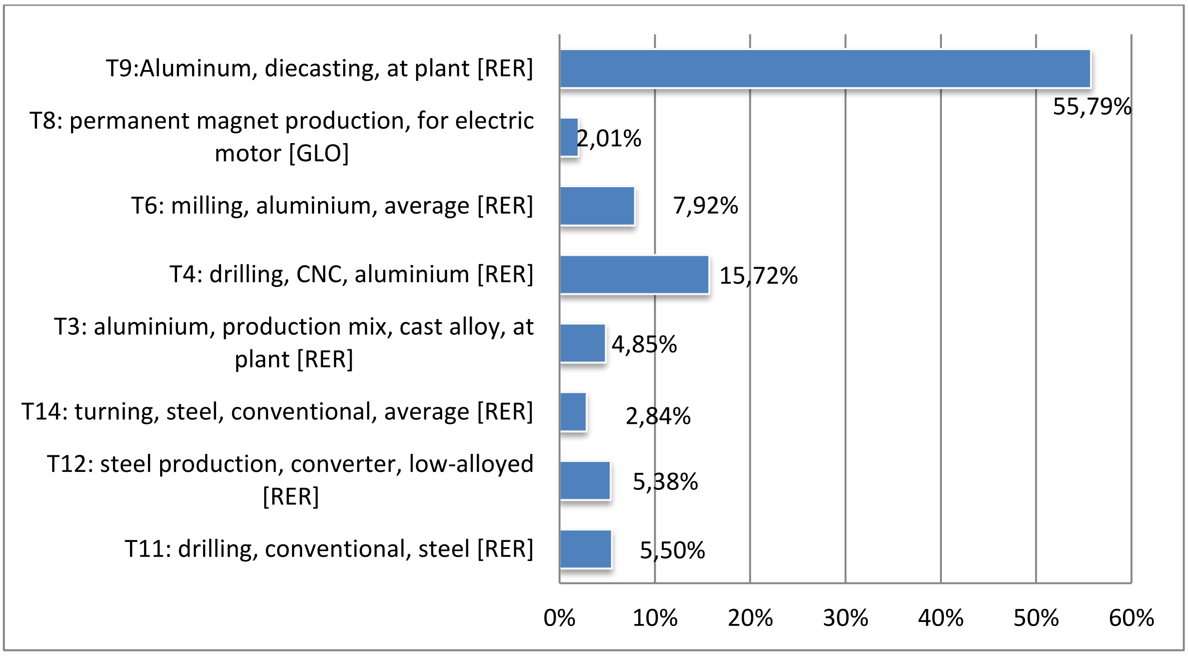


Figure 3.12 - Subnet Generator - Climate Change

Is also interesting, verify that the permanent magnets has only 1,99 % of the impact, which does not represent a considerable impact because its size is small.

Regarding to the engine, most of the impact is because of the transportation. In the Figure 3.13 are presented two different types of transportation. The "*T2: Transportation"*, is the transport of the car from the power plant, in Japan, whereas the *"T8: Transport, passenger car, medium size, petrol, EURO 5 [RER]"* is related to the transportation of the motor regarding its weight during its whole life span. Is possible to see in this model the two different transport, because the weight of the motor is relevant, and thus both contribute for the global warming. Once this model was taken from the Ecoinvent database is not possible to have a deeply analysis inside, in order to know which process, or processes were more harmful for the environment.

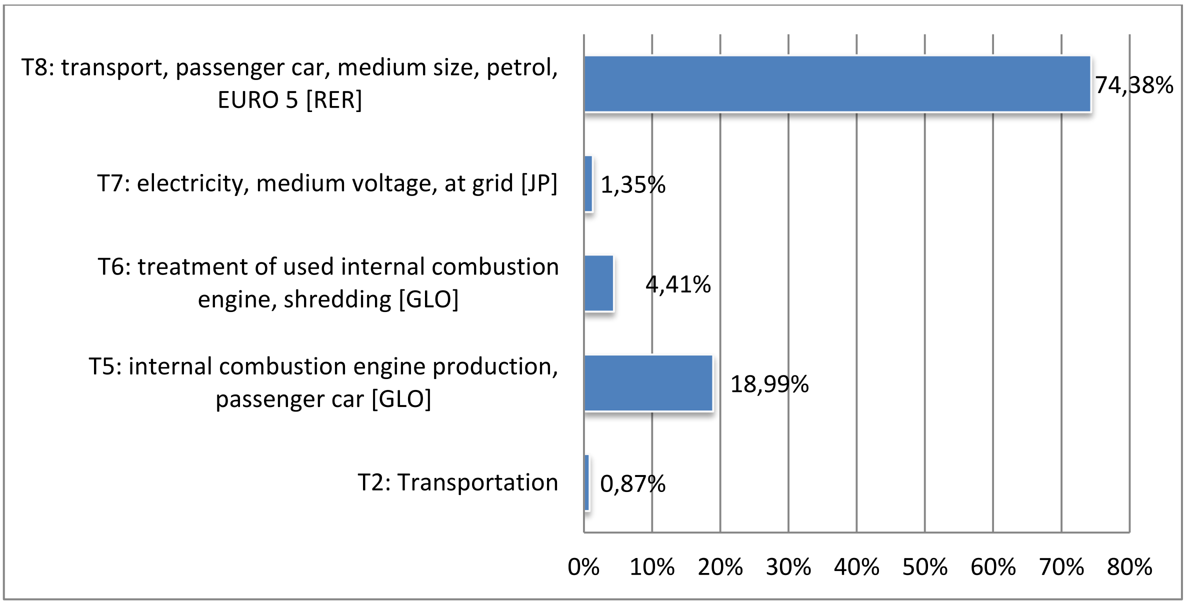


Figure 3.13 - Internal Combustion Engine – Climate Change

The wheels and tyres have a considerable impact within this indicator. This fact is due the additional production of tyres, as was mentioned in the Life Cycle Inventory. For this reason is not worth present the respective graphics. The breaking system has in this indicator a considerable impact, mainly because of the brake line pressure, and the regenerative storage with 40% and 46% respectively. The Figure 3.14, indicates that the impact come, mainly from the steel and its respective manufacturing processes. On the other hand the Figure 3.15 shows that in the regenerative storage is mainly made out of the aluminium, and mostly of its manufacturing processes involve aluminium namely drilling CNC and milling, which are harmful, for the environment.

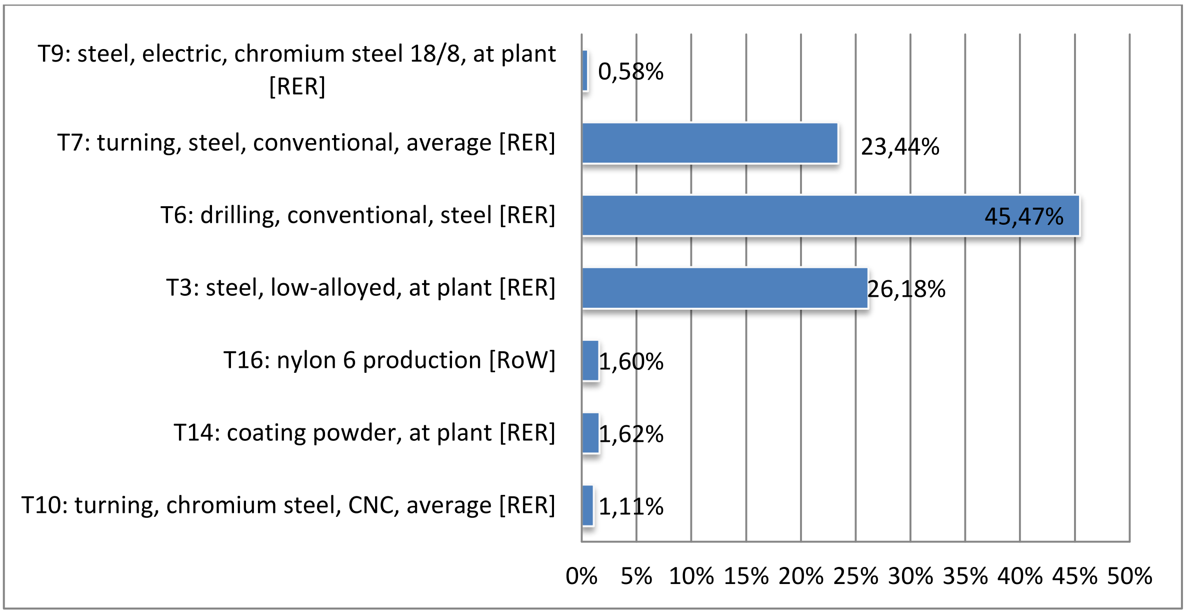


Figure 3.14 – Subnet Brake Line Pressure – Climate Change

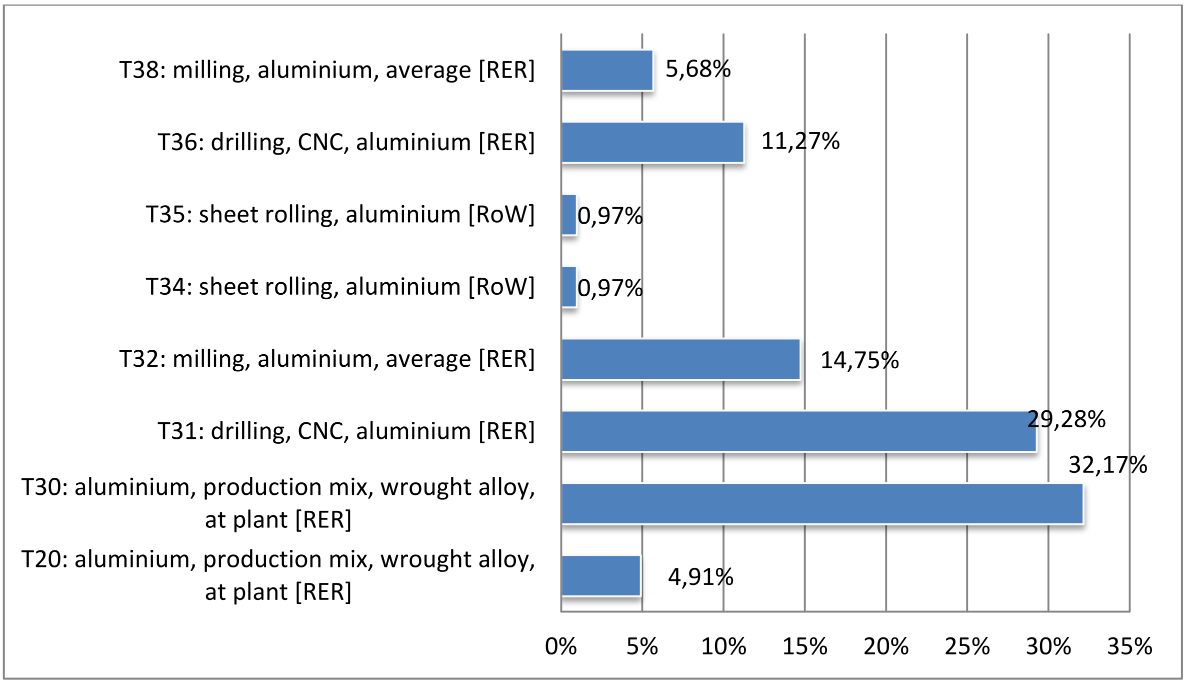


Figure 3.15 - Subnet Regenerative Storage - Climate Change

The power steering has a significant impact of 2711,7 kg $CO_{2\ Eq}$, considering that is one of the most lighter parts (models), where the transportation is only 32,97% of the this value.

The graphic of the Figure 3.16 shows, among all the processes, the die casting magnesium – alloy process is what stands out, with 77,8 % of share. This case is similar to the generator.

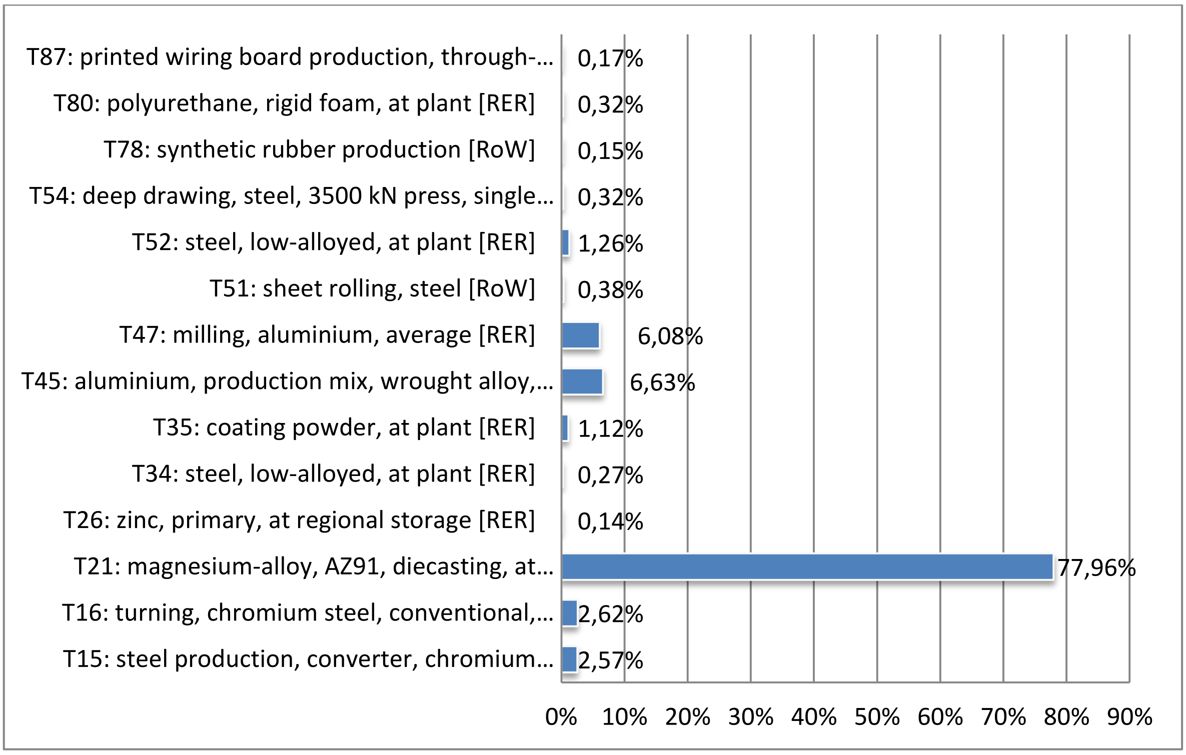


Figure 3.16 - Power Steering - Climate Change

The battery has no a big impact in this indicator. Earlier in this report was mentioned, that this battery was adapted to this model, thus the results may present somehow deviation of the reality. The transport in this indicator is the most responsible for the impact. However the cell of the battery among the other parts is the part with highest impact. The Figure 3.18 – Subnet – Cell – Climate Change Figure 3.18, shows in detail, the impact of the cell, where the metal nickel,  reveals to be highly hazardous to the environment.

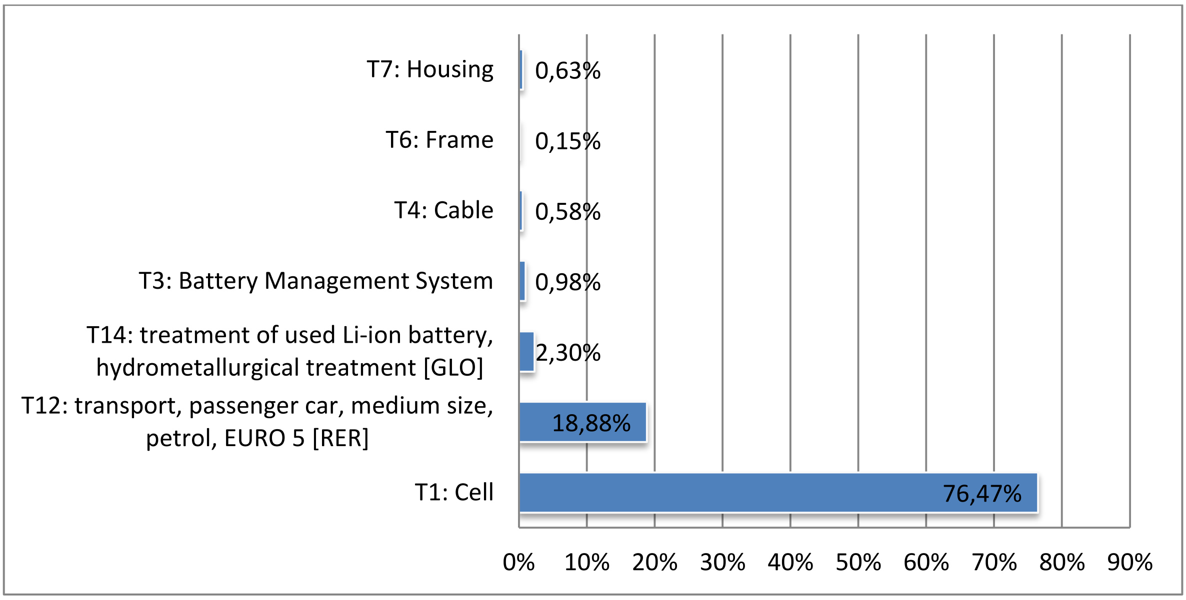


Figure 3.17 - Battery - Climate Change

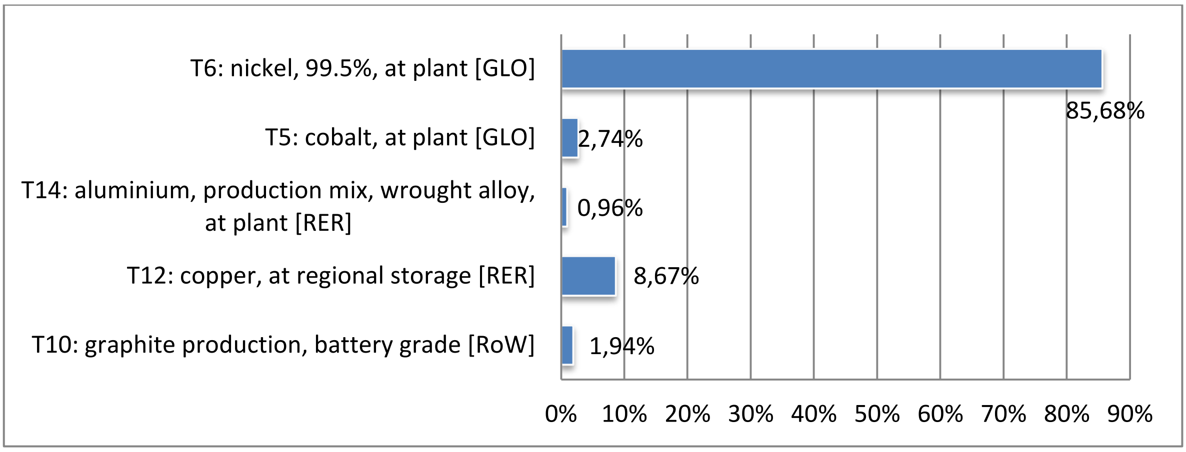


Figure 3.18 – Subnet – Cell – Climate Change

As a summary, in this impact category the magnesium – alloy AZ91 die casting stands out, as the most responsible process for the global warming potential. It is followed by aluminum production mix, wrought alloy at plant and several manufacturing processes using this aluminum for instance drilling CNC. The drilling of conventional steel, namely in the regenerative storage has a big impact.

Producing of aluminum and steel products is energy intensive, using finite natural resources and resulting in emission of greenhouse gases.[121]

***Resource depletion of abiotic resources***

This category indicator describes the exhaustion of raw materials within a region, reason why is widely used for LCA studies.

The chassis is the main reponsible for the impact in this category, due its weight. The transportation of the chassis during whole life, requires a large consumption from the internal combustion engine, during its whole live, involving a big amount of extraction of raw materials, to produce the fuel. However, from the Figure 3.19 is noticeable that the production of the raw materials to produce all the structure, are almost negligible when comparing with the transport.

[121] (Steel and Aluminium Fact Sheet, 2009) accessed on September 12

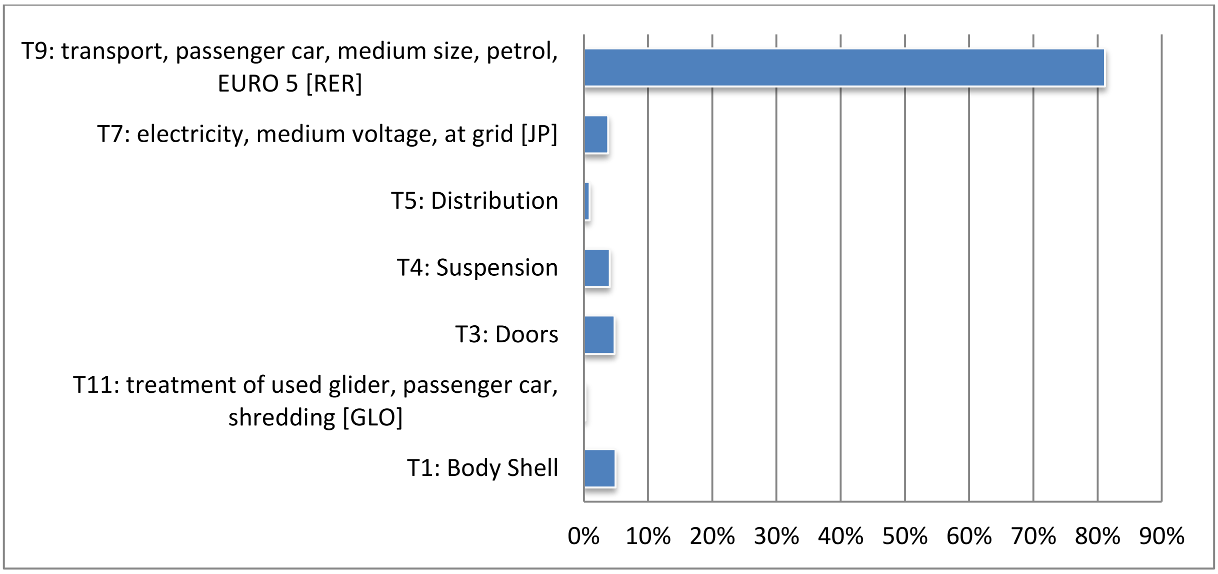


Figure 3.19 - Chassis – Resource depletion of abiotic resources

The engine comes up right after, and its impact is mainly for the same reason.

