Product Carbon Footprint of a Conventional Vehicle

Masterarbeit

am

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Abbreviations

GHG: Greenhouse gases

ICV: Internal Combustion Vehicle

EV: Electric Vehicle

PCF: Product Carbon Footprint

LCA: Life Cycle Assessment

LDV: Light-Duty Vehicles

VLC: Vehicle Life Cycle

PHEV: Plug-in Hybrid Electric Vehicles

AER: All-electric Range

EOL: End-of life

HEV: Hybrid Electric Vehicle

FEV: Fuel Cell Electric Vehicle

FLC: Fuel Life Cycle

GWP: Global Warming Potential

CO_2: Carbon Dioxide

CFC: Chlorofluorocarbon

NO_2: Nitrogen Dioxide

VOCs: Volatile Organic Compounds

ETIP: European Technology and Innovation Platform

IEA: International Energy Agency

BtL: Biomass to Liquid

LCI: Life Cycle Inventory

LCIA: Life Cycle Inventory Assessment

VMA: Manufacturing and Vehicle Assembly

NEDC: New European Drive Cycle

US Cycle: US City and Highway Driving Cycle

ADAC: Allgemeine Deutsche Automobil Club

SWR: Short Wood Rotation

RFW: Residual Forest Wood

GUI: Guide User Interface

CCS: Carbon Capture and Storage

Abstract

The transportation sector has become one of the most important sources of greenhouse gases (GHG) emissions and energy consumption in the world, and such emissions have impact in the global warming. For that reason, governments have put special attention in limiting and reducing these emissions. As example of these efforts for the reductions of the anthropogenic greenhouse gases emissions, the Regulation (EC) No 443/2009 of the European Parliament can be mentioned.

Internal Combustion Vehicles (ICV) represent the most important percentage of vehicles available and the most widely spread technology at the market, and it will be probably so still dominating the short and medium term future although alternatives technologies, such as Electric Vehicles (EV), have emerged as important competitors.

Said that, this study aims to calculate and estimate the Product Carbon Footprint (PCF), which is related to the impact category of climate change, of a conventional vehicle working with a renewable fuel.

After the statement of the most important technologies available at the market today and the reasons of why conventional vehicles will be probably still dominating in the near future, a complete analysis, based on ISO 14040/44 Standards (Life Cycle Assessment, LCA), of a VW Golf is performed. Ethanol and Fischer-Tropsch diesel are assessed as renewable fuels in order to evaluate both a gasoline and diesel replacement fuel, respectively. Moreover, the complete assessment is performed in a cradle-to-cradle system.

Finally, a sensitivity analysis is carried out based in some scenarios. These are evaluated from the point of view of electricity generation and driving profiles, in order to evaluate their impacts and variations in the PCF.

A Matlab program is developed with the objective to depict results and graphics in a quick way. The advantage of this is to adapt and evaluate the PCF for, as example, different geographical and manufacturing process conditions, since these ones differ from one country to another one.

Zusammenfassung

Der Transportsektor ist einer der hauptsächlichen Verursacher der Treibhausgasemissionen und des Energieverbrauchs in der Welt geworden und diese Emissionen haben Auswirkungen auf die globale Erwärmung. Aus diesem Grund haben die Regierungen besondere Aufmerksamkeit auf die Begrenzung und Verringerung dieser Emissionen gelegt. Als Beispiel für diese Bemühungen um die Verringerung der anthropogenen Treibhausgasemissionen kann die Verordnung (EG) Nr. 443/2009 des Europäischen Parlaments erwähnt werden.

Verbrennungsmotoren (ICV) stellen den wichtigsten Prozentsatz der verfügbaren Fahrzeuge und der am weitesten verbreiteten Technologie auf dem Markt dar und werden wahrscheinlich auch in der kurz- und mittelfristigen Zukunft dominieren, obwohl sich alternative Technologien, wie Elektrofahrzeuge (EV), als wichtige Wettbewerber herausgestellt haben.

Diese Studie zielt darauf ab, den Product Carbon Footprint (PCF), der mit der Wirkungskategorie des Klimawandels zusammenhängt, eines herkömmlichen Fahrzeugs, das mit einem erneuerbaren Kraftstoff arbeitet, zu berechnen und zu schätzen.

Nach der Feststellung der wichtigsten heute auf dem Markt verfügbaren Technologien und der Gründe, warum konventionelle Fahrzeuge in naher Zukunft wahrscheinlich noch dominieren werden, wird eine vollständige Analyse, basierend auf den Standards ISO 14040/44 (Life Cycle Assessment, LCA), von einem VW Golf durchgeführt. Ethanol und Fischer-Tropsch-Diesel werden als erneuerbare Kraftstoffe gewertet, um sowohl einen Benzin- als auch einen Dieselersatzkraftstoff zu bewerten. Darüber hinaus wird die komplette Bewertung in einem Cradle-to-Cradle-System durchgeführt.

Schließlich werden in einigen Szenarien Sensitivitätsanalysen durchgeführt. Diese werden unter dem Gesichtspunkt der Stromerzeugung und der Fahrprofile bewertet, um ihre Auswirkungen und Abweichungen im PCF zu beurteilen.

Ein Matlab-Programm wird mit dem Ziel entwickelt, Ergebnisse und Grafiken schnell darzustellen. Der Vorteil besteht darin, den PCF beispielsweise an verschiedene geographische und unterschiedliche Herstellungsbedingungen anzupassen und zu bewerten, da diese von Land zu Land unterschiedlich sind.

Résumé

Le secteur du transport est devenu l'un des plus grands émételur de gaz à effet de serre ainsi que l'un des plus grands consomateur d'énergie au monde. Toute cette emission a un impacte sur le réchauffement climatique. C'est pour cette raison que les gouvernements on prêté une attention toute particulière aux anthropique émissions de gazes à effet de serre. La réglementation No 443/2009 du Parlement Européen peut être mentionné ici.

Les véhicules à combustion interne représentent le pourcentage le plus important de véhicules disponibles et le plus répandues sur le marché. Ils vont sûrement encore dominer le marché dans le future sur le court et moyen terme. Bien que des technologies alternatives, tels que les véhicules électriques ont vu le jour en tant qu'importants concurrents.

Ceçi étant dit, l'étude a pour but d'estimer et de calculer l'empreinte du produit carbone, qui est relié à la catégorie de l'impacte sur le changement climtaque qu'on les véhicules roulant à l'énergie renouvelable.

Suite à constatation de l'état des majeures technologies disponibles aujourd'hui sur le marché et les raisons de la probable domination des marches par les véhicules dits "conventionnels", une analyse complete basé sur les Standards ISO 14040/44 (Life Cycle Assessment, LCA), d'une VW Golf est effectuée. Ethanol et Diesel FischerTropsch sont ainsi inclus et tant que carburants renouvelable afin d sont ainsi inclus et tant que carburants renouvelable afin d'évaluer un carburant de remplacement tant pour le Diesel que pour l'essence. Ansi, l'ensemble du test est effectué par un système "cradle to cradle".

Pour conclure, une analyse poussée est effectuée basée sur divers scenarios. Ces derniers sont evalué du point de vue de la generation d'électricité et des profiles de conducteurs, afin d'evaluer leur impacte selon le PCF.

Un Matlab-Program est développé dans le but d'offrir une analyse méticuleuse des résultats et graphiques tout en étant rapides et efficaces. On peut ainsi adapter et évaluer le PCF. Par exemple, différents manières de productions étant donné qu'elles variant d'un pays à un autre.

Resumen

El sector del transporte se ha convertido en una de las fuentes más importantes de emisiones de gases de efecto invernadero (GHG) y de consumo de energía en el mundo, y tales emisiones tienen un fuerte impacto en el calentamiento global. Por esa razón, los gobiernos han puesto especial atención en limitar y reducir estas emisiones. Como ejemplo de estos esfuerzos para reducir las emisiones antrópicas de gases de efecto invernadero, se puede mencionar el Reglamento (CE) Nº 443/2009 del Parlamento Europeo.

Los vehículos de combustión interna (ICV) representan el porcentaje más importante de vehículos disponibles y la tecnología más extendida en el mercado, y probablemente continuará dominando el futuro en el corto y mediano plazo, aunque las tecnologías alternativas, tales como vehículos eléctricos (EV), han surgido como importantes competidores.

Dicho esto, este estudio tiene como objetivo calcular y estimar la Huella de Carbono de Producto (PCF), que está relacionada con la categoría de impacto de cambio climático, de un vehículo convencional funcionando con un combustible renovable.

Después de enunciar las tecnologías más importantes disponibles en el mercado hoy en día y las razones de por qué los vehículos convencionales probablemente todavía dominen el futuro inmediato, se lleva a cabo un análisis completo, basado en las normas ISO 14040/44 (Evaluación del Ciclo de Vida), de un VW Golf. Como combustibles renovables se evalúan el Etanol y el Diesel Fischer-Tropsch con el objetivo de contar tanto con un combustible de reemplazo de la gasolina como del diesel, respectivamente. Adicionalmente, la evaluación completa se lleva a cabo en un sistema cradle-to-cradle (cuna-a-cuna).

Finalmente, se realiza un análisis de sensibilidad basado en algunos escenarios. Los mismos se evalúan desde el punto de vista de generación de electricidad y de los perfiles de conducción, con el fin de evaluar sus impactos y variaciones en el PCF.

Se desarrolló un programa en Matlab a fin de representar resultados y gráficos de una manera rápida. La ventaja de esto es adaptar y evaluar el PCF a, por ejemplo, diferentes condiciones geográficas y de proceso de fabricación, ya que estas difieren de un país a otro.

1. Introduction and Motivation

According with a study commissioned by World Business Council for sustainable Development (2004), Light-Duty Vehicles (LDV) ownership, represented by passenger cars and light duty vehicles, could increase from roughly 700 million to 2 billion over the period 2000-2050. If we considered that LDV account for approximately 10% of global energy use and greenhouse gas (GHG) emissions (Solomon et al. 2007), these forecasts lead to a dramatic increase in gasoline and diesel demands with concerns and implications for climate change and urban air quality among others.

Therefore, another transport alternatives and technologies have been being developed in the last decade, and their market availability is increasing. Despite some minor differences between models presented by different authors, the following technologies, indicated in Figure 1, can be pointed out as the most important and representative ones nowadays.

Figure 1. Vehicle technologies and alternatives

It is known that Internal Combustion Vehicles (ICVs), both diesel and gasoline, represents the most important quantities available in the market and it will keep in the following decades due to different reasons. However, among available transport alternatives, Electric Vehicles (EVs) have reemerged as a strong candidate. EVs offer advantages in terms of powertrains efficiency, maintenance requirements, and zero tailpipe emissions. This last one contributes to reducing urban air pollution relative to conventional ICEVs (Wang and Santini 1993). This idea has led to a general perception that EVs are an environmentally friendly technology. Nevertheless, the reality is more complex, requiring an exhaustive account of impacts throughout the Vehicle Life Cycle (VLC). As an important example, several studies have already demonstrated that promotion of EVs is counterproductive in areas or regions where electricity is primarily produced from lignite, coal, or heavy oil combustion and thus, EVs are good from moving emissions away from the roads rather than reducing them globally (Hawkins et .al, 2012).

While one side, it can easily be thought that EVs are supposed to produce an elimination of tailpipe emissions at the expense of increased ones in the vehicle and electricity production chains, on the other hand, however EVs would produce emissions at a few point sources, like power plants, mines, etc., instead of millions of mobile sources. This could make conceptually easier to control and optimize transportation systems. Similar concepts could be extended to

Plug-in Hybrid Electric Vehicles (PHEVs), with different All-electric Ranges (AERs), like 18 or 62, which plays a very important role to calculate and understand its emissions.

It is important to mention that another key parameter, or constrain, for an increase amount of EVs in the market is the impact it could produce to the grid, mainly if there is an uncontrolled or undefined charging profile.

Exists a trade-off between life cycle stages, which could lead to different calculations and thus to different decisions and conclusions. For example, while vehicle can be lighter by substituting materials, which indeed show a higher fuel economy during the operational stage, at the same time, part of that benefit is offset by the higher production energies of these alternative materials during the production stage.

After reviewing the literature, in the case of conventional ICEVs, although the use phase accounts for the majority of Global Warming Potential (GWP) impact, vehicle production phase is not insignificant, and contributes on the order of 10% of life cycle GWP. Accounting for production impacts is even more important when comparing technologies with significantly different powertrains such as ICEVs and EVs. It is especially important the production of electronic components and equipment, requiring a variety of different material, which is a challenge for recycling and raises concerns about toxicity (Johnson et al., 2007).

With the growth of EVs, carbon dioxide (CO_2) emissions from vehicle production account for a growing proportion, which has taken much attention in recent years all over the world. Therefore, production and manufacturing processes will play an important role in the future. Besides, it is also important to keep in mind that CO_2 emissions from vehicle production vary among different regions owing to discrepancies in manufacturing techniques (Qinyu Qiao et al., 2017).

It is also well known that to reach the goals of Paris Climate Agreement, nations have signed up to substantial reductions in GHG emissions. However, while decarbonization of stationary GHG emissions sources, such as power plants, has already begun some years ago and occurring at a large scale, the reductions for mobile sources will be more difficult (P. Wolfram, T. Wiedmann, 2017).

If the reasons for this problem are considered, the following barriers emerge:

- ✓ High technology cost (especially fuel cell vehicles)
- ✓ Insufficient infrastructure and high cost of public charging stations
- ✓ Limited policy intervention in terms of fiscal and non-fiscal incentives
- ✓ Limited driving range of BEVs
- ✓ Simultaneous integration of EVs and renewable energy sources as part of the electricity network

Points indicated above are especially important or challenging in countries with long geographical distances, such as USA, Australia, Canada, Brasil, etc.

All the information given before lead to the idea to evaluate the improvement of ICVs, from the point of view of emissions, in order to attend to requirements and restrictions in the short future, and a key factor to evaluate is the production and use of a renewable fuel.

1.1. Objective

As it was pointed out above, transport sector has become one of the most important sources of GHG emissions, and therefore one of the key player in environmental problems, such as global warming and air pollution. It was also indicated that ICVs will represent, and despite the increase amount of other technologies, the most important part of the vehicle available in the market.

Besides the forecasts available, the main reasons to explain that lie in following improvements and requirements:

- ✓ Fuel Consumption Efficiency
- ✓ Manufacturing Efficiency
- ✓ Alternative Fuels
- ✓ Policies, such as EC Regulation No 443/2009.

Gasoline	Diesel	Gas	Hybrid	Hybrid Plug-in	Electric	Others	Total
30.451.268	15.225.296	496.742	236.710	44.419	53.861	10.717	46.519.013

Table 1: Number of vehicles in Germany (2018); Total and by Type

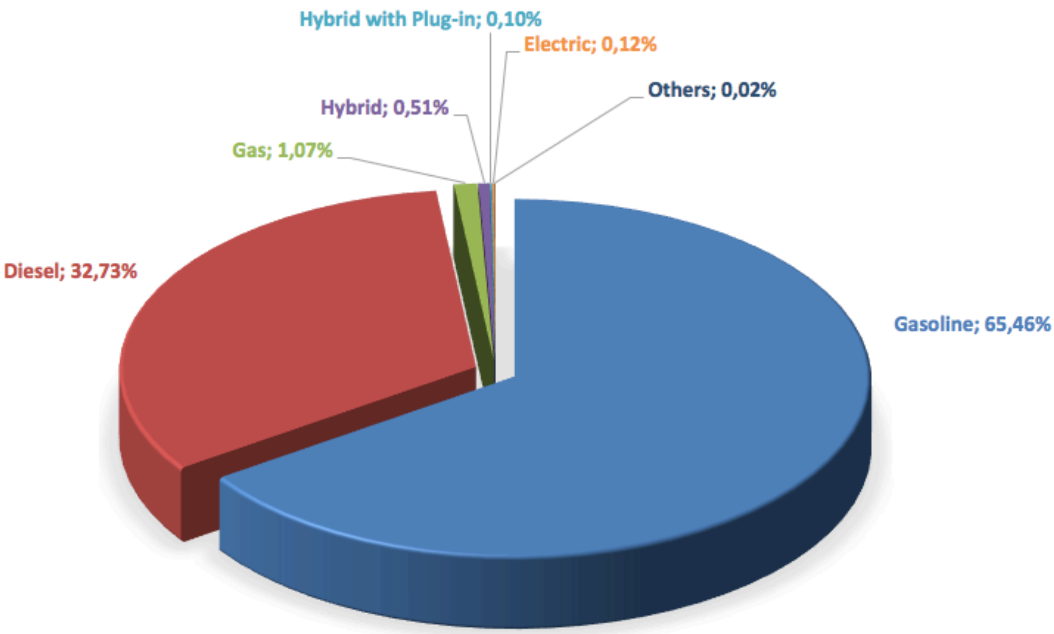

Figure 2. Vehicles in Germany (2018)

Source: Kraftfahrtbundesamt

Fuel Type	2017	2018	% Var.
Gasoline	29.978.635	30.451.268	1,58%
Diesel	15.089.392	15.225.296	0,90%
Gas	525.212	496.742	-5,42%
Electric	34.022	53.861	58,31%
Hybrid	165.405	281.129	69,96%
Other	10.894	10.717	-1,62%

Table 2: Number of vehicles and perceptual variation 2017 vs 2018

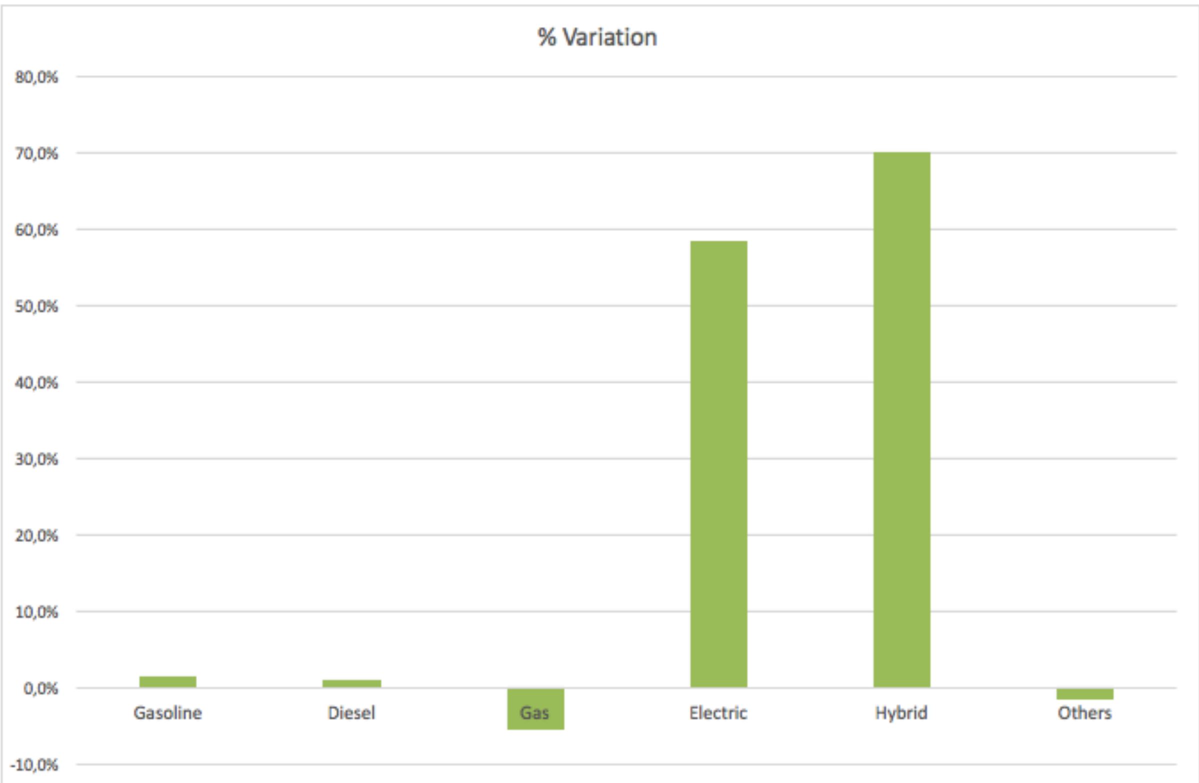

Figure 3. Variation 2017 vs 2018

Source: Kraftfahrtbundesamt

So, the goal of this study is to calculate and evaluate the PCF, of a conventional vehicle, driving with renewable fuels, and determine strengths, weaknesses and future possibilities for renewable fuels in the path to achieve the target reduction of CO_2 and other pollutants emissions. Likewise, this study will consider a cradle-to-cradle assessment in order to evaluate the results in a circular economy.

As it was emphasized before, even though EVs, PHEVs and HEVs are often considered a better option than ICVs in terms of GHG emissions, is actually not correct to give such a straightforward answer, since sources in the electricity production, geographical conditions, driving patterns, material and manufacturing processes, etc., lead to different results in final analysis depending on the scenarios.

The development of renewable fuels as well as the improvement in efficiency of ICV may produce interesting reduction emissions and consequently lean the scale in favor of these ones, and modify the trend of last years. It is also important to highlight that the motivation for liquid fuels is that they offer today the highest energy density in comparison with other sources like batteries and hydrogen.

This study is developed according with Life Cycle Assessment (LCA), which is a widely-accepted methodology to quantify the environmental impacts of product (or processes) throughout production, use, end-of- life and disposal/recycling, and focused in the impact category Climate Change.

This methodology is applied to a VW Golf and the scope includes vehicle production, use, which include fuel production and use, and end of life together with all relevant supply chains. The choice of a VW Golf is based on the reason that this vehicle offers an EV as counterpart and thus, it would let the comparison of different technologies and their consumptions and emissions.

1.2. Background und Current Situation

After reviewing a vast number of scientific publications and literature from different sources, it is observed that studies are mainly focused in just one or two phases of the Life Cycle, such as ICVs production and use phase, working mainly with fossil fuels, or biofuels production and use phase, without including vehicle production. Moreover, the results between studies show an important variation. Reasons for these variations could include, but not limited to, system boundaries, assumptions, uncertainties from data bases/processes, etc.

Additionally, studies are mainly based on cradle-to-gate system, which is not actually a Life Cycle Assessment since End of Life/Recycling is important to consider, although according with the literature, this phase does not count for a high percentage of the total emissions. In summary, it is important to work with the closed cycle of the vehicle's life cycle.

As a final point, and even though it is clear and understandable because manufacturing processes or driving patters differ from one region or country to another one, the studies are based on a specific place. This study has also the intention to offer a general idea or picture of the Carbon Footprint as a first sight. However, values used and indicated for the calculations will be either from EU or Germany, since most important and complete data bases are from these places.

Said that, it is relevant to perform a study considering a cradle-to-cradle system, as it is detailed in Figure 4, and analyzing different scenarios of fuels, driving patterns and electricity generation.

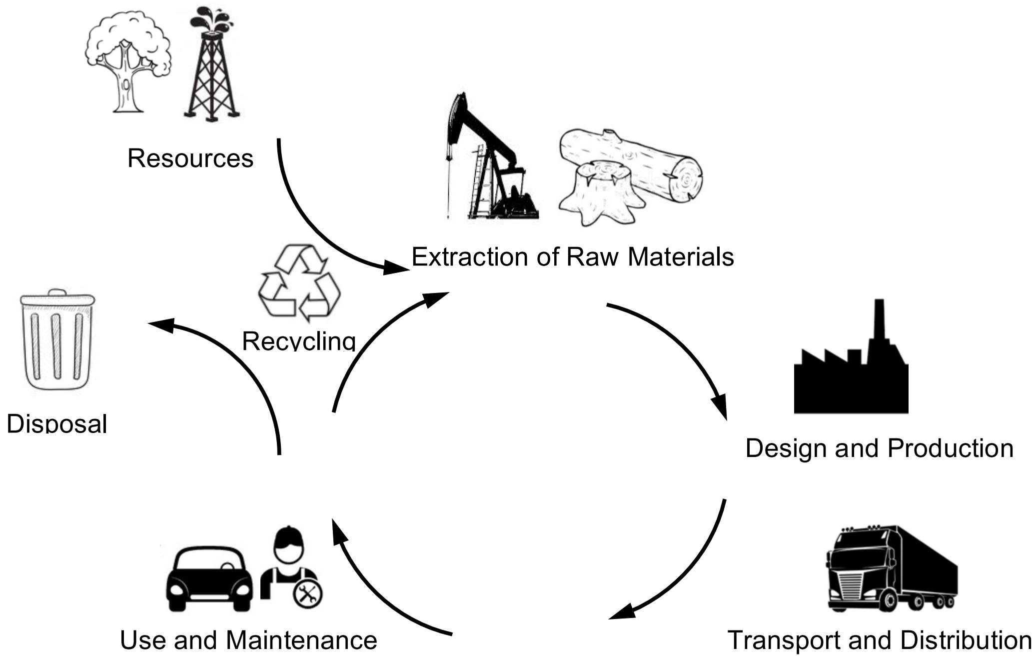

Figure 4. Life Cycle Stages (adapted).

