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Optimizing the implementation of biofuels in the Swiss energy and transport sectors

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Abstract

This thesis analyzes the environmental impacts of different biofuels' production pathways and their subsequent usage for powering different mid-sized cars in the Swiss territory. Starting from the available biomasses present in Switzerland which are mainly wood biomass (from the forests, landscape maintenance and industrial residues), and animal waste. Algae biomass is also considered even though it is not currently possible cultivate it in Switzerland with high yield, due to the non-optimal weather and latitude conditions, but the production abroad (e.g. in Italy) and the following importation of the finished fuels has been analyzed. Different processes have been investigated and the pathways examined are: *electricity* from a combined heat and power plant (CHP) or from an ORC (Organic Rankine Cycle) plant, *hydrogen* from wood gasification, *gasoline and biodiesel* from fast-pyrolysis of wood biomass, or from algae oil esterification or hydrothermal liquefaction processes, and the upgrade of *biogas and SNG* (Synthetic Natural Gas) into *methane* from wood biomass gasification, manure anaerobic digestion, and wood and manure biomass hydrothermal gasification (HTG). For reaching the goal of this study the functional unit for the biofuels production has been set equal to 1 MJ.

The different biofuels analyzed have been then considered in powering different mid-sized cars, whose data come from the THELMA project. In this way, a comparison among the different biofuels produced and the conventional fossil fuels or the different electricity mix have been used as references, in order to understand which are the most promising pathways for powering a vehicle. For this part of the thesis the functional unit has been set equalt to one vehicle kilometer (vkm), to allow the comparison of the different vehicles in covering one kilometer.

These processes are modeled using the SimaPro v8.04 software using information from available literature, personal interviews with experts and scientists, and the existing datasets in the ecoinvent database.

The results obtained suggest the best environmental way to exploit the different biomass resources for light duty vehicles in the Swiss transportation sector.

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List of Abbreviations

LCA – Life Cycle Assessment
SNG – Synthetic Natural Gas
WTT – Well to Tank
TTW – Tank to Wheel
WTW – Well to Wheel
PSI – Paul Scherrer Institut
SCCER – Swiss Competence Centers for Energy Research
BIOSWEET – Biomass
HTL – Hydrothermal Liquefaction
HTG – Hydrothermal Gasification
FP – Fast Pyrolysis
FU – Functional Unit
PSA - Pressure Swing Adsorption
SRF – Short Rotation Forestry
OPR – Open Ponds Race
PBR – Photo Bio Reactor
RER – European
RoW – Rest of the world
vkm – vehicle*kilometer
MJ – Mega Joule
LHV – Low Heating Value

1. Introduction

The global demand for fossil-based energy sources (e.g. crude oil, natural gas, coal) is growing due to an increasing population as well as a growing need for energy to further industrialization and mobility(Surendra, Takara, Hashimoto, & Khanal, 2014) .
Yet, this demand is progressively depleting existing fossil sources and contributing to the rising concern about global warming, as combusting fossil fuels increases emissions of greenhouse gases (GHGs) that warm the atmosphere (EC, 2006). Since 1990 to 2013 the increase in CO_2 emissions in the transport sector has been of the 68% (IEA, 2015). According to EPA 95% of global transports relies on petroleum-based fuels like gasoline and diesel (EPA, 2016). Therefore, to satisfy demand for more energy, increased efforts have been made to find alternatives to fossil-based sources. Biomass is one such alternative among many renewables energies.
In Switzerland, the transport sector has the largest energy demand of all sectors, larger even than the households and industry sectors (IEA, 2012). In 2010 the CO_2 emissions attributable to the transport sector were 44 Mt, and since 2000 the Swiss government has introduced a law for the reduction of the CO_2 emitted, the CO_2 act. This law attempts to reduce the emissions starting from a voluntary basis, but if these voluntary measures reveal insufficient, a tax on the CO_2 emissions will take place. In 2005 another initiative, coming from the private sector, is the Climate Cent initiative that also attempts as well to reduce the CO_2 emissions coming from the transport sector, by introducing a surcharge of CHF 0.015 per liter on gasoline and diesel. This surcharge will help financing the reduction of the CO_2 emissions, in order to avoid the introduction of the CO_2 tax on transport fuels. But from 2013 this initiative has been “replaced by a legal obligation on oil importers to offset directly a part of the CO_2 emissions from transport fuel use” (IEA, 2012). Lastly since 2012 the emissions limits of the new car fleet were set equal to those applied by the EU regulation (130gCO_2/km) (IEA, 2012).
Knowing all of this it is possible to assess how the current situation is not any more sustainable, especially from the environmental point of view, but also from the point of view of the human health. Recently in the COP21 (Conference of Parties 21, 2016) it has been declared that if the emissions trend continues in this way, it would be easier to get to the point of no return of the 2°C increase of global temperature. So now more than ever it is worldwide known that some measures must be undertaken.

Biofuels have the potential to play a large role globally as they have the excellent advantage as drop-in fuels to directly or even partially substitute in the existing fossil fuels, for example in the transport sector (EC, 2006) where infrastructures and vehicles are durable in the economy, easing the infrastructure concerns. Although on one hand biofuels will emit CO_2 that is carbon neutral when burned in engines, on the other hand when they are burned they will still, like fossil fuels, emit other hazardous compounds, like NOx, NMVOC, HC, so health concerns about this fuels are still present, and must be considered.

Starting from biomass there is thus the possibility to convert it to biofuels different from the most used ones (i.e. gasoline, diesel, methane), we are talking about electricity and hydrogen, which “can offer the opportunity to “de-carbonise” the transport energy system” (Kahn Ribeiro & Zhou, 2007) having the advantage of a better tank-to-wheel efficiency, and most of all they have no direct exhaust emissions at the tailpipe. Unfortunately the carbon reduction associated to these energy carriers is strictly related on how the hydrogen and electricity are made, so that the infrastructures and pathways might be more complex (Kahn Ribeiro & Zhou, 2007).

Moreover, the biofuels production is usually energy intensive, because many operations needs to be accomplished until the final product is finished, and in some cases the growth of the biomass must be enhanced by the use of fertilizers, which are energy intensive as well and which may cause further environmental problems through their production (e.g. water eutrophication).

The choice that needs to be made is not a simple one, as it is not easy to answer to the question: which are the best fuels for transportation?
That is why a tool in easing this decision must be adopted, like the Life Cycle Assessment (LCA), which may help in analyzing the environmental burden of the different fuels and the pathways investigated for producing them, providing a standardized methodology.

In Switzerland, as will be explained in more detail later, among the available biomass feedstock the ones really exploitable are wood and manure biomass. This feedstock can be used for producing biofuels in many different ways but both of them might have an optimal way to be used as transport biofuels.

However, in order to exploit the potential of biomass, it is necessary to resolve the food versus fuel debate; that is, biomass is an edible crop as well as a feedstock for fuel production. According to the (IEA, 2008) these are the definitions for first, second and third generation biofuels:

- First-generation biofuels are those coming directly from agricultural crops, thus they are in direct competition with the food production sector;

- Second-generation biofuels are those that have a non-fossil origin, and they can come from the forestry or industrial sector, as main products or as residues, but in any case, they are non-food feedstock. In this optic, also municipal waste can be seen as a second-generation biofuel source;

- Third-generation biofuels are those that do not come from any agricultural or forestall feedstock, but are those that can be cultivated into water fields, like open ponds (i.e. algae);

The production of current so called “first generation” biofuels requires intensive agricultural practice and large land areas (Iribarren, Peters, & Dufour, 2012), which competes with the land dedicated to growing food crops. In order to generate biofuels sustainably without threatening food supplies, the availability of “second (or third) generation” biofuels – biomass grown in areas not suitable for traditional food crops (e.g. algae ponds), will play a crucial role for a future sustainable biofuel production. Furthermore the Swiss government has modified on the 21/03/2014 the “Mineral Oil Law” specifying that no financial support will be given to those biofuels that come from crops feedstock (Federal Department of the Environment, 2016).

1.1 Swiss Situation

In the previous chapter, it has been determined why biofuels can be a valid replacement as a primary energy source for transportation, while in this chapter the Swiss energy and transport situation will be described.

According to the Transport Research Programme of the Swiss Federal Office of Energy (Federal Department of the Environment), it is possible to see, as stated above, how the transport sector is the country’s major energy consumer with its 36.4% of the energy consumption.

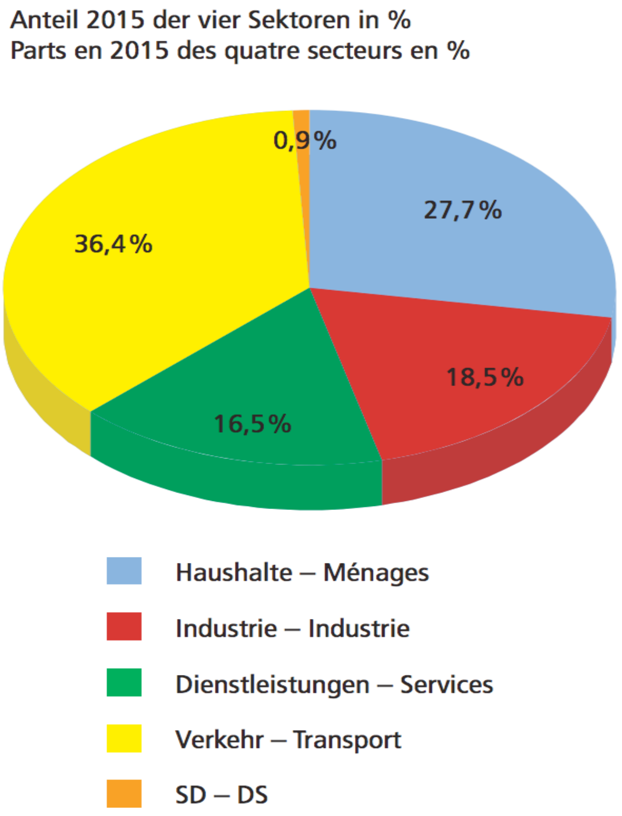


Figure 1: Energy consumption per energy sector

Regarding the energy sector instead, after the Swiss Federal Council and Parliament's decision to phase nuclear power out of Switzerland's energy mix goes into effect, the Swiss energy system will be restructured according to the long-term energy vision plan "Energy Strategy 2050". The new energy strategy is ambitious calling for reduction in energy demand through efficiency measures while retaining current CO2 targets, displacing large shares of conventional fossil energy, and expanding the use of renewables forms of energy (E4tech).