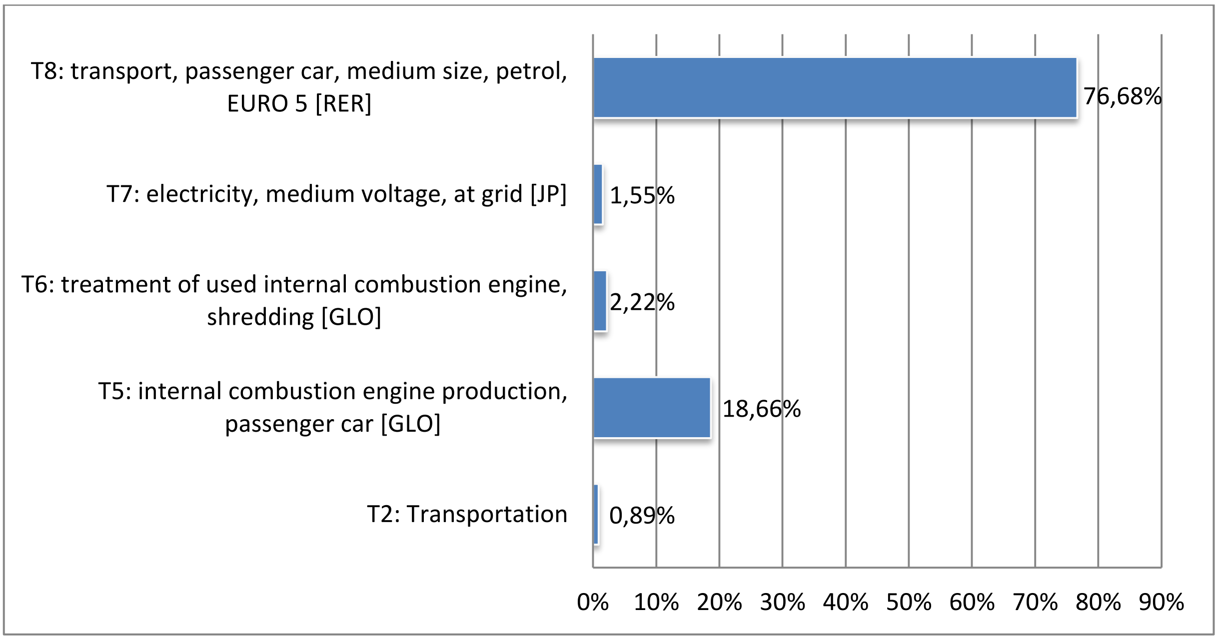


Figure 3.20 - Internal combustion engine - Resource depletion of abiotic resources

One difference is its production requires more materials in which extraction involves more impacts, for instance materials for coating to avoid rusting processes inside the engine.

The electric motor as mentioned for the global warming potential has a small portion of rare earth metals (neodymium) which gives to the motor the electric field necessary to make the spin the rotor, creating so the mechanical energy. Its extraction is difficult, however due their magnetic field, they are widely used nowadays namely in electric vehicles industry.

| Raw Materials and Processes | [kg antiminy Eq.] |
| --- | --- |
| **T11: drilling, conventional, steel [RER]** | 11,46% |
| **T12: steel production, converter, low-alloyed [RER]** | 9,44% |
| **T14: turning, steel, conventional, average [RER]** | 5,92% |
| **T16: cast iron, at plant [RER]** | 1,94% |
| **T20: steel production, converter, chromium steel 18/8 [RER]** | 1,35% |
| **T22: sheet rolling, chromium steel [RER]** | 0,10% |
| **T24: turning, chromium steel, conventional, average [RER]** | 1,46% |
| **T26: copper, at regional storage [RER]** | 0,39% |
| **T27: wire drawing, copper [RER]** | 0,15% |
| **T3: aluminum, production mix, cast alloy, at plant [RER]** | 9,17% |
| **T38: nylon 66, glass-filled, at plant [RER]** | 0,21% |
| **T4: drilling, CNC, aluminium [RER]** | 27,51% |
| **T48: drilling, CNC, aluminium [RER]** | 0,11% |
| **T56: steel, low-alloyed, at plant [RER]** | 0,61% |
| **T57: turning, steel, conventional, average [RER]** | 0,89% |
| **T6: milling, aluminium, average [RER]** | 13,89% |
| **T8: permanent magnet production, for electric motor [GLO]** | 4,44% |
| **T9: magnesium-alloy, AZ91, diecasting, at plant [RER]** | 10,97% |
| **Total** | 100,00% |

Table 3.3 - Electric Motor - Resource depletion of abiotic resources

In the Table 3.3 is shown processes used to produce the electric motor and some raw materials. Is important to point out, that this is a small motor that will be coupled to engine reason why uses only two kilograms of permanent magnets. The Table 3.3 aims to show the processes within the production, specially the drilling aluminum and steel. Drilling is a cutting process that waste material in a considerable amount. Therefore the amount of certain raw material is need in a bigger amount to compensate the waste flows.

The breaking system has again a considerable impact in this category, the main parts responsible for that, are once again the subnets brake line pressure and the regenerative storage, with 48,28 % and 36,21% respectively. The break line pressure subnet, within the breaking system model, is shown in the Figure 3.21 indicates the drilling and turning steel are the processes with more impact in this category, whereas the regenerative storage presented in the Figure 3.22, identifies the aluminum as material with more impact, and its respective manufacturing processes.

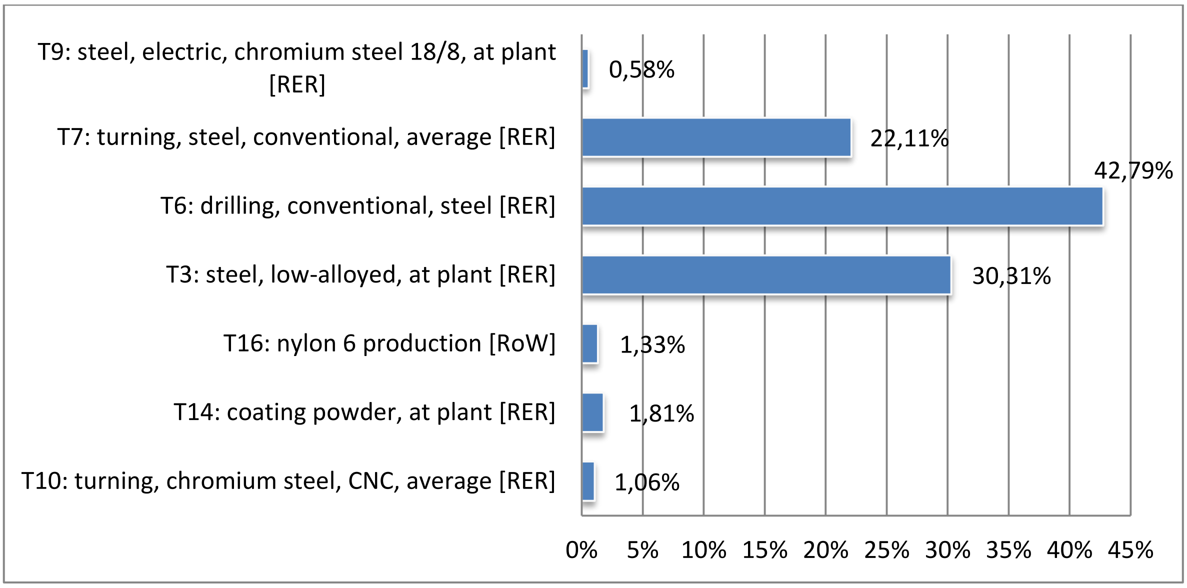


Figure 3.21 - Subnet brake line pressure - Resource depletion of abiotic resources

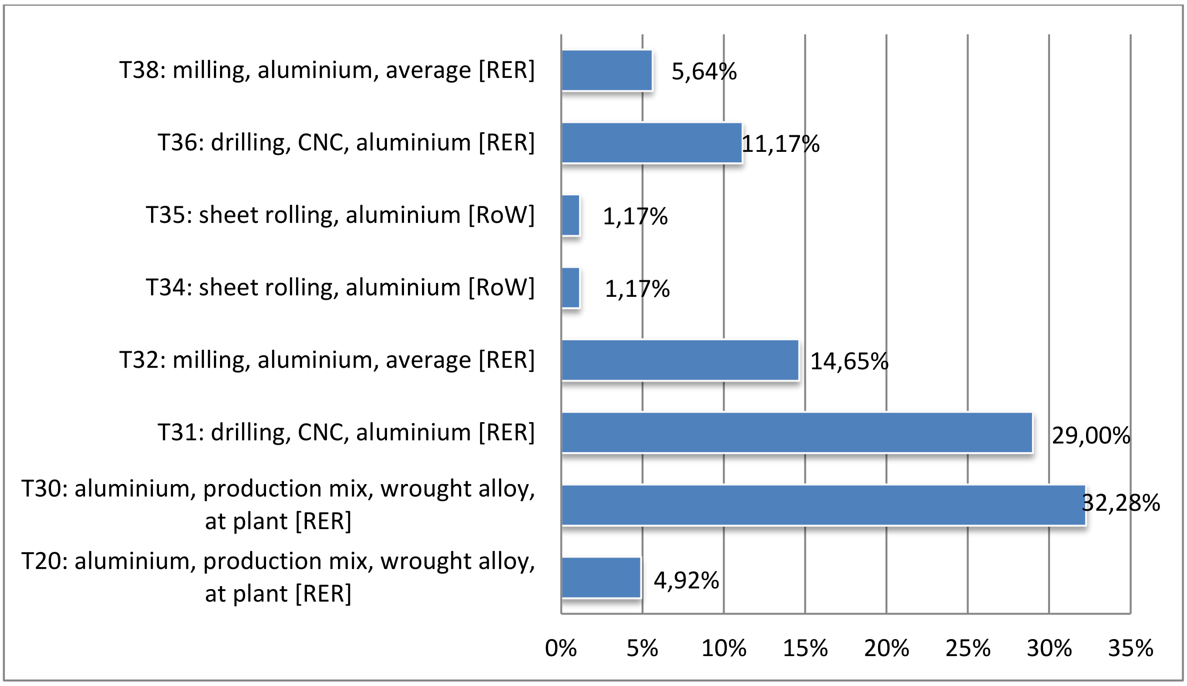


Figure 3.22 – Subnet regenerative storage - Resource depletion of abiotic resources

The wheels and tires have here 37,25 [kg antimony Eq.] and is mostly because of its weight (77,15%) , whereas the production represents only about 18% where 11,46 % is from the production of synthetic rubber.

***Human health, respiratory effects***

This category indicator aims to quantify the effects of the environmental pollution with particulate matter (PM 2.5), which has a negative human effects.

The chassis still the part with more impact also in this indicator. However the scenario in the subnets changed. The transportation has decreased and unlike, in the GWP and ADP indicators, the doors here have the impact of 11,6% and the body shell 6,47%. The suspension stands here with less than 5%.

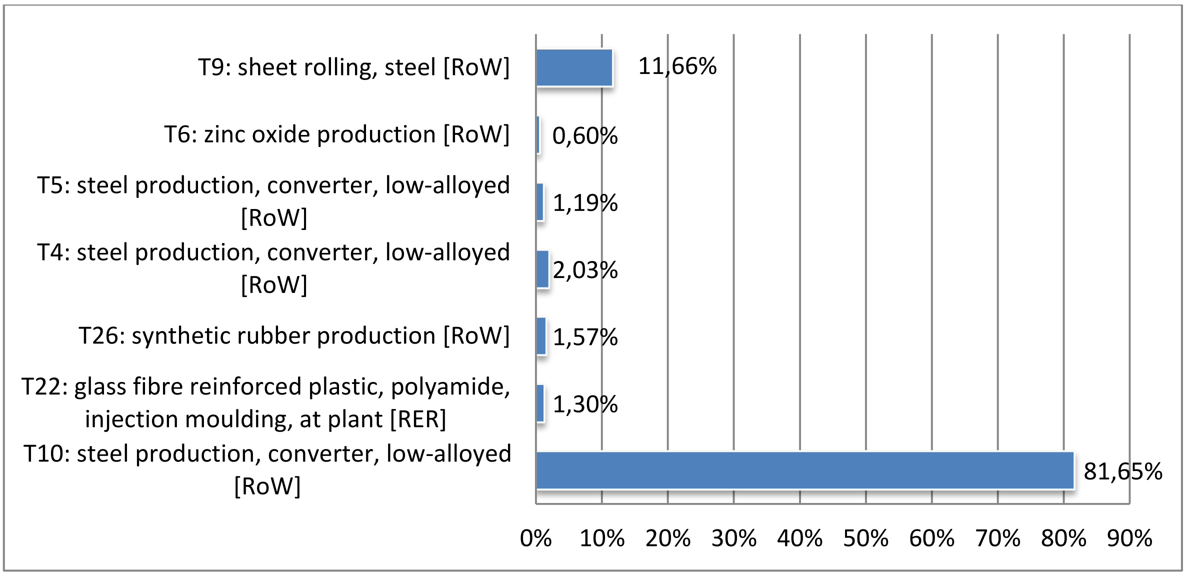


Figure 3.23 - Subnet doors – Human health, respiratory effects

The processes of sintering production steel and iron are the major air pollution sources[122].

In the Figure 3.23, the steel production has by far the highest impact. The body shell, presented in the Figure 3.24, the scenario is similar with the steel production. However, in this model there are production of aluminum, iron and polycarbonate.

The engine in this indicator, has reduced almost 25% for the transportation, whereas the production itself has increased in 32,17%, because the ICE is mostly made out of steel and iron.

The power electronics has in this indicator a big impact, it represents fourth biggest impact value with 5,4046 [kg PM 2.5 Eq]. This part of the car is mainly electronic components however includes also a small quantity of steel and chromium steel.

Within the power electronics, the subnet converter is where come from the most part of the impact (90%). The Figure 3.25, shows that the platinum is highly harmful for the humans health.

The platinum is used mostly in electronic industry due its characteristics. The converter used to modeled the Prius uses only 2,78 grams of Platinum.

[122] (Jiun-Horng, et al., 2006 pp. 111-113)

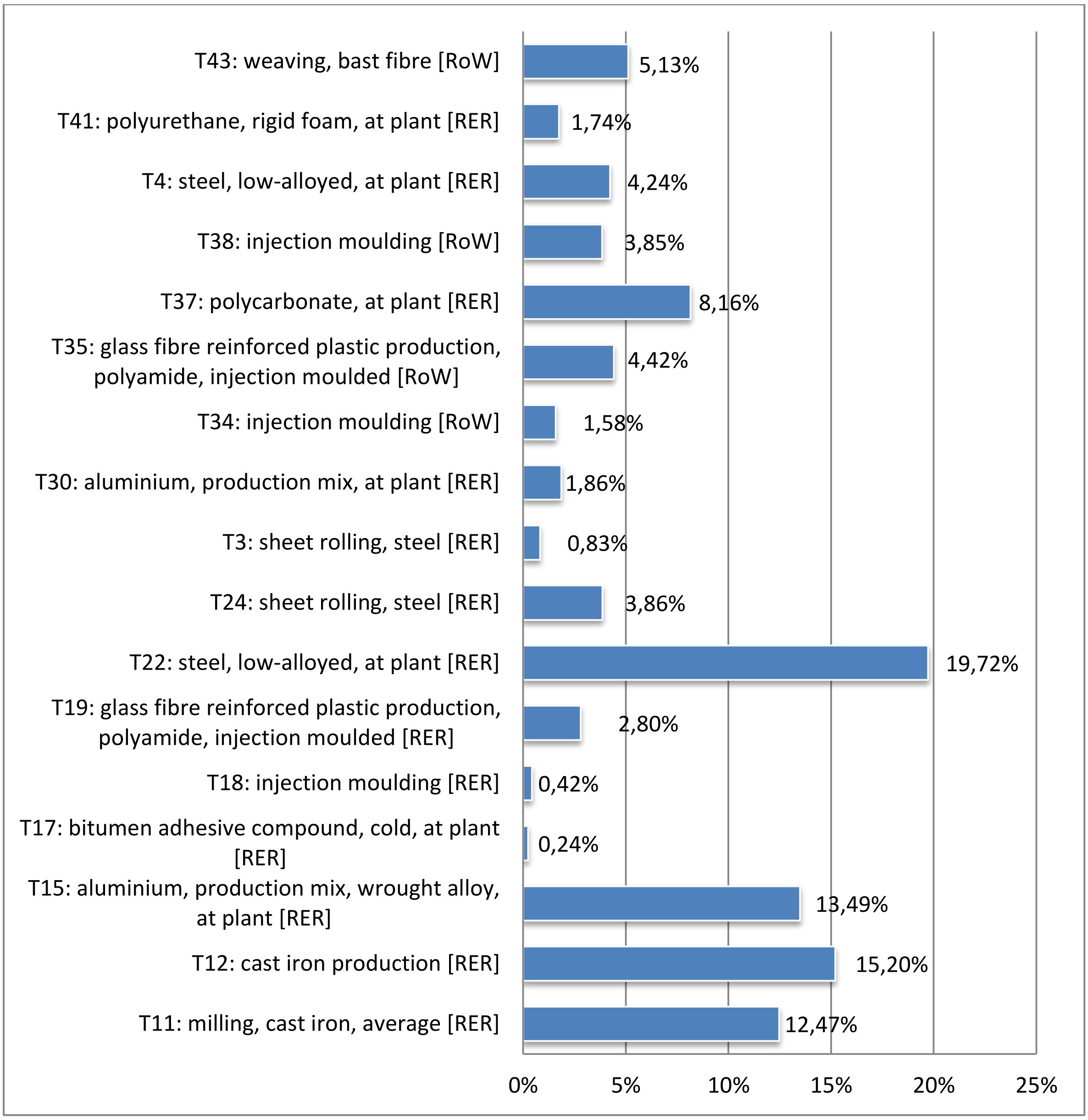


Figure 3.24 - Subnet body shell – Human health, respiratory effects

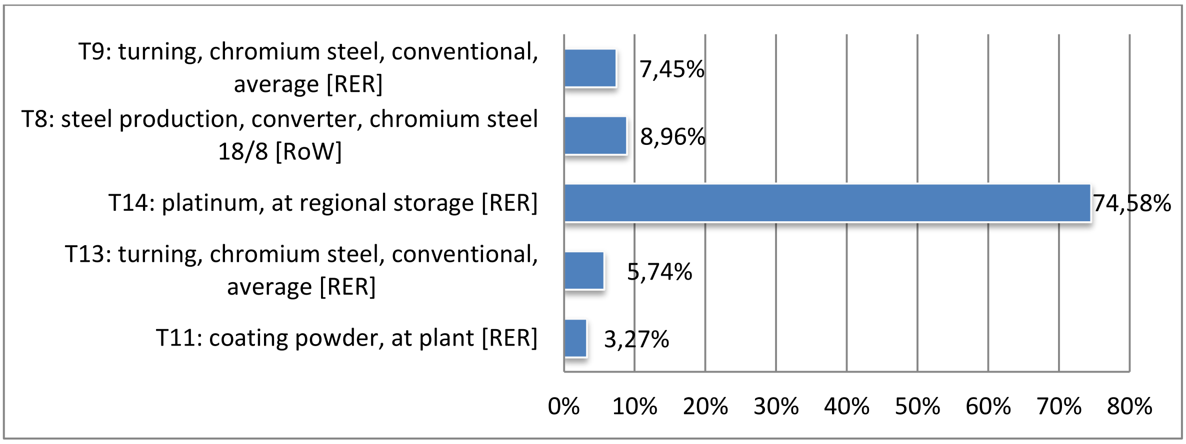


Figure 3.25 - Subnet converter – Human health, respiratory effects

The cell of the battery and transportation are the main source of particulate matter.

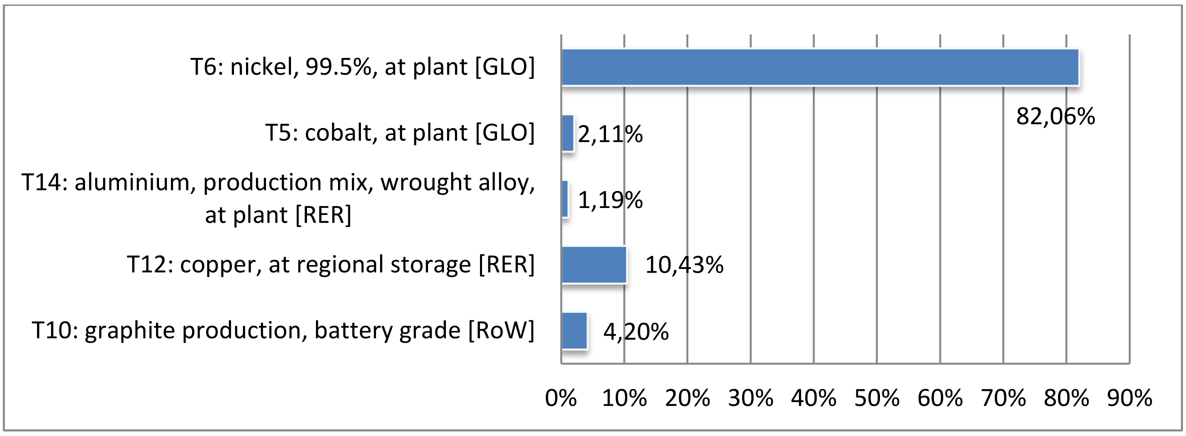


Figure 3.26 – Subnet cell – Human health, respiratory effects

The nickel stands out with its impact on particulate matter, followed by the copper.