Source: Ecoinvent

2. Life Cycle Assessment (ISO Series). Product Carbon Footprint

According with ISO series, the stages of an LCA are the ones depicted below in Figure 5.

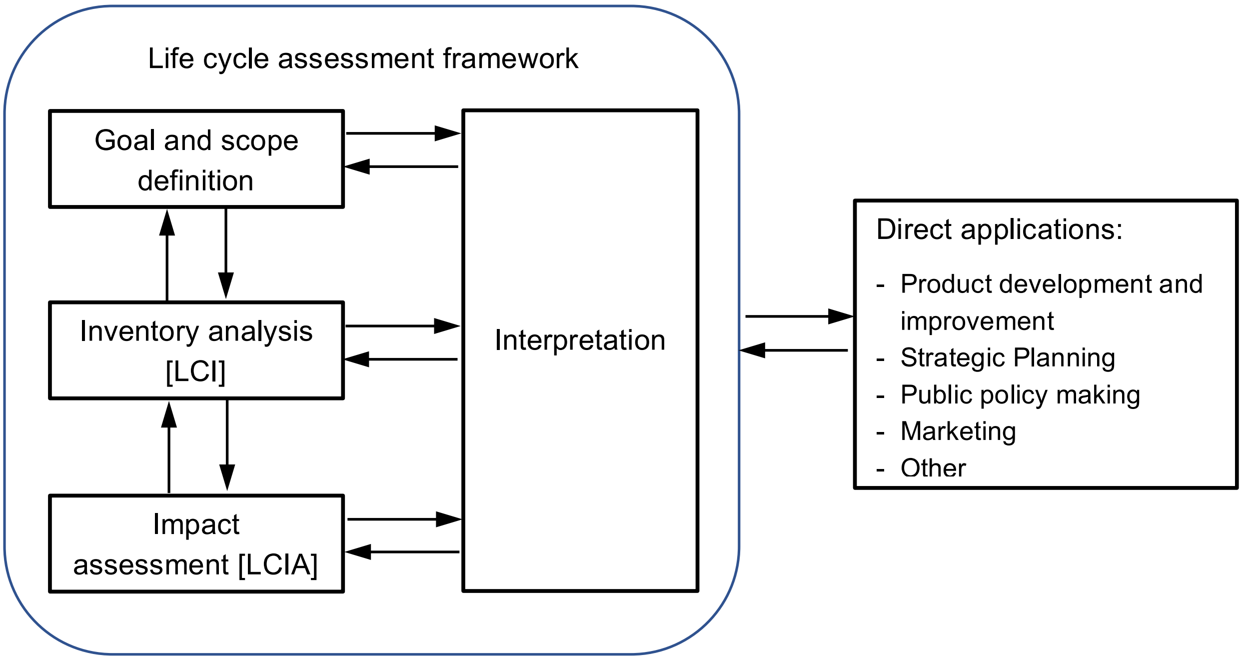

Figure 5. Stages of an LCA according with ISO EN DIN 14040 and 14044

2.1. Methodology

As aforementioned, LCA is the methodology to be applied in the study. This one is a technique which guides during assessing the environmental aspects and potential impacts associated with products or processes through:

- ✓ Compiling the inventory of inputs and outputs of the defined system.
- ✓ Evaluating the potential environmental impacts associated with the selected inputs and outputs.
- ✓ Interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA models the life cycle of a product as its product system which performs one or more define functions. The essential property of a product system is characterized by its function and cannot be defined solely in terms of the final product. Therefore, product systems are subdivided into a set of unit processes, as the example depicted below in Figure 6.

The elementary flows include the use of resources and releases to air, water and land associated with the system.

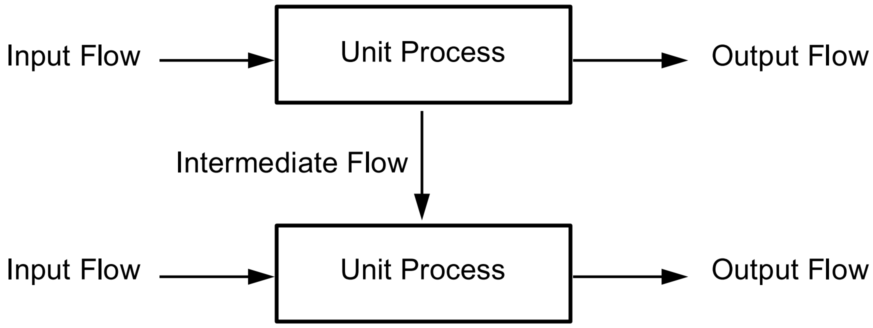

Figure 6. Set of unit processes within a product system (ISO EN DIN 14040)

The LCA methodology makes possible to objectively, systematically and scientifically assess the environmental and human health impacts associated with a product or service. One of the environmental impacts evaluated is Climate Change, in which GHG emissions from the whole life cycle are calculated. Thus, it is important to highlight that a PCF study is designed when only the impact on climate change is considered.

It is important to mention that the existing methods for impact assessment depicted in the following structure frame:

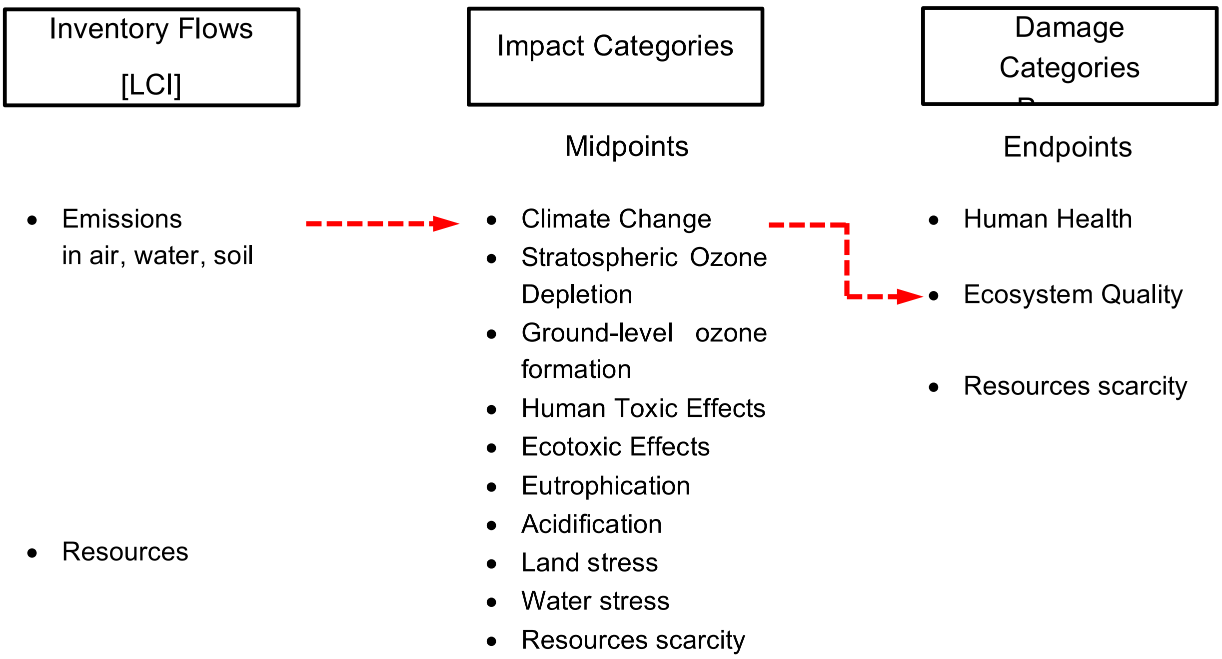

Figure 7. Current methods for impact assessment

The aforementioned impact assessment methods differ in their modeling approaches, aggregation level and weighting methods, and the geographical scope. Some of these methods focus on individual impact categories and they are often combined with other methods to ensure a complete assessment of all relevant impact categories.

- Climate change: It is known as the greenhouse effect. It is caused by absorption and reflection of heat radiation by so-called climate gases, e.g. carbon dioxide, methane, nitrous oxide. This natural continuous process has been exacerbated by anthropogenic emissions. Through the global warming is expected to affect human health (e.g., malaria) and ecosystems (loss of biodiversity).

- Stratospheric ozone depletion: Ozone in the stratosphere protects the earth from high-energy UVB rays. Emissions of chlorofluorocarbons (CFCs) and their decomposition products degrade ozone in the stratosphere. The Montreal Protocol has almost completely stopped the use of CFCs, but the persistence of these chemicals makes ozone depletion a problem even today. The UVB radiation can produce different diseases such as skin cancer.

- Ground level ozone formation: Ozone is toxic and can be inhaled. Emissions which contribute to this effect are Nitrogen Dioxide (NO_2) and Volatile Organic Compounds (VOCs). Pollution sources are mainly road traffic and other combustion processes. Ground level ozone is formed under the influence of UV radiation and is also knows as summer smog.

- Human Toxic Effects: Chemicals and particulate emissions can lead to toxic effects and represent a harmful for human health. For example, particulate emissions can cause respiratory effects. They include carcinogenic and other effects.

- Ecotoxic effects: Chemical compounds can cause harmful effects on living organisms, their population and natural environment. They include and differ between aquatic, terrestrial and sediment ecotoxicity.

- Eutrophication: Nutrient emissions such as phosphorus, which is available in plant as PO_4 and nitrogen, also in plants as NO_3 and NH_4, contribute to eutrophication or overfertilization. Sources of such emissions include agriculture (fertilizers), air emissions (NOx from combustion processes), and wastewater.
  In terrestrial systems, this leads to an increase of plant growth, disturbance of the natural nutrient balance and loss of biodiversity, since individual species spread at the expense of other species.

- Acidification: Pollutants such as SOx, NOx and NHx can cause the acidification of soils and waters, which is known as "acid rain". Sources of such emissions are primarily traffic, industrial combustion processes (e.g., power plants) and animal breeding. Acidification can cause plants damage, such root damage, through heavy metal mobilization and lead to a long-term change in species composition.

- Land stress: Land stress refers to the effects of land occupation and conversion. Environmental impacts include loss of natural ecosystems and biodiversity as well as the loss of soil fertility.

- Water stress: Many areas suffer today this water stress, which means a lower availability of water or relatively low compared with the use. This could be enhanced or aggravated in the future due to increased food consumption of a growing population, cultivation of biofuels and regional climate change.

- Resource scarcity: The quality of resources decreases with increasing extraction. Fossil resources such as oil could no longer be available as a primary resource in the future, but could only be obtained from other resources such as oil shale or coal. The ore content of mineral resources decreases with increasing production. Mining also causes other environmental effects, such as biodiversity loss by occupying large areas in often sensitive ecosystems, but these are developed by other impact categories.

2.2. Carbon Footprint of Products

The ISO EN DIN 14067 traces the Requirements and Guidelines for quantification (and communication) for Greenhouse Gases (GHG) – Carbon Footprint of Products (CFP).

According with this standard, GHGs are emitted (and removed) throughout the life cycle of a product from raw material acquisition through production, use and end-of-life treatment.

Between the terms and definitions indicated in this standard, it is important to mention the following:

2.2.1. Carbon Footprint of a Product

Sum of greenhouse gas emissions (and removals) in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change.

2.2.2. Greenhouse Gas (GHG)

Gaseous constituent of the atmosphere, both natural and anthropogenic, that absorbs and emits radiation at specific wavelengths within the spectrum of infrared radiation emitted by the earth's surface, the atmosphere and clouds.

2.2.3. Carbon Dioxide Equivalent (CO_2-Eq.)

Unit for comparing the radiative forcing of a greenhouse gas to that of carbon dioxide.

The mass of a greenhouse gas is converted into CO_2 equivalents using global warming potential

2.2.4. Global Warming Potential

Characterization factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time.

Industrial Designation or common name	Chemical Formula	GWP for 100-year time horizon
Carbon dioxide	CO_2	1
Methane	CH_4	25
Nitrous oxide	N_2O	298

Table 3: Global warming potential relative to CO2 for the 100 year-time horizon (abstract) List of greenhouse gases (IPCC 2007)

2.3. Goal and Scope of the CFP quantification

According with ISO Series, it is the first point to define, and its definition and assumptions, and constraints, will lead to a specific result. Main scope of this study is to calculate the CFP associated with a conventional vehicle working with renewable fuels, which are described in Chapter 3.2.

In our study, the objective of applying the LCA methodology is to develop part of an environmental picture of product, where the different burdens, such us CO_2 emissions are quantity and evaluated over all stages of a product life cycle.

This kind of assessment can help to identify improvement possibilities and/or a more comprehensive assessment of a product.

Additionally, the results are compared in different scenarios from the point of view of electricity generation and fuel consumption.

2.3.1. Functional Unit

With the objective to calculate the CFP, the GHG emissions are calculated per vehicle, which means kg CO_2 eq/Vehicle regarding Vehicle Life Cycle and per kg fuel, which means kg CO_2 eq/kg_{fuel} regarding Fuel Life Cycle. At the end, and after a complete estimation of all GHG emissions, they are expressed in terms of g CO_2 eq/km considering the whole life cycle.

Regarding the transport, it is a total distance of 150.000 km based on the New European Driving Cycle (NEDC).

The characteristics of the vehicle in which this study is based are the following:

	Characteristics	Values / Detail	Units
1.	Engine	1598	cm^3
2.	Output	77	kW
3.	Fuel	Diesel	-
4.	Standard Emission	EURO 5	-
5.	Max. Torque	250 / 1500-2500	Nm at rpm
6.	Max. Speed	189	km/h
7.	Curb weight	1314	kg
8.	Fuel Tank Capacity	55	liter

* Golf Generation VII shows similar values

Table 4: Technical description of Golf 1.6, 77 kW TDI Engine (Golf VI)

2.3.2. System Boundary

To calculate the PCF, both VLC and FLC are considered, according with the general flow chart depicted below in Figure 8.

Coming up next, in Points 2.3.2.1 and 2.3.2.2, the both detailed flow charts are depicted in Figures 9 and, 13 and 14 (because two renewable fuels are evaluated), respectively.

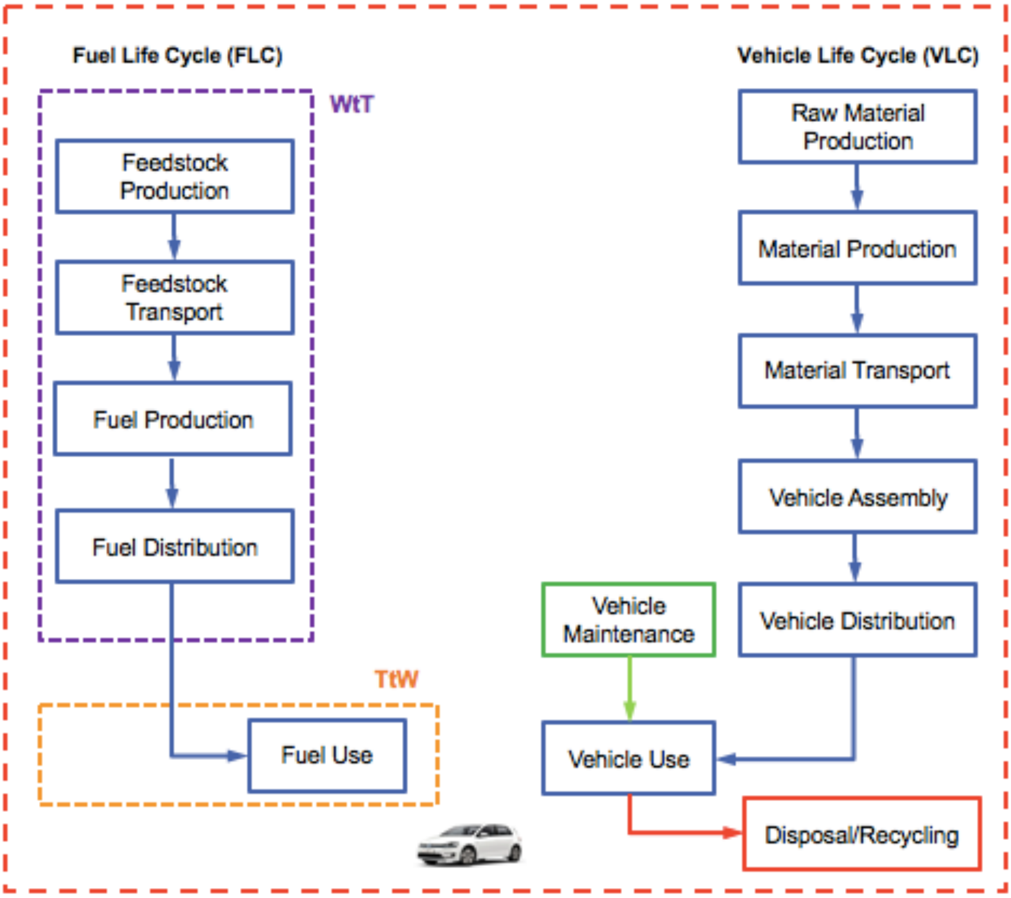

Figure 8. System Boundaries, adapted from Rose et al., 2013

2.3.2.1. Vehicle Life Cycle (VLC)

As depicted in Figure 9, VLC considers the following stages:

- Raw material extraction and material production
- Vehicle manufacture, assembly
- Vehicle distribution
- Vehicle use, including maintenance and washing.
- Final processing of the vehicle for disposal/recycling.

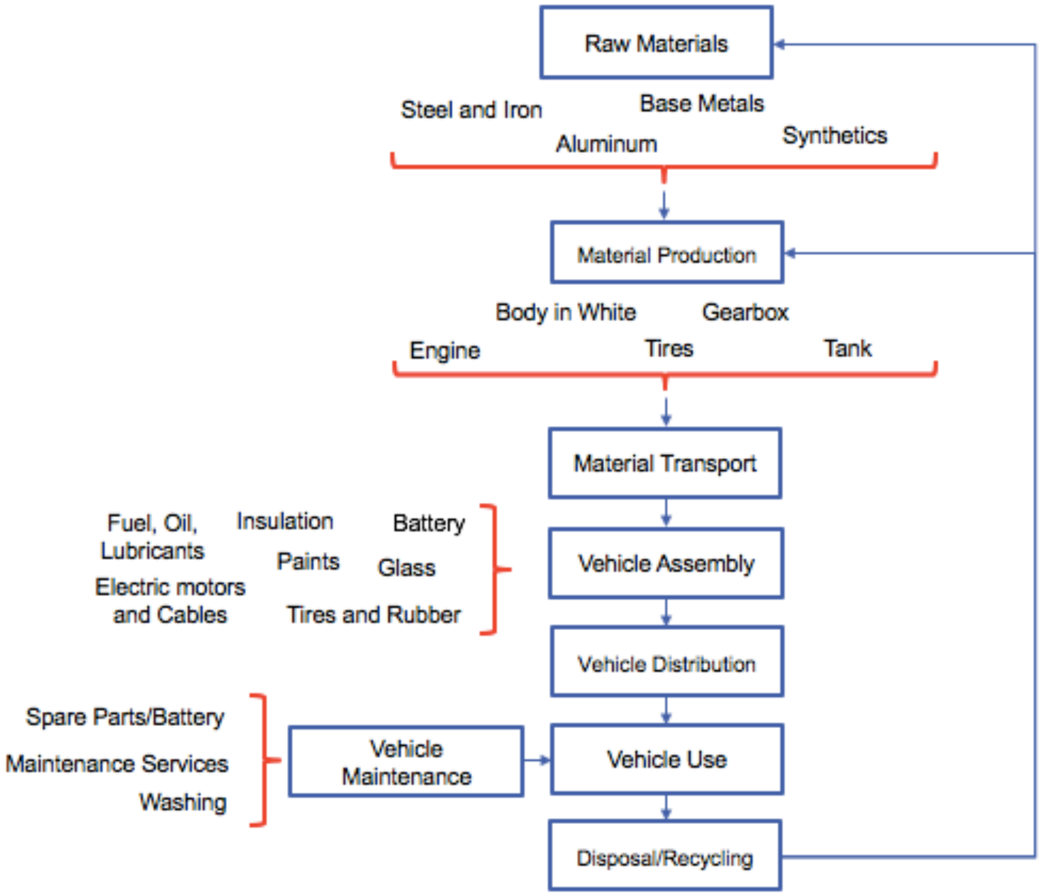

Figure 9. Detailed VLC, adapted from Qinyu et al., 2017

Regarding the transport of transformed materials, it is not going to be included because the impact of parts in a vehicle will be very small. It could be possible to consider de transport of the engine/motor and gearbox, since theirs weight represent an important percentage of the curb weight, from the plants of Salzgitter and Kassel plants respectively. However, evaluating that the distances are around 55 km and 180 km, it will not produce a high impact.

Additionally, and even though the values of the production are not exactly the same, since the gasoline vehicle has a slightly lower weight, it will be assumed that the production of a diesel vehicle and a gasoline one have the same carbon footprint from the production point of view.

This can be assumed, since from the powertrain technology perspective, they are similar and, according with Paul Wolfram and Thomas Wiedmann (2017), the amount of inputs processes is the same and they are equal to 72 processes. Meanwhile, for other powertrain types, such as BEV and PHEV, the amount of processes is 122 and 133, respectively. Thus, it can be inferred why the production of EV has a larger carbon footprint.

2.3.2.2. Fuel Life Cycle (FLC)

As it was mentioned in the introduction, since fossil fuels are finite and their combustion releases big amounts of CO_2 and other gases, called GHG, with negative effects for our environment, there are alternative fuels, which can be used in current engines instead of fuels based on crude oil.

It means that the current infrastructure supports the large-scale production and use for renewable fuels, which is an important advantage since would let a faster implementation than others alternatives.

Some examples of non-fossil fuels alternatives nowadays are Ethanol (C_2H_5OH), Methane (CH_4), Vegetable Oil, Hydrogen, etc.