The Energy Strategy 2050 plan is based on the "Energy Perspectives" document formulated by the Prognos AG company (Prognos, 2012), in which have been laid out different scenarios out to 2050:

- the "BAU" (Business As Usual) scenario in which current policies shall remain in place and improvements will remain at their historical rates;
- the "POM" (Political Measures) scenario, where current policy measures are implemented effectively, leading to a reduction of the final energy demand of the 33% (from 841 PJ to 565 PJ);
- the "NEP" (New Energy Policy) scenario, where the final energy demand decreases even further, dropping 46% (from 841 PJ to 451 PJ) of the final energy demand. In this scenario the annual reduction of GHGs are expected to be 1-1,5 t per capita.

To achieve the goals of the long-term energy plan, bio-energy will play a very important role in both the POM and NEP scenarios. In order to help in the shift to this new energy system, the Swiss government has created seven Swiss Competence Centers in Energy (E4tech). This thesis as a part of the SCCER Mobility, assesses which is the best environmental way to use the available biomass within the Swiss territory for converting it in biofuels, which then will be used for powering different mid-sized vehicles. The SCCER Mobility project "aims at developing the knowledge and technologies essential for the transition of the current fossil fuel based transportation system to a sustainable one, featuring minimal CO_2 output and Primary Energy Demand as well as virtually zero-pollutant emissions"(SCCER-Mobility) . The SCCER Mobility are parallel research competence centers with the SCCER BIOSWEET (BIOmass for Swiss EnErgy future) that is "a consortium of 15 partners from 9 academic institutions and more than 30 cooperating partners from private or public sector organizations", which is coordinated by PSI (Paul Scherrer Institut) (BIOSWEET, 2016). SCCER BIOSWEET "focuses on the engineering and implementation of biochemical and thermochemical biomass conversion processes with a high level of technological readiness and sustainability" (BIOSWEET, 2016) and with the vision in mind to increase the role of bio-energy to the Swiss energy system it is targeted that an extra 100 PJ can come from these kind of sources: 33 PJ from woody biomass, 33 PJ from bio-wastes and manure and 33 PJ from algae (Prognos, 2012).

A paper where the sustainable biomass potential in Switzerland is assessed is the one written by (Steubing, Zah, Waeger, & Ludwig, 2010). In this study is made a difference between the technical biomass potential and the sustainable one. The first is merely all the biomass that is technically available in Switzerland in one year, while the second is all the biomass that is sustainably available, where 'sustainably' means that other constraints apart from technical ones, namely economic, social, political and environmental ones. Then a further distinction is made between the sustainable biomass, and the already used one and the still available one are thus considered.

Below a summary table is presented:

Biomass Resource	***Sustainable Potential [PJ]***	***Used Potential [PJ]***	***Remaining Potential [PJ]***
Animal Manure	21.4	0.2	21.3
Forest Wood	23.7	15.7	8
Wood from Landscape maintenance	6.6	3	3.6
Waste wood	7.4	3.8	3.6
Food Industry Waste	2.6	2.3	0.3
Biowaste	5.6	3.2	2.4
Total	67.3	28.2	**39.2**

Table 1: Swiss biomass energy potential

Another work has been recently done and will be published next year, realized by (Thees, 2017), that assesses the Swiss biomass potential. It was however possible to get from the authors the data on which they are still working, and so far, it is possible to see that their counting does not differ substantially from those made by Steubing et al. in his study.

A summary table is then displayed:

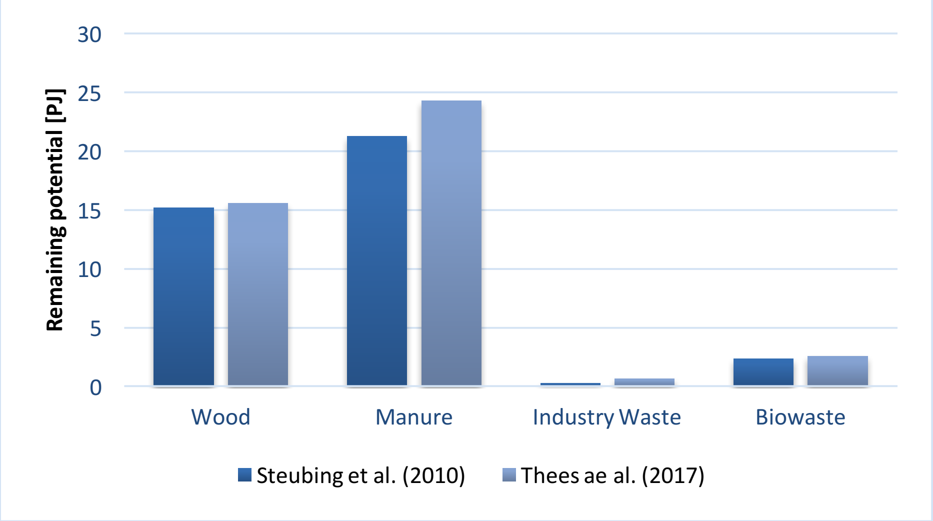


Table 2: Swiss biomass potential

According to these statements we are going to consider all sources that have a non-zero remaining potential. As it is possible to see from *Table 2* wood and manure are the sources taken into account because they are the most promising.

Nevertheless, the algae cultivation and exploiting for biofuels production is considered, even if their production is not possible in Switzerland due to the non-optimal weather and latitude conditions. Although is reasonable to think that if this technology reaches its technological maturity, an abroad production can be possible, and thus the import of the biofuels so produced can be a nice way to help in the transition to a cleaner and sustainable mobility system.

1.2 Research Goals

The most important goal of this thesis is to assess the environmental impacts of producing biofuels from wood, manure and algae for transportation and which could be the future improvements related to it.

To do that a Life Cycle Assessment (LCA) was performed in two parts. The first part assesses the environmental burden of the biofuels production, and the second one investigates the actual use of biofuels in different mid-sized vehicles.

The type of fuels produced are gasoline, diesel, methane, electricity and hydrogen. All of them have been produced starting from a specific biomass source.

A further explanation on how the two parts of the LCA have been carried on is the following:

1. Well-To-Tank (WTT) analysis of a biomass based fuel pathway including all steps that are in between the biomass collection through processing to finished fuel, that is ready to be fed to a car or can be blended to conventional fossil fuels (this depends on the type of car used).
2. Tank-To-Wheel (TTW) analysis including the combustion of the fuels modeled into *internal combustion engine vehicles* (ICEV), or the usage of the electricity produced into the *battery electric vehicles* (BEV), and of the hydrogen into the *fuel cell electric vehicles* (FCEV).
   WTT and TTW analysis are combined to provide a total Well-to-Wheel (WTW) analysis. The results of the WTW analysis examine the full environmental impacts of these fuels and with the availability of the data of different medium size cars from the THELMA Project, it is possible to assess also the burden of these fuels produced when burned or used in different transportation units. In other words this thesis will complete a full Cradle-to-Grave LCA analysis of transportation technologies powered by different bio energies sources that can also help to inform future policy decisions.

Using the same WTW analysis method, two scenarios are analyzed:

- A *“**Current or Baseline Scenario**”* where the existing technologies are evaluated with the present-day data inputs. These inputs have been gathered from the available literature when not present into the Ecoinvent database v3.1. This will help in considering where the weaknesses in these technologies are, and which actions should be pursued in the future to make them more efficient and environmentally competitive.

- An ***“Optimized Scenario”*** where the previouses processes considered are updated to an improved situation, considering an increase in potential efficiencies, the removal of leakages, and cleaner processes that may allow reduction in emissions.

The thesis is to be performed within the Technology Assessment group in the Laboratory for Energy Systems Analysis and the Paul Scherrer Institute (PSI) in Villigen, Switzerland. It is part of the THELMA project where good LCAs of different transport units are already available and will be a help to assess how the biofuels investigated in this work will behave, as in the THELMA project there is a lack of data concerning cars ran with biofuels.

2. Literature Review

This section has been conceived as a means of helping the reader to better realize the current status of the literature on the topic of the LCA of different biofuels and their possible updates, so that their understanding of the following chapter might be easier.

The papers chosen are those considered to be the most important in order to realize this research whose goal is to compare different ways to produce biofuels using the available biomass in the Swiss territory.
Some distinctions should be made to categorize the papers read:

1. Review papers to better understand the state of art for the current biofuels production and the available biomass in Switzerland;
2. Papers where the LCI is available and adaptable for the goal to compare different fuels' production;

Not all of the papers read are going to be here exposed, but is important to say that a great effort has been made in collecting and reviewing them in order to achieve a good result in the research work and in the LCA, so that the correct inputs are chosen, and in order to make the assumptions in the Optimized Scenario strong enough.