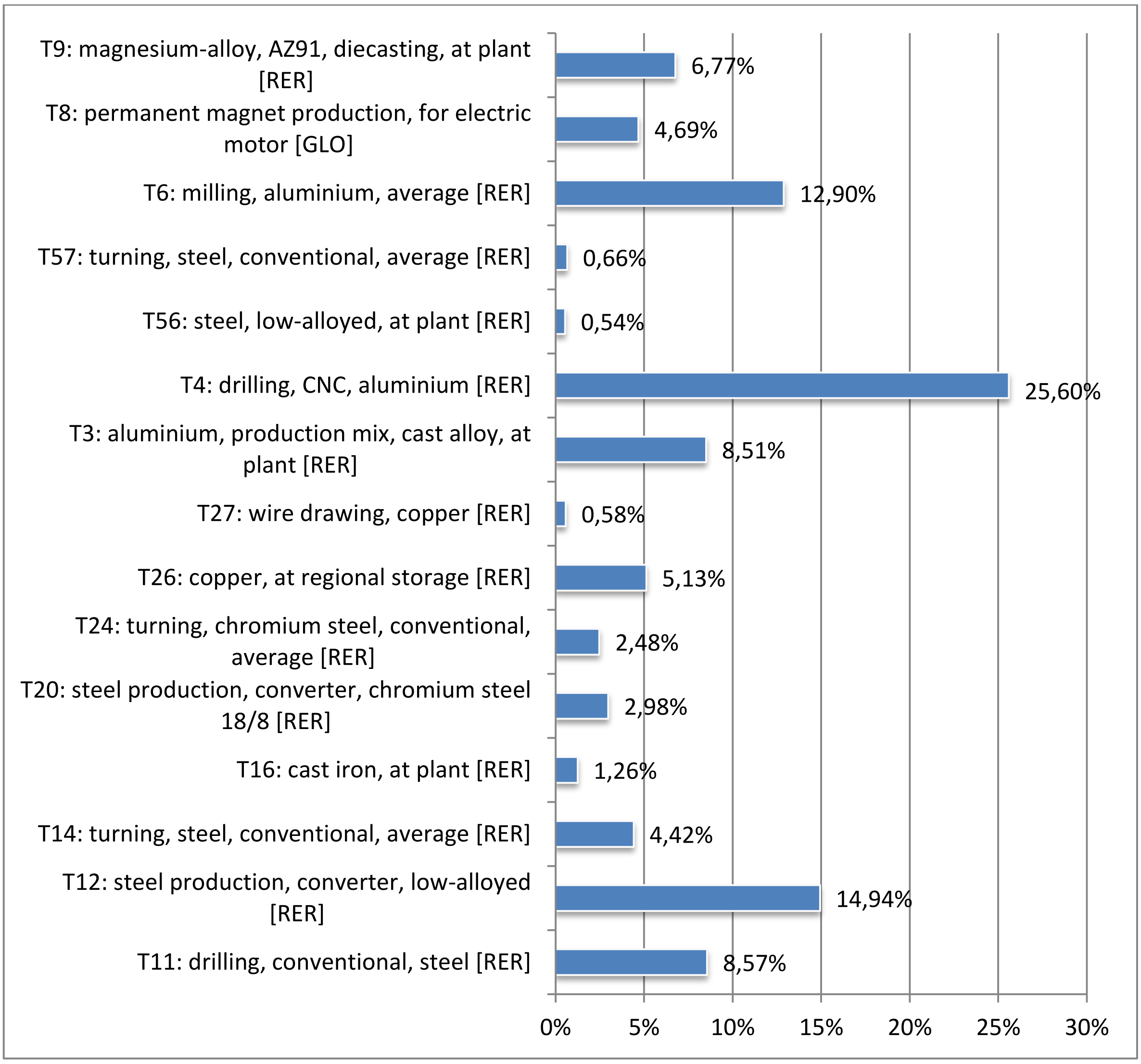


Figure 3.27 - Subnet generator – Human health, respiratory effects

The generator, from the electric motor is 75% responsible for the emissions of particulate matter.

The Figure 3.27, shows that the generator is made out of several materials which are harmful for the humans health, namely respiratory diseases.

Summing up, the models here analyzed the most relevant materials responsible for the impact in this indicator, are the steel production, converter low – alloyed, platinum and nickel, from the models chassis (doors), power electronics (converter), and battery (cell) respectively.

The previous analysis was made in general, without taking into account the impact categories throughout life cycle phases. In order to find out the behavior of the impact during the four phases, was created an extra excel sheet, containing all the phases for every impact category. However due the big amount of data and graphics, this study will focus in the most import indicators and in the most important phases (Production and Use phase), but all the others impact categories can be find in Appendix B.

***Global Warming Potential***

| Part/Component (Model) | GWP [kg CO2-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 367,1621 | 144,6350 | 2,3550 | 212,9114 | 7,2607 |
| 2 - Airbag / Cigarrete | 331,1044 | 75,5405 | 2,7047 | 244,5206 | 8,3386 |
| 3 - Audio / Media | 989,8120 | 931,6342 | 0,6157 | 55,6638 | 1,8982 |
| 4 - Battery | 2.113,6944 | 312,3663 | 19,0401 | 1.721,3677 | 60,9203 |
| 5 - Breaking System | 3.649,1762 | 2.221,3985 | 15,1103 | 1.366,0814 | 46,5861 |
| 6 - Chassis | 15.195,4711 | 3.380,2447 | 125,0414 | 11.304,6736 | 385,5115 |
| 7 - Clutch | 707,2414 | 525,8885 | 1,9250 | 174,0359 | 5,3919 |
| 8 - Cockpit / Cabling | 859,4012 | 189,5640 | 7,1793 | 649,0584 | 13,5995 |
| 9 - Connection Material | 761,6155 | 196,0054 | 6,1626 | 557,1475 | 2,2999 |
| 10 - Electric Motor | 7.265,2353 | 5.633,2804 | 17,3228 | 1.566,1115 | 48,5206 |
| 11 - Fluids and Oil | 922,6251 | 141,0235 | 7,9004 | 714,2573 | 59,4439 |
| 12 - Horn / Sun Protector / Jack | 151,5978 | 18,9811 | 1,4508 | 131,1615 | 0,0045 |
| 13 - Engine | 6.358,1790 | 1.293,1940 | 55,0638 | 4.729,2699 | 280,6513 |
| 14 - Lighting | 702,9126 | 145,3215 | 4,2224 | 381,7337 | 171,6350 |
| 15 - Power Electronics | 1.352,5671 | 759,9662 | 6,2903 | 568,6916 | 17,6190 |
| 16 - Power Steering | 2.711,6604 | 1.780,0957 | 9,8883 | 893,9795 | 27,6969 |
| 17 - Seats | 1.973,7541 | 366,9117 | 17,0053 | 1.537,4084 | 52,4286 |
| 18 - Wheels and Tyres | 5.403,7669 | 886,1753 | 19,2404 | 4.160,5427 | 337,8086 |
| 19 - Windows | 2.327,5750 | 218,7366 | 22,2587 | 2.017,9547 | 68,6251 |
| Total | 54.144,5515 | 19.220,9629 | 340,7772 | 32.986,5712 | 1.596,2401 |

Table 3.4 – Global Warming Potential [kg $CO_2$-Eq]

The Table 3.4 demonstrates that the use phase is largely responsible (61%) for the global warming potential, because of the emissions released by the tailpipe during this phase. After the combustion of petrol, a majority of the carbon is emitted as $CO_2$, and small portions of hydrocarbons and carbon monoxide. The production phase has a considerable value of 35,5%, including the extraction of the raw materials, production, ending with the assembly as mentioned before. The distribution and the end of life, have almost a negligible value of 1% and 2,9% respectively. The production of the electric motor has a considerable impact.

According to (Hawkins, et al., 2012 pp. 53-54), the electric vehicles when compared with conventional ones, have several advantages within the use phase, because of their "*zero tailpipe emissions*", powertrain efficiency and maintenance. However the scenario within the use phase is different. Indeed the Table 3.4 shows that all the parts that have electronic components in its constitution, for example the Audio/Media, Breaking System, Power electronics and Power steering, have the higher values. The production of electronic components needs a widely variety of materials, in which their extraction involves impacts for this indicator[123].

The chassis also has a high value, due its weight. As mentioned before, within the life cycle inventory, where was electricity assumed for the assembly, is 3,8MJ/kg multiplied by the weight of the part.

In the use phase, as well as the distribution, stands out the car consumption, therefore the weight of each part of the car here plays a key role.

The end of life for the ICE is bigger than for the electric motor contrary to what occurred for the production phase. The recycling process of aluminum has a higher burden than the steel for the $CO_2$ emissions, reason why the wheels and tires come up right after chassis. The

The lighting includes in its constitution aluminum, for this reason the end of life involves big amount of Kg $CO_{2eq}$ released.

In general, the aluminum entails a big burden in its recycling process, as well as in its extraction as a raw material (however less), thus shall be recovered and used in further product systems.[124]

### *Resource depletion of abiotic resources*

The table Table 3.5 shows how is the impact of the extraction of raw materials over all four phases, related to each part of the vehicle. The electric motor comes up again with the highest value among the other parts. The extraction of raw materials such aluminum, magnesium, and neodymium, present a high burden within the production phase and end of life.

[123] (Hawkins, et al., 2012 p. 53)
[124] (Koffler, et al., 2012 p. 34)

| Part/Component (Model) | ADP [kg antimony-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 2,4557 | 0,9635 | 0,0163 | 1,4707 | 0,0052 |
| 2 - Airbag / Cigarrete | 2,3146 | 0,6009 | 0,0187 | 1,6890 | 0,0060 |
| 3 - Audio / Media | 7,4616 | 7,0715 | 0,0043 | 0,3845 | 0,0014 |
| 4 - Battery | 14,5460 | 2,2103 | 0,1315 | 11,8903 | 0,3139 |
| 5 - Breaking System | 22,6147 | 13,0407 | 0,1043 | 9,4361 | 0,0335 |
| 6 - Chassis | 96,1790 | 16,9519 | 0,8635 | 78,0865 | 0,2771 |
| 7 - Clutch | 2,2185 | 0,9719 | 0,0133 | 1,2021 | 0,0312 |
| 8 - Cockpit / Cabling | 5,8656 | 1,2820 | 0,0496 | 4,4833 | 0,0507 |
| 9 - Connection Material | 5,2004 | 1,2940 | 0,0426 | 3,8485 | 0,0154 |
| 10 - Electric Motor | 29,1050 | 17,8872 | 0,1196 | 10,8178 | 0,2804 |
| 11 - Fluids and Oil | 5,8519 | 0,6580 | 0,0546 | 4,9337 | 0,2057 |
| 12 - Horn / Sun Protector / Jack | 1,0729 | 0,1569 | 0,0100 | 0,9060 | 0,0000 |
| 13 - Engine | 42,6014 | 8,6102 | 0,3803 | 32,6672 | 0,9437 |
| 14 - Lighting | 3,8337 | 0,9733 | 0,0292 | 2,6368 | 0,1944 |
| 15 - Power Electronics | 9,4000 | 5,3265 | 0,0434 | 3,9282 | 0,1018 |
| 16 - Power Steering | 10,0430 | 3,6396 | 0,0683 | 6,1751 | 0,1601 |
| 17 - Seats | 13,9999 | 3,2252 | 0,1174 | 10,6196 | 0,0377 |
| 18 - Wheels and Tyres | 37,2489 | 8,2431 | 0,1380 | 28,7387 | 0,1291 |
| 19 - Windows | 15,6723 | 1,5304 | 0,1537 | 13,9389 | 0,0493 |
| Total | 327,6851 | 94,6370 | 2,3585 | 227,8531 | 2,8366 |

Table 3.5 - Resources Depletion of Abiotic Resources [kg antimony Eq.]

The processes used in the production phase, are responsible for this indicator, namely all the manufacturing processes which involve aluminum and magnesium, for instance drilling and milling. The distribution and the use phase are according to the weight of each part.

The engine, the battery and the electric motor, are the higher burdens in the recycling phase, due the requirement of extraction of more raw materials to aid their complex recycling processes.

***Human health, respiratory effects***

The Table 3.6 shows, which are the responsible components for produce negative effects in human health. The production phase has a big impact (52%) comparing to the other phases. All electronic components in general are here highlighted, namely the power electronics. The usage of materials such as platinum (converter of power electronic) and some processes for example drilling CNC aluminum (generator-EM) and steel production used for the production of the doors (Chassis) and used within generator (EM) are the main reasons, responsible for within this impact category.

The battery stands out here, as the most harmful component to human health in both, production and recycling, due its hazardous components namely nickel present in its cell.

The distribution and the use phase, as mentioned in the others indicators, have been linked to the weight, their impact in the different phases is directly proportional to the weight.

Regarding to the end of life, the powertrain and chassis are the components with more impact .

| Part/Component (Model) | PM 2.5 [kg PM2.5-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 0,3151 | 0,1578 | 0,0077 | 0,1480 | 0,0017 |
| 2 - Airbag / Cigarrete | 0,3596 | 0,1790 | 0,0088 | 0,1699 | 0,0019 |
| 3 - Audio / Media | 1,0075 | 0,9664 | 0,0020 | 0,0387 | 0,0004 |
| 4 - Battery | 6,4031 | 4,9990 | 0,0621 | 1,1962 | 0,1458 |
| 5 - Breaking System | 3,6443 | 2,6350 | 0,0492 | 0,9493 | 0,0107 |
| 6 - Chassis | 11,4309 | 3,0790 | 0,4076 | 7,8555 | 0,0888 |
| 7 - Clutch | 0,3051 | 0,1645 | 0,0063 | 0,1209 | 0,0134 |
| 8 - Cockpit / Cabling | 0,6484 | 0,1648 | 0,0234 | 0,4510 | 0,0091 |
| 9 - Connection Material | 0,7207 | 0,3099 | 0,0201 | 0,3872 | 0,0036 |
| 10 - Electric Motor | 5,0131 | 3,7481 | 0,0565 | 1,0883 | 0,1203 |
| 11 - Fluids and Oil | 0,6291 | 0,0650 | 0,0258 | 0,4963 | 0,0420 |
| 12 - Horn / Sun Protector / Jack | 0,1201 | 0,0242 | 0,0047 | 0,0911 | 0,0000 |
| 13 - Engine | 6,6392 | 2,8162 | 0,1795 | 3,2863 | 0,3572 |
| 14 - Lighting | 0,4285 | 0,1035 | 0,0138 | 0,2653 | 0,0460 |
| 15 - Power Electronics | 5,4046 | 4,9453 | 0,0205 | 0,3952 | 0,0437 |
| 16 - Power Steering | 1,4884 | 0,7662 | 0,0322 | 0,6212 | 0,0687 |
| 17 - Seats | 1,5197 | 0,3839 | 0,0554 | 1,0683 | 0,0121 |
| 18 - Wheels and Tyres | 4,2248 | 1,2700 | 0,0310 | 2,8911 | 0,0327 |
| 19 - Windows | 1,8062 | 0,3156 | 0,0725 | 1,4023 | 0,0158 |
| Total | 52,1085 | 27,0935 | 1,0790 | 22,9221 | 1,0138 |

Table 3.6 – Human Health, Respiratory Effects [PM 2.5 Eq]

The Table 3.7 aims to give an overview about different impact categories, in order to quantify the indicators in their respective phase.

| | Phases | | | |
|---|---|---|---|---|
| | Production | Distribution | Use | End-of-Life |
| AP [ kg SO2-Eq] | 106,55 | 5,69 | 87,46 | 4,01 |
| GWP [kg CO2-Eq] | 19.220,96 | 340,78 | 32.986,57 | 1.596,24 |
| EP [kg PO4-Eq] | 11,41 | 0,55 | 12,33 | 1,07 |
| POCP [kg ethylene-Eq] | 6,63 | 0,19 | 8,78 | 0,25 |
| ADP [kg antimony-Eq] | 94,64 | 2,36 | 227,85 | 2,84 |
| PM 2.5 [kg PM2.5-Eq] | 27,09 | 1,08 | 22,92 | 1,01 |

Table 3.7 - Global Results all impact categories

***General Results***

The phase distribution and end of life were not analyzed deeply as the production and use phase did. Indeed, the focus of this report is the production and the use phase, reason why were given more attention to them.

The production phase has more impact in only in the Acidification, and Human health, respiratory effects. All the others impact categories have more impact within the use phase.

The distribution has more impact in the Human health, Eutrophication and Acidification.

The impact category with more impact within the end-of-life is the Eutrophication.

The outcomes in general are reasonable acceptable, even being relatively high, specially the global warming.

### 3.2.5 Life Cycle Interpretation

The interpretation is the last phase of an LCA. Is a systematic procedure to identify, qualify, check and evaluate information from the results of the previous parts[125].

#### IDENTIFICATION OF SIGNIFICANT ISSUES

According to the ISO 14043 the identification of the significant issues, aims the interaction of the assumptions made, and methods used. The significant issues, for this study are directly linked to the production phase. However the impact in the other stages of life, are also considered.

To choose the issue question is not an easy task, and the success of the interpretation depends on it. Therefore and in order to fulfil the stated goal of this study the focus will be given to the models: chassis, battery, electric motor and the power electronics and two category indicators, Global Warming Potential, and Human Health, Respiratory Effects.

#### EVALUATION

It is done to give credibility to the report, in order to enhance the confidence and the reliability of the results[126].

As was reported in the life cycle impact assessment, there are a few materials that their amounts play a key role in some impact categories.

In order assess their impact, for each model mentioned above, is presented two different tables, one for each material and different impact category.

Moreover each table has two different cases, the case A has more 50% comparing to the reference value, whereas the case B has less 50% of the reference value.

##### *Sensitivity Check*

According to the ISO 14043:2000, the aim of the sensitivity check is to assess the reliability of the final results as well as, whether they are affected by uncertainties in the data. The production phase is the only phase assessed, in the sensitivity evaluation.

[125] (ISO 14043, 2000 pp. 1-3)
[126] (ISO 14043, 2000 p. 5)

For each model is given their significant issue. There are flags in the production, aiming to give a visual perception for the increasing or decreasing of each indicator. The yellow is used for the reference value, and it presents the reference impact. The red and green flag show whether the impact improved or not, changing the amount of certain material.

### *Chassis – Global Warming*

In the suspension (subnet of chassis), the magnesium has a considerable impact, namely for the global warming therefore, this material and this impact category were chosen to be the significant issue.

The reference amount of "*magnesium-alloy, AZ91, diecasting, at plant [RER]"* is 3.556 g. Therefore the case A and B have 5.334 g and 1.778 g respectively (see table below).

| | Global Warming [kg CO2 eq] | | | | |
|---|---|---|---|---|---|
| **Chassis** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 3.380,24 | 3.822,86 | 2.796,64 | 420,27 | 12,43% |
| Body Shell | 18,14% | 16,04% | 21,92% | | |
| Doors | 22,06% | 19,51% | 26,67% | | |
| *Suspension* | 45,65% | 51,94% | 34,31% | | |
| Electricity medium voltage | 14,15% | 12,51% | 17,11% | | |
| **Distribution** | 125,04 | 125,04 | 125,04 | 0,00 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 85,49% | 85,49% | 85,49% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 14,51% | 14,51% | 14,51% | | |
| **Use** | 11.304,67 | 11.304,67 | 11.304,67 | 0,00 | 0,00% |
| **End-of Life** | 385,51 | 385,51 | 385,51 | 0,00 | 0,00% |

Table 3.8 – Magnesium – GWP – Sensitivity Analysis

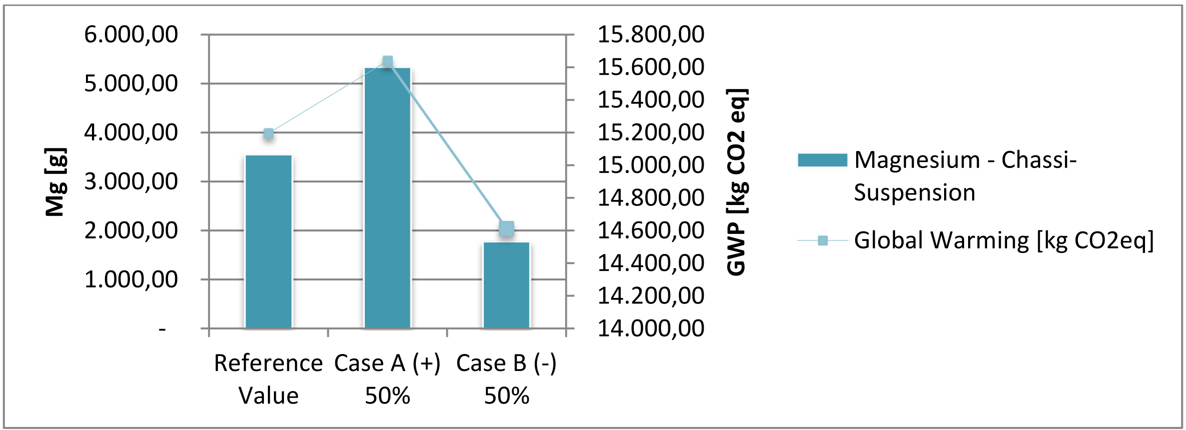


Figure 3.28 – Magnesium – GWP – Sensitivity Analysis

The sensitivity presented in the Table 3.8 is 12,43% and in the Figure 3.28 is possible to see the variation graphically. The variation of this material has a considerable impact. For instance by using less 50% of this material within the production of the suspension, the GWP, could decrease 583,61 [kg $CO_{2\ eq}$] the carbon dioxide released to the atmosphere.