Alternative fuels, based on Biomass, are normally gained by gasification or by squeezing and further processing a biomass. In the following figure the possible paths are depicted:

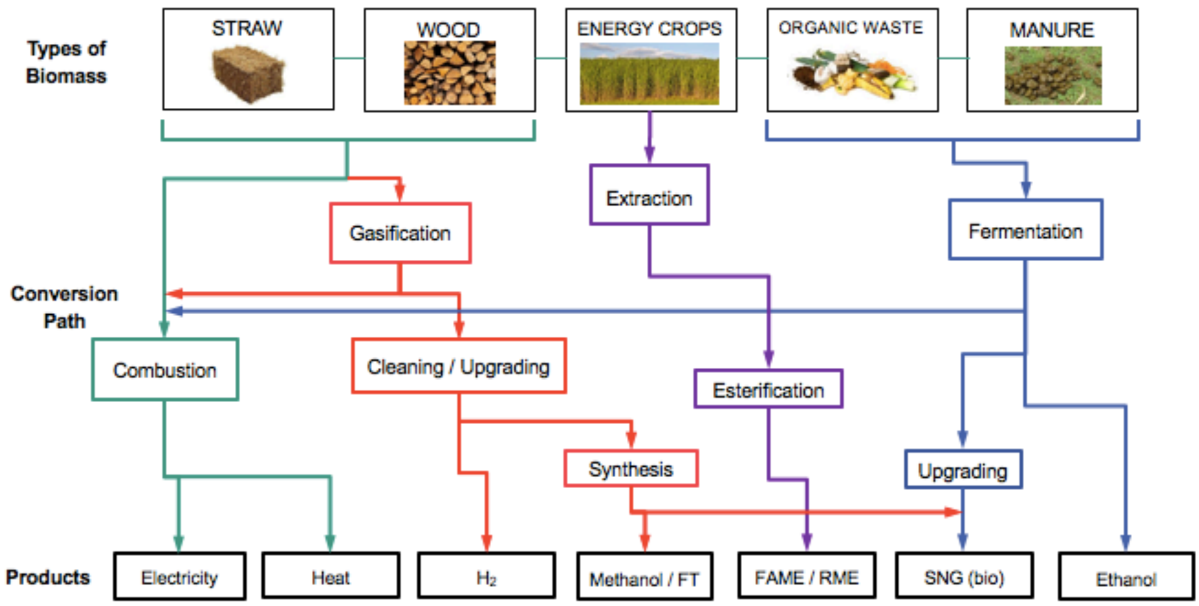

Figure 10. Conversion paths for renewable fuels

Source: EBI-CEB, Energy from Biomass

Main advantages of these alternative fuels, lay in their close CO_2 cycle and the possibility of production close to its future consumers, which encourage the development of reginal economies.

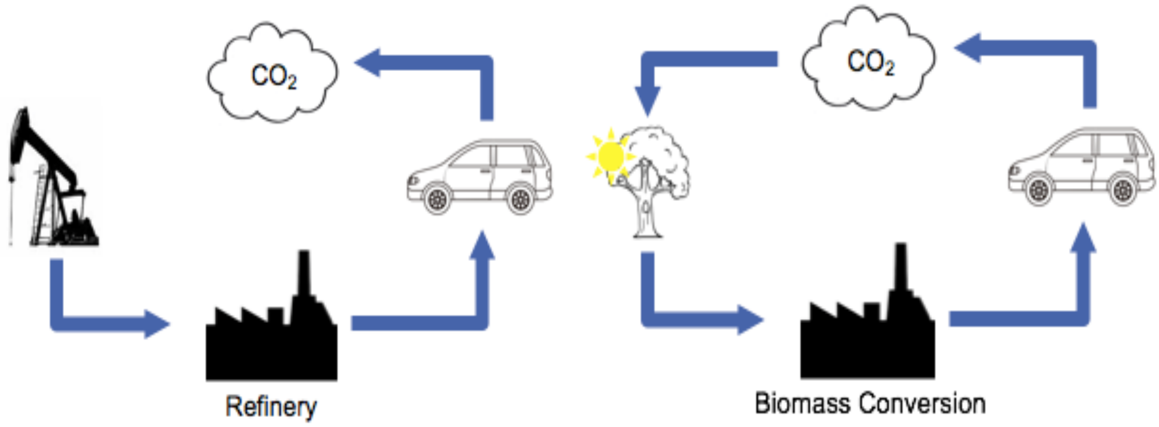

Figure 11. Open and Close CO_2 cycle

Regarding the close CO_2 cycle, it is known that plants need CO_2 to grow. The combustion of these plants releases the same amount of CO_2, which was withdrew from atmosphere during growing phase.

However, it is important to highlight that these fuels are not in fact CO_2 neutral, since during the production of the fuel, energy used to process them is gotten from non-renewable sources. Moreover, an overall evaluation of fuels depends on the efficiency of their production process.

As drivers for the development of renewable fuels, known also as biofuels, the following could be mentioned:

- Energy security
- Climate change mitigation
- Policy
- Technical developments
- User compatibility
- Quality, etc.

One more important point, which was already mentioned at the introduction, is that liquid fuels offer today the highest energy density.

Finally, and before defining the biofuels to analyze in the scope of this study, it is important to indicate the different generation of these ones and the state of them, which differ each other mainly based on type of feedstock, conversion technology used and properties of the fuel molecules produced. Despite there are also different approaches to classify biofuels and any of all of them could be considered as advanced biofuels, one suitable scientific definition or classification is according with the European Technology and Innovation Platform (ETIP), based on the carbon source from which the biofuel is derived:

- 1st Generation (1G): the source of carbon for the biofuel is sugar, lipid or starch directly extracted from a plant. The crop is actually or potentially considered to be in competition with food.
  From the point of view of the development state of this generation, it is in state of the art.
- 2nd Generation (2G): the biofuel carbon is derived from cellulose, hemicellulose, lignin or pectin. This may include agricultural, forestry wastes or residues, or purpose-grown non-food feedstocks, such as short rotation coppice, energy grasses.
  From the point of view of the development state of this generation, it is still in development. However, the advances in the last years have been very important and meaty.
- 3rd Generation (3G): the biofuel carbon is derived from aquatic autotrophic organism (process its food by itself) like for example algae. Light, carbon dioxide and nutrients are used to produce the feedstock extending the carbon resource available for biofuel production.
  From the point of view of the development state of this generation, it is still in research.

This classification does not mean that a generation is more environmental friendly or sustainable that the others ones because there are others factors such as land use, competition with food crops, and efficiency of the production process, total energy balance, etc., which need to be taken into account across each specific value chain.

According with ETIP, the following are some of the possible paths for renewable fuels production. Besides, among the following described below, some of the main ones developed and applied not only in Europe, but globally can be found.

A short description of the production and characteristics of renewable fuels is the following:

- Cellulosic Ethanol: it can be produced by hydrolysis and fermentation of lignocellulosic agricultural wastes such as straw or corn stover or from energy grasses or other energy crops. The end product is the same as conventional bioethanol, which is typically blended with gasoline.
  Cellulosic ethanol is chemically identical to first generation bioethanol (i.e. CH3CH2OH). However, it is produced from different raw materials via a more complex process (cellulose hydrolysis).
  In contrast to first generation bioethanol, which is derived from sugar or starch produced by food crops (e.g. wheat, corn, sugar beet, sugar cane, etc), cellulosic ethanol may be produced from agricultural residues (e.g. straw, corn stover), other lignocellulosic raw materials (e.g. wood chips) or energy crops (miscanthus, switchgrass, etc).
  These lignocellulosic raw materials are more abundant and generally considered to be more sustainable, however they need to be broken down (hydrolysed) into simple sugars prior to distillation. This may be achieved using either acid or enzyme hydrolysis. Both approaches have been the subject of continuing research interest since the 1970s, and large investments are being made in the US and Europe to speed up development of this route to bioethanol.

Parameter	Ethanol	Gasoline	Unit
Density at 20°	0,79	0,74	[kg/l]
Lower Heating Value [LHV]	26,7	43,9	[MJ/kg]
Octane Number	>100	92	-
Fuel Equivalence	0,65	1	-
GHG*	Sugar beet: 33 Farmed wood: 20 Wheat straw: 11		[gCO²eq/MJ]

* Total for cultivation, processing, transport and distribution.

Table 5: Comparison of fuel properties

Source: European Technology and Innovation Platform (ETIP)

- Biomass to Liquid (BtL): It is generally produced via gasification, heating in partial presence of oxygen to produce carbon monoxide and hydrogen (Syngas). Feedstocks include woody residues or wastes or energy crops. Gasification is followed by conditioning and then fuel synthesis via Fischer Tropsch or the "methanol-to-gasoline" process.
  The term Biomass to Liquid (BtL) is applied to synthetic fuels made from biomass through a thermochemical route. The objective is to produce fuel components that are similar to those of current fossil-derived petrol (gasoline) and diesel fuels and hence can be used in existing fuel distribution systems and with standard engines. They are also known as synfuels.
  Biomass is pretreated and then converted to synthesis gas via gasification. The resulting syngas is then cleaned prior to conversion to liquid biofuels, typically via Fischer-Tropsch.
  The properties of the resulting product are similar to those of conventional diesel fuel. When this advanced biofuel is combusted in a diesel engine, the pollutants in the exhaust gas are significantly reduce while the performance remains constant. Particle emissions are up to 40% lower. Since no sulphur is contained, combustion produces no sulphur oxides. It is CO_2-neutral and, as mentioned before, generates what is termed a closed CO_2 cycle.

- Hydrotreated Vegetable Oils (HVO) / Hydroprocessed Esters and Fatty Acids (HEFA): They do not have the detrimental effects of ester-type biodiesel fuels, such as increased NOx emission, deposit formation, storage stability problems, or poor cold properties. HVOs are straight-chain paraffinic hydrocarbons that are free of aromatics, oxygen and sulfur and have high cetane numbers.

- Vegetable Oil and Bio-Diesel: A number of plants, such as soy, rape, sunflowers, palm trees, can be processed into oils which can be considered for use as fuels. Vegetable Oil can be used in its pure form, RME (brand name Bio-Diesel) or blended with conventional diesel fuel.
  A difficulty arises from the very high dependency of the vegetable oil viscosity, as opposed to that diesel fuel, on the fuel temperature. This can cause problems during cold starts. So, the control system of a diesel engine in vegetable oil applications must be adapted to the respective fuel in order to achieve optimal combustion.
  Unlike other fuels, vegetable oils are not classified as dangers under soil and water protection rules. No special precautions must be taken while storing and transporting them. Such fuel can also be used in environmentally sensitive areas.
  Rape oil is esterified for many mobile applications. The vegetable oil is thereby converted from alcohol to mono-alcohol ester and glycerin be adding alcohol. This reduces its viscosity and improves its thermal properties to the point where it can be directly used in Diesel engines. Since additional energy is required to transesterify the oil into Bio-Diesel. This raises the production costs still further in comparison to Diesel fuel. Bio-Diesel has more favorable particle, CO and HC emission properties than conventional diesel fuel. Its higher NOx emissions are a drawback. Unlike raw Vegetable Oil, Bio-Diesel is acidic and does not react neutrally to water resources, i.e. tanking requires the same safety precautions as those applying to diesel fuel and it affects rubber aggressively.

- BioDME (dimethylether): It can be produced via catalytic dehydration of methanol or directly from syngas. Above -25°C or below 5 bar DME is a gas. Hence its use as a transport fuel can be considered similar to that of LPG.

- BioSynthetic Natural Gas (BioSNG): It is produced via an initial gasification step followed by gas conditioning, SNG synthesis and gas upgrading. BioSNG can be used in a similar way to biomethane (biogas) generated via anaerobic digestion (a biological process). Syngas may also be converted to liquid fuels.

- Bio-oil/Bio-crude: It is produced by pyrolysis, processes that use rapid heating or super-heated water to convert organic matter to oil. Flash pyrolysis involves rapid heating (1-2 seconds) of fine material up to 500°C. Thermochemical Conversion uses superheated water to convert organic matter to bio-oil. This may be followed by anhydrous cracking/distillation. The combined process is known as Thermal depolymerization (TDP). Bio-oil can be used as a heating fuel or can be further converted to advanced biofuels.

- Torrefaction (heating at 200-300°C in the absence of oxygen, at atmospheric pressure): It converts biomass to "bio-coal", which can be more easily used for power generation than untreated biomass.

- Biobutanol: It is an alcohol that can be used as a transport fuel. It is more compatible with existing fuel infrastructures and engines than ethanol. Novel fermentation techniques are being developed to convert sugars into butanol using modified yeast strains.

- Algal biofuels: They may be produced from macro algae (seaweeds) and microalgae via a range of technologies. A number of projects and pilot plants are now identifying the best types of algae to use and the best production technologies. Algal biofuels have attracted great interest as they do not compete with food crops for land use, but the technology is not yet as mature as that for some other advanced biofuels.

- Biohydrogen: Hydrogen can potentially be produced from biomass via various routes and can be used as a vehicle fuel. Biohydrogen is not currently being produced at significant volumes, but could be an important fuel in the future.

As part of this study, a 1st generation and a 2nd generation fuels will be analyzed. The aim to select these two different biofuels in order to study their PCF is to have, one side, a replacement fuel for gasoline and another for diesel, and on the other hand to work with a 1st Generation fuel as well as a 2nd Generation one, which will help to understand the different situations regarding production state and technology.

Furthermore, according with the International Energy Agency (IEA), in the coming decades, the following growth and development is expected, meanwhile the production costs, USD/liter fuel equivalent will decrease:

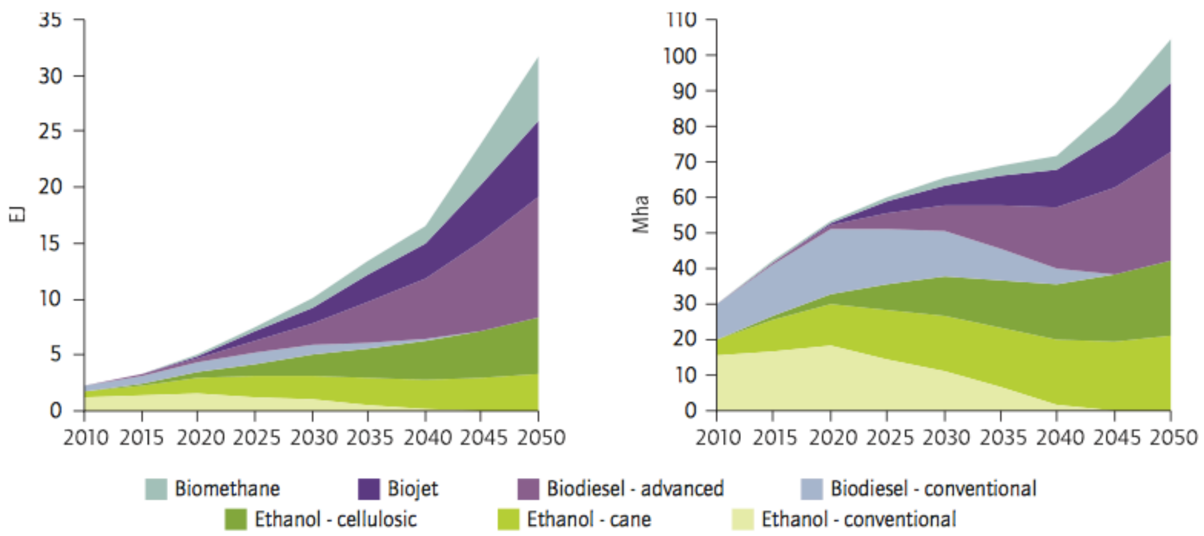

Figure 12. Demand for biofuels (left) and resulting land demand (right)

Source: International Energy Agency (IEA)

It can be seen that the 2nd Generation of biofuels, advanced biofuels, will be playing a very important role.

As depicted in Figure 8, FLC considers the following stages:

- Feedstock extraction
- Feedstock production
- Feedstock transport
- Fuel production
- Fuel distribution
- Fuel use.

For the replacement fuel for gasoline, the following detailed flow chart will be considered:

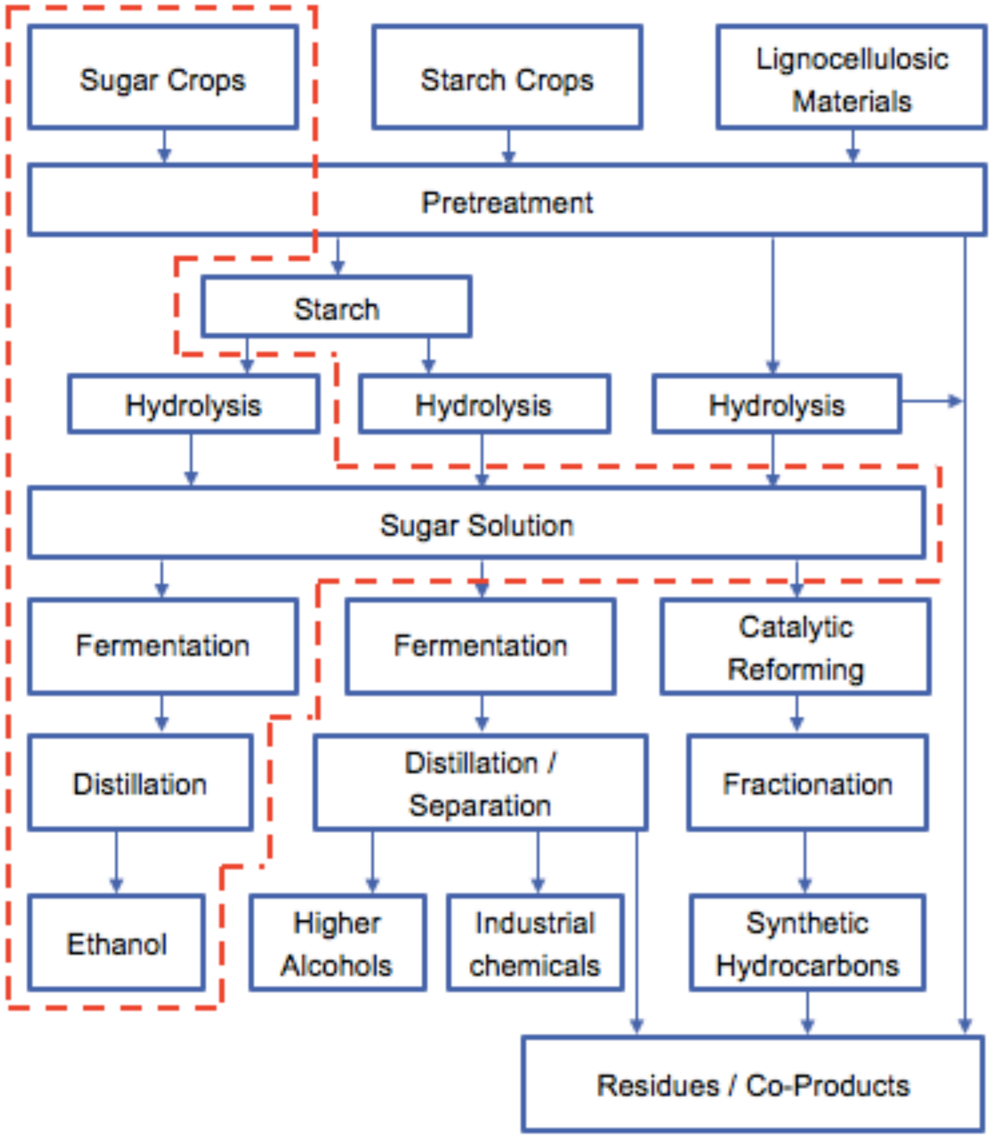

Figure 13. Detailed Life Cycle for Ethanol process, adapted from ETIP

For the replacement fuel for diesel, the following detailed flow chart will be considered:

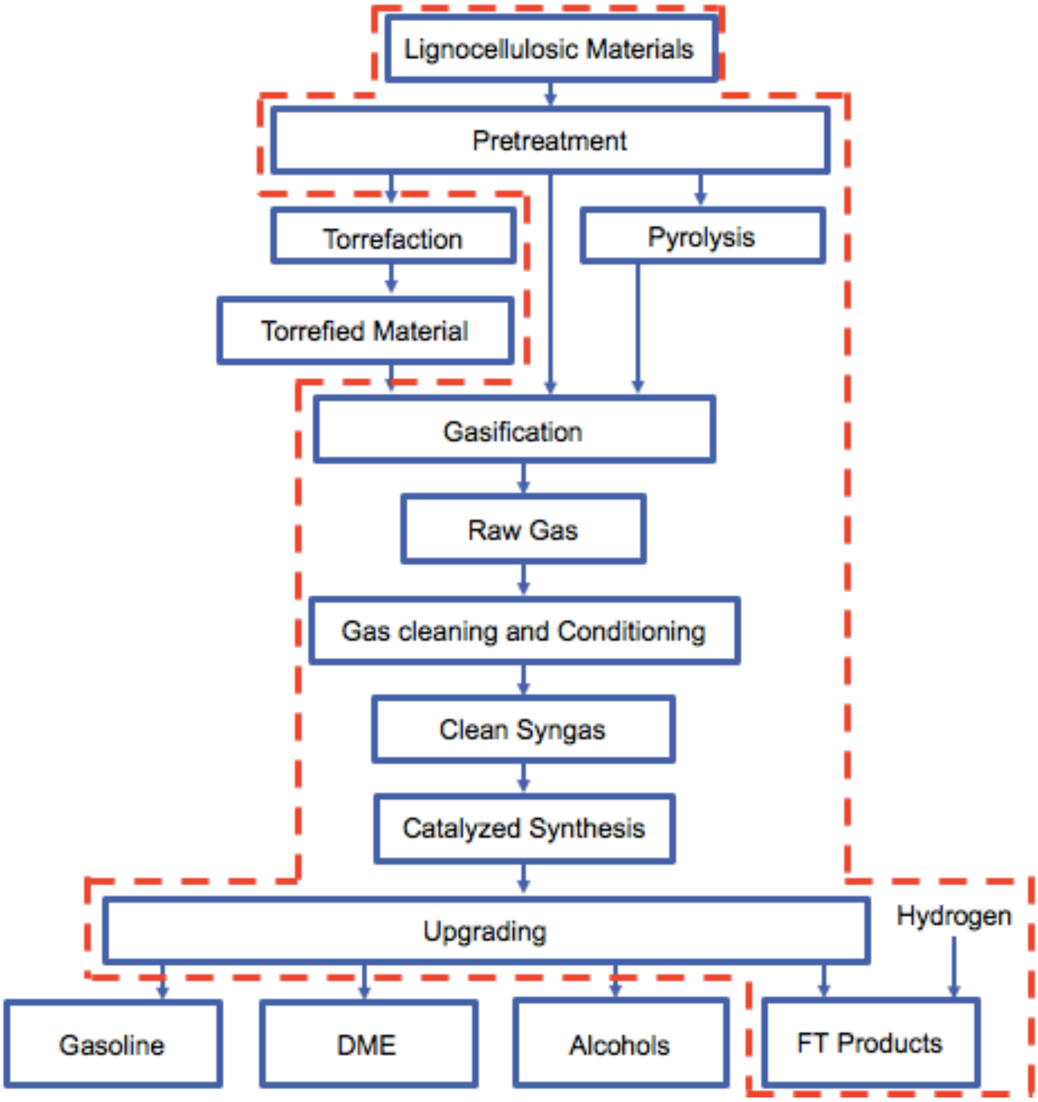

Figure 14. Detailed Life Cycle for BtL process, adapted from ETIP

2.3.3. Data Bases / Data Quality Requirements

In a first approach, the following Data Bases have been used to search for processes emissions and consumptions:

- Ecoinvent. www.ecoinvent.org
- GaBi Databases: www.gabi-software.com
- ProBas: www.probas.umweltbundesamt.de
- NREL: www.lcacommons.gov/nrel

Nevertheless, after a more detailed analysis and due to some advantages, this study is mainly focused on Ecoinvent 2.0 (Data V2.2, 2010).

2.3.4. Life Cycle Inventory

The Life Cycle Inventory (LCI) step is the most complicated and the one which require more time and effort. The aim is to collect all the information regarding consumption and emissions.

It was said that Ecoinvent 2.0 will be used to collect the required data and calculate the PCF.