2.1 Literature on the Swiss situation

"Bioenergy in Switzerland: Assessing the domestic sustainable biomass potential" (Steubing et al., 2010)

In this study the authors have analyzed the current situation in Switzerland related to the available biomass potential. Two kinds of biomass potential have been assessed: the technical and the sustainable one. The first is characterized by the biomass hypothetically and technically available in Switzerland considering one year. The second instead is under certain sustainable constraints like the economic, political, environmental and social ones. After this subdivision, other two categorizations have been accounted, in order to consider the biomass energetically already used, and the one that is not yet exploited.

The conclusion of this work has been summarized in table 1 in sub-chapter 1.1.

"Life Cycle Inventories of Bioenergy - ecoinvent report No. 17" (N. Jungbluth, 2007)

In this work, different pathways for producing fuels for powering transport devices are explored, because of the depletion of fossil fuels and the environmental impact due to their consumption. In order to do that biofuels, represent a viable solution because they are renewable and can directly substitute fossil fuels.

The main goal of the study of (N. Jungbluth, 2007) is to update the ecoinvent database v1.2 gathering life cycle inventory (LCI) data regarding the production of energy products from biomass. In ecoinvent v1.2 the data already available are related to the following products:

- Forestry
- Agricultural products from Switzerland
- Wood fuels
- Use of wood for heating and CHP

The report can be divided in three phases. The first one where different biofuels (e.g. ethanol, biogas) are produced and used considering also the agricultural products needed for the conversion process. The usage of these investigated biofuels in different transportation units is also examined.
The second phase studies instead the imported biofuels in Switzerland. This way an analysis on the biomass production and subsequent conversion has been performed considering different countries. Once again the use of these biofuels in transport devices has been considered.
In the last phase a particular focus was set on modern biogas plant with cover on the storage, that helps in reducing the methane emission.

Regarding this ecoinvent report, particular emphasis has been put in two chapters of it. The first is chapter 13 “Use and Upgrading of Biogas” (Spiellmann, 2005) where biogas purification process, and combustion in cogeneration engines are explored, and LCIs of them are produced. Only the purification process of the biogas has been considered for this thesis.
The second one used is chapter 18 “Synthetic biofuels”(A. Dauriat, 2006). Life cycle inventories of synthetic biofuels are in it explored. Mostly the focus is set on the upgrading of the synthetic natural gas (SNG) produced from the gasification of wood biomass. The two pathways explored are respectively the production of methanol and methane starting from the syngas. The only pathway considered in this thesis is the one related to the production of methane.

“Harmonization and extension of the bioenergy inventory assessment - end report” (Mireille Faist Emmenegger, 2012)

This study has been done with the purpose of upgrading and extend the ecoinvent inventories of 2007 by EMPA that is the Swiss Federal Laboratories for Materials Science and Technology.

Compared to this thesis many pathways and biofuels have been explored, considering different crops and conversion processes, and an unconventional way of producing fossil fuel (i.e. synthetic crude oil from Canadian Oil Sands).
The report can be divided in three parts. In the first one the main focus is toward the

biomass production and agricultural processes inventories. Regarding that a new way on counting nitrogen emissions was adopted. Furthermore, for counting the emissions related to the land use change a unified method has been developed, as in the ecoinvent database these emissions are associated only to the cutting of rain forest. Finally, new inventories of Jatropha and other grass mixtures were created.

In the second part the focus is shifted to the development of the inventories of the conversion steps from the raw biomass till the finished fuel, that are not included in the ecoinvent database, or the update of the present ones. The HTG pathway, the BCM (Biomass- CO2-Methane) purification process, the incineration of the MSW (Municipal Solid Waste) and the extraction of the oil contained in the sands from Canada have been taken in account.

In the final part an update of the work of (R. Zah, 2007) with the new crops and processes investigated has been performed.

This paper considers both the biofuels that are producible from crops in Switzerland and from outside of the country, without taking into account if there is a real possibility of doing that, this can be considered as a weakness of the study.

At the end of the report the authors show how the biofuels investigated do not perform much better than the fossil reference except for the Global Warming Potential and the Ozone Depletion Potential categories.

2.2 Papers directly used for modeling the processes

"Life cycle assessment of transportation fuels from biomass pyrolysis" (Iribarren et al., 2012)

In this paper the LCA of the production of diesel and gasoline fuels, through the fast pyrolysis process of poplar wood from short rotation forestry (SRF), has been conducted. The system used to process the woodchips obtained from the poplar wood is a circulating fluidized bed reactor (because it has been considered as the optimal technology solution for this process), where mainly a bio-oil among other gaseous or solid substances is produced. This bio-oil extracted is then upgraded through a hydrotreating and a hydrocracking process in order to get the finished fuels in different proportions, respectively 43% of gasoline and 57% of diesel.

Many indicators were analyzed for the LCA conducted, that goes from cradle to gate, meaning that no considerations are done regarding the fuel usage in a vehicle. In this way, the GWP emissions are considered negative, because the poplar wood is considered as CO_2 sink. A mass and economic allocation of the fuels produced is performed within the study. Respect to this work the data used in the thesis have been adapted to the Swiss contest, forest wood waste has been used instead of the poplar one (which requires also the usage of fertilizers to grow) and furthermore the actual usage of the fuel produced has been considered for powering a car covering one vehicle kilometer (vkm). In order to make this kind of analysis more complete and comparable with other studies on the same topic, we suggest that a different approach like the one carried out in this thesis should be done, to make easier the comparison among the data obtained, when comparing transport fuels.

"Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Assessment" (Luterbacher et al., 2009)

In this paper the hydrothermal gasification (HTG) of waste biomass (i.e. manure, waste wood) has been modeled. This is a promising process, because uses the water for processing the biomass in its critical conditions – temperature and pressure above the critical point – and in this way, it permits to save the energy usually needed in the pretreatment stage of the raw biomass for drying it. Three scenarios are considered in the paper of (Luterbacher et al., 2009):

- Large-scale plant for processing manure feedstock (155 MW_{SNG})
- Small-scale plant for processing manure feedstock (5.2 MW_{SNG})
- Medium-scale plant for processing wood biomass (35.6 MW_{SNG})

Only the first and the last one have been used in this thesis. The first one because of the larger manure biomass potential in Switzerland compared to the wood one, as stated in sub-chapter 1.1. The synthetic natural gas (SNG) produced at the end of the process is composed for its 95% with CH_4 and for its 4% of CO_2, so totally similar to the natural gas in the grid.

Considering the manure biomass feedstock an assumption made in this paper is that the quantity of manure not spread on the soil must be replaced with a mineral fertilizer that is even more efficient than the manure itself, and also not spreading the manure is considered an avoided process. Despite these assumptions in the paper of Luterbacher et al. are made, they have not been considered for this thesis, because in all the other processes considered using manure as input these assumptions are never contemplated.

In the process is assumed that part of the heat and of the electricity are produced in the plant itself through a CHP plant. For a good exploitation of the heat produced a pinch point analysis has been performed. Meanwhile a LCA has been conducted to calculate the environmental burden of the production of this type of fuel. The methods used for calculating the environmental impacts are the GWP indicator, the Ecoindicator and the Ecoscarcity methods. The allocation method instead used is the one that considers the avoided production of part of the mineral fertilizer needed and of the electricity produced in excess respect to the necessity of the plant, that is then distributed to the grid.

All of the processes considered have been modeled in theory, because there is a lack of available data for such a plant.

Considering the GWP indicator the results obtained by this paper are different respect to those obtained by this thesis, because are always negative and do not consider the actual use of the fuel produced for powering a vehicle. This is a weakness of this paper because in this way the comparison with other fuels modeled for powering a vehicle is not easy to make.

“Algae biodiesel life cycle assessment using current commercial data” (Passell et al., 2013)

This document has been used within this thesis because of the availability of the life cycle inventory in it. The study from Passell et al. deals with the production of biodiesel starting from the cultivation of microalgae and the subsequent extraction of the oil contained in it, using which are considered to be the current commercial data.

Two scenarios are hypothesized in it, a current scenario, like the one that has been assumed in this thesis and an optimized one. In the first scenario, all the current data taken from an existing facility operating in Israel have been taken. The size of the current facility considered is 1000 m^2. The algae strains used are: *Nannochloris sp.* and *Nannochloropsis sp.* with a biomass productivity of 3 $g/m^2/day$ and an oil yield of 0.24 kg oil/ kg dry algae. The source of CO_2 needed for the growing of the algae are the flue gas of a power plant co-located to the facility. The other nutrients needed are instead supplied using mineral fertilizers as a source of phosphorous P and nitrogen N.
The algae cultivated are then harvested and dewatered till the obtainment of a solution of 20% solid. After the dewatering step a wet extraction method is used for extracting the oil contained in the algae, using a chemical solvent for the recovery of the oil extracted. The solvent used is then retrieved.

Among the bio-oil extracted from the algae two other co-products are available at the end of the process, low value lipids and the residual biomass (also known as oilcake). These two co-products can have a good economic value if used in the pharmaceutical, or alimentary sectors, or as animal feed (Beal et al., 2015). Instead of an economic allocation an energy one has been performed and then maintained in the thesis because consistent with the allocation method chosen (for further explanation have a look at sub-chapter 3.2).

The optimized scenario instead represents the same facility, but scaled 100 times bigger. The same algae strains are supposed to increase their biomass productivity to 25 $g/m^2/d$, and their oil yield to 0.5 kg oil/ kg dry algae. Furthermore, the devices used for dewatering and drying the algae before the oil extraction are assumed to increase their efficiency accordingly to the scaling up of the facility.