### *Chassis – Human Health, respiratory effects*

As reported in the life cycle impact assessment, the subnet doors in the category indicator Human Health, respiratory effects has a big impact, mainly because the process T10, *“steel production, converter, low-alloyed [RoW]*”(see Figure 3.23). Thus the significant issues are the steel production and the impact category Human Health, respiratory effects. The reference value for steel production is 87.798,81 g.

| | Human Health, respiratory effects [kg PM 2.5eq] | | | | |
|---|---|---|---|---|---|
| **Chassis** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 3,08 | 3,09 | 2,07 | 0,48 | 15,58% |
| Body Shell | 24,01% | 24,01% | 35,78% | | |
| *Doors* | 43,07% | 43,07% | 15,16% | | |
| Suspension | 18,43% | 18,43% | 27,46% | | |
| Electricity medium voltage | 14,49% | 14,49% | 21,60% | | |
| **Distribution** | 0,41 | 0,41 | 0,41 | 0,00 | 0,06% |
| Transportation freight sea transoceanic ship [GLO] | 97,25% | 97,25% | 97,25% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 2,75% | 2,75% | 2,75% | | |
| **Use** | 7,86 | 7,86 | 7,86 | 0,00 | 0,00% |
| **End-of Life** | 0,09 | 0,09 | 0,09 | 0,00 | 0,00% |

Table 3.9 – Steel Production Converter – PM 2.5 – Sensitivity Analysis

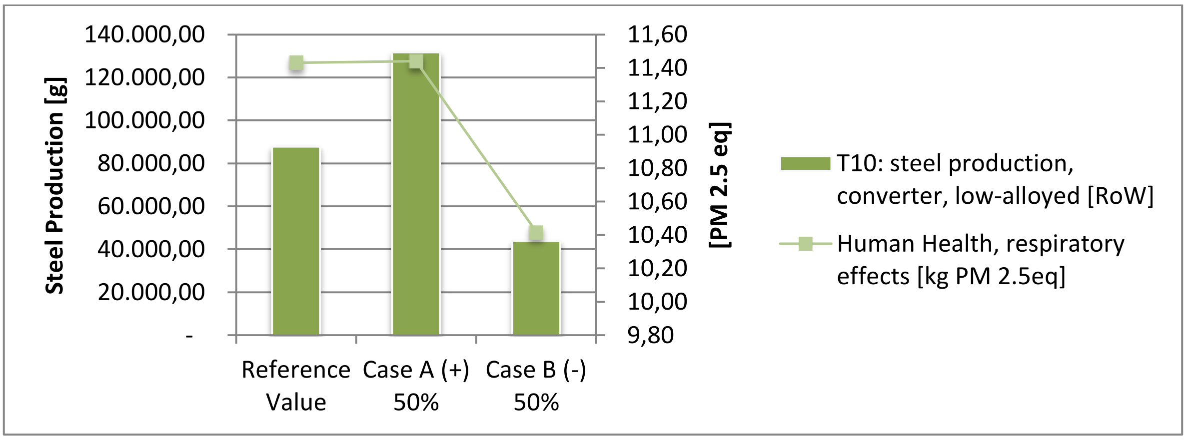


Figure 3.29 – Steel Production Converter – PM 2.5 – Sensitivity Analysis

Comparing the Table 3.9 with Figure 3.29 the increasing of steel production (case A) does not affect considerable the indicator PM 2.5. On the other hand, the decreasing of the steel production, has a substantially benefit. With the case B the reduction of the impact is nearly of 10%. The sensitivity in this indicator is higher than for the Global Warming.

### *Electric Motor – Global Warming*

The electric motor, in the life cycle impact assessment has revelled, its highest impact in the generator, due the use of aluminium, and some associated manufacturing processes (see Figure 3.12 and Figure 3.27). This material has more impact in both: global warming and human health, thus is the significant issue for the two different categories is the same, in this case. The reference value is 11.449,00 g for both indicators.

| Electric Motor | Global Warming [kg CO2 eq] Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
|---|---|---|---|---|---|
| **Production** | 5.633,28 | 7.194,74 | 4.186,91 | 1.228,2390 | 21,80% |
| *Generator* | 99,47% | 99,59% | 99,29% | | |
| Electricity medium voltage | 0,53% | 0,41% | 0,71% | | |
| **Distribution** | 17,32 | 17,32 | 17,32 | 0,0000 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 85,49% | 85,49% | 85,49% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 14,51% | 14,51% | 14,51% | | |
| **Use** | 1566,11 | 1.566,11 | 1.566,11 | 0,0000 | 0,00% |
| **End-of Life** | 48,52 | 48,52 | 48,52 | 0,0000 | 0,00% |

Table 3.10 – Aluminum – GWP – Sensitivity Analysis

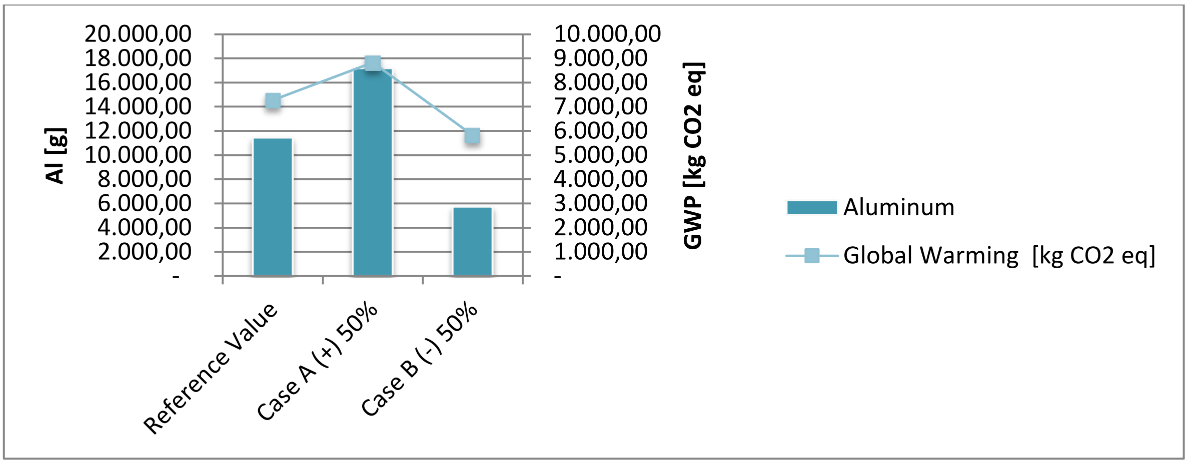


Figure 3.30 – Aluminum – GWP – Sensitivity Analysis

The sensitivity analysis, presented in the Table 3.10 shows that the variation of this metal, induces a big impact in this indicator. For example, with the increase of aluminum in 50% the $CO_2$ increases 1.561,45 kg eq, whereas with the decrease of the same material induces the release of 1.446,37 kg $CO_{2eq}$ less into the environment (values compared with the reference impact).

### *Electric Motor – Human Health, respiratory effects*

| Electric Motor | Human Health, respiratory effects [kg PM 2.5eq] Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
|---|---|---|---|---|---|
| **Production** | 3,72 | 4,31 | 3,44 | 0,3647 | 9,80% |
| Generator | 99,26% | 99,36% | 99,19% | | |
| Electricity medium voltage | 0,74% | 0,64% | 0,81% | | |
| **Distribution** | 0,06 | 0,06 | 0,06 | 0,0000 | 0,01% |
| Transportation freight sea transoceanic ship [GLO] | 97,25% | 97,25% | 97,25% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 2,75% | 2,75% | 2,75% | | |
| **Use** | 1,09 | 1,09 | 1,09 | 0,0000 | 0,00% |
| **End-of Life** | 0,12 | 0,12 | 0,12 | 0,0000 | 0,00% |

Table 3.11 – Aluminum – PM 2.5 – Sensitivity Analysis

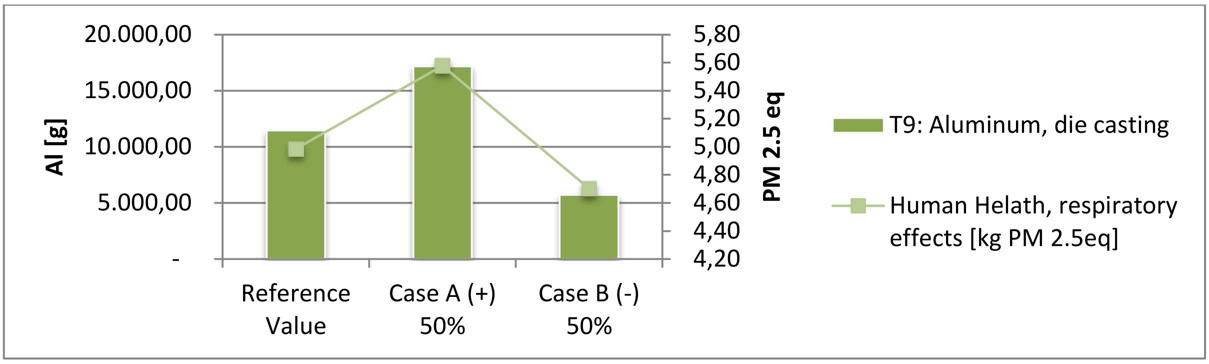


Figure 3.31 – Aluminum – PM 2.5 – Sensitivity Analysis

The sensitivity within this indicator is also considerable. By reducing the amount of aluminum in the production phase, brings considerable benefits to the environment as well as for humans health, namely respiratory effects. In fact, the impact is not only verified in the production, the recycling process has as well a big, being so most of the time reused to produce new materials, to decrease its impact.

### *Battery – Global Warming*

The NiMH battery uses nickel for its electrolyte, which is a rare earth metal, however has been widely used in hybrid vehicles. This metal, as the case of the electric motor has a big impact in GWP and PM 2.5, thus will be used as a significant issue for both indicators. The reference 12.631,58 g.

| | Global Warming [kg CO2 eq] | | | | |
|---|---|---|---|---|---|
| **Battery** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 312,37 | 379,04 | 279,23 | 41,5052 | 13,29% |
| Cell | 96,89% | 77,88% | 69,97% | | |
| Battery Management System | 1,24% | 7,31% | 9,93% | | |
| Cable | 0,74% | 1,65% | 2,24% | | |
| Frame | 0,19% | 3,58% | 4,86% | | |
| Housing | 0,80% | 7,64% | 10,38% | | |
| Electricity medium voltage | 0,14% | 1,93% | 2,62% | | |
| **Distribution** | 19,04 | 19,04 | 19,04 | 0,000 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 85,49% | 85,49% | 85,49% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 14,51% | 14,51% | 14,51% | | |
| **Use** | 1721,37 | 1.721,37 | 1.721,37 | 0,0 | 0,00% |
| **End-of Life** | 60,92 | 60,92 | 60,92 | 0,0 | 0,00% |

Table 3.12 – Nickel – GWP – Sensitivity Analysis

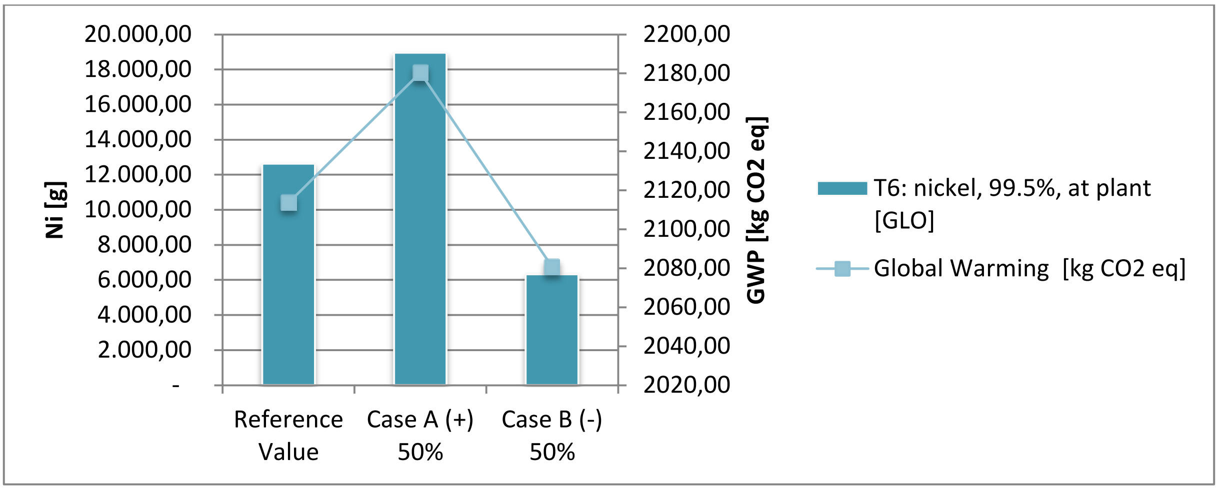


Figure 3.32 – Nickel – GWP – Sensitivity Analysis

The sensitivity analysis in the Table 3.12, shows a variation of 13,29%, which is a considerable value to take into account. According to the graphic of the Table 3.12, for the case A, the sensitivity is bigger, and consequently the impact is also higher (increases 3%).

***Battery – Human Health, respiratory effects***

In this indicator, the scenario for the battery gets even worse. The nickel is a hazardous metal for the human's health. TheTable 3.13 shows the highest sensitivity seen so far, with 33,5%. According to the Figure 3.33, the increase of the nickel induces more impact in this indicator than its reduction.

| | Human Health, respiratory effects [kg PM 2.5eq] | | | | |
|---|---|---|---|---|---|
| **Battery** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 4,999 | 7,309 | 3,214 | 1,68 | 33,53% |
| Cell | 96,89% | 97,88% | 95,17% | | |
| Battery Management System | 1,24% | 0,85% | 1,92% | | |
| Cable | 0,74% | 0,51% | 1,15% | | |
| Framework | 0,19% | 0,13% | 0,29% | | |
| Housing | 0,80% | 0,55% | 1,25% | | |
| Electricity medium voltage | 0,14% | 0,90% | 0,21% | | |
| **Distribution** | 0,062 | 0,062 | 0,062 | 0,0 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 97,25% | 97,25% | 97,25% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 2,75% | 2,75% | 2,75% | | |
| **Use** | 1,196 | 1,196 | 1,196 | 0,0 | 0,00% |
| **End-of Life** | 0,146 | 0,146 | 0,146 | 0,0 | 0,00% |

Table 3.13 – Nickel – PM 2.5 – Sensitivity Analysis

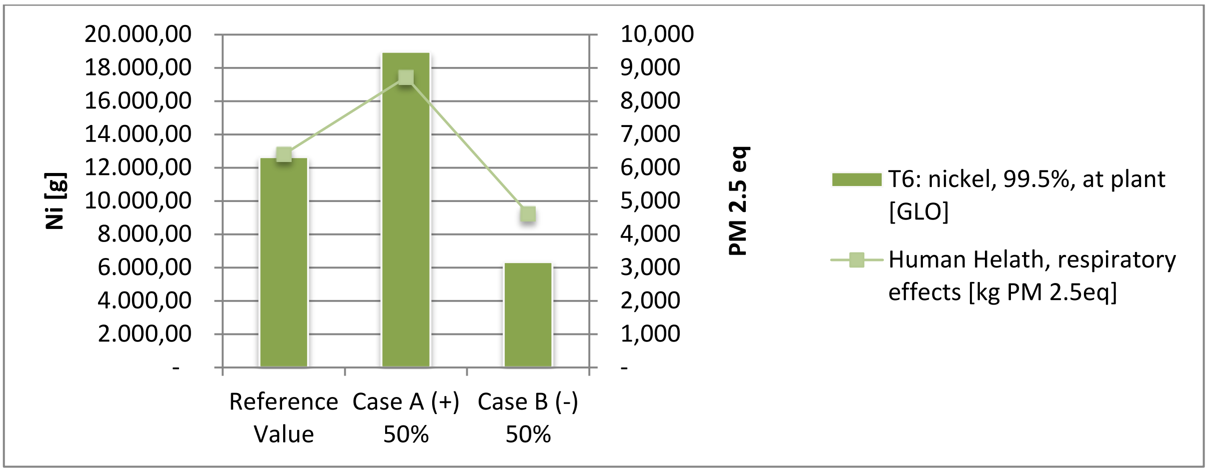


Figure 3.33– Nickel – PM 2.5 – Sensitivity Analysis

### *Power Electronics – Global Warming*

The power electronics is used to transfer the energy saved in the battery to feed the electric motor in a proper form (AC), and in correct voltage. This device is a necessary condition for powertrain electrification, reason why was chosen model, in order to meet the goal and the scope of this study. The Figure 3.34 is the convertor presented within the power electronics.

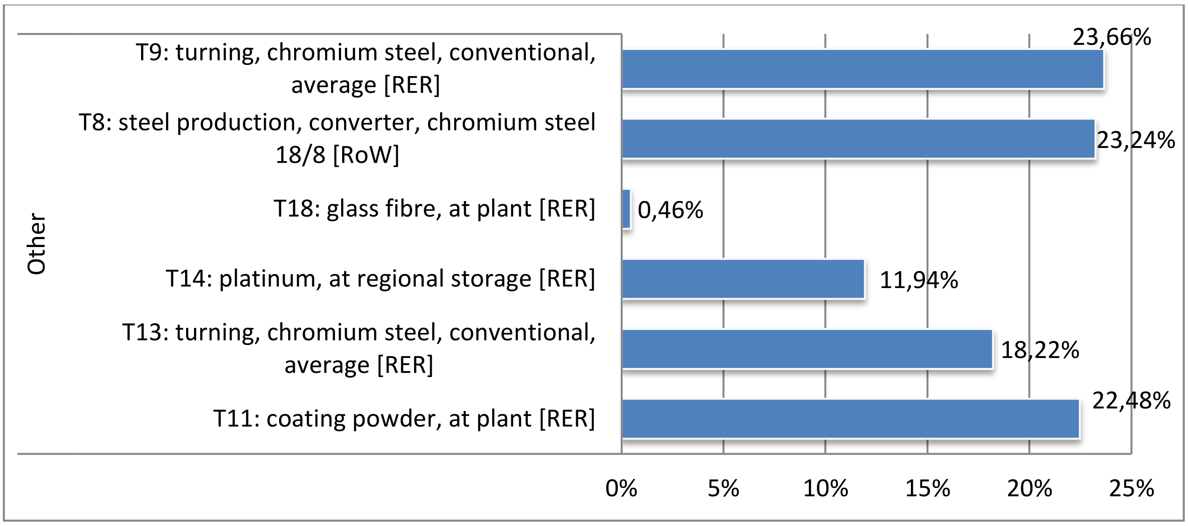


Figure 3.34 - Subnet Convertor - Global Warming

In the converter, for the global warming potential there is homogeneity among the processes that makes the impact difficult to assess. However the screenshot of the Figure 3.35 (from Umberto) shows the chain of manufacturing processes that are behind the whole process.

Now, looking again at the graphic of the Figure 3.34 the processes T9, T8, T11 and T13 are the processes with highest value, and all of them belong to the material, which is steel converter, chromium steel. For this reason the steel production, converter, chromium steel 18/8 and the global warming potential represent a good significant issues.

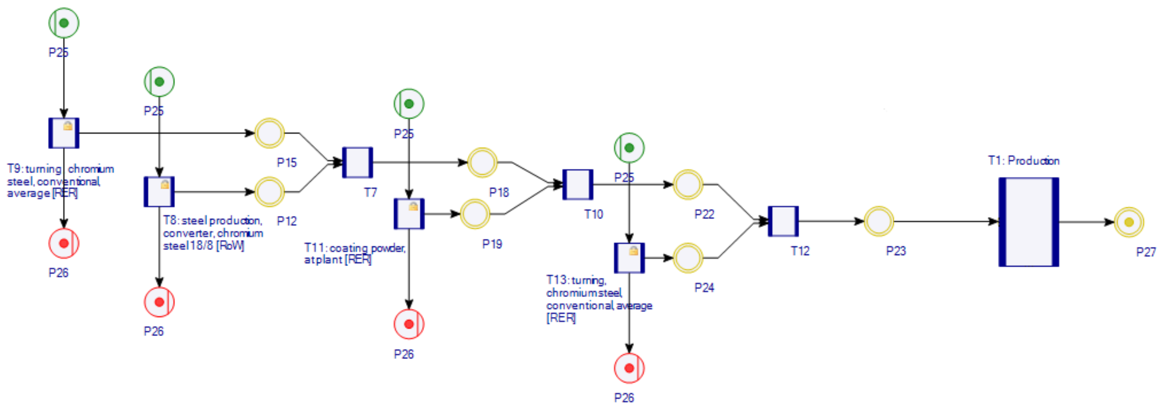


Figure 3.35 - Subnet Converter – Process (modulation Umberto)

The reference value for this material is 8.012,00 g.

The case A and case B does not represent a big impact, and because of that the sensibility as a small value in the Table 3.14.

| | Global Warming [kg CO2 eq] | | | | |
|---|---|---|---|---|---|
| **Power Electronics** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 759,97 | 767,11 | 742,44 | 10,36 | 1,36% |
| Body Computer | 9,38% | 9,29% | 9,60% | | |
| Capacitors | 4,40% | 4,36% | 4,50% | | |
| Control Sytem | 0,64% | 0,64% | 0,66% | | |
| Electronic Unit | 2,13% | 2,11% | 2,18% | | |
| Converter / Inverter | 80,72% | 80,90% | 80,26% | | |
| Electricity medium voltage | 2,74% | 2,71% | 2,80% | | |
| **Distribution** | 6,29 | 6,29 | 6,29 | 0,0 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 85,49% | 85,49% | 85,49% | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 14,51% | 14,51% | 14,51% | | |
| **Use** | 568,69 | 568,69 | 568,69 | 0,0 | 0,00% |
| **End-of Life** | 17,62 | 17,62 | 17,62 | 0,0 | 0,00% |

Table 3.14 – Steel – Chromium – GWP – Sensitivity Analysis

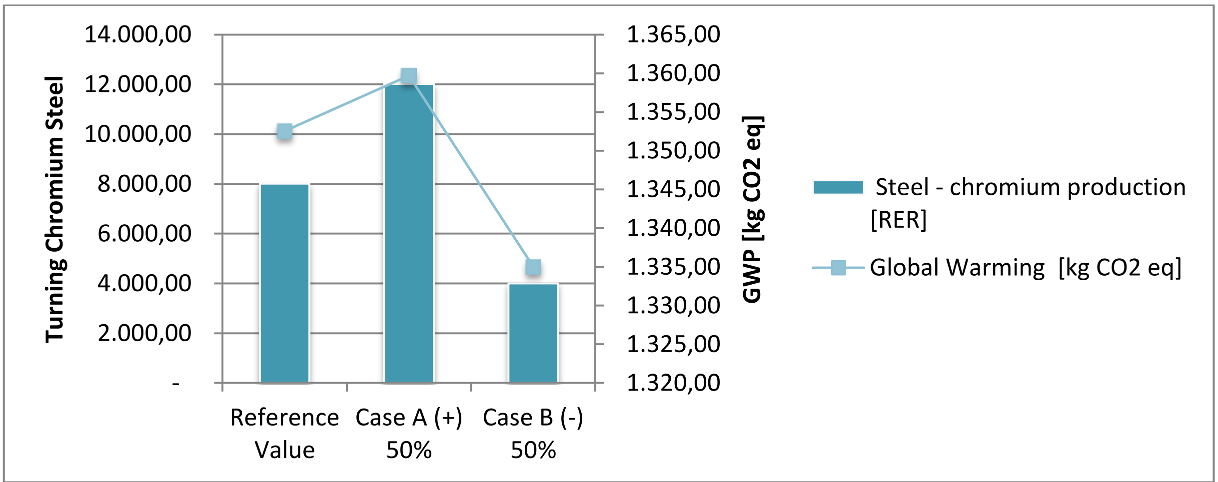


Figure 3.36 – Steel – Chromium – GWP – Sensitivity Analysis

### *Power Electronics – Human Health, respiratory effects*

In this indicator, the scenario change totally. The platinum represents here a big impact (see Figure 3.27), thus the human health as well as the material platinum are the significant issues. As was mentioned before, the platinum is one widely used in electronic components, because of its characteristics, for instance its capacity to support high temperatures.