This data base uses the following structure to estimate the consumption and emissions for the different processes:

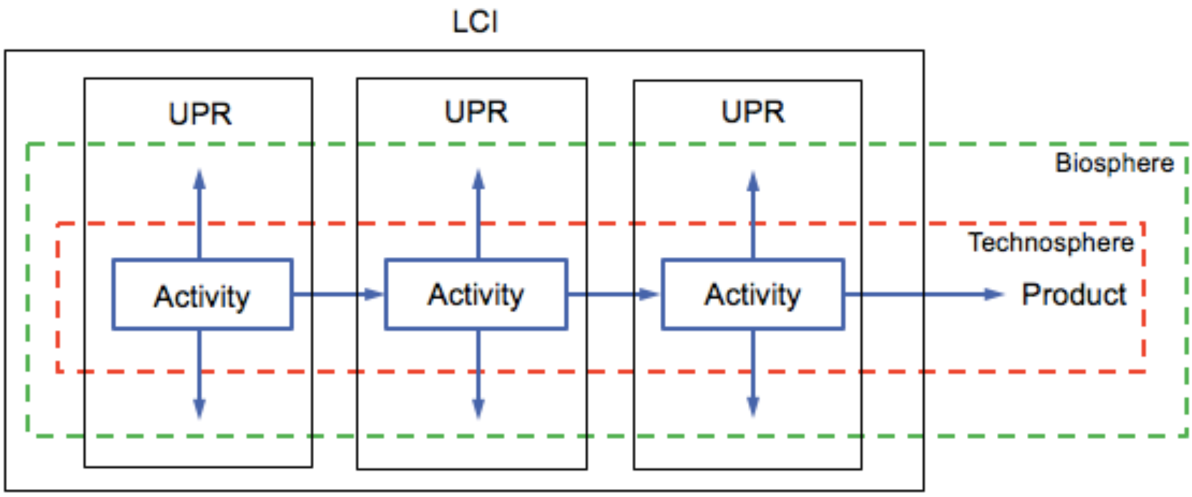

Figure 15. Ecoinvent Data Base, Flow Chart

In the cases where information or data are not available in the Ecoinvent data base, or in any other data base, values are estimated and calculated based on the literature, and it is clearly indicated in the study.

All the data collected from the production processes, as well as, the quantities required in each case and their impact, are indicated in the next Chapter 3, Life Cycle Inventory Assessment (LCIA), where all the tables with the different values are depicted.

3. Data collection and Assessment

One more time, it is pointed out that, since this study considerer VLC and FLC, two LCIAs are going to be performed considering both, vehicle and fuel cycle. The latter, will also be performed for two different fuels from 1st and 2nd Generation of biofuels, Ethanol and Fischer-Tropsch diesel.

3.1. Vehicle Life Cycle

3.1.1. Raw Material Extraction and Material Production

As a starting point, a generic vehicle glider is established, which is devoid of any specific ICEVs component. Then the powertrains are added (Hawkins et al., 2012). This information is summarized in Table 6 below. This one provides a comprised list of roughly 140 subcomponents of a vehicle. The advantage of this way of sorting would let later an easy comparison with other technologies with any other specific elements and components.

Category	Component	Data Sources
Glider/Common	Body and Doors	Burnham et al. (2006) Sullivan et. al (1998) USAMP (1999) Daimler AG (2008a)
	Brakes	Burnham et al. (2006) Tami (1991) Garg et. al (2000) Röder (2001)
	Chassis	Burnham et al. (2006) Schweimer and Levine (2000)
	Final Assembly	Schweimer and Levine (2000)
	Interior and Exterior	Burnham et al. (2006) IDIS 2 Consortium (2009)
	Tires and Wheels	Burnham et al. (2006) Schweimer and Levine (2000) IDIS 2 Consortium (2009) Nemry et. al (2008) NCDNR (2010)
Specific for ICEV	Engine	Burnham et al. (2006) Sullivan et. al (1998) USAMP (1999) Schweimer and Levine (2000)
	Fluids	Burnham et al. (2006) Sullivan et. al (1998) IDIS 2 Consortium (2009) Nemry et. al (2008)
	Other powertrain	Burnham et al. (2006) IDIS 2 Consortium (2009) Lloyd et. al (2005)

Transmission	Daimler AG (2008a) Schweimer and Levine (2000) Volkswagen AG (2008a, 2008b)
PbA batteries	Burnham et al. (2006) IDIS 2 Consortium (2009) Rantik (1999) Delucchi (2003)

Table 6: Vehicle Components, ICEVs, adapted from Hawkins et al., 2012

Despite being from 2000, according with LCA for the Golf A4 performed by VW, based on the parts list, shows that the 80 heaviest parts of the car contribute with a bit more than 50% of the vehicle weight. This correlation is assumed to keep in the vehicle of this study, Golf VI.

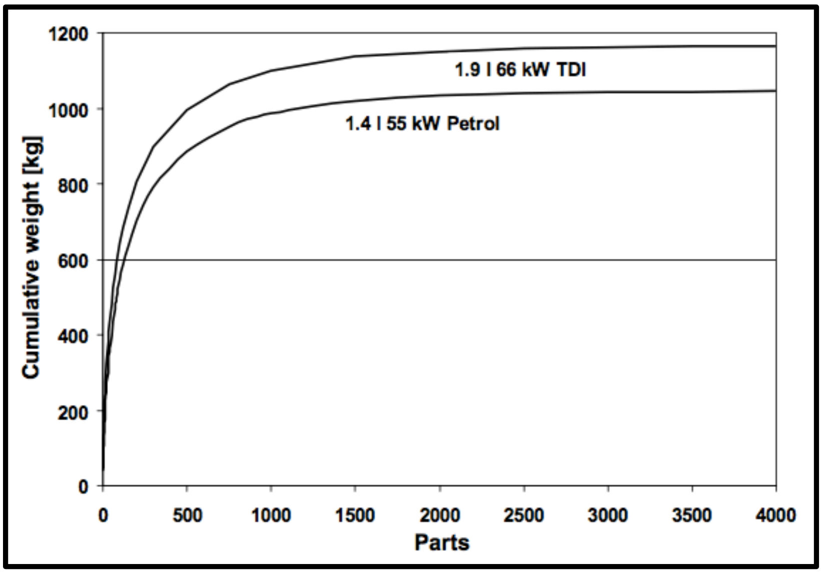

Figure 16. Vehicle weight distribution

Source: LCA of VW

Furthermore, from the same VW LCA study, it is showed that the required ore resources to the material production is the following:

Material	Amount	Unit	% on the Total
Bauxite (Al2O3H2O) (21,1% Al)	21,00	kg	0,42%
Chrome ore	5,50	kg	0,11%
Dolomite (CaMg(CO3)2)	6,30	kg	0,13%
Iron Ore (65%)	1622,00	kg	32,42%
Spar (Aluminium silicates)	6,00	kg	0,12%
Limestone (CaCO3)	730,00	kg	14,59%

Copper ore	84,00	kg	1,68%
Platinum group ore	1497,00	kg	29,92%
Sand	12,00	kg	0,24%
Rock salt (NaCl)	101,00	kg	2,02%
Titanium ore (0,6% Ti)	73,00	kg	1,46%
Zinc-lead ore (4,2% Zn, 5% Pb)	846,00	kg	16,91%
Resources to produce materials	**5003,80**	**kg**	**100%**

Table 7: Ore requirements for each vehicle

Source: LCA of VW

Then, based on the above information and in the distribution weights state by Qinyu Qiao et. al, which is likewise based and adopted in the Greenhouse Gases, Regulated Emissions and Energy Used in Transportation Model (GREET 2015), the emissions during material production are calculated.

It is important and necessary to clarify that GREET model, developed by Argonne National Laboratory, focused to examine material production, since the research showed that it accounts for the largest burden with regard to vehicle life cycle.

Following a bottom-up approach, i.e. disassembling a vehicle in its components until only raw materials remain, then the following structure and values for the raw materials extraction and production are set:

- Main Components: Powertrain system, transmission system, chassis (without battery) and body (incl. body in white, interior, exterior and glass)

Powertrain System								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Steel	131,22	kg	39,5%	9,5%	124,65	kg	2,09	260,81
Cast Iron	95,01	kg	28,6%	6,9%	90,25	kg	1,52	136,87
Cast Aluminum	56,81	kg	17,1%	4,1%	53,96	kg	12,04	649,79
Copper/Brass	9,63	kg	2,9%	0,7%	9,15	kg	1,85	16,96
Average Plastic (Polyethylene)	30,89	kg	9,3%	2,2%	29,35	kg	2,70	79,31
Rubber	8,64	kg	2,6%	0,6%	8,20	kg	2,66	21,79
Total	**332,2**	**kg**	**100%**		**315,56**	**kg**		**1165,53**

Table 8: Total kg CO_2-eq for the Powertrain Production

Transmission System								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Steel	24,42	kg	30,0%	1,8%	23,20	kg	2,09	48,54
Cast Iron	24,42	kg	30,0%	1,8%	23,20	kg	1,52	35,18
Wrought Aluminum	24,42	kg	30,0%	1,8%	23,20	kg	10,88	252,40
Average Plastic	4,07	kg	5,0%	0,3%	3,87	kg	2,70	10,45
Rubber	4,07	kg	5,0%	0,3%	3,87	kg	2,66	10,27
Total	**81,4**	**kg**	**100%**		**77,32**	**kg**		**356,83**

Table 9: Total kg CO_2-eq for the Transmission Production

Chassis (without Battery)								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Steel	259,87	kg	84,1%	18,8%	246,85	kg	2,09	516,51
Cast Iron	21,32	kg	6,9%	1,5%	20,25	kg	1,52	30,72
Cast Aluminum	3,09	kg	1,0%	0,2%	2,94	kg	12,04	35,35
Copper/Brass	3,71	kg	1,2%	0,3%	3,52	kg	1,85	6,53
Average Plastic	5,56	kg	1,8%	0,4%	5,28	kg	2,70	14,28
Rubber	13,60	kg	4,4%	1,0%	12,91	kg	2,66	34,30
Others (Chrome, Titanium)	1,85	kg	0,6%	0,1%	1,76	kg	35,05	61,73
Total	**309**	**kg**	**100%**		**293,52**	**kg**		**699,40**

Table 10: Total kg CO_2-eq for the Chassis Production

Body (include body in white, interior, exterior and glass)								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Steel	389,38	kg	68,3%	28,1%	369,87	kg	2,09	773,92
Wrought Aluminum	3,99	kg	0,7%	0,3%	3,79	kg	10,88	41,25
Copper/Brass	10,83	kg	1,9%	0,8%	10,29	kg	1,85	19,07
Glass (Silica Sand)	37,06	kg	6,5%	2,7%	35,20	kg	0,02	0,74
Average Plastic	103,19	kg	18,1%	7,5%	98,02	kg	2,70	264,89
Rubber	2,85	kg	0,5%	0,2%	2,71	kg	2,66	7,19

Others:	22,80	kg	4,0%	1,6%	20,58	kg	-	-
			According VW LCA: Insulation		16,43	kg	4,88	80,19
			According VW LCA: Paint		4,15	kg	2,87	11,90
Total	**570,1**	**kg**	**100%**		**561,04**	**kg**		**1199,14**

Table 11: Total kg CO_2-eq for the Body Production

Thus, it is estimated that for the materials of the main components, which represent **1247,45 kg**, the total kg CO_2-eq is equal to **3421,23**.

- Additional Components: Battery, tires and fluids

Lead-acid battery								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Polypropylene	0,99	kg	6,1%	0,1%	0,94	kg	1,98	1,87
Lead	11,25	kg	69,0%	0,8%	10,68	kg	2,12	22,68
Sulfuric Acid	1,29	kg	7,9%	0,1%	1,22	kg	0,78	0,96
Fiber Glass	0,34	kg	2,1%	0,0%	0,33	kg	4,88	1,59
Water	2,30	kg	14,1%	0,2%	2,18	kg	-	N/A
Others	0,13	kg	0,8%	0,0%	0,12	kg	-	N/A
Total	**16,3**	**kg**	**100%**		**15,48**	**kg**		**27,09**

Table 12: Total kg CO_2-eq for the Battery Production

Tires								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Rubber	30,35	kg	66,7%	2,2%	28,83	kg	2,66	76,55
Steel	15,15	kg	33,3%	1,1%	14,39	kg	2,09	30,11
Total	**45,5**	**kg**	**100%**		**43,22**	**kg**		**106,67**

Table 13: Total kg CO_2-eq for the Tires Production

Fluids								
Material	Amount [Class B]	Unit	% in Component	% in Total	Reference Golf	Unit	kg CO_2-eq.	Total kg CO_2-eq
Engine Oil	3,9	kg	13,5%	0,3%	3,70	kg	1,05	3,89
Brake Oil	0,9	kg	3,1%	0,1%	0,85	kg	1,05	0,90
Transmission fluid	10,9	kg	37,8%	0,8%	10,35	kg	1,05	10,88
Powertrain Coolant (Ethyl. glycol)	10,4	kg	36,1%	0,8%	9,88	kg	1,57	15,54
Windshield fluid (Alkylbenzene)	2,7	kg	9,4%	0,2%	2,56	kg	1,63	4,18
Total	**28,8**	**kg**	**100%**		**27,36**	**kg**		**35,39**

Table 14: Total kg CO_2-eq for the Fluids Production

Thus, it is estimated that for the materials of the additional components, which represent **86,06 kg**, the total kg CO_2-eq is equal to **169,15**.

In summary, during the stage of raw material extraction and material production a total amount of **3590,40 kg CO_2-eq** is emitted.

It is important to mention that in this part, the refrigerant gas R134a ($C_2H_2F_4$) for air conditioning was not included. According with Ecoinvent, the production of this gas would represent a burden of 103,31 kgCO_2-eq/kg and, according with VW LCA study, an amount of 1,5 kg is needed for the vehicle. Thus, it would mean a total amount of **155 kg CO_2-equiv** to include in the inventory, given a new total of **3745 kg CO_2-eq** for material extraction and material production.

3.1.2. Material Processing and Assembly

At this stage, the following analysis is performed with the help of the model Manufacturing and Vehicle Assembly (VMA), performed by Argonne National Laboratory (Energy Consumption and Carbon Emission Analysis of Vehicle and Components Manufacturing), which is likewise developed comparing results and conclusions with USAMP (Life Cycle Inventory of a Generic Vehicle).

The model developed by Argonne National Laboratory with respect to the assembly stage, uses data from a survey of assembly plants in United States which contained welding, painting and assembly operations. This survey collected data during three years from 35 plants of GM, Ford, Honda, Toyota and Subaru, and many factors such as utilization factor, capacity and climate were considered.

Said that, the results for this phase are depicted below:

Transformation	Material Group	Process - Surrogate	% Reference	Ref. Golf [kg]	Unit [kg]	kg CO2-eq.	Total kg CO2-eq
Metal Stamping	Steel	Steel stamping	37,7%	577,56	495,38	1,046	518,12
	Aluminium	Steel stamping	0,2%	3,06	2,63	0,452	1,19
Castings	Iron	Iron	8,6%	131,75	113,00	0,714	80,73
	Aluminium	Aluminium	4,7%	72,00	61,76	0,919	56,76
	Brass	Brass	0,6%	9,19	7,88	0,063	0,50
	Lead	Lead	0,8%	12,26	10,51	2,123	22,31
Forgings	Iron and Steel	Iron and Steel	3,8%	58,22	49,93	0,280	13,97
Extrusions	Aluminium	Aluminium	1,4%	21,45	18,40	0,919	16,91
Machining	Steel	Metals	14,0%	214,48	183,96	1,490	274,18
Wire Forming	Copper	Copper Wire	1,2%	18,38	15,77	0,482	7,60
Glass Pane Forming	Glass	Float Glass	2,8%	42,90	36,79	0,980	36,05
Blow Molding	Polymers	HPDE Bottles	0,2%	3,06	2,63	1,089	2,86
Compression Molding	Plastics and Rubber	Comp.-Molding Rubber	7,4%	113,37	97,24	0,694	67,46
Thermoset Molding (foaming, expanding)	Polymer Resins	PU Foams	2,6%	39,83	34,16	8,805	300,82
Extrusions	Plastics	HDPE Pipe	1,6%	24,51	21,02	0,378	7,94
Calendering	Plastics	PVC	0,2%	3,06	2,63	0,782	2,06
Injection Molding	Plastics and Rubber	PP Parts	4,7%	72,00	61,76	1,334	82,40
		Total Vehicle	**92,5%**	**1532,0**	**1314,0**		**1491,85**

Table 15: Total kg CO_2-eq for the Material Processing and Assembly

The value of 92,5% indicated above is due to this percentage is operated by one of the transformation process indicated before in Table 15. It can be observed that the analysis is based on a vehicle of 1532 kg (generic vehicle), while for raw material extraction and material production, the reference vehicle has a weight of 1383,3 kg.

In order to complete the calculation of the emissions in this phase, it is necessary to estimate the vehicle painting and the overhead burdens, which are represented by HVAC and lighting, heating, material handling, welding and compressed air.

Since this information cannot easily be calculated from Ecoinvent, it is also based on the model Manufacturing and Vehicle Assembly (VMA). Then, the calculation and values for these burdens are the following:

	Generic Vehicle: 1532 kg		Golf VI: 1314 kg	
Components of VMA	**Energy [MJ]**	**CO_2 [kg]**	**Energy [MJ]**	**CO_2 [kg]**
Vehicle Painting	4167,00	268,00	3574,05	229,86
HVAC and Lighting	3335,00	225,00	2860,44	192,98
Heating	3110,00	195,00	2667,45	167,25
Material Handling	690,00	46,00	591,81	39,45
Welding	920,00	62,00	789,09	53,18
Compressed Air	1380,00	93,00	1183,63	79,77
Total:	**13602,00**	**889,00**	**11666,47**	**762,50**

Table 16: Total kg CO_2-eq for the Material Processing and Assembly. Ancillary

In summary, during the stage of material processing and assembly a total amount of **2254,34 kg CO_2-eq** is emitted.

Regarding the Table 15, it was found that the value of **1491,85 kg CO_2-eq** is actually higher than the one indicated by the VMA for the processes of Material Transformation and Machining. The difference could lie in the average value adopted by the VMA model, since the variance of the studies included in this model is high.

3.1.3. Vehicle Distribution

In order to perform this analysis, the distances between the plant of VW in Wolfsburg and the capital city of each Bundesland are estimated considering both transport options, train and truck. The latter is just for information, since it is known that, at least in Germany, the transport of vehicles to the different points is by train. However, in other countries, the distribution is wholly carried out by train.

In the scenario to adopt for the distribution, an amount of 25 km by truck is added to the distances by train, in order to include a minimum possible distance that each vehicle travels from the factory and to the dealer.

According with Ecoinvent 2.0, the transport by train entails a burden equal to 29,18 g CO_2-eq/tkm, and by truck (Lorry >32t, EURO 5), it is equal to 107,04 gCO_2-eq/tkm.

The results for the different distributions paths are depicted below in Table 17:

Distance from Wolfsburg to:	Train			Truck		
	Unit [km]	kg CO2-eq/tkm	Total kg CO2-eq/t	Unit [km]	kg CO2-eq/tkm	Total kg CO2-eq/t
Kiel (Schleswig-Holstein)	352	0,03	**10,28**	316	0,107	**33,81**
Hamburg	254	0,03	**7,42**	221	0,107	**23,65**
Schwerin (Mecklenburg-Vorpommern)	386	0,03	**11,27**	172	0,107	**18,40**
Bremen	199	0,03	**5,81**	197	0,107	**21,08**
Hannover (Niedersachsen)	76	0,03	**2,22**	89	0,107	**9,52**
Postdam (Brandenburg)	211	0,03	**6,16**	198	0,107	**21,19**
Berlin	187	0,03	**5,46**	233	0,107	**24,93**
Magdeburg (Sachsen-Anhalt)	86	0,03	**2,51**	89	0,107	**9,52**
Düsseldorf (Nordrhein-Westfalen)	362	0,03	**10,57**	361	0,107	**38,63**
Wiesbaden (Hessen)	425	0,03	**12,41**	389	0,107	**41,62**
Erfurt (Thüringen)	492	0,03	**14,37**	255	0,107	**27,29**
Dresden (Sachsen)	378	0,03	**11,04**	309	0,107	**33,06**
Mainz (Rheinland-Pfalz)	424	0,03	**12,38**	394	0,107	**42,16**
Saarbrücken (Saarland)	623	0,03	**18,19**	543	0,107	**58,10**
Stuttgart (Baden-Württenberg)	557	0,03	**16,26**	527	0,107	**56,39**
München (Bayern)	714	0,03	**20,85**	601	0,107	**64,31**

Table 17: Total kg CO_2-eq/t for the different distribution paths and transport options

Source for the distances: https://www.luftlinie.org und https://www.entfernung.org

Distance from Wolfsburg to:	Emissions according to proposed scenario			
	Train Unit [km]	Truck Unit [km]	kg CO2-eq/t	x Golf
Kiel (Schleswig-Holstein)	352	25,00	12,95	17,02
Hamburg	254	25,00	10,09	13,26
Schwerin (Mecklenburg-Vorpommern)	386	25,00	13,95	18,33
Bremen	199	25,00	8,49	11,15
Hannover (Niedersachsen)	76	25,00	4,89	6,43
Postdam (Brandenburg)	211	25,00	8,84	11,61
Berlin	187	25,00	8,14	10,69
Magdeburg (Sachsen-Anhalt)	86	25,00	5,19	6,81

Düsseldorf (Nordrhein-Westfalen)	362	25,00	13,25	17,40
Wiesbaden (Hessen)	425	25,00	15,09	19,82
Erfurt (Thüringen)	492	25,00	17,04	22,39
Dresden (Sachsen)	378	25,00	13,71	18,02
Mainz (Rheinland-Pfalz)	424	25,00	15,06	19,78
Saarbrücken (Saarland)	623	25,00	20,87	27,42
Stuttgart (Baden-Württenberg)	557	25,00	18,94	24,89
München (Bayern)	714	25,00	23,52	30,91

Table 18: Total kg CO_2-eq for the Vehicle Distribution, according to the proposed scenario

3.1.4. Vehicle Maintenance and Washing

This phase, despite to be considered in many of the literatures, is not clearly explained regarding scope and assumptions.

Moreover, and although at a first sight, emissions could be supposed as negligible, washing is neither included nor explained in the literature.

Adopting a conservative position in comparison with the literature, and base on VW Golf maintenance plan, the emissions calculated at this stage are the following:

Maintenance	Parcial kg CO2-eq	Unit	Replacement [Qty.]	Total kg CO2-eq
Lead-acid battery	27,09	kg	1	27,09
Tires	85,90	kg	2	171,80
Engine Oil	3,89	kg	10	38,92
Brake Oil	0,90	kg	3	2,69
Transmission fluid	10,88	kg	1	10,88
Powertrain Coolant	15,54	kg	1	15,54
Total:	**144,20**	**kg**		**266,92**

Table 19: Total kg CO_2-eq for the Vehicle Maintenance

Washing	Parcial kg CO2-eq	Unit	Estimated [Qty.]	Total kg CO2-eq
Washing agents / tensides *water consumption is estimated	1,96	kg	60	11,78
			Total:	**11,78**

Table 20: Total kg CO_2-eq for the Washing

The estimation of the quantity of 60 units is based on a washing service every 2 months (8 weeks) during a life time of 10 years. Then, the total amount of kg CO_2-eq is calculated based on a used of 0,1 kg of washing agent every time.

In summary, during the stage of maintenance, including washing, a total amount of **278,70 kg CO_2-eq** is released.

3.1.5. Use Phase

The vehicle use, or operation, is going to be accounted in the FLC, which include among others, feedstock extraction, fuel production and distribution and the mentioned use phase, as depicted in Figure 8.

Nevertheless, at this point, it is important to state that, according with manufacturer, consumption and emissions during the operation of the vehicle are the following:

	Characteristics	Golf VI 1.6 TDI	Golf VI 1.2 TSI	Units
1.	Fuel	Diesel	Petrol	-
2.	Fuel Consumption [urban, highway, combined]	5,6 / 3,9 / 4,5	7,1 / 4,9 / 5,7	l/100km
3.	Emission Standard	Euro 5	Euro 5	-
4.	Carbon Dioxide emissions, combined	119	134	g/km
5.	CO	0,1825	0,6569	g/km
6.	HC	-	0,0468	g/km
7.	NOx	0,1474	0,0334	g/km
8.	NOx + HC	0,1743	-	g/km
9.	Particulate Emissions	0,00063	0,00025	g/km

* The values indicated are based on NEDC

** Golf Generation VII shows similar values

Table 21: Fuel Consumption and Emissions (Golf VI)

Source: Volkswagen AG, Wolfsburg, 2010

Additionally, it is important to emphasize that how much fuel a vehicle consume, and then, how much pollutants are emitted, depends on the driving style. The most used driving cycles, according to which fuel consumption and exhaust emissions are to be measured, are:

- New European Driving Cycle (NEDC) in Europe
- US City and Highway Driving Cycle in the United States

Some other institutions, as for example, the Germany automobile association (Allgemeine Deutsche Automobil Club; ADAC) considers that these driving cycles are not representative, and they use their own driving cycles to determine consumption.