A LCA has been conducted for both the base and the optimized scenario, considering the following indicators: GWP, Photochemical Ozone Formation, Particulate Matter, Water Depletion, NER (Net Energy Ratio), NO_x and SO_x. From the results obtained in the analysis is possible to show how using the current technology, and a small-scale facility, is nearly

impossible to produce a biofuel starting from this feedstock, because of the huge environmental burden. The main problem is the energy demand required for cultivating and processing the algae is massive, not to mention the fact that stronger and more productive algae strains must be discovered or created.
Already in the optimized case of this document the kg of CO_2 eq. emitted per MJ of fuel combusted in a vehicle are drastically reduced.

This document and the LCA assessment conducted in it are of great interest, because they point out how developments in the cultivation and harvesting steps are strongly needed. However, one weakness of this document analyzed is that no inventories for the structure required for the facility are implemented. That is why the structure of such a facility has been implemented in the thesis. Another limitation is then represented by not having included in the work the usage of the fuel produced for powering a vehicle, in this way a comparison among different fuels would have been much simpler.

"Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment" (Beal et al., 2015)

This is the last paper used in this thesis for modeling the production of biofuels starting from algae. This document has been considered because it includes in it an already well optimized model of a possible large-scale facility for cultivating and process algae. The facility included is 100 ha large, also in this case the source of carbon for the algae's growth is supplied by a CO_2 waste stream co-located to the plant and in many of the scenarios analyzed the fertilizers used as nutrients are reutilized. The functional unit chose is 1 ha to allow the comparison with conventional crops and co-products of the processes are not allocated of any environmental burden.
Many scenarios have been carried out in this work (i.e. 10) and two algae strains have been used, *Desmodemus sp.* and *Staurosira sp.* The first one is used for considering a base case, where the current but inefficient processes for harvesting and processing the algae in order to extract the oil contained in them. All the other scenarios investigated use the other strain and consider different ways for processing the algae produced. In the end two target cases are outlined by the authors, and these target cases have been used as our optimized cases. These optimized cases are the most promising, consider a less usage of energy, the electricity used come from a renewable source, and the processes for extracting the oil content are the hydrothermal liquefaction, in order to use the water in its critical conditions where it behaves as a solvent, and a wet extraction process named Openalgae that uses electromagnetic forces for splitting up algae's cells and allow an easier recovery of the oil extracted.

In the document an energetic, economic and environmental analysis are carried out. Even of the energetic and environmental analysis show great results in most of the cases analyzed the economic one shows how currently a large-scale plant as this one is not right now feasible if not with some further improvements in the design facility and in reducing the costs related to make the facility work. Nevertheless, this document shows how environmentally, there are great possibility of enhancing the cultivation of algae. One weakness though encountered in this document is that the fuel production is not really considered, but is just mentioned as an avoided product. Also, the functional unit could have been different as mainly from this biomass the first objective is to produce biofuels, and the 1 ha one maybe is not that effective. This leads as in the different papers already described to a situation where the comparison among the different biofuels becomes very difficult.

2.3 Comparison table

In this section a table, where the different documents analyzed will be compared, is presented below:

Authors	**LCIA methods (Midpoints Indicator)**	**Methodological Choices**
Jungbluth (1)	Environmental Impact Points UPB 06: Ecological Scarcity Eco-Indicator 99	Economic Allocation co-products
Emmeneger (2)	GWP 100a IPCC 2001 GWP 100a IPCC 2007 ILCD midpoints CML	When possible allocation on physical basis (mass or energy) otherwise economic allocation
Iribarren (3)	CML	Mass and economic allocation
Luterbacher (4)	GWP 100a 2007 Eco-Indicator Eco-Scarcity	Avoided Products and Emissions
Passell (5)	Various Indicators Considered	Energy Allocation
Beal (6)	Impacts 2002 Impacts Assessment Methods	Avoided Product Allocation

Table 3: Literature review comparison

(1) (N. Jungbluth, 2007); (2) (Mireille Faist Emmenegger, 2012); (3) (Iribarren et al., 2012); (4) (Luterbacher et al., 2009); (5) (Passell et al., 2013); (6) (Beal et al., 2015)

(1) and (2) have been used has references for comparing this thesis, as they deal with the biofuel production on the Swiss territory as well. (3)(4)(5)(6) have been harmonized and

used in order to reach the goal of this thesis.
In the discussion section the results obtained for the GWP indicator will be discussed.

3. Methodology

3.1 Life Cycle Assessment (LCA)

In order to assess the environmental burden of the processes explored in this thesis LCA is an important standardized method that quantifies the environmental impacts of goods and processes from "cradle to grave", thus considering the whole life of a product. This can be a significant tool for better understanding how a single process can affect human health and the environment, in this way is then possible to identify the actions that can be really undertake to improve and optimize the processes.

In order to explain to the reader the general concepts at the base of the LCA method, the information are gathered according to the document of (Stoppato, 2013).
For the standardization of the method the ISO 14000 series standards have been used, as they are worldwide generally accepted as a shared reference to execute an LCA.

The ISO 14040 series is constituted of two norms, each of them devoted to a specific part of the methodology:

- ISO 14040: 2006 - Environmental management- Life cycle management- Principles and Framework;
- ISO 14044: 2006- Environmental management- Life cycle management - Requirements and Guidelines;

According to the (ISO, 2006) the current definition of LCA is the *"compilation and evaluation of the inputs, outputs, and potential environmental impacts of a product system throughout its life cycle"* and this can be made in four different steps:

i. *Scope and goal definition*
ii. *Life Cycle Inventory analysis, LCI*
iii. *Life Cycle Impact Assessment, LCIA*
iv. *Interpretation*

3.2 Scope and Goal definition

It is very important that before starting a LCA, the goals and scope of the analysis are well defined. It must be very clear at the start of it what the motivations behind the analysis are, and what kind of audience could be interested in it and in its results (Stoppato, 2013).
It is then possible to fix the **Functional Unit** and the **Boundaries** of the system investigated. This is a central operation, as according to it the results may change significantly, and a good

choice could help the final reader to better understand what the work is trying to communicate.

In this thesis, the Functional Unit fixed for the first part of the LCA is 1 MJ of transport fuel in the form of gasoline, diesel, bio methane, hydrogen or electricity, because in this way it is possible to compare the results obtained with values found in literature. For the second part of the conducted LCA the function unit chose is vkm (vehicle kilometer), as it allows comparing different mid-sized vehicles covering 1 km. The results obtained when comparing the different vehicles are not directly comparable with the literature values, because of the large variation of the LCA results and energy consumption of the cars.
Other Functional Units (FUs) could have been chosen, but as we are comparing energy carriers, it seemed more appropriate to compare an energy functional unit for the first part and a vehicle unit for the second. The interest of this thesis resides in exploring the different pathways from biomass to transport, which is why we use the FU of vkm. However, in order to compare with other biofuel studies, we also calculate results with the FU of MJ.

Regarding the boundaries of the process considering the first part of the LCA they are related to the fuel production. In this case the process starts from the collection of the raw biomass that usually leads to an intermediate product (e.g. biogas). The intermediate is then upgraded to the finished fuel. Not in all the processes there is this intermediate step, as for example when burning the wood chips in a cogeneration plant for producing electricity.
Considering instead the second part of the LCA the produced fuels are used for powering different vehicles, so for every process also the production, the usage and the disposal of the car is considered.

3.3 Life Cycle Inventories (Collection) - LCI

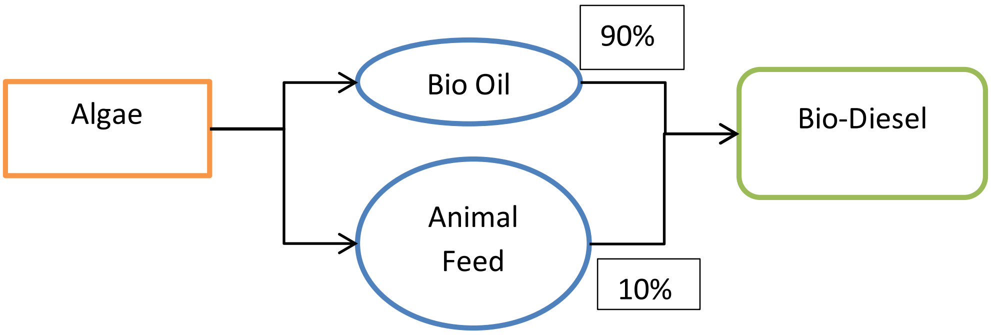
This phase of the analysis is about the gathering of the data that constitute the input and output flows of the system. This way it is possible to quantify the streams of materials and energies coming from the environment, and the emission into it, together with the wastes that are produced by the various processes.
This is a very delicate phase, as the results obtained at the end of the calculation, will be entirely dependent on this kind of data. That is why the LCA practitioner should put a lot of efforts in it, to make his analysis the most realistic possible, knowing however that it is by no means an easy task (Stoppato, 2013).

In this thesis, the ecoinvent database v2.2 and 3.1 have been used for modelling different processes that are available in it. The ecoinvent database is a Life Cycle Inventory (LCI) database, and is one of the most extensive ones, as it includes processes for different areas going from energy supply to waste treatments, and is worldwide known as one of the largest database (SimaPro, 2016). When the processes investigated were not present in the ecoinvent v2.2 and 3.1, LCI from the papers mentioned in the literature review have been used instead.

Furthermore, when a process has multiple outputs a way of determining how much the process burdens are allocated to each product must be decided.