The reference value for platinum is 2, 78 g.

The sensitivity of these significant issues (PM2.5 and Platinum) presents a big value in Table 3.15, when comparing to the reference value of the other materials, made so far, which means that this material is a strongly dangerous to the human health.

| | Human Health, respiratory effects [kg PM 2.5eq] | | | | |
|---|---|---|---|---|---|
| **Power Electronic** | Reference Value | Case A (+) 50% | Case B (-) 50% | Standard Deviation | Sensitivity [%] |
| **Production** | 4,945 | 6,706 | 3,186 | 1,437 | 29,06% |
| Body Computer | 2,32% | 1,71% | 3,61% | | |
| Capacitors | 0,81% | 0,60% | 1,26% | | |
| Control Sytem | 0,13% | 0,10% | 0,21% | | |
| Electronic Unit | 0,48% | 0,36% | 0,75% | | |
| Converter / Inverter | 95,86% | 96,94% | 93,57% | | |
| Electricity medium voltage | 0,39% | 0,29% | 0,61% | | |
| **Distribution** | 0,021 | 0,021 | 0,021 | 0,0 | 0,00% |
| Transportation freight sea transoceanic ship [GLO] | 97,25% | 97,25% | | | |
| Transportation freight lorry 16-32 metric ton EURO5 | 2,75% | 2,75% | | | |
| **Use** | 0,395 | 0,395 | 0,395 | 0,0 | 0,00% |
| **End-of Life** | 0,044 | 0,044 | 0,044 | 0,0 | 0,00% |

Table 3.15 – Platinum – Human Health – Sensitivity

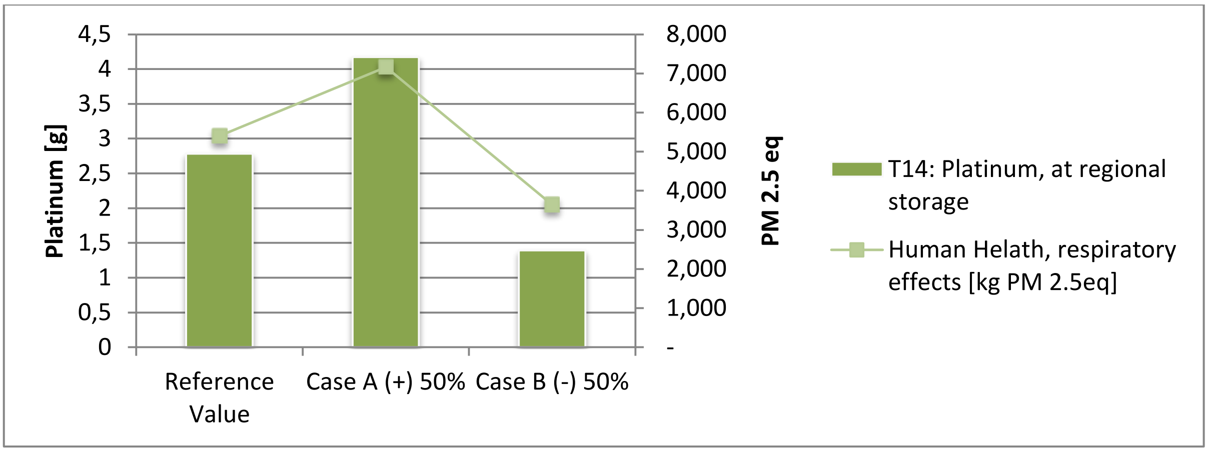


Figure 3.37 – Platinum – Human Health – Sensitivity

With the graphic of the Figure 3.37, is possible to see that with only 2,78 g with a variation of 50% causes a big variation in the PM 2.5 indicator.

## CONCLUSIONS AND RECOMMENDATIONS

The graphic of the Figure 3.38 aims to give an overview, for these four models. In the indicator GWP, the sintering of aluminum and steel, as well as their manufacturing processes in the electric motor, is highly hazardous for the environment reason, reason why the sensibility has this huge value. Their recycling and reuse process play a key role and is highly recommended, to reduce the impacts, especially in the production phase.

The second material is the nickel within the cell of the battery. This metal revels to be also highly harmful for the human health, it presents the highest value in the PM 2.5 indicator with 33,53 % of sensitivity. Indeed, the nickel batteries are mostly used in hybrid cars whereas the lithium batteries are commonly used in electric vehicles. The Lithium batteries have less environmental impact, besides they have more energy density when comparing with NiMH batteries. However they are not used yet, due its reliability.  By decreasing the nickel or even replace it, the impact will be reduced substantially.

Another harmful metal is platinum, which has presented also a huge sensitivity to variations in the category human health. It is recommended to use a substitute material because the platinum is powerfully harmful for the human's health.

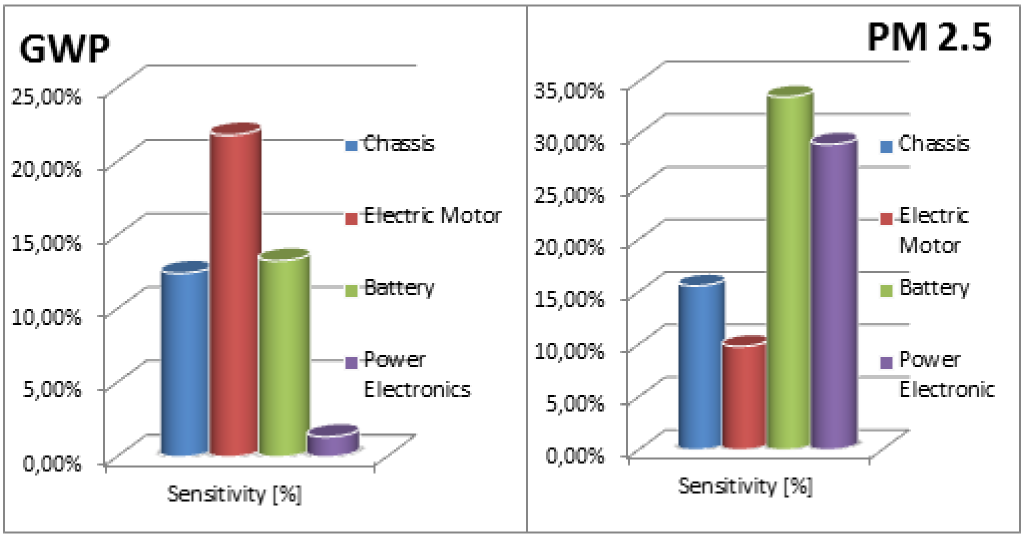


Figure 3.38 - Overall outcome

All of these materials chosen to be the significant issues are used in larger quantities in electric vehicles than in conventional ones. Therefore these significant issues aims to get results closer to the electrification of the powertrain in order to analyse in detail whether the electrification of the powertrain complies their potential to reduce emissions and the consumption of the resources, as set out in the goal of this study.

# 4 *Assessment of the environmental impact using different fuels*

The following chapter is intended to assess the environmental impacts using different fuels creating different scenarios for the Prius. The use phase, is the only stage modelled again in Umberto, all the others are assumed to be the same as in the previous chapter. The aim of this chapter is to create a different scenario for Toyota Prius, in order to find the most ecological and sustainable fuel for Prius.

Reduce greenhouse gas emissions from motor vehicles is a major challenge for climate policy, and a big concern for the society. The increasing cost of the fuels, climate change and environmental pollution have brought the great fear to the society. Various measures, including improving conventional technologies and developing new vehicles and fuel technologies have been implemented.

Each type of fuel has different economy and different emissions released. Therefore is necessary, objectively and holistically evaluate the environmental benefits that are associated to all life – stages for the vehicle.

The previous chapter was conducted a detailed life cycle assessment of the hybrid Toyota Prius, considering six impact categories, analysing all stages of life. In this chapter, in order to assess the environmental impacts using different fuels, is assumed the production distribution and the end of life, are the same, changing only the use phase, by replacing the process "t*ransport, passenger car, medium size, petrol, EURO 5*" by to the respective fuel considered. Afterwards, the impacts will be summed to their respective impact category, in order to compare and quantify the indicators for each different fuel.

The fuels that will be assessed, according to different scenarios, as following:

- Scenario A - Diesel with the same consumption
- Scenario B - Diesel with less consumption
- Scenario C - Gas
- Scenario D - Ethanol 5%
- Scenario E - Ethanol 15%
- Scenario F - Methanol

### DATA QUALITY CRITERIA AND CRITICAL REVIEW

All the assumptions made in the last chapter are valid for this chapter too. Is assumed, that the production, distribution and end of life are the same thus this chapter is focused in the use phase.

The use phase is modelled in Umberto, for each type of fuel. All the assumptions made in the previous chapter are valid for this chapter too.

### ALLOCATION

The allocation is included in Ecoinvent 2.2 and  Ecoinvent 3 database.

| | Production | Distribution | Use | End-of-Life | TOTAL |
|---|---|---|---|---|---|
| AP [ kg SO2-Eq] | 106,55 | 5,69 | 87,46 | 4,01 | 203,71 |
| GWP [kg CO2-Eq] | 19.220,96 | 340,78 | 32.986,57 | 1.596,24 | 54.144,55 |
| EP [kg PO4-Eq] | 11,41 | 0,55 | 12,33 | 1,07 | 25,36 |
| POCP [kg ethylene-Eq] | 6,63 | 0,19 | 8,78 | 0,25 | 15,85 |
| ADP [kg antimony-Eq] | 94,64 | 2,36 | 227,85 | 2,84 | 327,69 |
| PM 2.5 [kg PM2.5-Eq] | 27,09 | 1,08 | 22,92 | 1,01 | 52,11 |

Table 4.1 - Impact indicators

The Table 4.1 was already present within the previous chapter, however, is present here again to refresh the values of the impact for each life stage. The use phase is highlighted because is the only phase that will change.

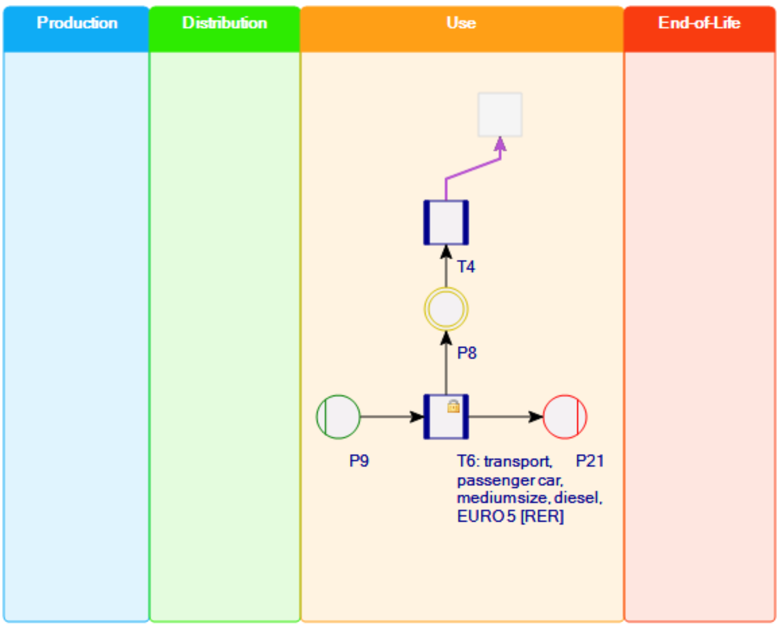


Figure 4.1 – Example for the modulation with Umberto

The modulation in Umberto was made according to the Figure 4.1, considering only the use phase.

For the different fuels will be presented one table with all the indicators related to the use phase and an extra column, to show the reduction or the increase of certain fuel when compared to the conventional petrol, used by the Prius (Table 4.1 - Impact indicators). The colours are used to know whether the impacts are positive (green) or negative (red).

## 4.1 Scenario A

Vehicles that use diesel fuel generally have higher fuel economy than comparable gasoline vehicles. However, was created this imaginary scenario, to compare the impacts using exactly the same amount of fuel.

The process chosen from Ecoinvent database "*transport, passenger car, medium size, diesel, EURO 5*". The category medium size includes passenger cars with the engine between 1.4 and 2.0 liters. The highest class (*EURO 5)* means the lowest emissions.

This dataset includes the fuel evaporation emissions from the tank. The emissions resulting from the tire, brake and road wear are considered to be by-products. However, does not include specifically cold start emissions. [127]

The Table 4.2, shows by using the same amount of fuel, the impacts are bigger, which means that the diesel has in general more impact on the environment and on human's health. The eutrophication (EP) has the highest impact. The indicator POCP, is the only which has less impact comparing to the gasoline.

| **Scenario A** | Use | [%] |
|---|---|---|
| AP [ kg SO2-Eq] | 102,35 | 🔴 17,02% |
| GWP [kg CO2-Eq] | 36.320,05 | 🔴 10,11% |
| EP [kg PO4-Eq] | 15,32 | 🔴 24,24% |
| POCP [kg ethylene-Eq] | 6,83 | 🟢 28,44% |
| ADP [kg antimony-Eq] | 251,15 | 🔴 10,23% |
| PM 2.5 [kg PM2.5-Eq] | 26,76 | 🔴 16,73% |

Table 4.2 - Scenario A

[127] (Ecoinvent 3 Database, 2013)

## 4.2 Scenario B

For this scenario, the consumption of the Prius was changed to 3,3 instead of 3,9 L/100 km. By using less diesel, comparing to gasoline, the scenario gets more favourable environmentally. Therefore, when comparing carbon dioxide emissions, the higher emissions from diesel fuel partially offset the fuel economy benefit.

| Scenario B | Use | [%] |
|---|---|---|
| AP [ kg SO2-Eq] | 88,89 | 1,63% |
| GWP [kg CO2-Eq] | 31.543,47 | 4,57% |
| EP [kg PO4-Eq] | 13,30 | 7,90% |
| POCP [kg ethylene-Eq] | 5,93 | 47,89% |
| ADP [kg antimony-Eq] | 218,12 | 4,46% |
| PM 2.5 [kg PM2.5-Eq] | 23,24 | 1,38% |

Table 4.3 - Scenario B

## 4.3 Scenario C

The process used to assess the environmental impact from Ecoinvent was *"Transport, passenger car, medium size, natural gas, Euro 5"*. All the designations "medium size" and "Euro 5" are the same as for the scenario A and B. This dataset includes operation, maintenance, direct emissions produced by the fuel combustion and evaporation as well as from tyre, brake and road wear. However, does not include specifically cold start emissions[128].

By using gas, the results shown in the Table 4.4, reveal that the tailpipe emissions result from combustion are reduced considerable such as carbon monoxide (CO), nitrogen oxides ($NO_x$) and carbon dioxide ($CO_2$), reason why the percentage is higher in these indicators, POCP and GWP respectively.

[128] (Ecoinvent 3 Database, 2013)

| | Scenario C | Use | [%] |
|---|---|---|---|
| 87,46290017 | AP [ kg SO2-Eq] | 80,45 | 8,72 |
| 32986,57124 | GWP [kg CO2-Eq] | 29.010,80 | 13,70 |
| 12,32881471 | EP [kg PO4-Eq] | 11,02 | 11,88 |
| 8,776238521 | POCP [kg ethylene-Eq] | 7,41 | 18,38 |
| 227,8530896 | ADP [kg antimony-Eq] | 239,42 | 5,08 |
| 22,9220828 | PM 2.5 [kg PM2.5-Eq] | 23,11 | 0,80 |

Table 4.4 – Scenario C

## 4.4 Scenario D

The scenario D is modelled using Ethanol 5%[129] (*"Transport, passenger car, ethanol 5% [CH]"*). This dataset includes operation of the car, ethanol 5% and maintenance[130].

Ethanol is widely used as fuel in some countries, such as Brazil and in the United States. This fuel has lower energy content per litre than petrol, thus consume up to 30 to 40 per cent more fuel than conventional petrol cars[131]. This fact is already included within the process, so is not necessary make any adaptation. The unit of this process is given in [km*person]. In the Table 4.5 all the impacts are with a green colour, it means that the impacts are beneficial, when comparing to the Table 4.1. However is important to notice that regarding to the global warming, in the scenario C, the value is lower, which means that the gas is more environmentally friendly, comparing to the ethanol 5%.

| Scenario D | Use | [%] |
|---|---|---|
| AP [ kg SO2-Eq] | 60,12 | 45,49 |
| GWP [kg CO2-Eq] | 29.584,43 | 11,50 |
| EP [kg PO4-Eq] | 7,01 | 75,78 |
| POCP [kg ethylene-Eq] | 7,02 | 25,02 |
| ADP [kg antimony-Eq] | 187,54 | 21,50 |
| PM 2.5 [kg PM2.5-Eq] | 12,54 | 82,82 |

Table 4.5 - Scenario D

[129] About 95% ethanol and 5% water
[130] (Ecoinvent 3 Database, 2013)
[131] (Sustainable, 2013)

## 4.5 Scenario E

The scenario E is modelled using the process *"Transport, passenger car, petrol, 15% ETBE with Ethanol biomass, EURO 4 [CH]"*. This dataset includes operation, passenger car and maintenance.

***Ethyl tert-butyl ether*** (ETBE) has superior properties, which blend well with gasoline is produced from ethanol and isobutylene in a catalytic reaction[132]. However the tert-butyl alcohol can be derived from biomass instead of isobutylene, using this way renewable energy. For this reason this type of fuel has gained popularity over the ethanol[133].

The standard consumption "EURO 5" is neither present in Ecoinvent database 2.2 nor 3, reason why was adopted the Euro 4.

| Scenario E | Use | [%] |
|---|---|---|
| AP [ kg SO2-Eq] | 66,69 | 31,14 |
| GWP [kg CO2-Eq] | 28.262,84 | 16,71 |
| EP [kg PO4-Eq] | 11,12 | 10,84 |
| POCP [kg ethylene-Eq] | 6,71 | 30,80 |
| ADP [kg antimony-Eq] | 180,14 | 26,49 |
| PM 2.5 [kg PM2.5-Eq] | 13,18 | 73,89 |

Table 4.6 - Scenario E

The scenario E, as shown in the Table 4.6, is quite similar to the Ethanol 5%. For example the global warming, photochemical oxidation and resources depletion has decreased 5,2%, 5,7% and 4,9%, respectively, when comparing with the scenario D. The reason for that might be explained by the fact of blend ethanol with renewable energies.

## 4.6 Scenario F

Methanol is a desirable choice for transportation fuel, due its efficient combustion, easy distribution and extraction and low costs compared to other fuels[134].

The process chosen for this scenario was *"Transport, passage car, methanol"* from Ecoinvent. This dataset includes operation, passenger car and maintenance.

---

[132] (European Biofuels)
[133] (Quitain, et al., 2013 pp. 357-358)
[134] (Methanol Institute)

| Scenario F | Use | | [%] |
|---|---|---|---|
| AP [ kg SO2-Eq] | 33,01 | ● | 164,97 |
| GWP [kg CO2-Eq] | 4.054,28 | ● | 713,62 |
| EP [kg PO4-Eq] | 7,37 | ● | 67,20 |
| POCP [kg ethylene-Eq] | 4,19 | ● | 109,41 |
| ADP [kg antimony-Eq] | 26,99 | ● | 744,10 |
| PM 2.5 [kg PM2.5-Eq] | 7,27 | ● | 215,13 |

Table 4.7 - Scenario F

Emissions of unburned carbons and carbon monoxide are much lower, when comparing with other fuels, and also reduce greatly $NO_x$ emissions as well. And almost has no particulate matter, which decreases the risk of respiratory problems like asthma.

## 4.7 Overall analysis

The results show that methanol is by far the most environmentally friendly fuel in all indicators among the others fuels and the biggest difference can be seen in the global warming as shows the graphic of the Figure 3.1. When this fuel is combusted, the numbers of harmful and toxic by-products are drastically reduced. The emissions of unburned carbons such as, carbon monoxide and carbon dioxide are reduced as well as, the emissions of $NO_x$, by consuming methanol as a fuel.

All the graphics not presented here, are attached in Appendix C.