According with VW LCA, for the Golf IV (2000), the most important driving-style-related, and their estimated fuel consumption, are the following:

	55 kW Otto	66 kW Diesel
US City	6,0 l/100 km	5,0 l/100 km
NEDC	6,5 l/100 km	4,9 l/100 km
ADAC	8,1 l/100 km	5,9 l/100 km

Table 22: Consumption according with driving style/profile

Although these values have already some years and the fuel consumption has been improved since then, it is clear that the key difference between the profiles lies in how much aggressive they are.

Additionally, it is also important to indicate, and as it is pointed out in many studies, that these profiles do not represent actually the real word conditions. However, those real conditions are very difficult to represent and they are beyond the aim of this study.

3.1.6. End of Life and Recycling

Despite this phase is neither clearly described in the literature nor recycling is calculated or evaluated, this is an important point to evaluate in order to have a defined dimension of its impact and value. Moreover, it was defined as an aim of this study, to evaluate the life cycle in a cradle-to-cradle system.

According with VW LCA (2000) one important advantage of conventional vehicle is its high rate of recycling. However, not all materials are available for recycling in the same factor or percentage. For example, while car manufacturers mainly use steel form fresh ore because the recycled iron is used in other steel industries, secondary aluminum reaches up to 85%.

Two different scenarios were thought for the evaluation of this point. In the first one, it was considered to evaluate the diminution in the required minerals amount for the production of a vehicle according with the availability to recycle different materials. In Point 3.1.1 (Table 7), the required amount of minerals by vehicle were indicated, according with data from VW AG.

The second one, developed below, was found to be more feasible and with a lower uncertainty. Thus, working with data from Ecoinvent 2.0 within category “waste management/disposal”, and with different recovery factors or percentages the following values are calculated:

Material	Recovery %	Disposal kg CO2-eq	Disposal - Recycling Total kg CO2-eq without Recycling	Disposal - Recycling Total kg CO2-eq with Recycling
Steel	0,6	0,045	35,11	14,04
Iron	0,6	0,004	0,52	0,21
Aluminium	0,85	0,082	6,87	1,03
Copper	0,6	0,074	1,71	0,68
Glass	0	0,025	0,87	0,87
Plastic	0,7	2,033	277,53	83,26
Rubber	0,7	3,139	177,41	53,22
Battery (Polypropylene + Lead)	0	-	9,40	9,40
Paint	0	2,380	9,88	9,88
Lubricants/Oils	0	2,85	42,54	42,54
Coolant	0	2,76	27,31	27,31
		Total:	**589,15**	**242,45**
		Emissions saved / avoided by Recycling:	**346,70** kg CO_2-eq	

Table 23: Emissions in kg CO_2-eq. for End of Life, considering savings by recycling

As indicated above, **346,70 kg CO_2-eq** are saved to release to the environment, while the amount for the final disposal, represent **242,45 kg CO_2-eq**.

The materials listed represent 98,5% of the total weight of all materials.

In cases were no recycling factors were available or were unknown a conservative approach was adopted. Despite this phase could have a high uncertainty, it could also be easily corrected when further factors or information are available.

It is important to clarify that it was not evaluated if recycled materials have any impact in the final mechanical properties of the new materials. Additionally, the recycling technology was not available or the information was roughly general. Nevertheless, these two points are beyond the target this study.

3.2. Fuel Life Cycle. 1st Option: Fischer-Tropsch Diesel Fuel

As it was pointed out in Figure 8, the analysis of this part includes two parts: WtT (Weel To Tank) and TtW (Tank to Wheel). The first refers to the Fuel Cycle production and the second one to the Fuel Use/Consumption Cycle.

From Mobolaji B. Shempe et al. (2016), biofuels are projected to contribute with 27% of global transport fuel supply by 2050, with the aim of cutting CO_2 emissions by 2.1 Gt CO_2-eq per annum.

3.2.1. Why choosing a 2nd Generation Fuel

Also from Mobolaji B. Shempe et al. (2016), as a commitment to cut global, GHG emissions, the EU decided to set a goal of 10% energy used in the transport sector from renewable fuels by 2020. However, EU also set a limit of 7% on biofuels from food crop sources with the objective to enhance the production of advance biofuels from non-food sources, i.e. 2nd generation fuels.

According with scientific papers and literature, it can be said that nowadays synthetic XtL (X to Liquid) fuels are state of the art for coal and natural gas, but for biomass it is still in development. However, comparing literature from 2010 and 2016, it is seen that very important milestones have been reached. This is in line with exposed by EU biofuels advisory indicated below:

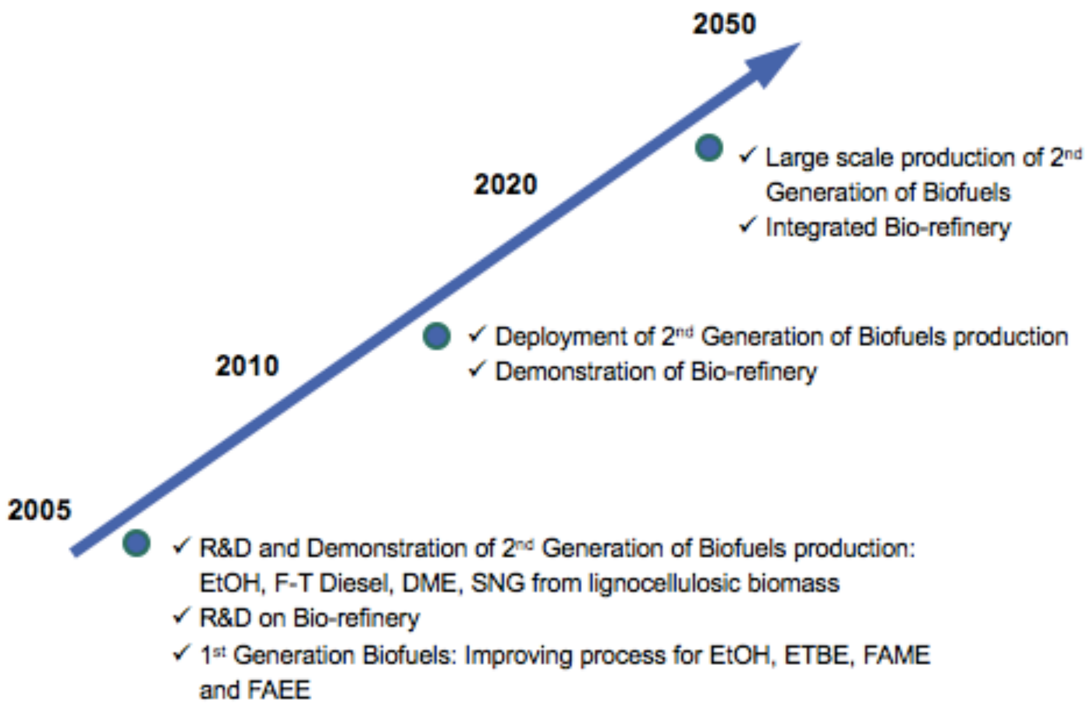

Figure 17. Roadmap of EU biofuels

Source: Report of the Biofuels Research Advisory Council (2006)

Several authors have published works relating to the reductions of GHG emissions, which impacts reduction, for example, go from 53% to 112%, depending on system boundary and scenarios. However, the information or sourcing available to perform the quantification of GHG emissions is limited.

3.2.2. Fischer-Tropsch Process

Before starting with the calculations of the CO_2-equiv. emissions, it is important to offer a brief explanation of Fischer-Tropsch process.

The Fischer-Tropsch (FT) synthesis was discovered in the 1920s by the German chemists F. Fischer and H. Tropsch. It was briefly used by Germany before and during World War II to produce fuels, and had had different levels of interest worldwide since that time.

The resources, i.e. raw materials, which can be use in this process are Coal, Natural Gas, including stranded Natural Gas, and Biomass. The latter is the one evaluated in this study, since a renewable fuel is the focus of the current study.

The products derived from this process are very varied and include transportation fuels, such as diesel and gasoline, and chemicals, such as methanol and dimethylether (DME).

The production F-T process for BtL (Biomass to Liquid) starts with the grinding and drying of biomass, since the objective is to get pellets. Then, the pellets are divided into a hot gas and a solid fraction (charcoal) in a low temperature gasification process and transformed into a synthetic gas in a subsequent step.

Following with a purification process, the gas is liquefied in a F-T reaction. In this process a catalyst is used, which normally is a cobalt or iron catalyst. The resulting liquid can be "hydro-treated" in order to increase stability and to produce a fuel more suitable for the engines.

As a summarized flow chart for this process, the following chart is depicted:

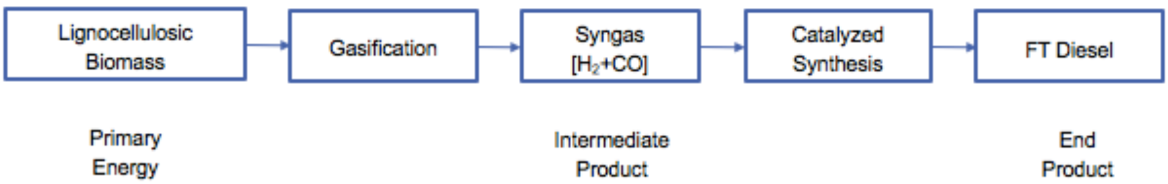

Figure 18. Conversion process for lignocellulosic biomass, adapted from A. Tsokalis et al., 2011

Additionally, according with, as example, bioliq® process (Biomass to Liquid Karlsruhe), a Fast Pyrolysis is performed before Gasification with the objective to produce a slurry, so-called Biosyncrude, which lead to energy densification. The advantages of this process are:

- Liquids are better for transport, storage and feeding
- Energy Production can be separated from biomass production
- Increase of Heating Value
- Use of both plants and residues.

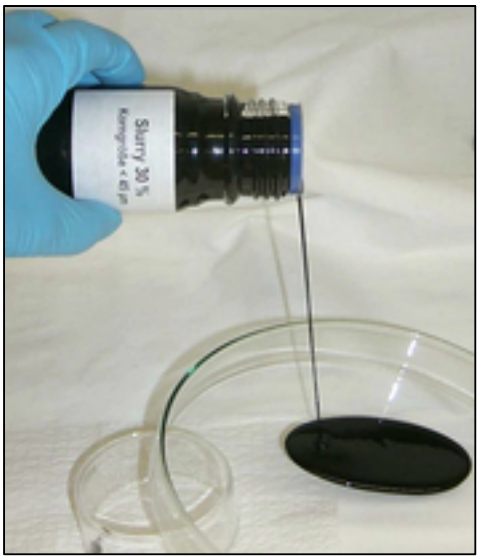

Figure 19. Biosyncrude (slurry)

Source: Institut für Katalyseforschung und -technologie (IKFT)

Since for the production of FT Diesel specific processes are applied and there is no enough information available on the data bases, and after reading a vast number of publications, the calculation of emissions relating FLC are based on the following works, which were found to be the most helpful ones:

- Comprehensive techno-economic assessment of DME Synthesis and Fischer-Tropsch synthesis as alternative process steps within BtL production
- Fischer-Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis
- Comparative Evaluation of GHG emissions from the use of Miscanthus for bio-hydrocarbon via fast pyrolysis and bio-oil upgrading
- Challenges for suitable biomass utilization. Ecological evaluation of selected 1st nd 2nd Generation Biofuels (Chilean-German Biociclo Workshop)
- Combustion characteristics and emissions of Fischer-Tropsch diesel fuels in IC engines.

It is important to state the characteristics parameters of FT diesel. These, together with diesel fossil, as reference, are indicated below:

	Density [kg/l]	HV [MJ/kg]	HV [MJ/l]
FT Diesel	0,76	43,9	33,36
Diesel (Fossil)	0,83	43,1	35,77

Table 24: Characteristics of Fischer-Tropsch and Fossil diesel

The biomass to be considered in this study as part of the Fischer-Tropsch process are Short Wood Rotation (SWR) and Residual Forest Wood (RFW), although it is important to remark that different kinds of biomass are suitable for this process. However, the emissions would be different, since some steps from the production process, such feedstock production and extraction, lead to different emissions.

3.2.3. Feedstock Production and Extraction

Based on the study of Ecological Evaluation of Selected 1st and 2nd Generation Biofuels, Chilean-German Biociclo Workshop, the emissions relating this part are estimated as follow:

Biomass	Emissions [kg/tdry biomass]			kg CO2-eq./kg Fuel
	CO_2 fossil	N_2O	NOx	
Short Rotation Wood	88	0,003	0,8	0,83
Residual Forest Wood	23	0,001	0,21	0,22

Table 25: Emissions in kg CO_2-eq. for biomass provision

3.2.4. Feedstock Transport

As considered in many studies, it is assumed that the transport of biomass is performed by truck, Lorry 16-32t EURO 5, for a distance of 100 km to the process plants.

However, at this point, it is important to emphasize that the energy density of the biomass plays an important role for the transportation. As it was pointed out before, for the Fischer-Tropsch production, a fast pyrolysis is performed. Through this process, a slurry (biosyncrude) is produced which increase the heating value between 10 to 15 times. The heating value of the slurry and its density are about 17.6 MJ/kg and 1300 kg/m^3, respectively.

Another advantage is that this lets the integration of different types of biomass in a flow gasifier, which is probably to take place as input in biomass-to-liquid (BtL) fuel production.

Moreover, and since complex technology is applied in the gasification and synthesis plant, economies of scale can be achieved in commercial scale plants. Thus, biomass from large distances has to be transported to the centralized facility, which is only economical if the biomass energy density based on volume can be significantly increased.

The emissions during biomass transportation are indicated below:

Biomass	wt [%]	HHV [MJ/kg_{dry}]	HHV [MJ/kg_{dry}]	kg Fuel / kg_{dry}	kg CO2-eq./kg Fuel	Density Fuel kg/liter	kg CO2-eq./liter Fuel

Short Rotation Wood	50	18,5	43,9	0,145	0,231	0,76	0,176
Residual Forest Wood	50	18,4	43,9	0,145	0,231	0,76	0,176

Table 26: Emissions in kg CO_2-eq. for biomass transportation

3.2.5. Fuel Production

The process steps of gas conditioning, Fischer-Tropsch synthesis and reconditioning of Fischer-Tropsch, were studied and estimated by Leible et al. (2007), which likewise used basis data.

However, after reading and analysis of several studies relating biofuels, and in particular Fischer-Tropsch Diesel, it is seen that emissions from the different process, such as pyrolysis, synthesis, etc., are not available or were just weakly studied. Therefore, some ancillary process emissions cannot be estimated, but there are considered to be negligible.

Most of the authors and studies conclude that Fischer-Tropsch process lead a to positive amount of electricity production, which can be supplied to the electricity market, and also lead to a heat net balance of zero, i.e. production is equal to demand.

In summary, regarding the fuel production and according again with the study of Challenges for Suitable Biomass Utilization (Chilean-German Biociclo Workshop), we get:

Process	Electricity [kWh/tdry biomass]			Heat [MJ/tdry biomass]		
	Production	Demand	Balance	Production	Demand	Balance
FT fuel from wood	484	457	27	Production = Demand		0

Table 27: Energy balance for Fischer-Tropsch diesel production

3.2.6. Fuel Distribution

For the fuel distribution, a longer distance is considered, since the fuel distribution is assumed to be more complicated than biomass distribution. Thus, a distance of 250 km is adopted as the one for the distribution from the process plants to the tank stations. It is also assumed that it is carried out by truck.

Based on this concept, the emissions during fuel distribution are indicated below:

Biomass	kg CO2-eq. / tFuel	kg CO2-eq. / kg_{Fuel}	Density Fuel kg/l	kg CO2-eq. / l_{Fuel}
Short Rotation Wood	41,950	0,04195	0,760	0,0319

Residual Forest Wood	41,950	0,04195	0,760	0,0319

Table 28: Emissions in kg CO_2-eq. for fuel distribution

3.2.7. Allocation

According with ISO series, e.g. ISO 14040, consideration should be given to the need for allocation procedures when dealing with systems involving multiple products and recycling systems. Moreover, and according with ISO 14044, there are different allocation procedures such as physical properties or economic value.

Since the synthesis can lead to the production of different products and a surplus of electricity production during Fischer-Tropsch process, as it was pointed out before, it is important to talk about allocation and indicate the corresponding assumptions.

The synthesis process is open for different products. However, depending on the desired product, the synthesis requires different pressures, starting with 20-40 bar for FT fuels and reaching 80 bar for the production of Methanol.

Additionally, and according with Gill et al. (2011), Fischer-Tropsch synthesis is classified in two categories: HTFT (High Temperature Fischer-Tropsch) and LTFT (Lower Temperature Fischer-Tropsch). The first one ranges between 310-340ºC and the second one between 210-260ºC. The Fischer-Tropsch composition and yield are mainly determined by the catalyst type (iron and cobalt based) and the reactions conditions. Thus, an important difference of HTFT and LTFT is the final composition. Whereas that HTFT leads to mainly aromatics and olefins, LTFT is mainly composed of paraffin. So, HTFT is more suitable for gasoline fuel and LTFT for diesel fuel. It is important to emphasized that, despite density of Fischer-Tropsch diesel is a bit lower than diesel standards, good ignitability is a key feature for a diesel fuel, and it is given by a high cetane number.

Said that, in this study, it is going to be assumed that only Fischer-Tropsch diesel is produced, although it is not totally truth and others products are gotten at the same time.

Regarding the electricity production, and since it could be considered as a credit (with negative value) during the sum up of the different emissions, it will not be included in this study. However, as information, it is important to indicate that gas combustion in the gas turbine would result in 1,55 kg NOx emissions per ton of dry wood input.

3.2.8. Fuel Use

According with Gill et al. (2011), and the publications reviewed by the authors, some literature reports an increase in fuel consumptions as well as a decrease in rated power. However, it also pointed out by Gill et al. that the majority of the studies showed that Fischer-Tropsch diesel do not cause any loss of power whilst significant improvements in all regulated emissions are appreciated. It is beyond the scope of this work to analyze any variations. However, it is going to be stated that combustion parameters as well as load engine play an important role in emissions, consumption, etc., and several strategies in actual engines can be applied.

	Increase	Same	Decrease
Effective Power	-	75	25
Brake specific fuel consumption	17	-	83
Thermal efficiency	58	33	8
NOx emissions	-	21	79
PM emissions	5	16	79
THC emissions	-	-	100
CO emissions	-	6	94
CO_2 emissions	11	22	67

Table 29: Publications which reported increases, similarities or decreases in engine performance and emissions; Fischer-Tropsch diesel vs conventional diesel (Gill et al., 2011)

On the other hand, and based on PROBAS (Prozessorientierte Baisdaten für Umweltmanagement-Instrumente, 2009), the emissions from the Fischer-Tropsch combustion, are the following:

	Emissions	Conventional Diesel	Fischer-Tropsch Fuel
1.	CH_4 fossil	1,88E-05	1,92E-05
2.	CO fossil	4,89E-03	4,99E-03
3.	CO_2 fossil	3,20	-
4.	N_2O	1,57E-04	1,60E-04
5.	NH_3	1,96E-05	2,00E-05
6.	NMVOC	7,64E-04	7,80E-04
7.	NOx	4,90E-03	5,01E-03
8.	PAH	8,29E-09	8,46E-09
9.	SO_2	3,31E-03	-
10.	Particulates	1,73E-04	1,77E-04

Table 30: Emissions from Fischer-Tropsch combustion in kg/kg fuel

Source: PROBAS, from Challenges for suitable biomass utilization (Chilean-German Biociclo Workshop)

In Table 21, in Point 3.1.5 Use Phase, fuel consumption and emissions of Golf VI (Diesel), based on study of VW (2010), were indicated. Emissions indicated in that table and the ones showed above were compared in order to verify the values. As example, CO_2 emissions from diesel fuel combustion yield to a value of 3,185 kg CO_2/liter diesel vs 3,2 kg CO_2/liter diesel (difference of 0,47%). It lets us consider that emissions are in line one each other.

Considering the GWP equivalence factors, and that CH4, N_2O and NOx contribute to the Product Carbon Footprint (Climate Change category), the following values are gotten for the use phase:

Fischer-Tropsch Diesel	
Emissions in kg CO2-Eq./kg Fuel	0,250
Emissions in kg CO2-Eq./l Fuel	0,190

Table 31: Emissions of Fischer-Tropsch combustion in kg CO_2-eq. during use phase

3.3. Fuel Life Cycle. 2nd Option: Ethanol

3.3.1. Why choosing a 1st Generation Fuel

Despite it is always indicated that 1st generation biofuels lead to the discussion of either biofuels or food, bioethanol (and biodiesel) represents currently the most important production of biofuels. Moreover, as indicated in Figure 18, the production of this 1st generation biofuels are state of art.

Ethanol can be added in different percentages to fossil fuels, going from 5% up to 100%. Even though in the last option of 100% some changes are required in the fuel system of the vehicle, they do not represent important changes in the ICV itself and these changes can be implemented easily. Nevertheless, these changes are going to be considered negligible regarding the emissions during VLC.

As a last point, and although it is not developed in this study, it is important to point out that bioethanol can be produced form lignocellulosic biomass (2nd generation biofuels), such as agricultural residues, which is an important choice to expand the ethanol production.

3.3.2. Ethanol Process

In a similar way as it was done for the Fischer-Tropsch diesel, before starting with the calculations of the CO_2-equiv. emissions, a brief explanation of ethanol production process will be developed.

First generation bioethanol is produced by distillation from crops such as wheat, corn, sugar cane and sugar beet.

In Brazil, ethanol for fuel is derived from sugarcane and is used pure or blended with gasoline. In United States, the ethanol is derived from corn.

The European Union has proposed to limit biofuel produced from food crops at 7% of energy use in transport, due to concerns about food price and land use impacts. However, there are different studies and opinions from several players, who state different opinions and point out that impacts of ethanol production from starch crops have been exaggerated.

Ethanol from biomass can be produced from any feedstock containing appreciable amounts of sugar or materials that can be converted into sugar. Fermentation (biotechnology) is the predominate pathway for ethanol production. However, biomass can also be converted to ethanol via biotechnological and thermochemical pathways.

As a summarized flow chart for this process, the following chart is depicted:

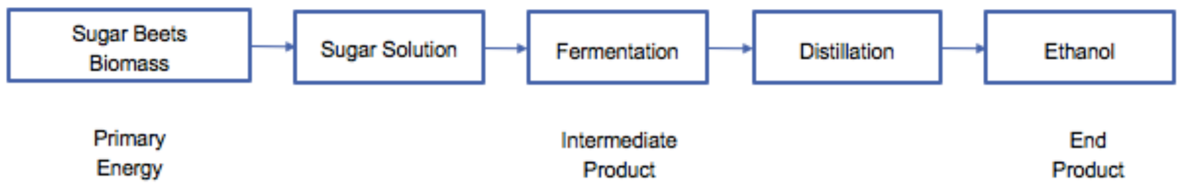

Figure 20. Conversion process for sugar beets biomass, adapted from ETIP

In the coming points, the emissions from the different ethanol processes are going to be indicated in the same way it was depicted for the Fischer-Tropsch diesel, and based in the same studies, but with the corresponding values for the ethanol.

The characteristics parameters of ethanol, and again with gasoline fossil as reference, are indicated below:

	Density [kg/l]	HV [MJ/kg]	HV [MJ/l]
Ethanol	0,79	26,7	21,09
Gasoline (Fossil)	0,74	43,9	32,49

Table 32: Characteristics of Ethanol and Fossil Gasoline

The biomass to be considered in this study as part of the Ethanol process is sugar beet, although the same comments done by Fischer-Tropsch process apply also for this process.