Most of the time the allocation method used is the one that considers the mass of the different products (Stoppato, 2013). In this work an energy allocation method has been chosen when dealing with multi products outcome (e.g. gasoline or diesel produced together from the pyrolysis process) or an exergy allocation method when dealing with the cogeneration plants. Instead of the energy allocation method this one has been preferred, as it is a good way to consider the electricity a form of energy more valuable respect to the heat co-produced, for which a heavier environmental burden must be attributed to it. Another way of considering these processes was realized when modeling one of the algae pathways investigated in this thesis. In that case an energy allocation, among the different outputs has been performed, in order to consider only the environmental burden associated with the biofuel production. Nevertheless, also a system expansion of the process has been considered, which means that together with the biofuel production the biomass remaining after the oil extraction was considered as an avoided production of animal feed. In this way, this avoided product represent a credit in different impact categories.

An example will be shown below:



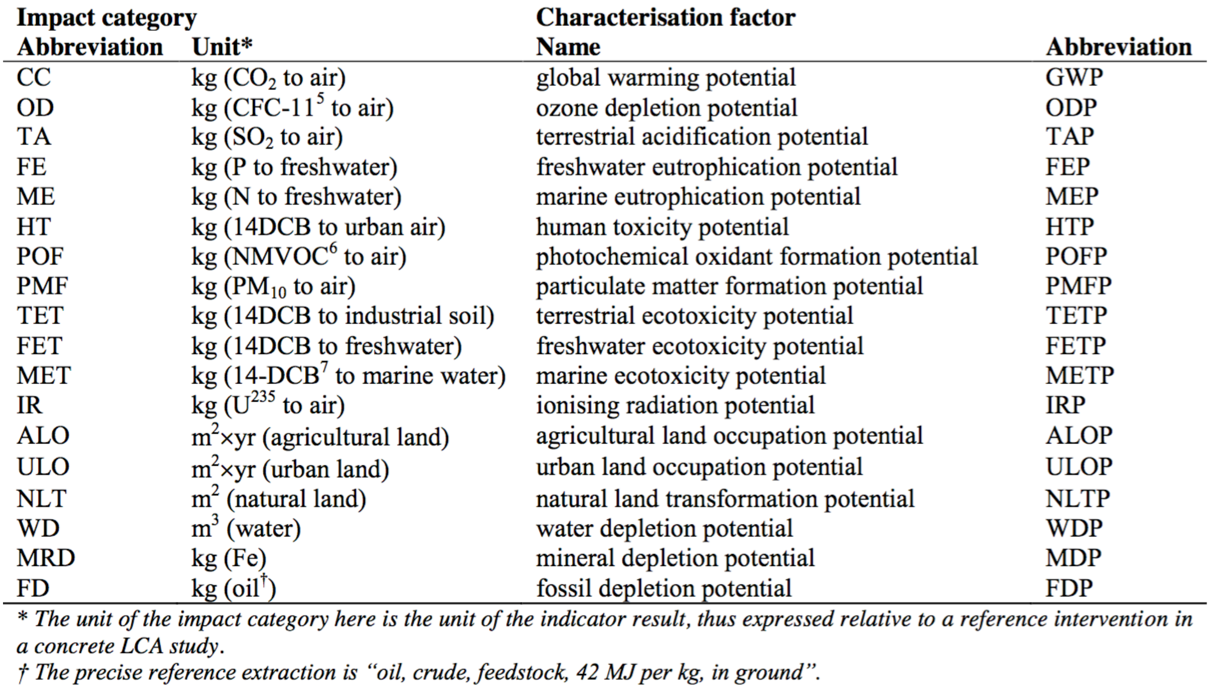
From the same input, which is algae, it is possible to obtain two coproducts, which are the Bio-oil extracted from the algae and the animal feed that is constituted by the remaining biomass. When allocating the different burdens, the 90% of it can be referred to the bio-oil produced, while the remaining 10% to the coproduct.

3.4 Life Cycle Impact Assessment (LCIA)

In this phase the environmental burden carried by all the inputs and outputs in the LCI are evaluated and shown in different impact categories, related to the human health, the environment and the resource depletion. In other words, the scope of this phase is to quantify the environmental changes due to human activity.

The calculated impact categories are strictly related to the method chosen. This work is based on the ReCiPe Method v1.08 according to (Mark Goedkoop, 2013), with the Hierarchical (H) perspective, which consider a lifetime of 100 years. This method has been chosen above the others, because it is well accepted in the LCA community and is quite up-to-date (Mark Goedkoop, 2013).

The midpoint indicators are those shown in the table below:



Impact category		Characterisation factor	
Abbreviation	**Unit***	**Name**	**Abbreviation**
CC	kg (CO_2 to air)	global warming potential	GWP
OD	kg (CFC-11[5] to air)	ozone depletion potential	ODP
TA	kg (SO_2 to air)	terrestrial acidification potential	TAP
FE	kg (P to freshwater)	freshwater eutrophication potential	FEP
ME	kg (N to freshwater)	marine eutrophication potential	MEP
HT	kg (14DCB to urban air)	human toxicity potential	HTP
POF	kg (NMVOC[6] to air)	photochemical oxidant formation potential	POFP
PMF	kg (PM_{10} to air)	particulate matter formation potential	PMFP
TET	kg (14DCB to industrial soil)	terrestrial ecotoxicity potential	TETP
FET	kg (14DCB to freshwater)	freshwater ecotoxicity potential	FETP
MET	kg (14-DCB[7] to marine water)	marine ecotoxicity potential	METP
IR	kg (U^{235} to air)	ionising radiation potential	IRP
ALO	m^2×yr (agricultural land)	agricultural land occupation potential	ALOP
ULO	m^2×yr (urban land)	urban land occupation potential	ULOP
NLT	m^2 (natural land)	natural land transformation potential	NLTP
WD	m^3 (water)	water depletion potential	WDP
MRD	kg (Fe)	mineral depletion potential	MDP
FD	kg (oil[†])	fossil depletion potential	FDP

** The unit of the impact category here is the unit of the indicator result, thus expressed relative to a reference intervention in a concrete LCA study.*

† The precise reference extraction is "oil, crude, feedstock, 42 MJ per kg, in ground".

Image 1: Mid-point Indicators - Source:(Mark Goedkoop, 2013)

The midpoint indicators considered for this thesis and a short description of them is therefore shown:

- Climate Change: was chosen for obvious reasons. It regards the effect of the Green House Gases (GHGs) on the human health and on the environment, which are responsible of the global warming. Each compound considered in this category has its own potential, based on the value given to them by the Intergovernmental Panel on Climate Change (IPCC), founded on its capacity to absorb the radiations and on the permanence time in the atmosphere. For example the CO2 has a potential impact value of 1 while the CH4 has a potential impact value of 25;

- Freshwater Eutrophication: is the potential due to the rise of the nutrients levels into the water bodies, especially nitrogen and phosphorus (Mark A. J. Huijbregts, 2014). This indicator was chosen because in some of the processes investigated there is the use of fertilizers (i.e. algae) or of catalysts;

- Particulate Matter Formation: this impact can affect the human health, because the small particles emissions from the combustion of the fossil fuels, or from the interaction with the atmosphere, can deeply enter into the lungs and cause dangerous respiratory problems. This indicator is commonly used when dealing with transports;

- Natural Land Transformation: the impact caused by the transformation of the original characteristic of a land (Abhishek Chaudhary, Francesca Verones, Laura de Baan, Stephan Pfister, & Hellweg, 2014). As biofuels are worldwide known for being responsible of the land use change, we thought that is worth considering this impact category as well;

The other midpoints will not be displayed not because they are less important than the one considered, but because for the goal of the thesis these midpoint indicators seemed to be more effective, and also for a matter of space to be dedicated in the work. Nevertheless at the end of the thesis, the results calculated for all the others indicators will be showed for those who may be interested in it.

3.5 Interpretation

At this phase the results obtained can finally be analyzed, so that significant problems, completeness, reliability and sensitivity can be outlined.
After running a process with the SimaPro software v8.04, it is possible to discern which are the items in the process that require more investigations, in order to explain why they are so badly affecting the entire process, or some specific impact categories. Doing that it is possible to give specific recommendations about which actions can be undertake, or what can be done in the future.
As the LCA is an iterative procedure because of the huge difficulties in retrieving the data. In addition, once the results from the chosen data are obtained, is possible to see which process is more important, and where it is necessary to intervene for making some improvements.
Furthermore, based on the preliminary results, also the scope and goals of the studies may be changed.

3.6 Biogenic Emissions

In this thesis, we evaluate biogenic CO_2 emissions when biological feedstocks are used. With the term biological feedstocks we include all those materials that have a non-fossil origin or are biodegradable (e.g. forest and agriculture products or wastes) (United States Environmental Protection Agency & Office of Atmospheric Programs, 2014).

Because the carbon in the biomass was originally taken from CO2 in the atmosphere, it should not be counted to contribute to global warming when it is re-released to the atmosphere. This is because the sequestration of the CO2 from the atmosphere by the plant was not counted in the first place.

However, great care was taken when defining which emissions from the biofuel pathways were from fossil sources and which from biogenic sources.

3.7 Base & Optimized Scenario

Considering the different pathways investigated a harmonization work have been performed for all the assumptions found out in the different papers in order to create a base case for each of them. Usually the FUs used in the literature were different for the ones chosen ion this study, thus this was the first important change to be done. The electricity mix used in the base case is always the same and is the Swiss average mix, taken from the ecoinvent database. The only exception is for the base case processes considering the algae cultivation, because as it was said earlier, Swiss weather condition are non-optimal for their cultivation (Mariluz Bagnoud-Velasquez, 2016), in those cases the Italian average mix has been used (still from the ecoinvent database).
The heat source considered in the processes harmonized from the literature review is natural gas.
The allocation method used is the energy one with multi-products processes, while the exergy allocation one has been chosen for the processes producing both heat and electricity.