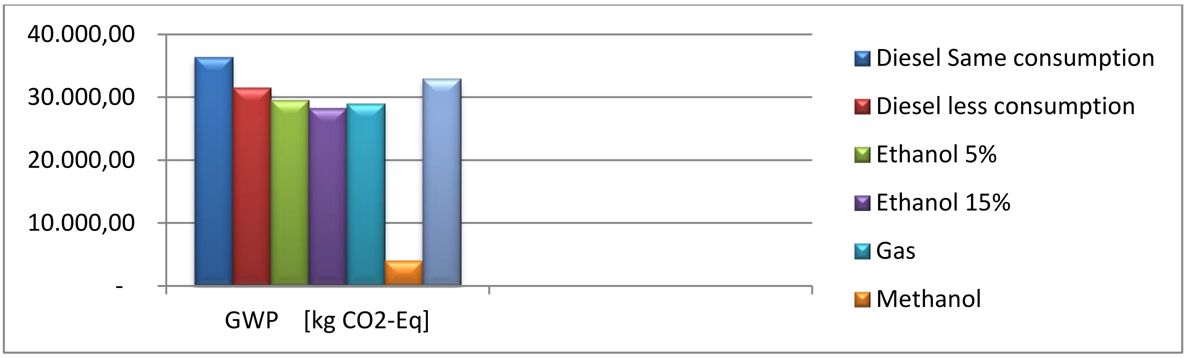


Figure 4.2 - Global Warming

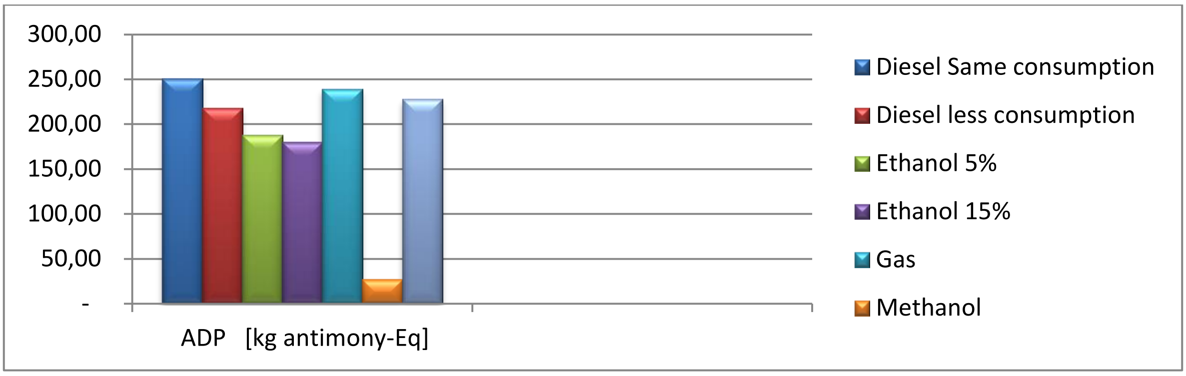


Figure 4.3 - Resources depletion of abiotic resources

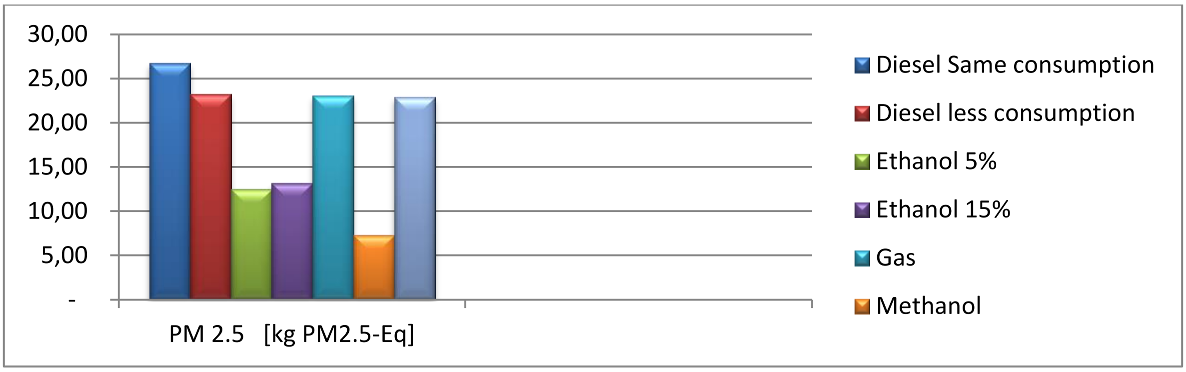


Figure 4.4 - Human Health, respiratory effects

By the fact of using renewable energies (biomass), also reduces the resources depletion of petroleum reason why the indicator ADP shown in the Figure 4.3 has a small impact. With less unburned carbons, the effect on humans health, namely respiratory effects decrease, reason why has almost no particulate matter (Figure 4.4).

Analysing now all the stages of life (considering the production, distribution and the end-of-life from the previous chapter), the final results are impressive, especially in the indicator GWP, ADP and PM 2.5, with reductions of 114,75%, 158,37% and 42,92% respectively, as shown in the three graphics below.

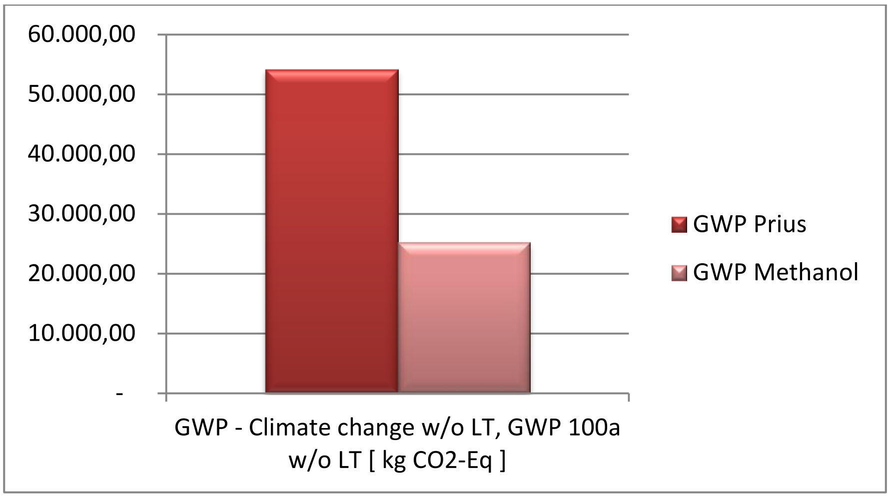


Figure 4.5 - Global Warming

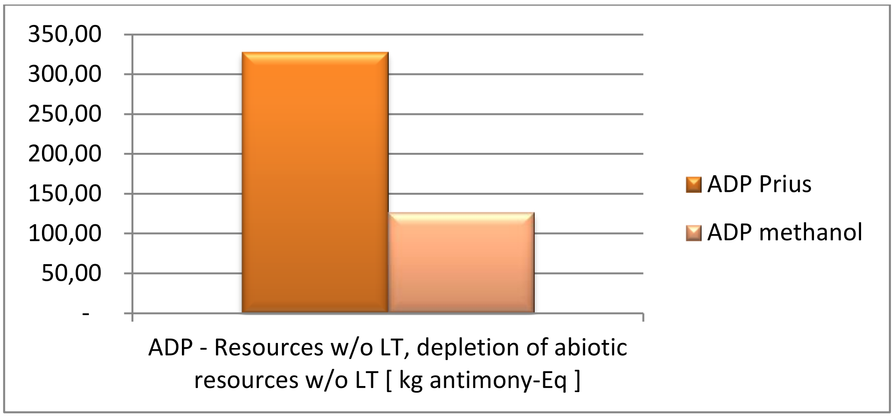


Figure 4.6 – Resources depletion

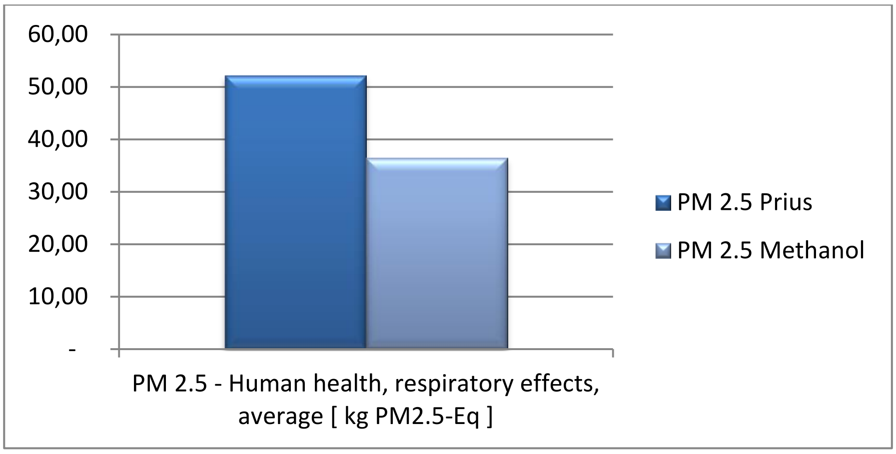


Figure 4.7 - Human Health

By using methanol as fuel, Prius could avoid 28, 93 ton of $CO_{2eq}$ and 200,86 kg of antimony eq. These values are hugely high. However is important to point out, this result only assesses the use phase, assuming that the other phases have the same impact.

# 5 *Comparison with conventional vehicles and electrical vehicle*

This is the last and the shorter chapter of this study. It seeks in general to find, a simplified comparison between conventional and electrical vehicles.

The overall transportation is responsible for 30% of all fossil fuel emissions [135]. The continuous increasing fuel costs and the climate change are the reality that the present society has to face.

The transportation sector has made the major investments in R&D to cope with the actual concern of dependency of fossil fuels. Several alternatives have arisen. Since the improvement of the conventional propulsion, by using either efficient engines or using alternative fossil fuels until all electric propulsion, exist a vast huge of different technologies and different ways to decrease the global warming and to reduce the dependency of petroleum.

The powertrain electrification has been seen the most promising alternative put forwarded till now, because it can lead to significant improvements in polluting emissions higher performance, using energy more efficiently inducing less impact on the environment, for instance, the typical efficiency of an ICE is 28-30% while the electric motors can achieve 85-95% of efficiency.[136]

The hybridization is seen as the middle term between the conventional and electric vehicle. It is the bridge to prepare the market to launch the all-electric vehicle. The term all electric refers to cars that use only electric drive system to proper the wheels, using for that an electro-chemical battery pack for electricity storage to feed the electric motor.

Even with advances in battery technology over the last decades, the main obstacle lies in their low reliability for driving range, and this represents the main reason why this technology has not yet attracted actively the attention of customers. Many researchers have made studies and there are nowadays several types of batteries with different characteristics to suit all typologies of electric or even hybrid vehicles, as mentioned in the second chapter.

[135] (European Union, 2007)
[136] (Lowry J, 2003)

## 5.1 Life Cycle Assessment – General overview

According to the annual report of Volkswagen[137] *"The "life" of a car begins long before it takes to the road"*. It means to conduct a detail assessment of the environmental impacts is necessary to take into account all the life stages, especially to compare the impact using different topologies of powertrain (conventional and electric vehicles).

The LCA is the tool able to quantify the impacts at different stages throughout the whole life. If considered only the use phase for instance, the electric vehicles would have almost a negligible impact because their emissions are largely dependent on the sources of electricity used whereas the ICEVs would have a huge impact, by comparing with the electric ones. Thereby both technologies must be assessed using a cradle – to – grave perspective for the vehicle (tank – to – wheels (TTW)) and well – to – wheels (WTW) to take into account the energy upstream from the use phase. The system boundary shown in the Figure 5.1 consists in a generic system boundary generic for three different technologies, Electric, Conventional and Plug – in - Hybrid.

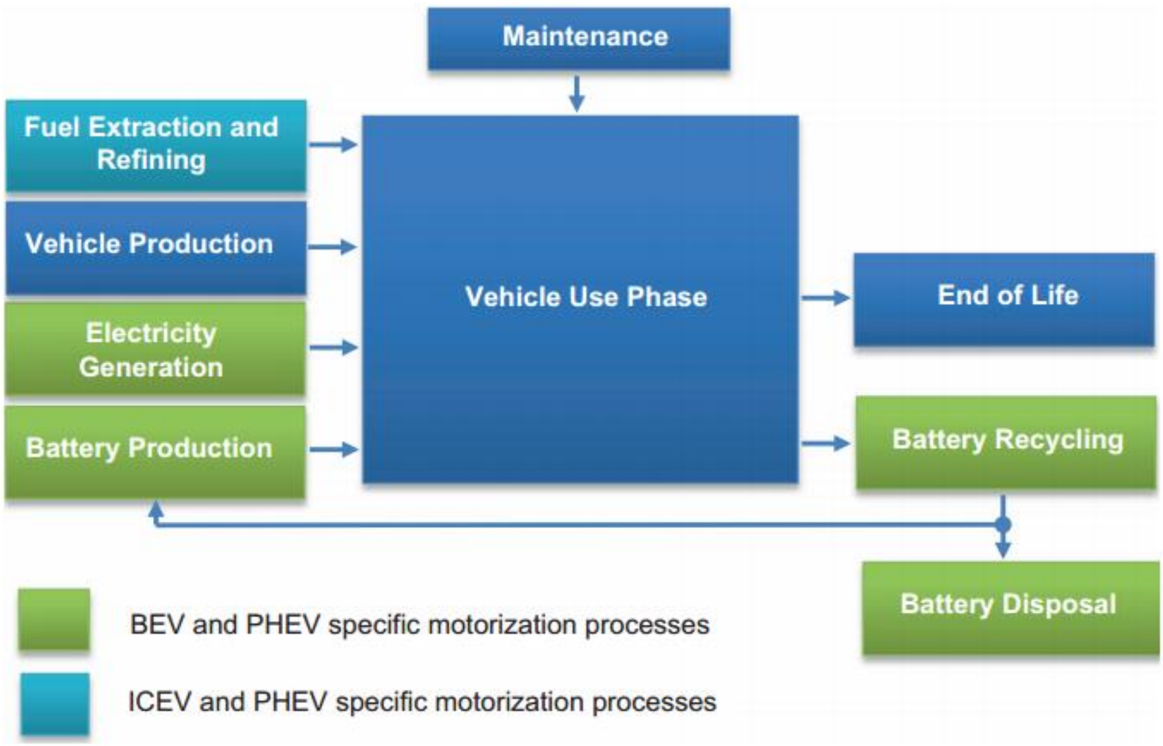


Figure 5.1 – Generic system boundaries for three vehicle technologies[138]

[137] (Volkswagen AG, 2010 p. 12)
[138] (Faria, et al., 2013 p. 273)

### 5.1.1 Life Stages

#### PRODUCTION PHASE

The inventory for the glider[139] is quite similar for both. The powertrain is the part with more modifications.

- The EV powertrain includes battery package, motor, power electronics (control and invertor) fluids, differential. The battery presents here a key role, it is the most critical component regarding to GHG emissions, contributing 30% - 50% of the total emissions[140]. Its lifetime is hard to predict once depends on how is used. If the battery needs to be replaced the results from the battery manufacturing would approximately double[141]
- The ICE powertrain includes the engine, fluids, and transmission Pb batteries.

#### DISTRIBUTION PHASE

This phase is common for both technologies, and is assumed to be in the form of road transportation using diesel as a fuel.

#### USE PHASE

LCAs studies have demonstrated that this is the most critical phase in terms of GHG emissions[142]. The emissions result from are from fossil fuels or electricity for the ICEVs and EVs, respectively. The electricity mix plays a key role, because if it is produced by renewable energies the EV has almost zero emissions within this phase.

When the fuel is burned is necessary to take into account all the upstream stages, such as crude oil extraction, transportation, refining and fuel distribution. This process is called fuel life cycle. However for the electric vehicles, the production of the electricity has to be also taken into account. All the upstream shall be include, the coal mining, transportation, electricity generation, distribution and the respective transformation processes.

To be precise in the study, the emissions of GHG released during the use phase by losses are necessary be accounted. The losses of ICEVs are around 30 - 35%, whereas for BEVs the losses are around 9 – 10%, (energy from the grid to charge the batteries, and from the batteries to power the wheels). Most of the losses in EVs occur in the batteries[143].

[139] It is assumed to be the same the body and doors, brakes, chassis, final assembly interior and exterior, tires and wheels.
[140] (Faria, et al., 2013 p. 273)
[141] (Samaras, et al., 2008 pp. 3170-3171)
[142] (Faria, et al., 2013 p. 273)
[143] (Faria, et al., 2013 p. 274)

The maintenance and repair makes a relatively small contribution to the whole life cycle of the fuel and the vehicle[144]

### END – OF – LIFE

Generally the batteries life time is smaller than the vehicle. It always depends on the consumer usage. The end of life for the glider is similar.

## 5.2 Scenarios

After some research, was found several studies from several authors comparing these two different powertrain technologies. In order to evaluate and compare them was created two different scenarios each one from the respective author.

### 5.2.1 Scenario A

The scenario A[145] aims to evaluate different typologies of car, by using different fuels. This study does not specify brands, so was assumed, that all these cars are generic vehicles.

| | Gasoline | | Diesel | | EV | |
|---|---|---|---|---|---|---|
| | $MJ_{eq}$/km | $gCO_{2eq}$/km | MJeq/km | $gCO_{2eq}$/km | $MJ_{eq}$/km | $gCO_{2eq}$/km |
| **WTT** | 0.27 | 24.5 | 0.27 | 23.7 | 1.06 | 72.9 |
| **TTW** | 1.98 | 144.0 | 1.76 | 128.0 | 0.54 | 0.0 |
| **Vehicle material** | 0.43 | 17.7 | 0.43 | 18.5 | 0.86 | 24.8 |
| **Infrastructure: min-max (Best est.)** | 0.03–0.05 (0.05) | 0.6–1.2 (1.0) | 0.02–0.05 (0.05) | 0.7–1.2 (1.2) | 0.07–0.16 (0.96) | 4.0–8.1 (5.3) |
| **Total (Best est.)** | 2.73 | 187.3 | 2.51 | 171.4 | 2.56 | 103.0 |
| **Impact of infrastructure** | 1.0%–1.9% | 0.3%–0.6% | 1.0%–1.9% | 0.4%–0.7% | 2.7%–6.3% | 3.9%–7.9% |

Table 5.1 – LCA values fuels technologies[146]

The Table 5.1presents the values for global warming and is expressed in [g $CO_2$eq/km driven] using different power sources.

Concerning to the fuel life cycle, the electric vehicle revels to have higher impact among the internal combustion engines (diesel and gasoline). Between the ICEVs the production of diesel has less emissions of $CO_2$, due their higher efficiency in fuel saving. Contrary to the fuel life cycle, the vehicle life cycle (Tank – to – Wheels) has no impact in electric vehicles, because the electricity was already produced, and in the use phase is assumed to have zero emissions, so-called "*Zero Emission Vehicles"*. However in vehicle life cycle, of the conventional vehicle it presents the biggest impact. The use phase as mentioned before is the most important phase, when is aimed to compare the LCA of EV and ICE vehicles.

[144] (Ma, et al., 2012 p. 172)
[145] The graphics and tables were taken from (Lucas, et al., 2012)
[146] (Lucas, et al., 2012 p. 544)

It is also important to point out the impact of the infrastructure, which plays the key role namely for electric vehicles (see Figure 5.2). Charging points facilities are almost ten times higher than the conventional refuel station in terms of energy used, as well as, $CO_2$ emissions[147]. The same authors have revealed in their study that even the maintenance activities, are greatly higher compared to the conventional refinery maintenance activities.

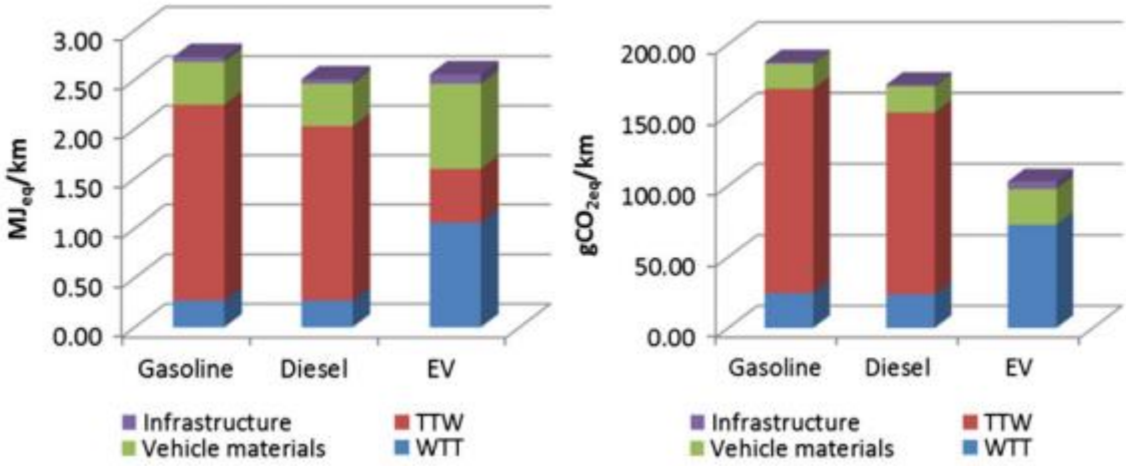


Figure 5.2 - LCA energy use and LCA emissions comparisons

### 5.2.2 Scenario B

The scenario B[148], aims to evaluate the comparison between ICEVs and EVs by using 4 examples for ICEVs and 3 examples of EVs, and the examples are respectively VW Golf 1.6 TDI, VW Golf 1.4 TSI, Smart CDI and Smart for the ICEVs and Nissan Leaf, Smart ED and Peugeot iOn for EVs.

| Characteristics | ICEV | | | | BEV | | |
|---|---|---|---|---|---|---|---|
| | VW Golf 1.6 TDI | VW Golf 1.4 TSI | Smart CDI | Smart | Nissan Leaf | Smart ED | Peugeot iOn |
| Emissions ($gCO_2$/km) | 118 | 144 | 98 | 86 | – | – | – |
| Fuel consumption (l/100 km) | 4.2 | 6.2 | 3.3 | 4.2 | – | – | – |
| Electricity consumption (Wh/km) | – | – | – | – | 140 | 110 | 120 |
| Combustion engine (cc) | 1600 | 1400 | 800 | 1000 | – | – | – |
| Electric motor (kW) | – | – | – | – | 80 | 30 | 47 |
| Battery capacity (kW h) | – | – | – | – | 24 | 16.5 | 16 |
| Battery weight (kg) | – | – | – | – | 300 | 140 | 200 |
| Battery type | – | – | – | – | Li-Ion | Li-Ion | Li-Ion |
| Range (km) | 700+ | 700+ | 500+ | 500+ | 160 | 135 | 120 |
| Curb weight (kg) | 1240 | 1290 | 770 | 750 | 1521 | 870 | 1080 |

Table 5.2 - Comparison with different car brands

The Table 5.2 shows the results of the study (Faria, et al., 2013) and it is in agreement with the scenario A, especially the impacts of the ICEV gasoline for VW Golf 1.4 TSI. For the EVs

[147] (Lucas, et al., 2012 p. 544)
[148] Graphics and tables were taken from (Faria, et al., 2013)

is not present in the table, the fuel life cycle, reason why the EVs have zero emissions of $CO_{2\,eq}$/km.

The Figure 5.3 belongs to the same study, and here is easy to have an overview about the different life stages related the GHG intensity per km travelled and by electricity mix considered. The graphic contains the Plug – in hybrid Chevrolet Volt, the electric vehicle Nissan Leaf, and the VW Golf with their respective fuel.