3.3.3. Feedstock Production and Extraction

The emissions relating this part are estimated as follow:

Biomass	Emissions [kg/tdry biomass]			kg CO2-eq./kg Fuel
	CO_2 fossil	N_2O	NOx	
Sugar Beet	77	0,63	0,76	0,80

Table 33: Emissions in kg CO_2-eq. for biomass provision

3.3.4. Feedstock Transport

The emissions during biomass transportation are indicated below:

Biomass	wt [%]	HHV [MJ/kg_{dry}]	HHV [MJ/kg_{dry}]	kg Fuel / kg_{dry}	kg CO2-eq./kg Fuel	Density Fuel kg/liter	kg CO2-eq./liter Fuel
Sugar Beet	77	16,4	28,1	0,38	0,192	0,79	0,152

Table 34: Emissions in kg CO_2-eq. for biomass transportation

3.3.5. Fuel Production

As it was developed before, based on the study of Challenges for suitable biomass utilization (Chilean-German Biociclo Workshop), we get:

Process	Electricity [kWh/tdry biomass]			Heat [MJ/tdry biomass]		
	Production	Demand	Balance	Production	Demand	Balance
Ethanol from sugar beets	35	80,4	-45,4	1.212,9	1.692,7	-479,8

Table 35: Energy balance for Ethanol production

The deficiency in electricity and heat is provided by electricity from the German electricity mix and heat from natural gas burning. This leads to an amount of about 67 $kgCO_2$ emitted per dry ton of sugar beets, which is equal to **0,176 $kgCO_2$-eq/kg fuel** or **0,137 $kgCO_2$-eq/liter fuel**.

It was only found in the study of Oliveira et al. (2005), and referring to the Brazilian case, that in the ethanol conversion process, the distilleries are self-sufficient in terms of production and consumption of energy. It is indicated in this study that the energy supplied by the burning of bagasse, which is sugarcane waste left after the juice is extracted.

3.3.6. Fuel Distribution

The emissions during fuel distribution are indicated below:

Biomass	kg CO2-eq. / tFuel	kg CO2-eq. / kg_{Fuel}	Density Fuel kg/l	kg CO2-eq. / l_{Fuel}
Sugar Beet	41,950	0,04195	0,790	0,0331

Table 36: Emissions in kg CO_2-eq. for fuel distribution

3.3.7. Allocation

In the ethanol production, it could also be considered to apply the allocation procedures based on any of the available allocation procedures, if we think in the food or fuel discussion.

However, we are not going to enter in the discussion of tank or food, since as it was indicated before, the maximum amount of ethanol to be produced from this kind of biomass is actually limited to a maximum and it would avoid the mentioned discussion.

3.3.8. Fuel Use

According with Bioenergy Australia Association, depending on the car a slight increase in fuel consumption between 1 and 3% can be observed. Besides, they assure that not only blend percentage but also other factors such as driving style, tires pressure and conditions are important factors in consumption. However, it was not found the percentage of ethanol in fuel behind the affirmation of the Bioenergy Australia Association. This association also states that after taking into account lower prices per litre and ethanol higher octane rating, ethanol impact on fuel consumption is negligible.

The results offered by different studies go from small variations to bigger ones and therefore there is a high variance.

Y. Barakat et al (2015) found a linear relation between fuel consumption and ethanol concentration, between 0% and 25% of blending, and depending also on the engine speed (rpm). These equations are:

- ✓ At 1200 rpm:

$$Y = 0{,}0126 * x + 3{,}8871$$

- ✓ At 1600 rpm:

$$Y = 0{,}0224 * x + 4{,}2947$$

- ✓ At 2000 rpm:

$$Y = 0{,}0264 * x + 5{,}6905$$

Considering the equations above, the consumption of a vehicle working with Ethanol would have an increase consumption between 32,5% and 52% which is less probably to happen. The problem lays in that we cannot assure that the linear relation would keep for any blending percentage.

On the other hand, according with US Department of Energy, a gallon of ethanol contains less energy than a gallon of gasoline, resulting in lower fuel economy when operating your vehicle and it is also stated that the impact to fuel economy varies depending on the energy difference in the blend used. For example, E85, which contains 83% ethanol content, has about 27% less energy per gallon than gasoline. It could be explained or indicated as follow:

$$E_g = m_g * H_u$$

where:

E_g: Energy flow supplied

m_g: Supplied fuel mass per time unit

H_u: Calorific value of the fuel

Moreover, due to ethanol lower energy content, vehicle operating on E85 get about 15% to 27% fewer miles per gallon. It is going to be assumed that a 30% It is important to highlight that this assumption would probably introduce a high uncertainty and high variation and therefore would be part of the sensibility analysis.

In the same way, it was done for Fischer-Tropsch diesel, based on PROBAS (Prozessorientierte Baisdaten für Umweltmanagement-Instrumente, 2009), the emissions from the ethanol combustion, are the following:

	Emissions	Conventional Gasoline	Ethanol
1.	CH4 fossil	3,29E-04	3,93E-05
2.	CO fossil	7,09E-02	1,17E-02
3.	CO2 fossil	3,26	-
4.	N2O	1,10E-04	1,15E-04
5.	NH3	-	1,15E-04
6.	NMVOC	4,99E-03	2,99E-04
7.	NOx	5,17E-03	1,20E-03
8.	PAH	n.s.	3,18E-10
9.	SO2	3,101E-04	-
10.	Particulates	2,05E-09	7,59E-06

Table 37: Emissions from Ethanol combustion in kg/kg fuel

Source: PROBAS, from Challenges for suitable biomass utilization (Chilean-German Biociclo Workshop)

In Table 21, in Point 3.1.5 Use Phase, fuel consumption and emissions of Golf VI (Gasoline), based on study of VW (2010), were indicated. Emissions indicated in that table and the ones showed above were compared in order to verify the values. As example, CO_2 emissions from diesel fuel combustion yield to a value of 3,176 kg CO_2/liter gasoline vs 3,2 kg CO_2/liter gasoline (difference of 2,6%). Despite the variation in this case is higher than in case of diesel, it can we assumed that emissions are in line one each other.

Again, considering the GWP equivalence factors, and that CH4, N_2O and NOx contribute to the Product Carbon Footprint (Climate Change category), the following values are gotten for the use phase:

Ethanol	
Emissions in kg CO2-Eq./kg Fuel	0,084
Emissions in kg CO2-Eq./l Fuel	0,067

Table 38: Emissions of Ethanol combustion in kg CO_2-eq. during use phase

4. Electricity Consumption

It was already indicated before and will be considered again in the sensitivity analysis, the electricity consumption during VLC could play an important role since sources or origin of electricity lead to different emissions amount.

Based on study of Onat et al. (2015), the classification of electricity sources and emissions is the following:

Energy Source	GHG emission factors [gCO_2-eq/kWh]	
	Direct	Indirect
Coal	1050,0	61,0
Wind	0,0	15,0
Hydropower	0,0	8,0
Biomass	43,0	2,0
Photovoltaic	0,0	11,0
Nuclear	0,0	11,0
Natural Gas	588,0	60,0
Fuel Oil	806,0	99,0

Table 39: GHG emissions of different energy generation sources (Onat et al., 2015)

Based on European Environment Agency (2016; updated 2018), the EU-28 energy mix leads to emissions of about of 393 gCO_2-eq/kWh. This is the results of 22% solid (coal), 2% petroleum (fuel oil), 20% gases (natural gas), 26% nuclear, 30% renewables (a mix of renewables sources) and 1% wastes (non-renewables),

On the other hand, from processes on Ecoinvent and from Manufacturing and Vehicle Assembly (VMA) model the energy required during the vehicle production is equal to 2106,50 kWh. This value will be used during sensitivity analysis in order to evaluate the impact, either reduction or increase, in VLC emissions.

Heat requirement, mainly integrated by natural gas, can also represent an important point to evaluate the possibility of reduce or increase emissions during VLC. However, since neither reliable information nor specific consumption were available, it is finally not considered in this study.

5. Validation Data

According with Point 4.3.3.2 in ISO 14044, a check on data validity has to be performed during the collection of data collection since it is necessary to provide evidence of the data quality requirements.

Therefore, in the Table 40 below, it is shown that data source used and the assumed accuracy of each one:

Stage or Phase	Data Origin	Accuracy
VLC		
Raw Material Extraction and Production	Data Base / Literature / Extrapolation	High
Material Processing and Assembly	Data Base / Literature / Extrapolation	High
Electricity Consumption	Data Base / Literature / Extrapolation	Medium
Distribution	Data Base / Specific on place (Germany)	High
Maintenance and Washing	Data Base / Literature / Extrapolation	Medium
Disposal	Data Base / Literature / Extrapolation	Medium
Recycling	Literature	Low
FLC		
Feedstock Production and Extraction	Literature	High
Transport biomass	Data Base / Assumptions	Medium
Fuel Production	Literature	High
Fuel Distribution	Data Base / Assumptions	Medium
Fuel Use	Literature	High

Table 40: Data sources and Quality

Additionally, in Annex 1, the specific processes taken from Ecoinvent and used in this study are indicated. This offers an easy and clear understanding the way an important part of VLC was calculated.

It is seen that extrapolation based on weight plays an important role in the calculation during the VLC, while in the case of the FLC, the literature is especially important for the calculations, since as it was indicated before, due to scarcity of information available to perform a specific quantification (mass balance and ancillary processes) of GHG based in data bases.

6. Carbon Footprint Calculation

In this chapter, it is going to be calculated the total emissions, which means total emissions produced during VLC and FLC, based on a so-called “Base Case”, which is defined with the following parameters and conditions:

Parameter / Condition	Value	Unit
Total km	150.000,00	km
Electricity Mix EU-28	393	gCO_2-Eq/kWh
Consumption FT Diesel*	4,5	l/100km
Consumption Ethanol*	7,4	l/100km

*Based on NEDC and assumptions regarding Ethanol consumption

Table 41: “Base Case” definitions

6.1. Vehicle working with Fischer-Tropsch Diesel

The summary of emissions during the different phases of VLC and FLC are as follows:

Phase / Stage	Emissions in $kgCO_2$-eq.
VLC (Diesel)	
Raw Material Extraction and Production	3590,00
Material Processing and Assembly	2254,00
Distribution	0,00
Maintenance and Washing	278,00
End of Life (Disposal)	589,00
Recycling	-346,00
FLC (Fischer-Tropsch Diesel)	
Feedstock Production and Extraction	
Short Rotation wood	4278,00
Residual Forest	1121,00
Transport biomass	1187,00

Fuel Production	0,00
Fuel Distribution	215,00
Fuel Use	1284,00
Total Emissions	
Short Rotation wood	13331,00
Residual Forest	10174,00
Emissions per km	
Short Rotation wood	88,88
Residual Forest	67,83

Table 42: Total emissions in kg CO_2-eq./km for a diesel Golf

6.2. Vehicle working with Ethanol

The summary of emissions during the different phases of VLC and FLC are as follows:

Phase / Stage	Emissions in kgCO_2-eq.
VLC (Gasoline)	
Raw Material Extraction and Production	3590,00
Material Processing and Assembly	2254,00
Distribution	0,00
Maintenance and Washing	278,00
End of Life (Disposal)	589,00
Recycling	-346,00
FLC (Ethanol)	
Feedstock Production and Extraction	6985,00
Transport biomass	1683,00
Fuel Production	1546,00
Fuel Distribution	367,00
Fuel Use	740,00
Total Emissions	17689,00
Emissions per km	117,93

Table 43: Total emissions in kg CO_2-eq. for a gasoline Golf

7. Interpretation

It was indicated in Figure 5 of Chapter 2 that one of the stages of LCA framework is the interpretation of the results.

In this study, the aim of this interpretation is to figure out which are the points or parameters that lead to higher as well as lower emissions. In other words, which are the key parameters with influence on our results.

Based on the values got in Chapter 6, points 6.1 and 6.2, the following graphics can be depicted:

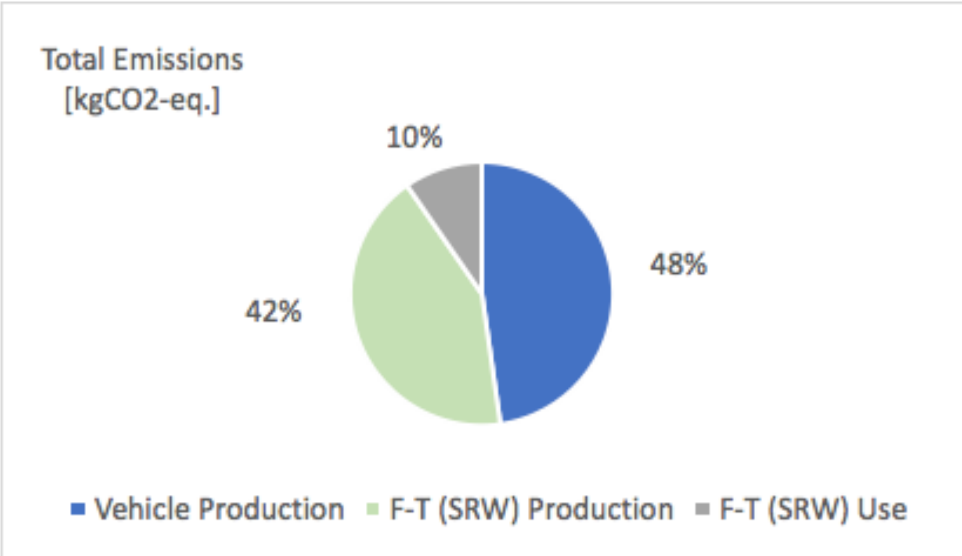

Figure 21. Emissions from the different phases. Fischer-Tropsch Diesel (SRW)

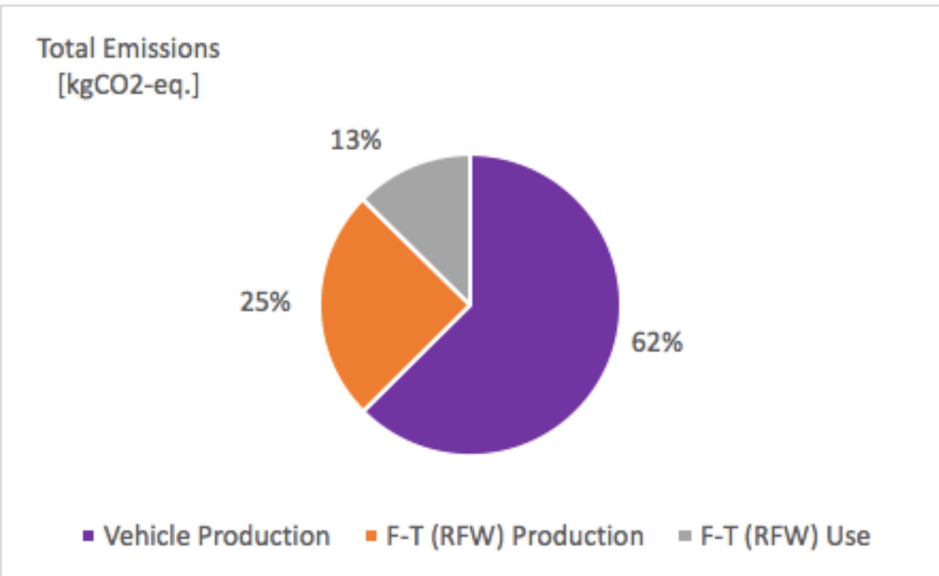

Figure 22. Emissions from the different phases. Fischer-Tropsch Diesel (RFW)

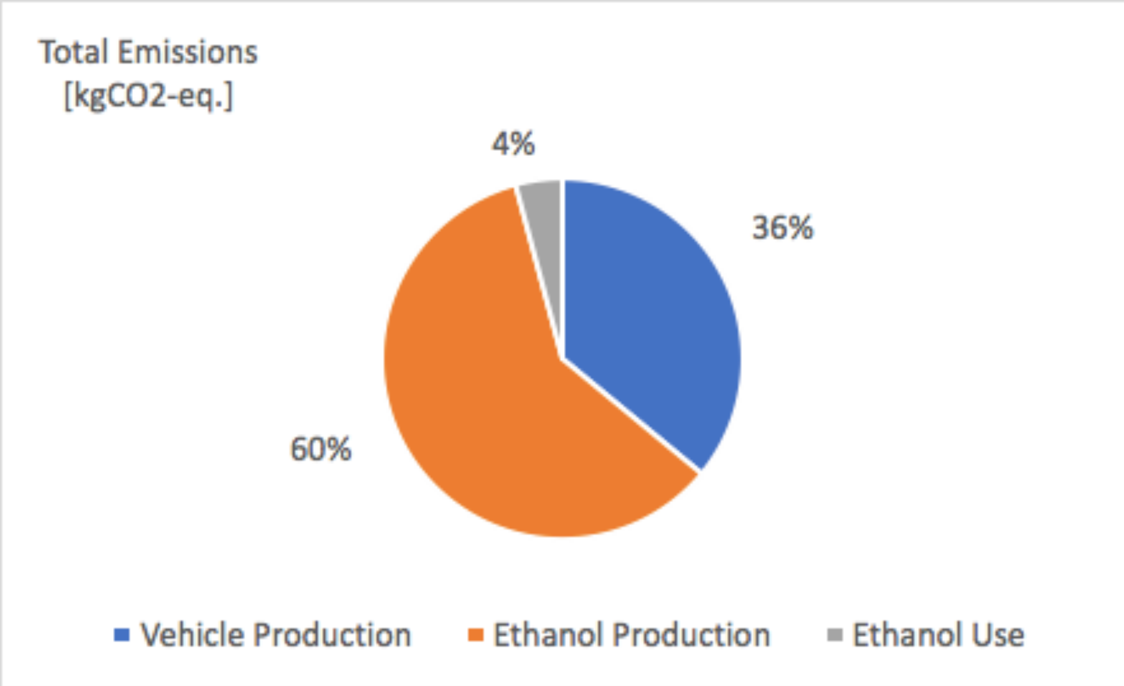

Figure 23. Emissions from the different phases. Ethanol

From Figure 21 and 22, it can easily be concluded that the vehicle production, i.e. VLC, represents the most important part of emissions when the vehicle works with Fischer-Tropsch Diesel, although these percentages are different whether the Short Rotation Wood or the Residual Forest Wood is considered. Nevertheless FLC, excluding use itself (combustion) in vehicle, represents a considerable percentage of 42% and 25% respectively.

For the case of a vehicle working with Ethanol, the production of the fuel, i.e. a part of the FLC (in this case also excluding the use in vehicle, which is separately depicted), takes the major part of the emissions.

In the case of the VLC, it is important to consider the consumption of electricity during the manufacturing of the vehicle, since it could be an important point of reduction (or increase) in the emissions when different electricity sources are evaluated. Moreover, and it was indicated in Chapter 1, while a vehicle can be lighter by substituting materials, part of that benefit is offset by the higher production energies of these alternative materials during the production stage.

A very important point to indicate is consumption. Although use phase in the vehicle does not represents a very high amount of the emissions, the fuel consumption during the whole life cycle impacts directly in the fuel production, increasing the emissions in this part of the FLC.

Based on the information given in the previous paragraphs, during the sensitivity analysis developed in Chapter 8, both VLC and FLC will be evaluated. In the first case, the energy consumption (only electricity and its sources) and in the latter one, the fuel consumption and fuel yield, since these ones impacts directly in the FLC.

In summary, when the way to reduce emissions is considered, the key parameters to reduce are fuel consumption and electricity consumption, as well as the increase of fuel yield. A last point to mention is the recyclability, since a circular economy is associated with raw material requirements and electricity consumption.

8. Sensitivity Analysis

According with ISO 14044, a sensitivity check is required. The objective of this one is to assess the reliability of the final results and conclusions by determining how they are affected by uncertainties in the data, allocation methods or calculation of category indicator results, etc.

Thus, in this study a sensitivity analysis is performed in order to account for the uncertainties implied with the estimation done throughout the whole process. Besides, it is a form to check the robustness of the calculations, and to evaluate the impacts of different scenarios in the Product Carbon Footprint.

In the coming points, and having a base case as a starting point, different power mix (sources), fuel yield and driving profile are assessed, and theirs impacts on the results.

8.1. Electricity Generation Mix

As pointed out in Chapter 4, the electricity consumption during VLC could play an important role since sources or origin of electricity lead to different emissions amount and therefore it should be evaluated.

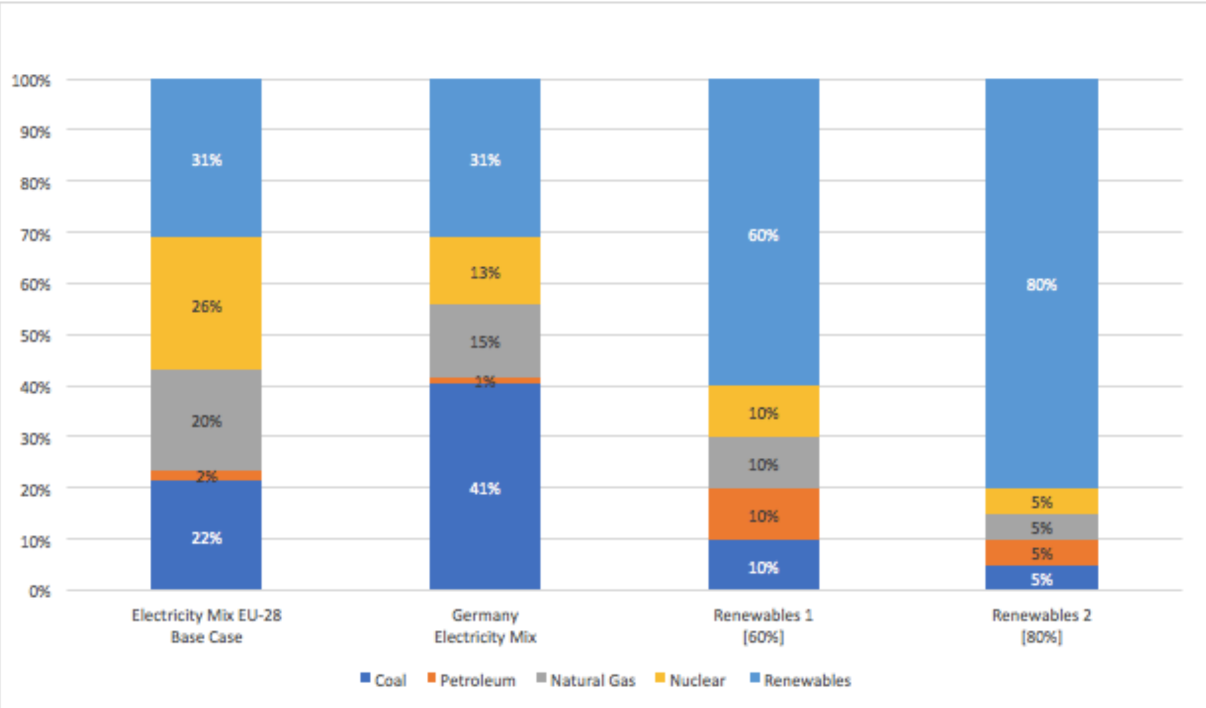

Figure 24. Share in electricity generation. Different cases

The assumed “Base Case” is the Mix EU-28 since the values of the data bases are in function of the European basis. Then, the electricity mix in Germany is considered and finally two scenarios with a high percentage of renewable energy are included. These percentages of renewable energy are composed by wind and photovoltaic, because they offer average values of emissions and they represent an important percentage themselves in the renewable part.