One of the aspects of this harmonization was to consider the future development of each pathway. This is because some papers reported data for current technology performance, while others considered many future improvements. For this reason for each process a base case and an optimized one was quantified. However, for some pathways it was not possible to find literature describing the potential for future improvements. This is why different assumptions have been carried out for upgrading the processes, in order to show to the reader how they could be if optimizing solutions were adopted for them.
With these assumptions, we are not trying to say that they are always feasible for the different plants and locations, but the aim of this scenario is to show what the same process would be if specific changes were made.

The assumptions therefore made are the following:

- **Renewable electricity source**: for the processes concerning the different biofuels production instead of the Swiss electricity mix at the consumer, or the electricity mix used for the production of algae in different countries with better weather conditions (e.g. Italy), it has been chosen the electricity produced in a hydropower plant. This is because among the various ways of producing electricity from renewable sources, this pathway has been proven to have the smallest environmental impact. In order to be consistent in the work, the electricity used in all the optimized scenarios of the different processes is the same.

- **Least impacting transportation**: as in the literature review it was found that the transports used had a strong influence in the final results; it was considered that the best currently available transports to be used, instead of the fleet average ones.
- **Emissions cut**: according to the Directive 70/220/EEC it is possible to see how, for the light duty vehicles, since this directive has been applied, the emissions cut for many compounds like CO, NO_x, HC, PM, have been drastically reduced starting from the EURO1 standards till the EURO6 standards. Based on this document, it is reasonable to apply the same lines of thought to the process that are investigated within the thesis, and to apply an emission cut of the same kinds of compounds and others hazardous types, given that the process itself can be cleaner and more efficient. The emissions have been thus reduced by 50%, except when it comes to dealing with CO_2 and water emissions, as they have been considered as strictly related to the quantity of biomass itself used, so if there is an increase in efficiency that permits the use of less biomass, the reduction applied will be of the same amount.

  The reduction among the other substances is considered consistent because they are strictly associated with the process itself, that is to say considered more efficient and cleaner. For example, we may assume that the combustion processes, if there are any, are much better.

  Also the leakages of methane in the anaerobical digestion plants have been removed in the optimized case.
- **Car's Standard Used**: the vehicles used for the comparison among the different fuels investigated for powering them are all under the EURO5 standards. This choice is driven by the fact that the best available car for simulating the burning of the biofuels, uploaded in the ecoinvent database from the Thelma project has such standards.

  The cars used for the comparison are all mid-sized and the typologies considered are the following:

  - Internal Combustion Engine Vehicle (ICEV) for gasoline, diesel and natural gas (NG);

  - Battery Electric Vehicle (BEV) for electricity;

  - Fuel-Cell Electric Vehicle (FCEV) for Hydrogen;

- **LHV of Biofuels equal to conventional fossil fuels:** we assumed that low heating values of the biofuels investigated are the same of the conventional fossil fuels used as reference.
- **Increased efficiency of processes**: this assumption is based on the assumptions made in (Weinberg & Kaltschmitt, 2013). It is considered that in the near future an

increase of the efficiency of different processes for converting biomass into biofuels will increase by at least 10%. According to this assumption a reduction of the same amount of the quantity of biomass needed by the process.

- **Algae Optimized Scenario:** According to different papers (Passell et al., 2013; Zhou et al., 2014) considering the current situation many assumptions must be taken into account, if it is desired that the production of biofuels from algae becomes a real possibility.

  A further explanation of the improvements made will be given in chapter 6.

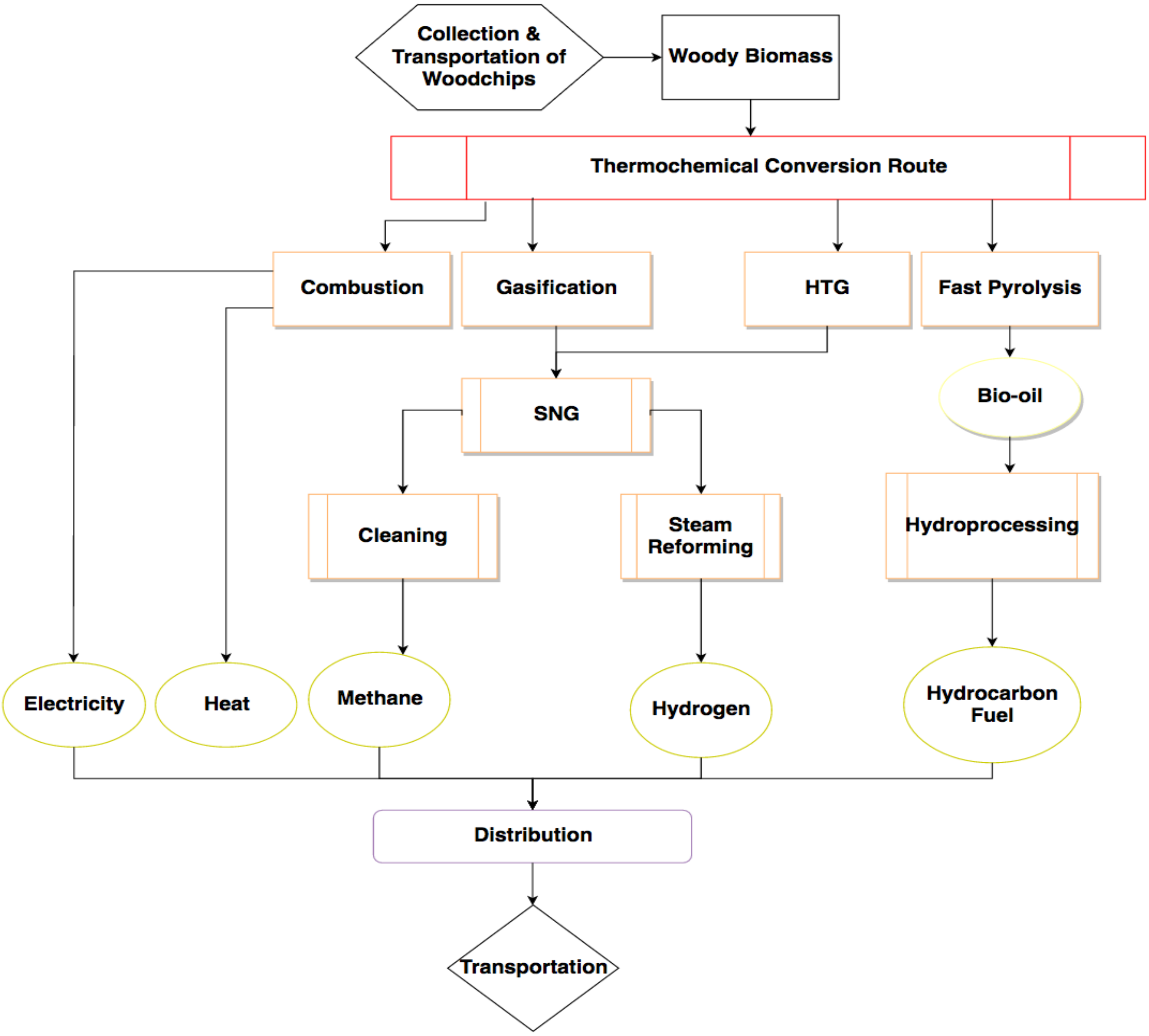
4. LCI of the processes using Wood Biomass

The processes that are going to be investigated in this chapter, considering only the use of woody biomass are the followings:

- Wood Gasification & Methanation
- Hydrothermal Gasification (HTG)
- Fast Pyrolysis
- Wood Gasification & Hydrogen production
- Cogeneration Heat and Power Plant (CHP)

These processes have been chosen for manifold reasons. The production of different energy carriers (methane vs electricity versus liquid hydrocarbons) is one of them. Secondly because the Wood Gasification process for the production of SNG and the CHP plant, because are those with the highest level of technological maturity, compared to the Hydrothermal Gasification and Fast Pyrolysis processes. The last two have nevertheless been investigated because they represent promising technologies for the near future, especially the HTG, even if they are at their early stage of their technological maturity.

A flow chart assessing the different pathways explored is presented below:



Flowchart 1: Wood Biomass Pathways

Where:

- HTG: Hydrothermal Gasification
- SNG: Synthetic Natural Gas

4.1 Wood Gasification & Methanation Process - LCI

This process refers to the conversion of wood chips mix (i.e. wood chips from wood industry, from forestry waste and from waste demolition and urban wood) into syngas (SNG) a mixture of mainly H_2 and CO, with traces of CO_2 and CH_4, that is subsequently converted into methane (96%). The LCI is present in the ecoinvent database, and is documented by the ecoinvent report of (A. Dauriat, 2006).