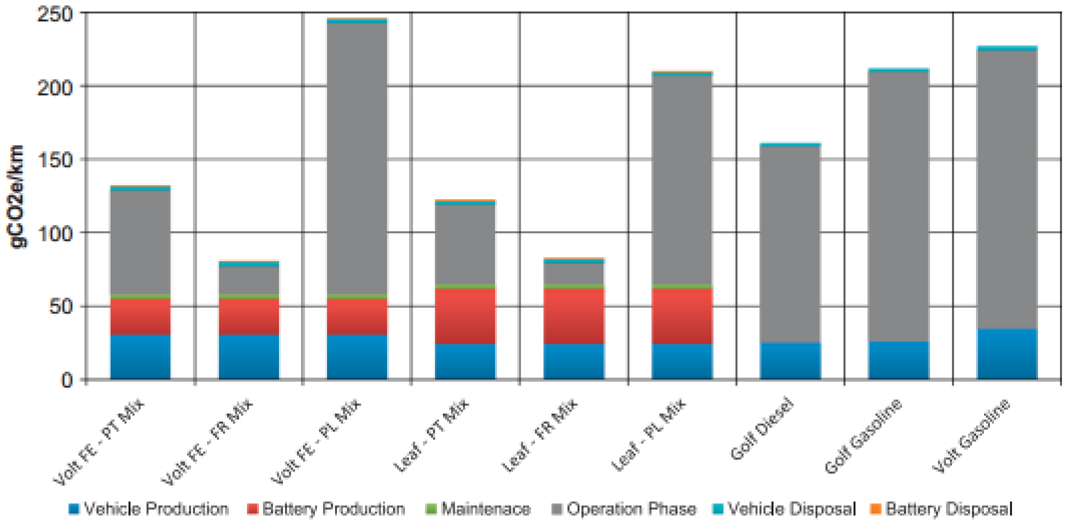


Figure 5.3 - Global Warming intensity per km traveled and by electricity mix

Now the study includes an approach WTW, and contains three different electricity mixes, from different countries, Portugal (PT Mix), France (FR Mix) and Poland (PL Mix).

The Chevrolet Volt, using electricity mix from France has a quite close impact comparing with the scenario A (72,9 kg $CO_2$/km).

This study is proper to understand how much impact has the electricity mix. Thereby the overall emissions are highly dependent on the electricity mix. For instance the Chevrolet Volt using the electricity mix from Poland has more impact than the internal combustion engines. Nevertheless is important to bear in mind that by using additional weight in PHEV technology, due two power sources (electric and ICE), the energy needed to power the wheels is higher, and consequently its impact is higher too.

## 5.3 Results

Based on life cycle analysis of GHG emissions, including well to wheels approach the EVs can deliver significantly GHG saving compared to ICEVs. The life cycles WTT and TTW, are different for both technologies, reason why must be taken into account, when is conducted a comparative LCA.

The vehicle life considering vehicle manufacturing and disposal are higher for EV than ICE, due the manufacture of batteries.

The infrastructures for EVs such as charging points facilities are almost ten times higher than the conventional refuel station in terms of energy used, as well as, $CO_2$ emissions.

The EVs and PHEVs perform better than ICEVs due their electric motors, and their impact performance is highly dependent on electricity mix. The electric vehicle can achieve zero emissions by using renewable ones instead of the electricity from the coal.

# 6 *Conclusion*

## 6.1 Summary

The aim of this thesis has been to conduct a detailed life cycle assessment of the hybrid vehicle Toyota Prius.

At first was given an overview about the state of art in general, showing the actual situation of the dependency of the petroleum resources and the importance of powertrain electrification from economic and social perspective. The purpose was to emphasize this major environmental concern that affects the present humanity which is the transportation sector, by releasing about 30% of all fuel emissions.

There are some many possible ways to reduce the environmental impact from the transportation. Starting from the use of alternative fuels to the electrification of the powertrain exist a wide range of measures that can be taken into account to reduce the impact of emissions and prevent depletion of fuel fossils.

Then a new term came up, the term hybridization, which means, more than one power source, gathering the advantages of both. The powertrain electrification has been seen as the most promising measure put forward till now to reduce the environmental impact.

However, to quantify correctly the environmental impacts of a car is necessary to carry out a detailed life cycle for the vehicle and for the fuel, including all the life stages, in agreement with the ISO 14040 series. The life cycle assessment is a complex task, which involves all the processes related to a product life. The goal and the scope definition are the first step and right after comes up the life cycle inventory which is the most laborious part. The life cycle impact assessment shows the quantified results in specific units called indicators. The interpretation is the final stage of the study that aims to give credibility and reliability to the study. It provides the sensitive analysis, involving the variation of certain significant issue, to see the variation on the environment, quantifying whether that material is beneficial or not.

The continuous increasing of the fuels allied with the climate change has brought a great fear to the society. The carmakers have been tasked to bring new solutions to deal with this concern. They have offered many different typologies up to now. The hybridization is seen by carmakers and researchers the bridge between the ICE and EV. The hybrid technology plays here a key role, because is preparing the market and the infrastructures for the all range vehicles. In the meantime researchers and carmakers are doing improvements to overtake the weakness of the batteries, aiming the enhancement of the driving range and their associated costs.

In the study case was modeled the Prius, with the software Umberto.

This car is particularly attractive by the costumers, due its performance, fuel saving and eco-friendly. This model of Toyota is a full hybrid and it uses a particular architecture within its powertrain. This particular architecture is named power-split, and as the name stands for itself provides the separation in two paths. The electric path (from the motor) and the mechanical path (from the engine). This configuration allows the possibility of the motor work alone for launch stages for instance, or together with the engine, aiming to reach the highest efficiency.

This car also is endowed with a particular engine that uses the Atkinson cycle enhancing even more the fuel economy. The Prius and the Honda Civic have triumphed successfully on the market, even being the pioneer with this technology (Prius).

The life cycle assessment of the Prius was conducted aiming to find out, whether the powertrain electrification complies their potential to reduce the emissions and the consumption of the resources in order to aid the governmental project “Fleets Go Green”. This approach takes into account the life cycle of the vehicle, as well was the fuel, being so an integrated approach *“well to wheels”*.

The functional unit for this study is the kilometers driven by the car, and was assumed a life time of 200.000,00 km. The car had to be built up in small parts, called models (in a total of 19 models), because Umberto software has itself a huge amount of information (inputs and outputs) behind each process.

The system boundary includes all the upstream processes, along its 4 life stages (production, distribution and end of life). In order to quantify the environmental impacts, was chosen six different impact categories: Acidification, Photochemical oxidation, Climate change, Eutrophication, Resource depletion and Human health, respiratory effects. All these categories indicators were chosen in agreement with IWF by being important within automotive sector.

The data was given by IWF, and it consists in an excel sheet containing all the raw materials and their respective manufacturing processes. All the allocation is included in Ecoinvent database (V2.2 and V3.0).

Right after, all the scope definition and all assumptions made, came up the data collection with all the data needed to start the modulation. There some components that underwent to assumptions and some of them had to be adapted to make the modulation possible afterwards. Some of the cases are the Combustion Engine, Battery, and Electric Motor.

Within the production was assumed the value of 3,8 MJ/kg, need for the assembly process.

Once the production of the Prius is in Japan, the distribution phase is made up by two different transports, by ship transoceanic over the distance of 22 thousands km and by truck in Germany over the 250 km.

After all data collected, the calculation was done in Umberto. The outcomes were exported directly from Umberto to excel data sheets.

In general the results were reasonable acceptable. The chassis was the model with the highest value in all indicators. Its weight might be the reason the values are higher than usual. It is important to point out, that the chassis itself includes the doors, the body shell and suspension making it, by far the highest model.

Concerning the climate change also named global warming potential was the category indicator which has bigger impact, when comparing to the others impact categories

Within this impact indicator the metals such as aluminum and steel production have revealed the principal materials responsible for releasing a huge amount of carbon dioxide into the atmosphere. Both materials need in their production, intensive energy consequently resulting in emission of greenhouse gases. The models that contain these materials in a considerable amount are the chassis, motor, braking system and power steering.

The alkaline metal, magnesium stands out in the global warming too. The treatment used to protect this material to avoid its rapid and hazardous oxidation is the sulfur hexafluoride ($SF_6$) which is the most powerful and persistent greenhouse gas.

Concerning to the Resources depletion of abiotic resources impact category the drilling aluminum is the process, which has revealed the highest impact in this category. Indeed the drilling process wastes a considerable part of the material during the process of drilling, thus its impact is bigger. If the material is aluminum, the impact is even bigger. This process was widely used for the chassis, breaking system, electric motor, engine and wheels and tires. The fact of this motor uses neodymium as induction field to create the magnetic field, did not present a big impact because is a small motor and it uses only 2 kg of this rare earth metal.

Due their complex and difficult extraction, involving several processes during their synthesizing, the aluminum and the steel are highly recommended to be recycled, in order to offset the emission during the production phase, namely in these two indicators.

Relating to the impact category Humans Health, the situation changed. The responsible materials for the values in the particulate matter were revealed to be the metal nickel, present in big quantities within the electrode of the NiMH battery. In fact these batteries are extremely hazardous to the human health more than the Lithium batteries. However due their reliability is the factor why they are widely used in the hybrid technologies, even having less energy density compared to the lithium batteries. The Prius' battery, is a small one. Its complete package weighs only 60 kg, reason why the results of the battery do not present a big values among the indicators. The platinum is highlighted in this impact category for being hazardous to the human health. This transitional metal is frequently used in electronic devices, due its characteristics, namely the capacity to support high temperatures. Therefore is present in the power electronics. The production of steel present in the subnet doors, and body shell from the mode chassis also release some particulate matters which induces negative effects in the human health.

The analysis per phase regarding the global warming potential has indicated the electric motor as the model among the others 19 models with more impact within the production phase. Is also worth to notice that the electric motor has more impact in the production phase when compared with the engine. The chassis leads the other phases, because of its weight.

The analysis per phase regarding the human health, respiratory effects impact indicator has indicated the battery as the most hazardous component for the humans health within the production phase.

In the life cycle interpretation, many significant issues were identified. The scenario with the highest sensitivity was for the battery assuming the significant issues as the material nickel, and the impact indicator Human Health. By increasing the reference value in more 50% (case A) or decreasing 50% (case B) was found a sensitivity of 33,53%. The second biggest sensitivity was found meeting the significant issues platinum with the impact indicator human health. By changing the reference value for more 50% or decreasing the reference value in 50% was found sensitivity of 29,06%.

The sintering of aluminum and steel as well as their manufacturing processes in the electric motor have shown a sensibility being so, highly recommended their recycling processes as well as their reuse. It is also recommended decrease the amount of nickel, by replacing this metal, or by using less. The same scenario for the power electronics, it should be reduced or replaced the use of platinum, once it is harmful for the humans health.

For the assessment of the environment impacts were created six different scenarios using for each different fuels to propel a vehicle.

By using renewable energies in the scenario E (ETBE with Ethanol Biomass) the GWP has reduced as well has the resources depletion of petroleum. With less unburned carbons, the effect on humans health, namely respiratory effects decrease.

However the greenest fuel found was the methanol. It has a few impact in almost all the indicators.

By using the methanol as fuel in the Prius the impacts are reduced substantially. For instance the GWP could reduce 114,75% whereas the ADP could reduce 158,37%, or in another words the total amount of GWP (regarding all life stages) could come up to 25,2 ton $CO_{2eq}$ instead of 54,14 ton $CO_{2eq}$ by using petrol, and the ADP could decrease to 126,89 kg antimony eq, instead of 327,69 kg antimony eq by using petrol.

The last chapter has brought the comparison between conventional and electrical vehicles. Based on life cycle analysis of GHG emissions, including well to wheels approach the EVs can deliver significantly GHG saving compared to ICEVs. The life cycles WTT and TTW, are different for both technologies, reason why must be taken into account, when is conducted a comparative LCA. The energy used for the infrastructure such as charging points facilities are bigger than the conventional refuel station in terms of energy used.

And at last but not least, the impact of an electric vehicle is highly dependent on the electricity mix. It can achieve zero emissions by using renewable energies, instead of non-renewable ones.

At last, to summarize all the results the table below presents all the important results related to the global warming. It was taken the values from the Scenario B to evaluate and compare with the results found in this study.

| **Total GWG [kgCO2]** | |
|---|---|
| **Prius** | 54.144,55 |
| **petrol** | 33.700,00 |
| **Electric** | 14.580,00 |
| **Methanol** | 25.212,26 |

Table 6.1 - Final Results

Even using methanol for Prius as a fuel, the results revels that the electric vehicles have less the greenest, being so the most suitable measure to mitigate the environmental impact, once its overall impact is lower than all other technologies here mentioned. It is also important to point out the electricity mix plays a key role to minimize the environmental impact during the use phase.

## 6.2 Suggestions for Future work

The research presented in this thesis seems to have raised more questions that it has answered. There are several lines of research arising from this work which should be proposed.

LCA is a complex task, at the end of all there are always something else to desire to assess.

The data quality is the main reason why the results are higher than the results found in the literature. Definitely they are important for the reliability of the study.

The software Umberto is a powerful tool for LCA, and its interface with excel is greatly helpful to analyze the results. However the software itself is really slow when has to process a considerable amount of data, besides crashes down frequently, it necessary separates into small parts, which takes longer to simulate the whole model.

The infrastructures needed for electric vehicles, such as charging points facilities should be assessed and evaluated with more accuracy and afterwards compared with the results of hybrid vehicles and conventional vehicles in order to find out the greenest technology.

Assess in detail different fuels, namely methanol and ethanol blended with biomass. However the study should take into account all the infrastructure need.

It would be interesting after all these tasks, conduct an life cycle cost for each technology.

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# 8 Appendix A

| ***Prius*** | ***General Specifications*** |
|---|---|
| ***Hybrid System net power*** | 124 hp (100kW) |
| | |
| ***Engine*** | |
| Type | 1,8 litres, 4 cylinders, 16 (VVT-i) |
| Power Output | 73 [kW] |
| Torque | 142 Nm @ 4000 rpm |
| Compression Ratio | 13.0:1 |
| Fuel System | Electronic fuel injection |
| Advanced technology | (AT-PZEV) |
| | |
| ***Electric Motor*** | |
| Type | Permanent magnet AC synchronous motor |
| Power Output | 36 hp (60 kW) |
| Torque | 153 lb.ft (207 N.m) |
| Voltage | 650V maximum |
| | |
| ***Battery*** | |
| Type | Sealed Nickel Metal Hydride (NiMH) |
| Power Output | 36 hp (27 kW) |
| Number of modules | 38 Modules |
| Capacity | 273.6 volts and 6.5 Ah capacity |
| Weight | 60 Kg |
| | |
| ***Transmission*** | (ECVT) |
| | |
| ***Performance*** | |
| Maximum Speed | 180 Km/h |
| 0-100 (km/h) | 4,2 sec. |
| Drag coefficient | 0,25 |
| | |
| ***Dimensions and Weights*** | |
| Kerb weight | 1425 kg |
| Gross vehicle weight 1805 kg | 1805 kg |
| Fuel tank (gal.) | 11.9 |
| Overall height/width/length (mm) | 1490/1745/4480 |
| | |
| ***Brakes*** | |
| Front Brakes | Ventilated disc |
| Rear brakes | Disc |

Table 8.1 – Prius Specifications

# 9 *Appendix B*

**IMPACT CATEGORIES IN GENERAL AND PER PHASE -**

**RESULTS**

| Part/Component (Model) | AP [ kg SO2-Eq] | GWP [kg CO2-Eq] | EP [kg PO4-Eq] | POCP [kg ethylene-Eq] | ADP [kg antimony-Eq] | PM 2.5 [kg PM2.5-Eq] |
|---|---|---|---|---|---|---|
| 1 - Air Conditiong | 1,24 | 367,16 | 0,21 | 0,10 | 2,46 | 0,32 |
| 2 - Airbag / Cigarrete | 1,37 | 331,10 | 0,34 | 0,10 | 2,31 | 0,36 |
| 3 - Audio / Media | 4,76 | 989,81 | 0,95 | 0,19 | 7,46 | 1,01 |
| 4 - Battery | 29,12 | 2.113,69 | 1,85 | 1,45 | 14,55 | 6,40 |
| 5 - Breaking System | 13,69 | 3.649,18 | 1,58 | 1,18 | 22,61 | 3,64 |
| 6 - Chassis | 42,81 | 15.195,47 | 5,71 | 3,91 | 96,18 | 11,43 |
| 7 - Clutch | 1,16 | 707,24 | 0,17 | 0,11 | 2,22 | 0,31 |
| 8 - Cockpit / Cabling | 2,59 | 859,40 | 0,43 | 0,22 | 5,87 | 0,65 |
| 9 - Connection Material | 2,47 | 761,62 | 0,34 | 0,23 | 5,20 | 0,72 |
| 10 - Electric Motor | 17,18 | 7.265,24 | 2,73 | 1,51 | 29,11 | 5,01 |
| 11 - Fluids and Oil | 2,51 | 922,63 | 0,31 | 0,28 | 5,85 | 0,63 |
| 12 - Horn / Sun Protector / Jack | 0,46 | 151,60 | 0,06 | 0,04 | 1,07 | 0,12 |
| 13 - Engine | 25,68 | 6.358,18 | 3,67 | 2,02 | 42,60 | 6,64 |
| 14 - Lighting | 1,80 | 702,91 | 1,21 | 0,15 | 3,83 | 0,43 |
| 15 - Power Electronics | 22,75 | 1.352,57 | 1,34 | 1,05 | 9,40 | 5,40 |
| 16 - Power Steering | 5,15 | 2.711,66 | 0,75 | 0,45 | 10,04 | 1,49 |
| 17 - Seats | 6,01 | 1.973,75 | 0,80 | 0,84 | 14,00 | 1,52 |
| 18 - Wheels and Tyres | 15,78 | 5.403,77 | 1,94 | 1,39 | 37,25 | 4,22 |
| 19 - Windows | 7,17 | 2.327,58 | 0,96 | 0,62 | 15,67 | 1,81 |
| Total | 203,71 | 54.144,55 | 25,36 | 15,85 | 327,69 | 52,11 |
| Maximum impact | 42,8100 | 15.195,4711 | 5,7146 | 3,9128 | 96,1790 | 11,4309 |
| Minimum impact | 0,4587 | 151,5978 | 0,0632 | 0,0422 | 1,0729 | 0,1201 |

Figure 9.1 - Indicators – General

| Emissions kg/car | AP [ kg SO2-Eq] | GWP [kg CO2-Eq] | NP [kg PO4-Eq] | POCP [kg ethylene-Eq] | ADP [kg antimony-Eq] | PM 2.5 [kg PM2.5-Eq] | Weight [kg] |
|---|---|---|---|---|---|---|---|
| 1 - Air Conditiong | 0,16 | 48,95 | 0,03 | 0,01 | 0,33 | 0,04 | 7,50 |
| 2 - Airbag / Cigarrete | 0,16 | 38,44 | 0,04 | 0,01 | 0,27 | 0,04 | 8,61 |
| 3 - Audio / Media | 2,43 | 504,83 | 0,49 | 0,10 | 3,81 | 0,51 | 1,96 |
| 4 - Battery | 0,48 | 34,86 | 0,03 | 0,02 | 0,24 | 0,11 | 60,63 |
| 5 - Breaking System | 0,28 | 75,84 | 0,03 | 0,02 | 0,47 | 0,08 | 48,12 |
| 6 - Chassis | 0,07 | 25,40 | 0,01 | 0,01 | 0,16 | 0,02 | 598,19 |
| 7 - Clutch | 0,19 | 115,37 | 0,03 | 0,02 | 0,36 | 0,05 | 6,13 |
| 8 - Cockpit / Cabling | 0,11 | 37,59 | 0,02 | 0,01 | 0,26 | 0,03 | 22,86 |
| 9 - Connection Material | 0,13 | 38,81 | 0,02 | 0,01 | 0,26 | 0,04 | 19,62 |
| 10 - Electric Motor | 0,16 | 66,24 | 0,02 | 0,01 | 0,27 | 0,05 | 109,68 |
| 11 - Fluids and Oil | 0,10 | 36,67 | 0,01 | 0,01 | 0,23 | 0,03 | 25,16 |
| 12 - Horn / Sun Protector / Jack | 0,10 | 32,81 | 0,01 | 0,01 | 0,23 | 0,03 | 4,62 |
| 13 - Engine | 0,15 | 36,26 | 0,02 | 0,01 | 0,24 | 0,04 | 175,35 |
| 14 - Lighting | 0,13 | 52,28 | 0,09 | 0,01 | 0,29 | 0,03 | 13,45 |
| 15 - Power Electronics | 1,14 | 67,52 | 0,07 | 0,05 | 0,47 | 0,27 | 20,03 |
| 16 - Power Steering | 0,16 | 86,11 | 0,02 | 0,01 | 0,32 | 0,05 | 31,49 |
| 17 - Seats | 0,11 | 36,45 | 0,01 | 0,02 | 0,26 | 0,03 | 54,15 |
| 18 - Wheels and Tyres | 0,11 | 36,87 | 0,01 | 0,01 | 0,25 | 0,03 | 146,55 |
| 19 - Windows | 0,10 | 32,84 | 0,01 | 0,01 | 0,22 | 0,03 | 70,88 |
| Total | 6,2741 | 1.404,1501 | 0,9843 | 0,3746 | 8,9361 | 1,4788 | 1.425,000 |

Figure 9.2 - Indicators - General / kg

| Part/Component (Model) | AP [ kg SO2-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 1,24 | 0,63 | 0,04 | 0,56 | 0,01 |
| 2 - Airbag / Cigarrete | 1,37 | 0,67 | 0,05 | 0,65 | 0,01 |
| 3 - Audio / Media | 4,76 | 4,60 | 0,01 | 0,15 | 0,00 |
| 4 - Battery | 29,12 | 23,62 | 0,33 | 4,56 | 0,61 |
| 5 - Breaking System | 13,69 | 9,76 | 0,26 | 3,62 | 0,04 |
| 6 - Chassis | 42,81 | 10,34 | 2,15 | 29,97 | 0,35 |
| 7 - Clutch | 1,16 | 0,62 | 0,03 | 0,46 | 0,05 |
| 8 - Cockpit / Cabling | 2,59 | 0,71 | 0,12 | 1,72 | 0,04 |
| 9 - Connection Material | 2,47 | 0,87 | 0,11 | 1,48 | 0,02 |
| 10 - Electric Motor | 17,18 | 12,29 | 0,30 | 4,15 | 0,43 |
| 11 - Fluids and Oil | 2,51 | 0,30 | 0,14 | 1,89 | 0,18 |
| 12 - Horn / Sun Protector / Jack | 0,46 | 0,09 | 0,02 | 0,35 | 0,00 |
| 13 - Engine | 25,68 | 10,78 | 0,95 | 12,54 | 1,41 |
| 14 - Lighting | 1,80 | 0,51 | 0,07 | 1,01 | 0,21 |
| 15 - Power Electronics | 22,75 | 20,98 | 0,11 | 1,51 | 0,16 |
| 16 - Power Steering | 5,15 | 2,37 | 0,17 | 2,37 | 0,25 |
| 17 - Seats | 6,01 | 1,60 | 0,29 | 4,08 | 0,05 |
| 18 - Wheels and Tyres | 15,78 | 4,45 | 0,16 | 11,03 | 0,15 |
| 19 - Windows | 7,17 | 1,38 | 0,38 | 5,35 | 0,06 |
| Total | 203,71 | 106,55 | 5,69 | 87,46 | 4,01 |
| Maximum impact | 42,81 | 23,62 | 2,15 | 29,97 | 1,41 |
| Minimum impact | 0,46 | 0,09 | 0,01 | 0,15 | 0,00 |