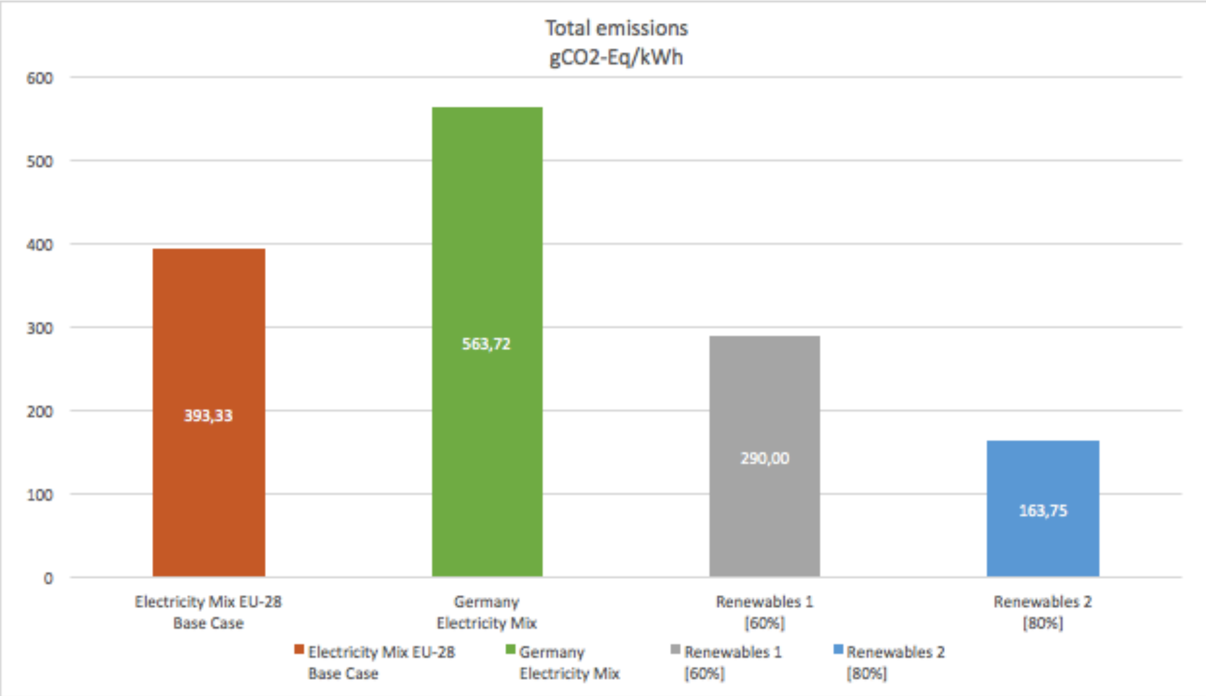

Figure 25. Emissions in gCO_2-Eq/kWh for the four-electricity generation mix

It is observed that an adoption of 60% of renewables (wind + photovoltaic) sources leads to a reduction of 26% and 48% with regards to the Mix EU-28 and Germany mix, respectively. Whilst an additional increase of 20%, i.e. 80% of renewables, represent a reduction of 58% and 70%, respectively.

Although the calculated value for the Germany Mix differs and is higher than in some literature, the main reason lies in the different percentage of renewable energy. A secondary and smaller reason could be due to different specific emissions of each energy source.

In summary, an increase percentage of renewable energy result in lower electricity emissions and thus in lower emissions during VLC.

8.2. Fuel Yield

The idea of fuel yield refers directly to the amount of fuel that can be obtained from each ton of biomass.

As "Base Case", an amount of 0,38 and 0,145 of kg of fuel, of ethanol and F-T diesel, respectively, per kg of biomass are adopted. These amounts were the ones used for the calculation of the Carbon Footprint in Chapter 6 and are based in the literature.

The other cases to be defined and assumed correspond to an increased fuel yield, since it is clear that the technical and economical improvements would lead to higher yield. Thus, scenarios of 0,42 (10,5%) and 0,45 (18,5%) are considered for the ethanol, and other ones of 0,2 (38%) and 0,25 (72,5%) are for the F-T diesel.

8.3. Driving Profile

It was introduced in previous chapters the idea of different driving profiles, and consequently in Point 3.1.5, the NEDC, US City and Highway Driving Cycle, and ADAC were indicated.

It was also pointed out that despite the values have already some years and although there some differences due to improved fuel consumption in the last years, the key difference between the profiles lies in how much aggressive they are, and more aggressive means more consumption.

Taking the NEDC as the “Base Case” and based on Table 21, the US City and Highway represents an increase of 2% for the diesel vehicle and a decrease of almost 8% for the gasoline one. On the other hand, the ADAC represents an increase of 20% and 25% for the diesel and gasoline vehicle, respectively.

In this way, the following table is stated to define the scenarios to be analyzed relating fuel consumption:

	Golf VI Gasoline	% Diff.	Golf VI Diesel	% Diff.
NEDC	7,4 l/100 km		4,5 l/100 km	
US City and Highway	6,6 l/100 km	-10%	4,0 l/100 km (*)	-11%
ADAC	8,3 l/100 km	+12%	5,3 l/100 km	+18%

* This value should be actually similar to the NEDC

Table 44: Consumption according with three defined driving style/profile

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8.4. Total driving mileage

A last point to be considered is the total mileage of the vehicle during its whole useful life.

Recalling the Points 6.1 and 6.2, the total mileage has a direct impact in the emissions per driven kilometer. Thus, it could be assumed that the increase in the total mileage would lead to lower emissions and vice versa. However, an analysis and distinction between VLC and FLC is required before considering such assumptions.

Therefore, in the following figures, four different total amount of driving mileage are assessed from the point of view of emissions and their impacts in total and specifics ones for the ethanol and F-T diesel (SRW and RFW).

The following charts compare the individual mileages in order to assess the different proportions of the individual phases of VLC and FLC.

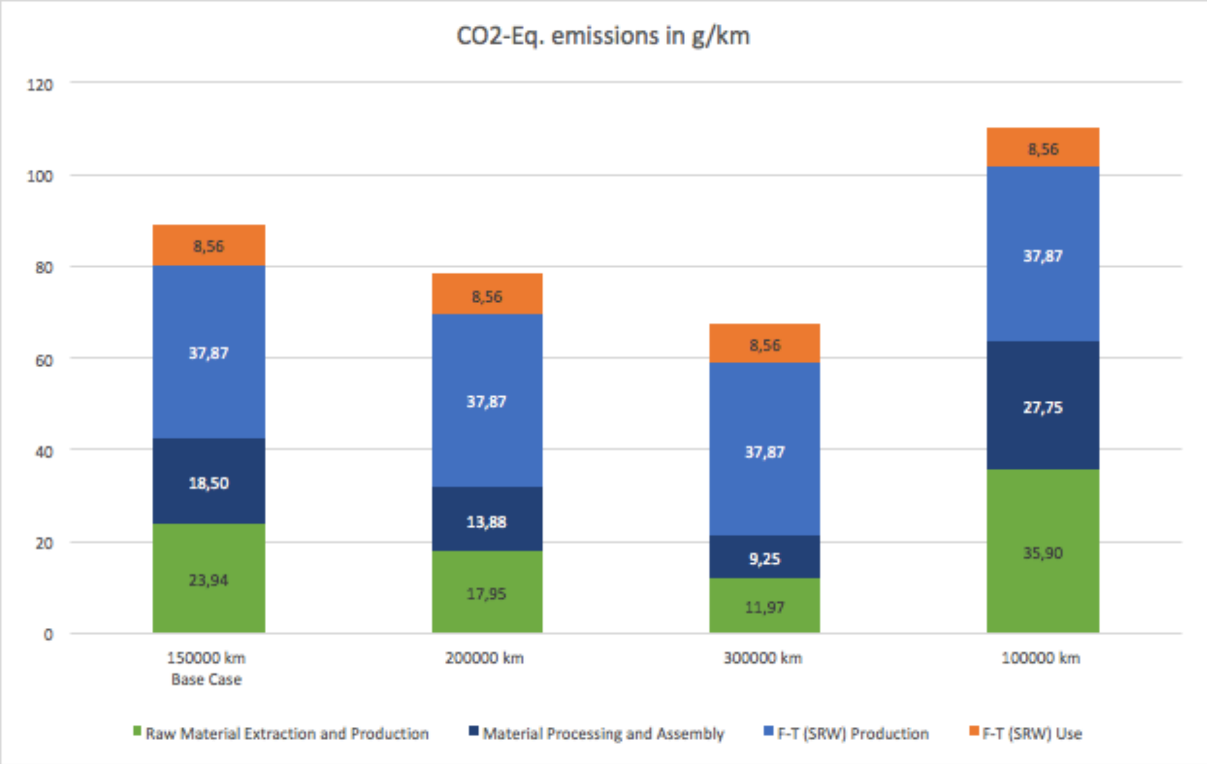

Figure 26. Emissions for different total mileages. F-T diesel (SRW)

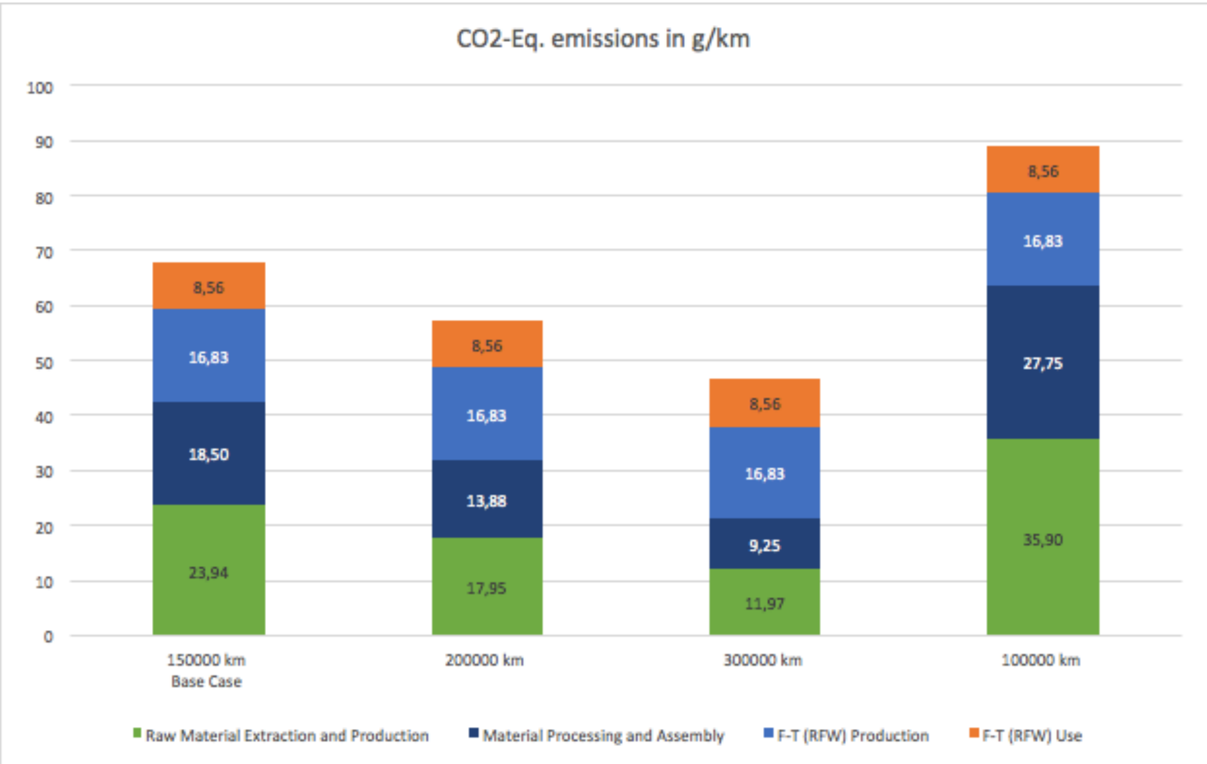

Figure 27. Emissions for different total mileages. F-T diesel (RFW)

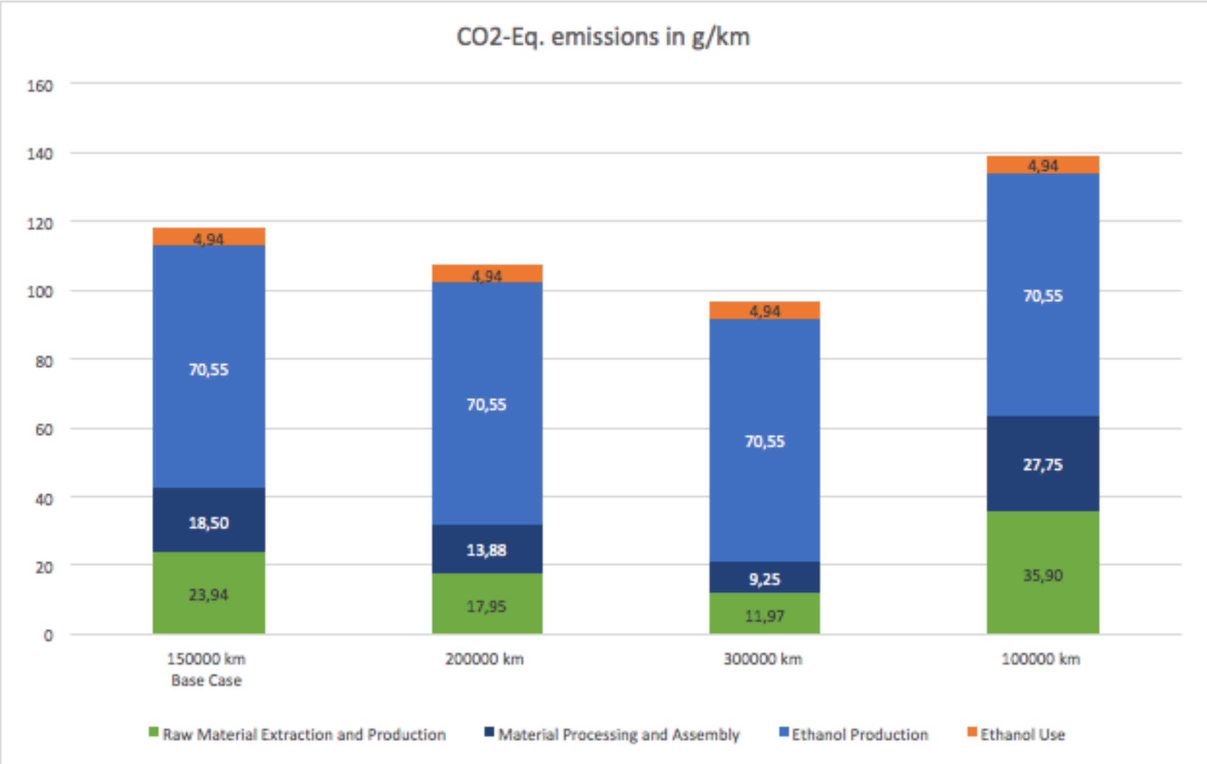

Figure 28. Emissions for different total mileages. Ethanol

From figures 27 to 29, it can be observed that the driving mileage impact directly in the VLC, whilst the emissions relating to FLC, keep constant. The reason for this latter lies in fuel production and fuel consumption, since while the total driving mileage increase, the fuel production and consumption increase as well. Thus, the proportion of emissions relating FLC keeps constant. The situation would be different if the total driving mileage together with another parameter, such fuel yield, were modified at the same time. In this case, an impact in emissions of both, VLC and FLC, would be noticed.

In summary, it can be stated the following:

- ✓ An increase from 150000 km to 200000 km lead to a reduction of 9% for Ethanol, 12% for F-T diesel (SRW) and 15,6% for F-T diesel (RFW)
- ✓ An increase from 150000 km to 300000 km lead to a reduction of 18% for Ethanol, 23% for F-T diesel (SRW) and 31% for F-T diesel (RFW)
- ✓ A decrease from 150000 km to 100000 km lead to a rise of 18% for Ethanol, 23% for F-T diesel (SRW) and 31% for F-T diesel (RFW) [1]

[1] Note: It is clear that the difference between 100000 km and 300000 km have the same impact, but with opposite signs.

8.5. Analysis of the different scenarios

In points 8.1 to 8.4, four different parameters were depicted. Thus, as conclusion of the sensitivity analysis, and based on this previous information and data, four scenarios are finally presented and evaluated.

Although many alternatives and configurations can be assumed considering the previous points of electricity generation mix, fuel yield, driving profile and total driving mileage, the proposed scenarios are set below and presented in the following Table:

Parameter	Base Case	Scenario 1 better option	Scenario 2 better option	Scenario 3 Worse option
Electricity Generation Mix	Mix EU-28	Renew. 60%	Renew. 80%	German Mix
Fuel Yield (ethanol)	0,38	0,42	0,45	0,38
Fuel Yield (F-T diesel)	0,145	0,2	0,25	0,145
Driving Profile	NEDC	US City&Highway	US City&Highway	ADAC
Total driving mileage	150000	200000	300000	100000

Table 45: Scenarios for the sensitivity analysis. Ethanol and F-T diesel

Regarding the distribution, it is assumed 0 km (self-pick-up) because there is a large number of possibilities and combination. Nevertheless, in the proposed scenario for distribution in Germany, the burden of emissions to the distribution is insignificant. As reference, the best option would be Hannover (6,43 kg CO_2-Eq./Golf) and the worst one would be München (30,91 kg CO_2-Eq./Golf). Moreover, if only the transport by truck is considered, the best and worst options are still Hannover and München but the burdens are 9,52 kg CO_2-Eq./Golf and 64,31 kg CO_2-Eq./Golf).

In the following figures, the results for Ethanol and F-T diesel, both SRW and RFW, are depicted:

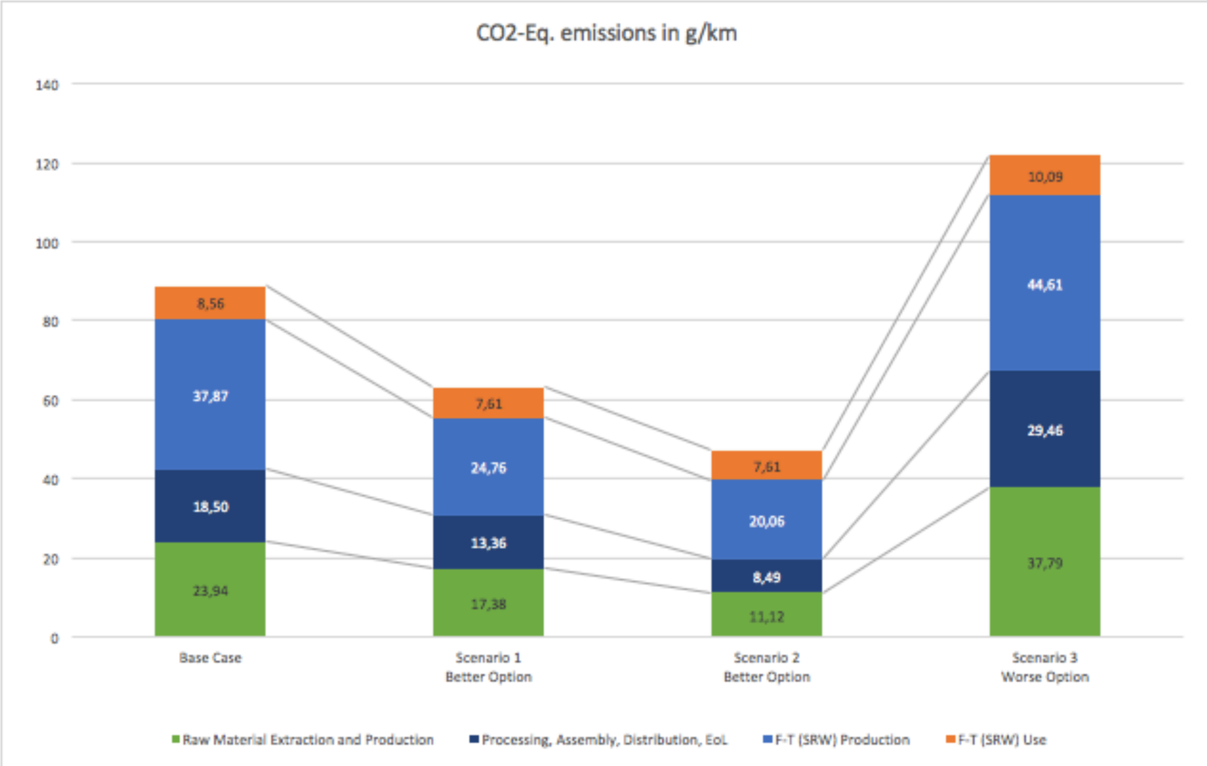

Figure 29. Emissions for different scenarios. F-T diesel (SRW)

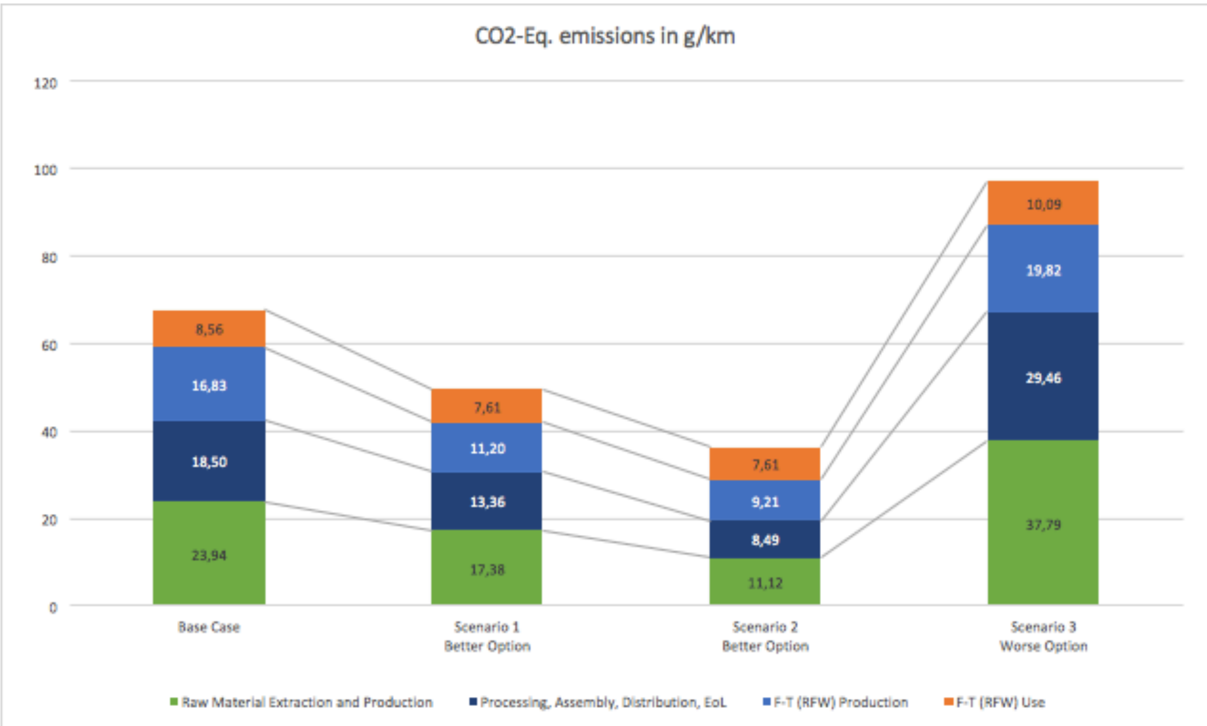

Figure 30. Emissions for different scenarios. F-T diesel (RFW)

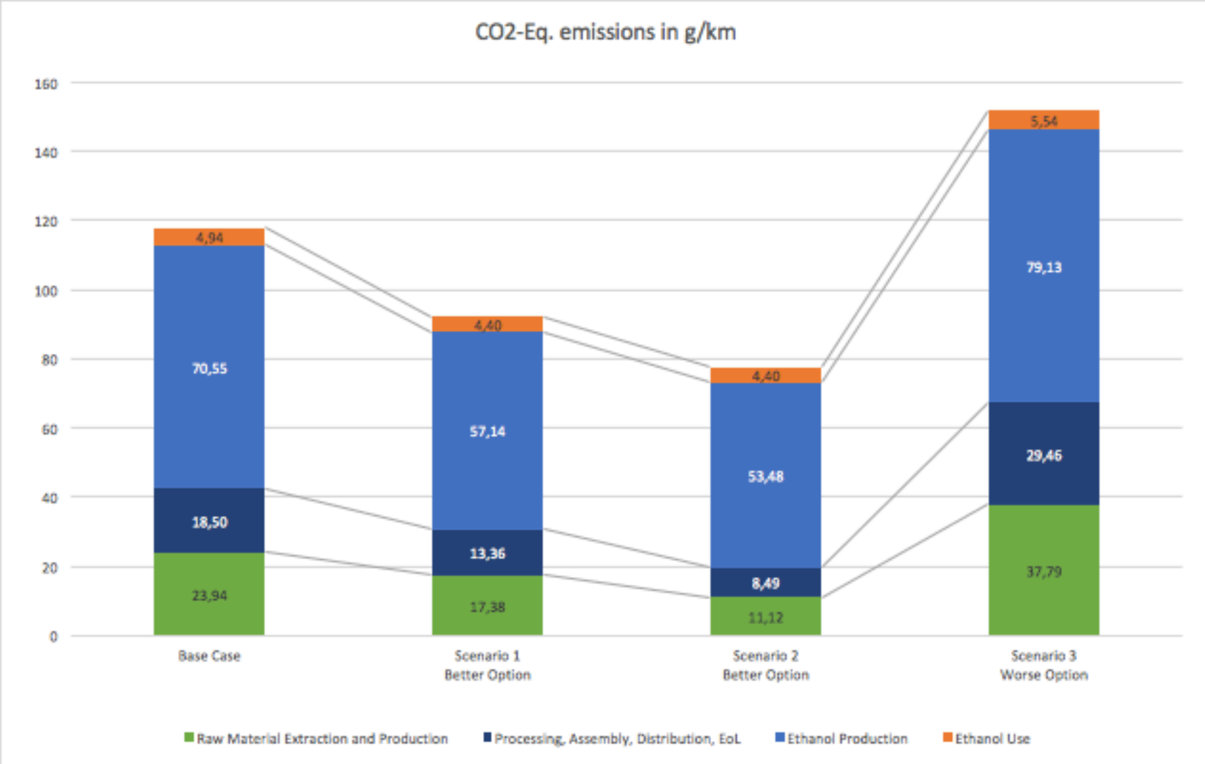

Figure 31. Emissions for different scenarios. Ethanol

At a first sight, as highlights from the graphics, it is observed that fuel production, as for ethanol as well as for F-T diesel, represents the most important variations and differences. The reason lies basically in fuel yield, which means a better use of biomass.