The chemical reaction happening when converting the syngas into methane is the following:

$$C + H_2O \rightarrow CO + H_2$$

An image taken from the report will show the system boundaries of the process:

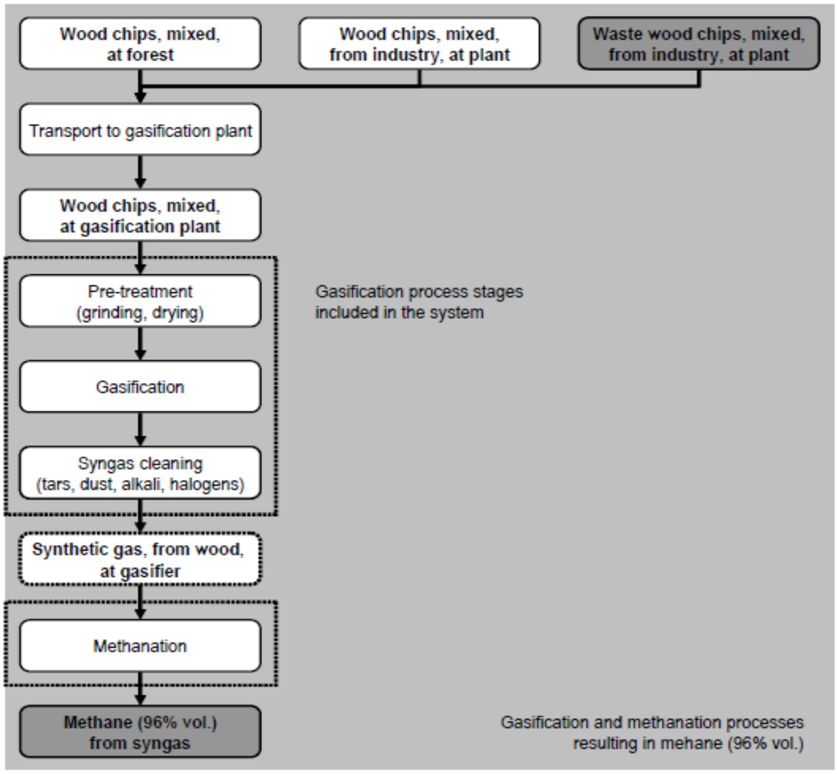


Figure 2: Wood Gasification & Methanation process boundaries - Source:(A. Dauriat, 2006)

The wood chips are gasified through the gasification stage in a FICFB (Fast Internally Circulating Fluidized Bed) with an overall efficiency of the 73%. The bed material considered is made by olivine, a magnesium-iron silicate that is though replaced by the process silica sand. For the cleaning of the SNG rape methyl ester is used for the tar removal, and other chemical compound like soda (NaOH) and sulphuric acid are used to get rid of the impurities.

The methanation stage with an efficiency of the 76.5% leads to the production of a gas with this composition and energy content:

Compound	**Percentage (vol.)**
CH_4	97.3%
CO_2	2.6%
H_2O	0.1%
Energy Content	34.4 MJ/Nm^3

Table 4: Gas composition from wood gasification

The catalyst used is in the process is respectively 50% Aluminum Oxide and 50% Nickel. The carbon dioxide present in the SNG is removed by a pressure-swing adsorption (PSA) process, through a zeolite sieve.
The heat required in all the process is obtained from the burning of some of the methane produced with 95% efficiency.
The transport distance considered is 50 km, using a 28t truck. The electricity consumed into the process is needed for the following operations: wood chips drying, compression of syngas and methane, pumping of the biomass and air compression.
The lifetime of the plant is assumed to be 50 years.

The assumptions made for the Optimized Scenario, carried on to assess the improvements that can be made to the very same process analyzed in the Baseline Scenario, are the following, and are based on those made in the 3.6 chapter:

- Increase of the efficiency of the process by 10%;
- Reduction of the direct atmospheric emissions of the process by 50%;
- Transport is provided by a Euro 6 Lorry;
- Electricity is assumed to come from Hydropower. The electricity used is a low voltage one, and the process is named “Electricity, low voltage, hydropower, 2030+, at grid CH/U” , which was created for the Thelma project (Stefan Hirschberg, 2016);

The datasets shown below concern the production of 1 m^3 of SNG in both the Base and the Optimized cases:

Products	**Base**	**Optimized**	**Unit**
Methane, 96 vol.-%, from synthetic gas, wood, at plant/CH U	1	1	MJ
Materials/fuels			
Wood chips, mixed, u=120%, at forest/RER U	3,64E-04	3,64E-04*0.9	m3
Wood chips, mixed, from industry, u=40%, at plant/RER U	1,25E-04	1,25E-04*0.9	m3
Waste wood chips, mixed, from industry, u=40%, at plant/CH U	7,97E-05	7,97E-05*0.9	m3
Synthetic gas plant/CH/I U	8,42E-11	8,42E-11*0.9	p
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	1,78E-05	1,78E-05*0.9	MJ
Electricity, medium voltage, at grid/CH U	2,40E-02	2,40E-02*0.9	kWh
Tap water, at user/CH U	3,05E-02	3,05E-02*0.9	kg
Rape methyl ester, at esterification plant/CH U	4,24E-04	4,24E-04*0.9	kg
Aluminium oxide, at plant/RER U	1,25E-11	1,25E-11*0.9	kg
Zinc, primary, at regional storage/RER U	5,42E-05	5,42E-05*0.9	kg
Nickel, 99.5%, at plant/GLO U	1,25E-11	1,25E-11*0.9	kg
Charcoal, at plant/GLO U	5,74E-04	5,74E-04*0.9	kg
Silica sand, at plant/DE U	1,02E-03	1,02E-03*0.9	kg
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	3,53E-05	3,53E-05*0.9	kg
Sulphuric acid, liquid, at plant/RER U	2,99E-04	2,99E-04*0.9	kg

Transport, freight, rail/CH U	1,56E-03	1,56E-03*0.9	tkm
Transport, lorry 20-28t, fleet average/CH U	1,20E-04	1,20E-04*0.9	tkm
Transport, lorry 3.5-20t, fleet average/CH U	1,03E-02	1,03E-02*0.9	tkm
Electricity, low voltage, production UCTE, at grid/UCTE U	2,37E-04	2,37E-04*0.9	kWh
Industrial furnace, natural gas/RER/I U	5,98E-10	5,98E-10*0.9	p
Emissions to air			
Carbon dioxide, biogenic	1,42E-01	1,42E-01*0.9	kg
Heat, waste	1,15E+00	1,15E+00*0.9	MJ
Acetaldehyde	2,14E-10	2,14E-10*0.9	kg
Acetic acid	3,20E-08	3,20E-08*0.9	kg
Benzene	8,54E-08	8,54E-08*0.9	kg
Benzo(a)pyrene	2,14E-12	2,14E-12*0.9	kg
Butane	1,50E-07	1,50E-07*0.9	kg
Carbon monoxide, biogenic	9,94E-05	9,94E-05*0.9	kg
Dinitrogen monoxide	1,07E-07	1,07E-07*0.9	kg
Dioxin, 2,3,7,8 Tetrachlorodibenzo-p-	6,38E-18	6,38E-18*0.9	kg
Formaldehyde	2,14E-08	2,14E-08*0.9	kg
Mercury	6,41E-12	6,41E-12*0.9	kg
Methane, biogenic	4,27E-07	4,27E-07*0.9	kg
Nitrogen oxides	6,04E-05	6,04E-05*0.9	kg
PAH, polycyclic aromatic hydrocarbons	2,79E-08	2,79E-08*0.9	kg
Particulates, < 2.5 um	1,58E-06	1,58E-06*0.9	kg
Pentane	2,56E-07	2,56E-07*0.9	kg
Propane	4,27E-08	4,27E-08*0.9	kg
Propionic acid	4,27E-09	4,27E-09*0.9	kg
Sulfur dioxide	1,17E-07	1,17E-07*0.9	kg
Toluene	4,27E-08	4,27E-08*0.9	kg
Hydrocarbons, aliphatic, alkanes, unspecified	2,14E-06	2,14E-06*0.9	kg
Hydrocarbons, aliphatic, unsaturated	7,27E-06	7,27E-06*0.9	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	1,43E-06	1,43E-06*0.9	kg
Waste to treatment			
Treatment, sewage, from residence, to wastewater treatment, class 2/CH U	3,12E-05	3,12E-05*0.9	m3
Disposal, inert material, 0% water, to sanitary landfill/CH U	2,17E-03	2,17E-03*0.9	kg
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	4,24E-04	4,24E-04*0.9	kg
Disposal, wood ash mixture, pure, 0% water, to municipal incineration/CH U	5,78E-04	5,78E-04*0.9	kg
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill/CH U	4,37E-04	4,37E-04	kg

Table 5: Methane wood gasification LCI

4.2 Fast Pyrolysis Process - LCI

This process is modelled based on the paper of (Iribarren et al., 2012). This process analyzed consist in "the thermal decomposition of biomass in the absence of oxygen, producing charcoal, non-condensable gas and a liquid rich in oxygenated hydrocarbons, which is of major interest for biofuel applications" (Iribarren et al., 2012). The process conditions are very important in order to modify the yields of the different products. To maximize the liquid yield, that is the most interesting one if we are dealing with biofuel production for transportation, the process must be carried on at 500°C, atmospheric pressure, with very short residence time (Iribarren et al., 2012).

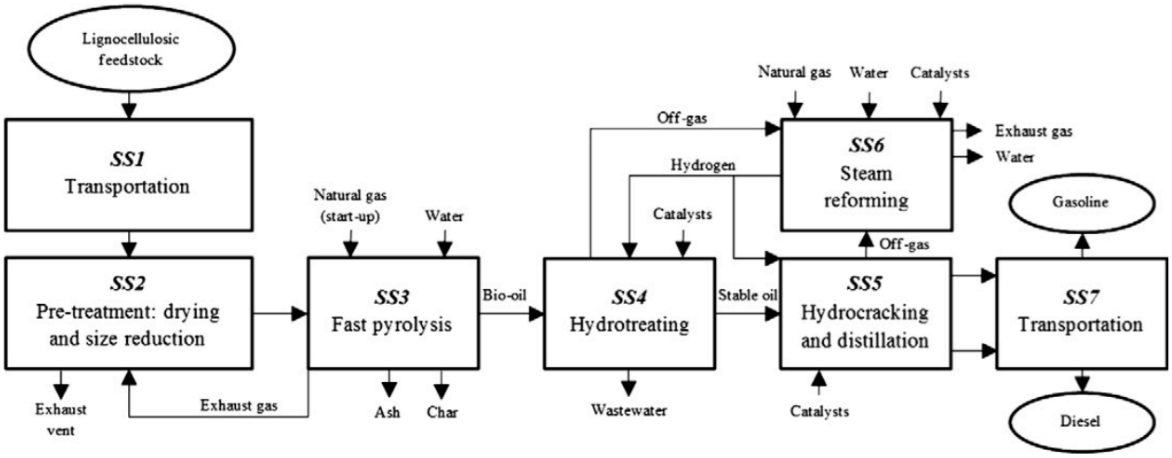


Figure 2: Fast Pyrolysis system boundaries - Source: (Iribarren et al., 2012)

Few modifications have been made in respect to the original work, in order to adapt the LCI present in it to the purpose of the thesis. For example in the original work poplar wood chips from short rotation forestry were used to perform the analysis, while now softwood forestry wood chips from Switzerland substitute them; this choice was made because the density difference of this two kind of wood species is negligible (410 versus 430 kg/m^3). Also the functional unit has been changed, because instead of analyzing the production of 1 ton of the conventional transportation fuels produced (e.g. gasoline and diesel) with the upgrading of the biocrude, that is the oil produced with the pyrolysis process, we analyze the production of 1 MJ of gasoline and 1 MJ of diesel respectively. To do that, firstly the original data for the production of the biocrude were adapted to the production of just 1 kg of it. Secondly for the upgrade of the biocrude, and the production of 1 MJ of gasoline and diesel, an energy allocation method has been used. Furthermore, instead of using Spanish inputs, or the Spanish electricity mix, Swiss inputs and the Swiss electricity mix have been used instead.