Figure 9.3 - AP - Acidification potential w/o LT, average European w/o LT [ kg SO2-Eq ]

| Part/Component (Model) | GWP [kg CO2-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 367,16 | 144,64 | 2,36 | 212,91 | 7,26 |
| 2 - Airbag / Cigarrete | 331,10 | 75,54 | 2,70 | 244,52 | 8,34 |
| 3 - Audio / Media | 989,81 | 931,63 | 0,62 | 55,66 | 1,90 |
| 4 - Battery | 2.113,69 | 312,37 | 19,04 | 1.721,37 | 60,92 |
| 5 - Breaking System | 3.649,18 | 2.221,40 | 15,11 | 1.366,08 | 46,59 |
| 6 - Chassis | 15.195,47 | 3.380,24 | 125,04 | 11.304,67 | 385,51 |
| 7 - Clutch | 707,24 | 525,89 | 1,93 | 174,04 | 5,39 |
| 8 - Cockpit / Cabling | 859,40 | 189,56 | 7,18 | 649,06 | 13,60 |
| 9 - Connection Material | 761,62 | 196,01 | 6,16 | 557,15 | 2,30 |
| 10 - Electric Motor | 7.265,24 | 5.633,28 | 17,32 | 1.566,11 | 48,52 |
| 11 - Fluids and Oil | 922,63 | 141,02 | 7,90 | 714,26 | 59,44 |
| 12 - Horn / Sun Protector / Jack | 151,60 | 18,98 | 1,45 | 131,16 | 0,00 |
| 13 - Engine | 6.358,18 | 1.293,19 | 55,06 | 4.729,27 | 280,65 |
| 14 - Lighting | 702,91 | 145,32 | 4,22 | 381,73 | 171,64 |
| 15 - Power Electronics | 1.352,57 | 759,97 | 6,29 | 568,69 | 17,62 |
| 16 - Power Steering | 2.711,66 | 1.780,10 | 9,89 | 893,98 | 27,70 |
| 17 - Seats | 1.973,75 | 366,91 | 17,01 | 1.537,41 | 52,43 |
| 18 - Wheels and Tyres | 5.403,77 | 886,18 | 19,24 | 4.160,54 | 337,81 |
| 19 - Windows | 2.327,58 | 218,74 | 22,26 | 2.017,95 | 68,63 |
| Total | 54.144,55 | 19.220,96 | 340,78 | 32.986,57 | 1.596,24 |
| Maximum impact | 15.195,47 | 5.633,28 | 125,04 | 11.304,67 | 385,51 |
| Minimum impact | 151,60 | 18,98 | 0,62 | 55,66 | 0,00 |
| Percentage | 1,00 | 0,35 | 0,01 | 0,61 | 0,03 |

Figure 9.4 - GWP - Climate change w/o LT, GWP 100a w/o LT [ kg CO2-Eq ]

| Part/Component (Model) | EP [kg PO4-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 0,21 | 0,13 | 0,00 | 0,08 | 0,00 |
| 2 - Airbag / Cigarrete | 0,34 | 0,25 | 0,00 | 0,09 | 0,00 |
| 3 - Audio / Media | 0,95 | 0,93 | 0,00 | 0,02 | 0,00 |
| 4 - Battery | 1,85 | 1,16 | 0,03 | 0,62 | 0,04 |
| 5 - Breaking System | 1,58 | 1,05 | 0,02 | 0,49 | 0,01 |
| 6 - Chassis | 5,71 | 1,38 | 0,19 | 4,06 | 0,09 |
| 7 - Clutch | 0,17 | 0,09 | 0,00 | 0,06 | 0,02 |
| 8 - Cockpit / Cabling | 0,43 | 0,18 | 0,01 | 0,23 | 0,00 |
| 9 - Connection Material | 0,34 | 0,13 | 0,01 | 0,20 | 0,00 |
| 10 - Electric Motor | 2,73 | 1,95 | 0,03 | 0,56 | 0,19 |
| 11 - Fluids and Oil | 0,31 | 0,03 | 0,01 | 0,26 | 0,01 |
| 12 - Horn / Sun Protector / Jack | 0,06 | 0,01 | 0,00 | 0,05 | 0,00 |
| 13 - Engine | 3,67 | 1,60 | 0,08 | 1,70 | 0,29 |
| 14 - Lighting | 1,21 | 0,35 | 0,06 | 0,63 | 0,18 |
| 15 - Power Electronics | 1,34 | 1,06 | 0,01 | 0,20 | 0,07 |
| 16 - Power Steering | 0,75 | 0,31 | 0,01 | 0,32 | 0,11 |
| 17 - Seats | 0,80 | 0,21 | 0,03 | 0,55 | 0,01 |
| 18 - Wheels and Tyres | 1,94 | 0,41 | 0,02 | 1,49 | 0,02 |
| 19 - Windows | 0,96 | 0,19 | 0,03 | 0,72 | 0,02 |
| Total | 25,36 | 11,41 | 0,55 | 12,33 | 1,07 |
| Maximum impact | 5,71 | 1,95 | 0,19 | 4,06 | 0,29 |
| Minimum impact | 0,06 | 0,01 | 0,00 | 0,02 | 0,00 |

Figure 9.5 - EP - Eutrophication potential w/o LT, generic w/o LT [ kg PO4-Eq ]

| Part/Component (Model) | POCP [kg ethylene-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 0,10 | 0,04 | 0,00 | 0,06 | 0,00 |
| 2 - Airbag / Cigarrete | 0,10 | 0,03 | 0,00 | 0,07 | 0,00 |
| 3 - Audio / Media | 0,19 | 0,18 | 0,00 | 0,01 | 0,00 |
| 4 - Battery | 1,45 | 0,96 | 0,01 | 0,46 | 0,03 |
| 5 - Breaking System | 1,18 | 0,81 | 0,01 | 0,36 | 0,00 |
| 6 - Chassis | 3,91 | 0,82 | 0,07 | 3,01 | 0,01 |
| 7 - Clutch | 0,11 | 0,06 | 0,00 | 0,05 | 0,00 |
| 8 - Cockpit / Cabling | 0,22 | 0,04 | 0,00 | 0,17 | 0,00 |
| 9 - Connection Material | 0,23 | 0,08 | 0,00 | 0,15 | 0,00 |
| 10 - Electric Motor | 1,51 | 1,06 | 0,01 | 0,42 | 0,02 |
| 11 - Fluids and Oil | 0,28 | 0,01 | 0,00 | 0,19 | 0,07 |
| 12 - Horn / Sun Protector / Jack | 0,04 | 0,01 | 0,00 | 0,03 | 0,00 |
| 13 - Engine | 2,02 | 0,67 | 0,03 | 1,26 | 0,06 |
| 14 - Lighting | 0,15 | 0,03 | 0,00 | 0,10 | 0,02 |
| 15 - Power Electronics | 1,05 | 0,89 | 0,00 | 0,15 | 0,01 |
| 16 - Power Steering | 0,45 | 0,20 | 0,01 | 0,24 | 0,01 |
| 17 - Seats | 0,84 | 0,42 | 0,01 | 0,41 | 0,00 |
| 18 - Wheels and Tyres | 1,39 | 0,27 | 0,01 | 1,11 | 0,01 |
| 19 - Windows | 0,62 | 0,07 | 0,01 | 0,54 | 0,00 |
| Total | 15,85 | 6,63 | 0,19 | 8,78 | 0,25 |
| Maximum impact | 3,91 | 6,63 | 0,19 | 8,78 | 0,25 |
| Minimum impact | 0,04 | 0,01 | 0,00 | 0,01 | 0,00 |

Figure 9.6 - POCP - Photochemical oxidation w/o LT, high NOx POCP w/o LT [ kg ethylene-Eq ]

| Part/Component (Model) | ADP [kg antimony-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 2,46 | 0,96 | 0,02 | 1,47 | 0,01 |
| 2 - Airbag / Cigarrete | 2,31 | 0,60 | 0,02 | 1,69 | 0,01 |
| 3 - Audio / Media | 7,46 | 7,07 | 0,00 | 0,38 | 0,00 |
| 4 - Battery | 14,55 | 2,21 | 0,13 | 11,89 | 0,31 |
| 5 - Breaking System | 22,61 | 13,04 | 0,10 | 9,44 | 0,03 |
| 6 - Chassis | 96,18 | 16,95 | 0,86 | 78,09 | 0,28 |
| 7 - Clutch | 2,22 | 0,97 | 0,01 | 1,20 | 0,03 |
| 8 - Cockpit / Cabling | 5,87 | 1,28 | 0,05 | 4,48 | 0,05 |
| 9 - Connection Material | 5,20 | 1,29 | 0,04 | 3,85 | 0,02 |
| 10 - Electric Motor | 29,11 | 17,89 | 0,12 | 10,82 | 0,28 |
| 11 - Fluids and Oil | 5,85 | 0,66 | 0,05 | 4,93 | 0,21 |
| 12 - Horn / Sun Protector / Jack | 1,07 | 0,16 | 0,01 | 0,91 | 0,00 |
| 13 - Engine | 42,60 | 8,61 | 0,38 | 32,67 | 0,94 |
| 14 - Lighting | 3,83 | 0,97 | 0,03 | 2,64 | 0,19 |
| 15 - Power Electronics | 9,40 | 5,33 | 0,04 | 3,93 | 0,10 |
| 16 - Power Steering | 10,04 | 3,64 | 0,07 | 6,18 | 0,16 |
| 17 - Seats | 14,00 | 3,23 | 0,12 | 10,62 | 0,04 |
| 18 - Wheels and Tyres | 37,25 | 8,24 | 0,14 | 28,74 | 0,13 |
| 19 - Windows | 15,67 | 1,53 | 0,15 | 13,94 | 0,05 |
| Total | 327,69 | 94,64 | 2,36 | 227,85 | 2,84 |
| Maximum impact | 96,18 | 17,89 | 0,86 | 78,09 | 0,94 |
| Minimum impact | 1,07 | 0,16 | 0,00 | 0,38 | 0,00 |

Figure 9.7 - ADP - Resources w/o LT, depletion of abiotic resources w/o LT [ kg antimony-Eq ]

| Part/Component (Model) | PM 2.5 [kg PM2.5-Eq] | Production | Distribution | Use | End-of-Life |
|---|---|---|---|---|---|
| 1 - Air Conditiong | 0,32 | 0,16 | 0,01 | 0,15 | 0,00 |
| 2 - Airbag / Cigarrete | 0,36 | 0,18 | 0,01 | 0,17 | 0,00 |
| 3 - Audio / Media | 1,01 | 0,97 | 0,00 | 0,04 | 0,00 |
| 4 - Battery | 6,40 | 5,00 | 0,06 | 1,20 | 0,15 |
| 5 - Breaking System | 3,64 | 2,64 | 0,05 | 0,95 | 0,01 |
| 6 - Chassis | 11,43 | 3,08 | 0,41 | 7,86 | 0,09 |
| 7 - Clutch | 0,31 | 0,16 | 0,01 | 0,12 | 0,01 |
| 8 - Cockpit / Cabling | 0,65 | 0,16 | 0,02 | 0,45 | 0,01 |
| 9 - Connection Material | 0,72 | 0,31 | 0,02 | 0,39 | 0,00 |
| 10 - Electric Motor | 5,01 | 3,75 | 0,06 | 1,09 | 0,12 |
| 11 - Fluids and Oil | 0,63 | 0,06 | 0,03 | 0,50 | 0,04 |
| 12 - Horn / Sun Protector / Jack | 0,12 | 0,02 | 0,00 | 0,09 | 0,00 |
| 13 - Engine | 6,64 | 2,82 | 0,18 | 3,29 | 0,36 |
| 14 - Lighting | 0,43 | 0,10 | 0,01 | 0,27 | 0,05 |
| 15 - Power Electronics | 5,40 | 4,95 | 0,02 | 0,40 | 0,04 |
| 16 - Power Steering | 1,49 | 0,77 | 0,03 | 0,62 | 0,07 |
| 17 - Seats | 1,52 | 0,38 | 0,06 | 1,07 | 0,01 |
| 18 - Wheels and Tyres | 4,22 | 1,27 | 0,03 | 2,89 | 0,03 |
| 19 - Windows | 1,81 | 0,32 | 0,07 | 1,40 | 0,02 |
| Total | 52,11 | 27,09 | 1,08 | 22,92 | 1,01 |
| Maximum impact | 11,43 | 5,00 | 0,41 | 7,86 | 0,36 |
| Minimum impact | 0,12 | 0,02 | 0,00 | 0,04 | 0,00 |

Figure 9.8 - PM 2.5 - Human health, respiratory effects, average [ kg PM2.5-Eq ]

# 10 *Appendix C*

**THE ALTERNATIVE FUELS -**

**RESULTS**

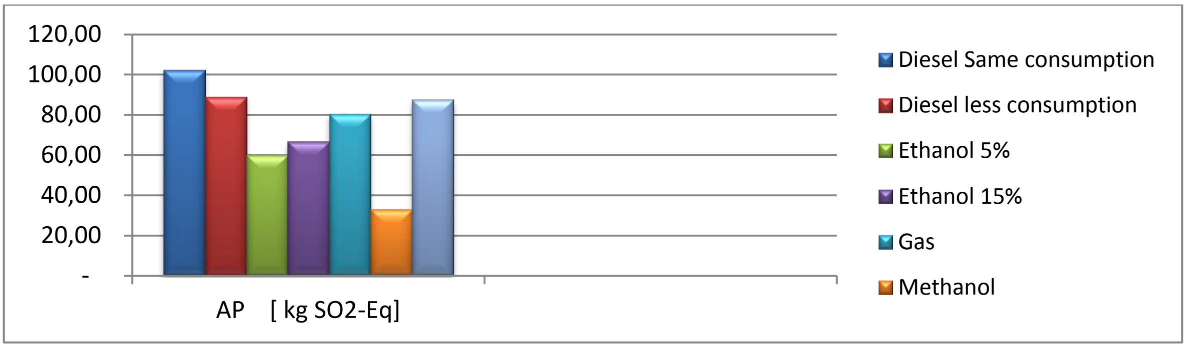


Figure 10.1 - AP - Acidification potential w/o LT, average European w/o LT [ kg SO2-Eq ]

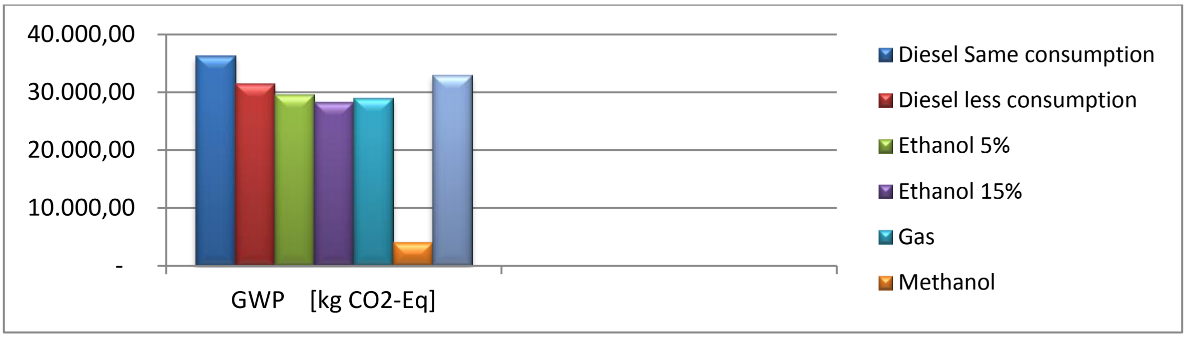


Figure 10.2 - GWP - Climate change w/o LT, GWP 100a w/o LT [ kg CO2-Eq ]

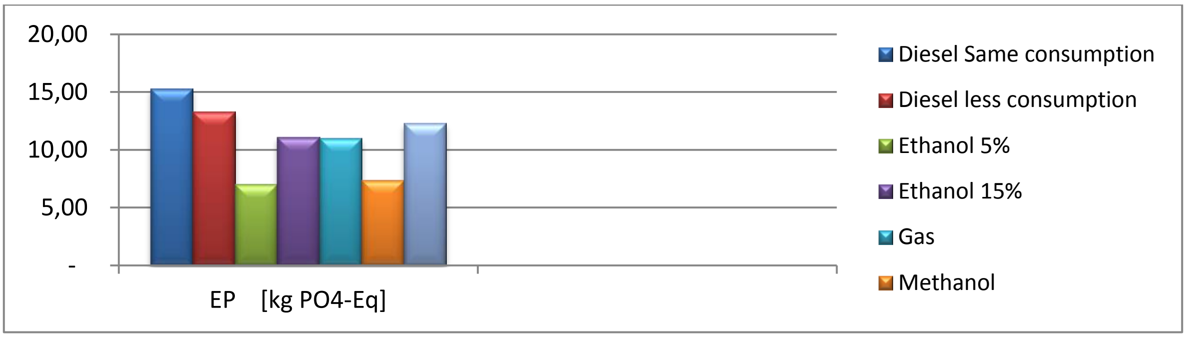


Figure 10.3 - EP - Eutrophication potential w/o LT, generic w/o LT [ kg PO4-Eq ]

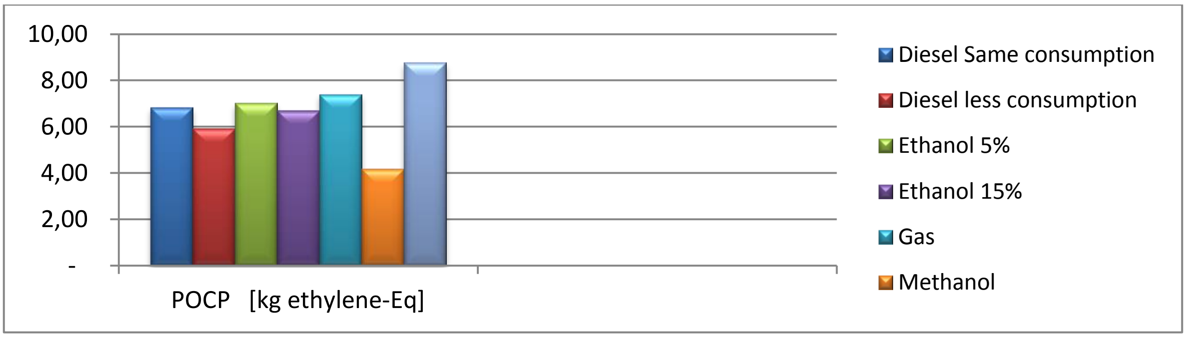


Figure 10.4 - POCP - Photochemical oxidation w/o LT, high NOx POCP w/o LT [ kg ethylene-Eq ]

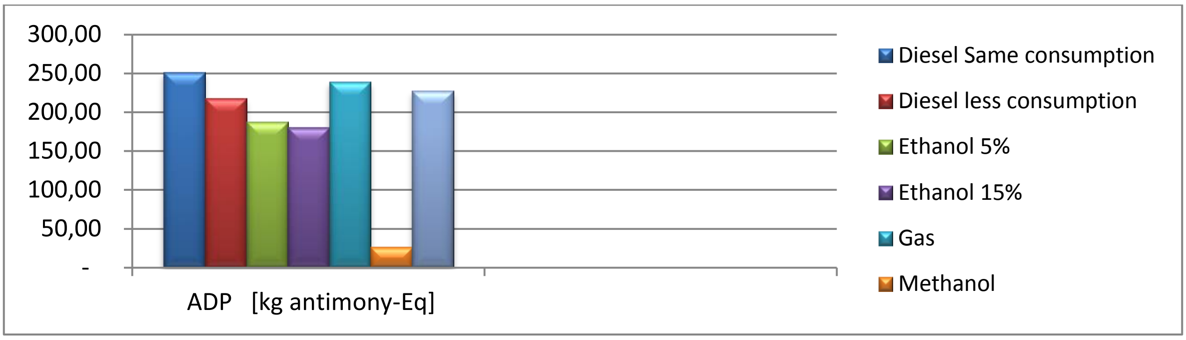


Figure 10.5 - ADP - Resources w/o LT, depletion of abiotic resources w/o LT [ kg antimony-Eq ]

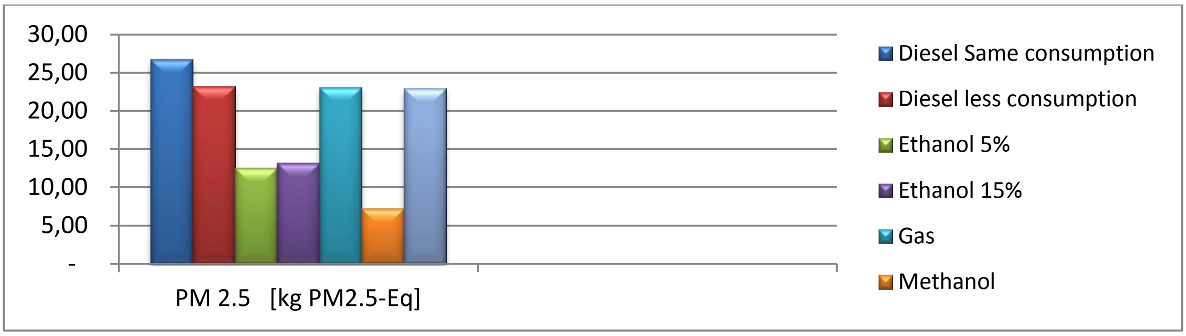


Figure 10.6 - PM 2.5 - Human health, respiratory effects, average [ kg PM2.5-Eq ]