Secondly, another important difference is observed during VLC. In this case, this variation lies in the total driving mileage. However, if we consider only the variation due to different electricity mix, the percentage goes from -8% (best option 2) to +6% (worse option).

Regarding the use phase, and for all fuels, it could be thought that this does not represent an important variation or variable. However, here is important to emphasized that total driving mileage and fuel consumption vary together from one scenario to another one. The situation would be different if the fuel consumption varies while total mileage keeps constant, where the role of the first one would be more important. It is going to be shown in the Tornado diagram in Chapter 9.

In the following Table, the results of the assessed scenarios are indicated:

Parameter	Base Case	Scenario 1 better option	Scenario 2 better option	Scenario 3 Worse option
Total Ethanol	117,93	92,29	77,49	151,92
Total F-T diesel (SRW)	88,88	63,11	47,28	121,94
Total F-T diesel (RFW)	67,83	49,55	36,43	97,16

Table 46: Emissions in g/km for the scenarios. Ethanol and F-T diesel

After performing this analysis, it is observed that CO_2-Eq. emissions are influenced by several parameters and the combinations of them lead to different results.

Nevertheless, the best option in order to have the lower emissions is achieved with a non-aggressive driving profile, i.e. lower consumption, higher fuel yield, cleaner electricity generation mix (more renewables), and higher total driving mileage, although the impact of each of them in the total emissions are different.

9. Matlab Program

At the beginning of this study, it was indicated that even though it is clear and understandable, due to manufacturing processes or driving patters differ from one region or country to another one, the studies are based on a specific one.

Furthermore, sensitivity analysis has lead also to the conclusions that there is a large number of different combinations of variables or parameters which can be lead to different results.

With the objective to let a quick variation of some parameters in order to adapt them to different circumstances, it was developed a Guide User Interface (GUI) in Matlab. This one helps to adjust some key parameters, which are also part of the sensitivity analysis, and calculate the Carbon Footprint to different situations.

The program lets the setting of several parameters and then calculates the emissions according with the chosen parameters. Besides three different graphics are available: a 3D graphic, a bar graphic and a tornado diagram.

The first one sets a plane which lets to see the incidence in emissions form electricity and consumption perspective.

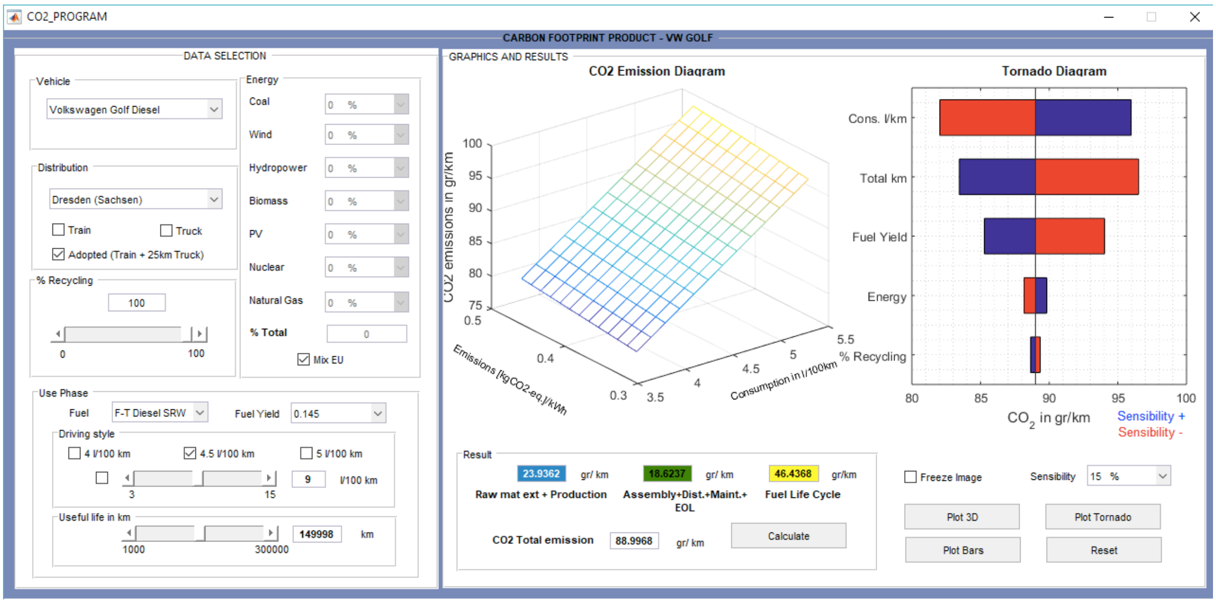

Figure 32. Guide User Interface in Matlab for PCF calculation. 3D + Tornado

The second one shows the amount of emissions relating to VLC and FLC. The first one, VLC, is shown in two different bars: Raw Material Extraction and Production, and Processing and Assembly, Distribution, Maintenance and EoL.

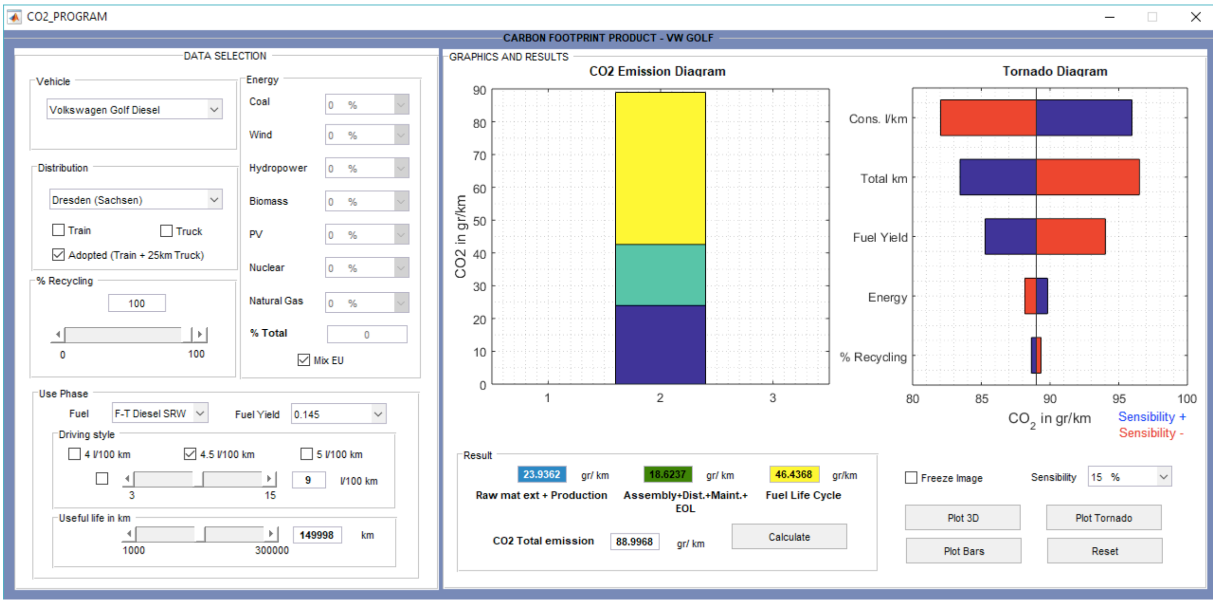

Figure 33. Guide User Interface in Matlab for PCF calculation. Bars + Tornado

The Tornado Diagram helps to easily shown which are the most important variables that influence in a given or defined situation, graphing these variables in corresponding order: upper, higher influence; lower, lower influence.

10. Conclusion and Future

10.1. Conclusion

The key aim of this study, and as it was indicated at the beginning, was to calculate the Product Carbon Footprint (PCF) for a conventional vehicle working with a renewable fuel.

It was considerable important that this estimation and calculation was carried out not only for renewable fuel as replacement for diesel fuel, but also for a one as replacement for gasoline. Thus, two PCF were actually estimated. This means that the 98% of the vehicles, considering market share of diesel and gasoline, available in the current was assessed and studied.

It could be showed that renewable fuels offer a very interesting and feasible possibility to attend to current environmental and political concerns, and equally important is that these concerns could be attended in a short and middle term. However, to achieve this, it is important the fast development of the so-called 2nd generation renewable (bio) fuels, since the 1st generation does not show to be the best option, since while having low emissions in the use phase, high emissions arise during production phase.

Although Fisher-Tropsch diesel has clearly showed a good alternative as diesel substitute, it is not the same with the conventional Ethanol. Therefore, a feasible option would be the 2nd Generation ethanol or to follow the path methanol-to-gasoline, also using the syngas production.

The sensibility analysis allowed to figure out which are the main parameters to focus when better results want to be gotten and which parameters are important to keep under control.

The additional point of developing a program in Matlab for a fast calculation let to adapt the results to different conditions, such as geographical or composition of electricity matrix.

Finally, this study helps to set a base for the discussion with other technologies available today.

10.2. Points to Develop

In this case, it deserves and must be mentioned again that the PCF only assesses an impact category, climate change, which despite being very important, is not the only one. There are also other impact categories which are equally important to evaluate and lead to other environmental impacts. These other categories were stated and briefly described in Chapter 2. They are as important as climate change impact category because all together are part of a complete Life Cycle Assessment (LCA) and because it is probably to find out a trade-off between impacts categories.

Just as an example, the study of Oliveira et. al (2005) concluded that the use of Ethanol as a substitute for gasoline proved to be neither a sustainable nor an environmentally friendly option considering ecological footprint values.

Although it is beyond this study, the CCS technology, as indicated in many literature, would lead to lower emissions and therefore would have a positive impact in the PCF.

Finally, it is important to evaluate another renewable fuel production paths in order to evaluate different alternatives.

10.3. Outlook and Future

After carefully treatment of all information provided and assessed in this study, it reasonable and advisable to conclude that the substitution of fossil fuels by renewable fuels cannot be done using just an option, since it would require huge production quantities which can actually not be achieved today.

However, the growth and development of other technologies will contribute to achieve increasingly stringent requirements, from different environmental perspectives, and to obey to national or global guidelines and objectives.

On the other hand, according with the literature analyzed and part of this study, it is important to highlight that no option comes free from environmental problems. Therefore, a mix of vehicle's alternatives and technologies would help to take benefit and exploit the advantages of each one of them.

Finally, while the transport sector has been under scrutiny in the last years, just a little literature was found relating maritime transport. This specific sector produces high emissions but no policy nor requirements were found in the assessed literature.

11. Appendix A

In this point, all the materials and processes chosen from the Ecoinvent data base are indicated:

Material / Process	Number #
Steel	#1150
Cast Iron	#1069
Cast Aluminum	#1054
Copper	#1087
Average Plastic (Polyethylene)	#1827
Rubber	#1847
Wrought Aluminum	#1058
Chrome	#1073
Titanium	#355
Glass (Silica Sand)	#479
Insulation	#1816
Paint	#1670
Polypropylene	#1834
Lead	#10777
Oil	#416
Ethyl. Glycol	#402
Alkylbenzene	#1998
Metal stamping: Steel and Aluminum	#8298 and #8309
Casting: Iron, Aluminum, Brass and Lead	#8264, #8304, #1159 and #10777
Forgings: Iron and Steel	#1165
Extrusions: Aluminum	#8304
Machining: Steel	#8214
Wire Forming: Copper	#1178
Glass Pane Forming	#806
Blow Molding: Polymers	#1848
Compression and Injection Molding: Plastics and Rubber	#1853

Thermoset Molding (foaming, expanding): Polymer Resins	#1815
Extrusions and Calendering: Plastics	#1851

Table 47: Materials and processes adopted from Ecoinvent and used in this study

12. Attachments

As part of this study of the Carbon Footprint Product of a conventional vehicle working with a renewable fuel, the program “Carbon Footprint Product” developed in Matlab and explained in Chapter 9 is attached.

Along with the program CO2_PROGRAM.m, a brief instructive is attached. This one shows which parameters need to be loaded and which results and graphics can be gotten with the execution.

Bibliography

- **PAS 2050:2011:**

  Specification for the assessment of the life cycle greenhouse gas emissions of goods and services.

- **DIN EN ISO 14040:**

  Environmental management – Life cycle assessment – Principles and framework (ISO 14040:2006).

- **DIN EN ISO 14044:**

  Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006).

- **DIN CEN ISO/TS 14067**:

  Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification and communication (ISO/TS 14067:2013).

- **Introduction of the GREET 2 Model**

  Argonne National Laboratory.

- **Development and Applications of GREET 2.7 — The Transportation Vehicle-Cycle Model**:

  A. Burnham, M. Wang, and Y. Wu Energy Systems Division, Argonne National Laboratory (November 2006)

- **Energy-Consumption and Carbon-Emission Analysis of Vehicle and Component Manufacturing**

  J.L. Sullivan, A. Burnham, and M. Wang Center for Transportation Research Energy Systems Division, Argonne National Laboratory (September 2010)

- **Global Warming Potential Values**

  Greenhouse Gas Protocol. www.ipcc.ch

- **Biochemical Conversions of Lignocellulosic Biomass for Sustainable Fuel-Ethanol Production in the Upper Midwest**

  Michael James Brodeur-Campbell. Michigan Technological University (2012)

- **Energies: Investigation of Ethanol Production Potential from Lignocellulosic Material without Enzymatic Hydrolysis Using the Ultrasound Technique**

  Manoj Kandasamy, Ihsan Hamawand, Leslie Bowtell, Saman Seneweera, Sayan Chakrabarty, Talal Yusaf, Zaidoon Shakoor, Sattar Algayyim and Friederike Eberhard (January 2017)

- **Biotechnology for Biofuels: The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe**

  Raphael Slade, Ausilio Bauen and Nilay Shah (August 2019)

- **SPRINGER: Bioethanol from Lignocellulosic Biomass**

  Xin-Qing Zhao, Li-Han Zi, Feng-Wu Bai, Hai-Long Lin, Xiao-Ming Hao, Guo-Jun Yue and Nancy W. Y. Ho (December 2011)

- **NREL: Process Design and Economics for Biochemical Conversion of Lignocellulosic Biomass to Ethanol. Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover**

D. Humbird, R. Davis, L. Tao, C. Kinchin, D. Hsu, and A. Aden National Renewable Energy Laboratory Golden, Colorado (May 2011)

- **EMPA: Vergleichende Ökobilanz individueller Mobilität: Elektromobilität versus konventionelle Mobilität mit Bio- und fossilen Treibstoffen**

  Hans-Jörg Althaus Marcel Gauch (Oktober 2010)

- **ELSEVIER: ScienceDirect, Energy Procedia 105 (2017) 3584-3595**

  Qinyu Qiao et al.: Comparative Study on Life Cycle CO_2 Emissions from the Production of Electric and Conventional Vehicles in China.

- **ELSEVIER: Applied Energy, 150 (2015) 36-49:**

  N.C. Onat et al.: Conventional, hybrid, plug-in hybrid or electric vehicle? State-based comparative carbon and energy footprint analysis in the United States.

- **ELSEVIER: Applied Energy, 206 (2017) 531-540:**

  P. Wolfram, T. Wiedmann: Electrifying Australian Transport: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity.

- **SPRINGER: CrossMark, (2017) 250:309-340:**

  Chunguang Bai, Behnam Fahimnia, Joseph Sarkis: Sustainable transport fleet appraisal using a hybrid multi-objective decision making approach.

- **Skript Ökobilanz Teil 1 und 2.**

  Stand: April 2013.

- **ELSEVIER: Transportation Research Part D, 52 (2017) 156-171**

  Javier Perez et al.: A methodology for estimating the carbon footprint of waste collection vehicles under different scenarios: Application to Madrid.

- **ELSEVIER: Applied Energy, 112 (2013) 547-559**

  Geoffrey P. Hammond, Shashank M. Seth: Carbon and environmental footprinting of global biofuel production

- **Journal of Industrial Ecology, 53-64**

  Troy R. Hawkins, Bhawna Singh, Guillaume Majeau-Bettez, and Anders Hammer Strømman: Comparative Environmental Life Cycle Assessment of Conventional and Electric Vehicles

- **ELSEVIER: Applied Energy, 206 (2017) 531-540**

  Paul Wolfram, Thomas Wiedmann: Hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity.

- **ELSEVIER: Journal of Cleaner Production, 137 (2016) 249-257**

  David Lazarevic, Michael Martin: Analyzing environmental systems analyses of transportation biofuels.

- **ELSEVIER: Energy, 136 (2017) 7-15**

  F. Al-Mansour, V. Jejcic: A model Calculation of the carbon footprint of agricultural products.

- **Challenges for Sustainable Biomass Utilization**

  Proceeding of the Chilean-German Biociclo Workshop (March 2009)

- **Ecoinvent Centre**

Code of Practice. Data v2.1 (2009)

- **Ecoinvent Centre**

  Overview and Methodology. Data v2.0 (2007)

- **SAE Technical Paper Series: Emissions from Trucks using Fischer-Tropsch Diesel Fuel**

  Paul Norton et al. NREL (October 1998)

- **Environmental Commendation Background Report. The Golf.**

  Volkswagen AG (December 2010)

- **Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint**

  Marcelo E. Dias de Oliveira, Burton E. Vaughan, and Edward J. Rykiel Jr (July 2005).

- **Energy and Environmental Solutions: Life-Cycle Greenhouse-Gas Emissions Inventory for Fischer-Tropsch Fuels**

  John J. Marano, Jared P. Ciferno (June 2001)

- **WIT Transactions on The Built Environment, Vol 111: A model to estimate road transport emissions from the entire life cycle**

  J. Lumbreras, D. Ballarín, J. M. López, R. Villimar, B. Arenas, F. Aparicio and E. Rodríguez (2010)

- **WIT Transactions on The Built Environment, Vol 128: Comparison of greenhouse gas emissions from different vehicles covering the entire life cycle**

  J. Perez, J. Lumbreras, J. M. López, J. A. Garcia, M. Vedrenne, J.M.deAndrés and D.Paz (2012)

- **Life Cycle Inventory for the Golf A4**

  Georg W. Schweimer Research, Environment and Transport, Volkswagen AG, Wolfsburg

  Marcel Levin Center of Environmental Systems Research, University of Kassel

- **ELSEVIER: Transportation Research Part D, 48 (2016) 63-84**

  Mashael Yazdanie et.al: Well-to-wheel costs, primary energy demand, and greenhouse gas emissions for the production and operation of conventional and alternative vehicles

- **National Renewable Energy Laboratory (NREL)**

  S. Huffnagle and R. Westby: Laboratory Life Cycle Assessment of Environmental Footprint

- **Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity. Volume 1: Main Text**

  Argonne National Laboratory. M. A De Luchi (1993).

- **SAE TECHNICAL (2001-01-3518): Emissions from Fischer-Tropsch Diesel Fuels**

  Jack W. Johnson and Paul J. Berlowitz (ExxonMobil Research and Eng), D. F. Ryan, R. J. Wittenbrink, W. B. Genetti and L. L. Ansell (ExxonMobil Process Research) and Y. Kwon and D. J. Rickeard (Esso Research Centre)

- **ELSEVIER: Energy Procedia 1 (2009) 4379-4386**

  Robert H. Williams1, Eric D. Larson, Guangjian Liu, and Thomas G. Kreutz: Fischer-Tropsch Fuels from Coal and Biomass: Strategic Advantages of Once-Through (“Polygeneration”) Configurations

- **ELSEVIER: Progress in Energy and Combustion Science 37 (2011) 503-523**

S.S. Gill a, A. Tsolakis a, K.D. Dearn a, J. Rodríguez-Fernández,: Combustion characteristics and emissions of Fischer-Tropsch diesel fuels in IC engines

- **ELSEVIER: Egyptian Journal of Petroleum (2016) 25, 309-315**

  Y. Barakat, Ezis N. Awad, V. Ibrahim: Fuel consumption of gasoline ethanol blends at different engine rotational speeds

- **ELSEVIER: Applied Energy 176 (2016), 22-33**

  Mobolaji B. Shemfe, Carly Whittaker, Sai Gu, Beatriz Fidalgo: Comparative evaluation of GHG emissions from the use of Miscanthus for bio-hydrocarbon production via fast pyrolysis and bio-oil upgrading

- **Environmental Science. School of Engineering. Murdoch University, Australia**

  Phillip Calais, Ralph Sims: A Comparison of Life-Cycle Emissions of Liquid Biofuels and Liquid and Gaseous Fossil Fuels in the Transport Sector

- **Energy, Sustainability and Society 2012**

  Nicolaus Dahmen, Edmund Henrich, Eckhard Dinjus and Friedhelm Weirich: The bioliq® bioslurry gasification process for the production of biosynfuels, organic chemicals, and energy

- **Biotechnology for Biofuels (2009)**

  Raphael Slade, Ausilio Bauen and Nilay Shah: The greenhouse gas emissions performance of cellulosic ethanol supply chains in Europe

- **Official Journal of the Europian Union**

  Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009

- **Official Journal of the Europian Union**

  Regulation (EC) No 443/2009 of the European Parliament and of the Council of 23 April 2009

- **Fischer-Tropsch synfuels from cereal straw via fast pyrolysis and gasification. Costs and Benefits**

  Ludwig Leible, Stefan Kälber, Gunnar Kappler, Stephan Lange, Eberhard Nieke and Beate Fürniss Forschungszentrum Karlsruhe / Institute for Technology Assessment and Systems Analysis (ITAS)

- **Waste Biomass Valor (2010) 1:415-430**

  Frederik Trippe, Magnus Fröhling, Frank Schultmann, Ralph Stahl, Edmund Henrich: Techno-Economic Analysis of Fast Pyrolysis as a Process Step Within Biomass-to-Liquid Fuel Production

- **ELSEVIER: Alexandria Engineering Journal (2017), 56, 721-726**

  Ahmed Al-Samari: Study of emissions and fuel economy for parallel hybrid versus conventional vehicles on real world and standard driving cycles

- **ELSEVIER: Journal of Cleaner Production 137 (2016) 249-257**

  David Lazarevic, Michael Martin: Life cycle assessments, carbon footprints and carbon visions: Analysing environmental systems analyses of transportation biofuels in Sweden

Erklärung

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Karlsruhe, den 07. August 2018