Another difference is that the energy required for the treatment of the raw biomass (e.g. drying, commuting) is not taken into account as it has already been with the ecoinvent process.

The catalyst that was not clearly showed into the study was modelled based on the paper of (Snowden-Swan, Spies, Lee, & Zhu, 2016).

The transportation distances considered are respectively, 80 km for the collection of the wood chips, and 200 km for the final products (Iribarren et al., 2012).

The diesel and gasoline in the original work are coproduced when upgrading the biocrude created from the fast pyrolysis. Here for a better comprehension of the singular products an energy allocation has been performed as showed in Table 5:

Product	Mass Percentage [%]	LHV [MJ/kg]	Energy Allocation
Diesel	57	42.8	0.56
Gasoline	43	44.4	0.44

Table 6: Energy allocation pyrolysis products

The LCIs for the production of 1 kg of biocrude from the pyrolysis process, and for the production of 1 MJ of diesel and gasoline respectively are presented below, including the base and the optimized case.

In the optimized case the assumptions taken into account are the same ones stated in the previous subchapter:

- Increase of the efficiency of the process by 10%;
- Reduction of the direct atmospheric emissions of the process by 50%;
- Transport is provided by a Euro 6 Lorry instead of the fleet average one;
- Electricity is assumed to come from Hydropower and it has been substituted with a hydropower low voltage electricity datasets, modelled within the Thelma project (Stefan Hirschberg, 2016) ;
- The bio-crude used into the optimized case has been also optimized using the different assumptions carried on in sub-chapter 3.6, like the reduction of the emission of 50%, the use of hydropower electricity (Stefan Hirschberg, 2016) , and the transports are provided by a EURO 6 lorry;

Products	**Base**	**Optimized**	**Unit**
Bio-crude base case	1	0	kg
Bio-crude Optimized	0	1	kg
Resources			
Air	2.2238	2.2238*0.9	kg
Materials/fuels			
Wood chips, wet, measured as dry mass (CH)| softwood forestry, mixed species, sustainable forest/ Alloc Rec, U	2.3392	2.3392*0.9	kg
Water, deionised, at plant/CH U	0.0388	0.0388*0.9	kg
Transport, lorry 20-28t, fleet average/CH S	0.187	0	tkm
Transport, freight, lorry 16-32 metric ton, EURO6 | transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	0	0.000168	tkm
Electricity/heat			
Electricity, low voltage, at grid/CH U	0.1356	0	kWh
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.1356*0.9	kWh
Heat, natural gas, at industrial furnace >100kW/RER U	0.000683	0.000683*0.9	MJ
Waste to treatment			
Wood ash mixture, pure (waste treatment) | treatment of, landfarming | Alloc Def, U	0.0135	0.0135*0.9	kg

Table 7: Biocrude from wood fast pyrolysis LCI

Products	**Base**	**Optimized**	**Unit**	**Comments**
Gasoline	1	1	MJ	
Materials/fuels				
Water, deionised, at plant/CH U	0.043	0.043*0.9	kg	
Natural gas, low pressure, at consumer/CH U	0.01315	0.01315*0.9	MJ	
Transport, lorry 20-28t, fleet average/CH S	0.00459	0	tkm	
Transport, freight, lorry 16-32 metric ton, EURO6| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	0	0.00459	tkm	Transport of the finished fuel
Bio-crude oil Base Case	0.116	0	kg	
Bio-crude oil Optimized	0	0.116	kg	
MoS2/NiS on Al2O3	0.00008	0.00008*0.9	kg	Catalyst
Electricity/heat				
Electricity, low voltage, at grid/CH U	0.00172	0	kWh	Hydrotreating
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.00172*0.9	kWh	
Electricity, low voltage, at grid/CH U	0.00241	0	kWh	Hydrocracking
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.00241*0.9	kWh	
Electricity, low voltage, at grid/CH U	0.00275	0	kWh	Steam Reforming (SR)
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.00275*0.9	kWh	
Emissions to air				
Water_kg	0.02188	0.02188*0.9	kg	From SR
Carbon dioxide	0.05967	0.05967*0.9	kg	From SR
Emissions to water				
Water_kg	0.01472	0.01472*0.9	kg	
Waste to treatment				
Wastewater, average treatment of, capacity 1.6E8l/year | Alloc Def, U	0.05519	0.05519*0.9	l	

Table 8: Gasoline from wood fast pyrolysis LCI

Products	**Base**	**Optimized**	**Unit**	**Comments**
Diesel	1	1	MJ	
Materials/fuels				
Water, deionised, at plant/CH U	0.035	0.035*0.9	kg	
Natural gas, low pressure, at consumer/CH U	0.0107	0.0107*0.9	MJ	
Transport, lorry 20-28t, fleet average/CH S	0.0189	0	tkm	
Transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	0	0.0189	tkm	Transport of the finished fuel
Bio-crude oil Base Case	**0.094**	**0**	**kg**	
Bio-crude oil Optimized	0	0.094	kg	
MoS2/NiS on Al2O3	0.000063	0.000063*0.9	kg	Catalyst
Electricity/heat				
Electricity, low voltage, at grid/CH U	0.001404	0	kWh	Hydrotreating
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.001404*0.9	kWh	

Electricity, low voltage, at grid/CH U	0.001966	0	kWh	Hydrocracking
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.001966*0.9	kWh	
Electricity, low voltage, at grid/CH U	0.002246	0	kWh	Steam Reforming (SR)
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.002246*0.9	kWh	
Emissions to air				
Water_kg	0.0178	0.0178*0.9	kg	From SR
Carbon dioxide	0.0486	0.0486*0.9	kg	From SR
Emissions to water				
Water_kg	0.012	0.012*0.9	kg	
Waste to treatment				
Wastewater, average (CH)| treatment of, capacity 1.6E8l/year | Alloc Def, U	0.045	0.045*0.9	l	

Table 9: Diesel from wood fast pyrolysis LCI

4.3 Hydrothermal Gasification – LCI

This process is based directly and entirely on the paper "Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Assessment" (Luterbacher et al., 2009), that is based on a catalytic hydrothermal process developed here at the PSI.

With this process, it is possible to convert waste biomass, such as wood waste or manure, into renewable SNG, and the conversion process is done through a catalytic hydrothermal gasification stage.
Different scenarios are analyzed within the paper, but for the purpose of this thesis just the large-scale manure gasification plant ($155MW_{SNG}$) and the wood gasification plant (35.6 MW_{SNG}) are considered.

It has been thought that this process is actually a very promising one, because it allows for overcoming some of the stringent barriers linked with the biomass, like the high content of moisture and accordingly the need of using more energy to dry and process it, therefore in this way the result is an increase in the energy efficiency.

For the Wood Scenario, the transport distance considered is of 80 km for carrying the wood chips to the plant, with a moisture content of 50%. The moisture content that has been used for the thesis is about the 40%, using the waste wood chips process present in the ecoinvent data base. The catalyst used in the process is a Ruthenium catalyst. The composition of the crude gas is 50% of Carbon Dioxide (CO_2) and 50% of Methane (CH_4), the present traces of hydrogen are considered negligible. The produced raw gas is then cleaned or sent to a Heat and Electricity stage. For the cleaning of the synthetic natural gas produced from the CO_2,

three processes have been considered in the paper: pressure swing adsorption (PSA), membrane separation and physical absorption. The latter was the one taken into account because allows not using any additional drying step.
In order to model the physical absorption of CO_2 into the polyethylene glycol dimethyether (DMPEG), the “DMPEG production and delivery” data set has been created because it is not present in the ecoinvent database. This process is also known as the Selexol process. After the cleaning the SNG will have this composition: 95% CH_4 and 5% CO_2, in order to be compatible with the natural gas into the grid.

The plant used in this process is a Methanol one, this assumption is taken directly from the paper of (Luterbacher et al., 2009), because as a plant like this does not exist and is not available in the literature.

The catalyst used in the process is Ruthenium that is not present in the ecoinvent database, that is why according to (Luterbacher et al., 2009) to calculate it the environmental load of the platinum groups metal (that is instead present in the ecoinvent inventory) has been used. The extraction of 1 kg of Ruthenium has been considered and it corresponds to the extraction of 0.008 kg of Rhodium, plus a distance of 15’000 km, to be accounted for the transportation from the South African mines (chosen instead of the Russian ones because of the higher presence of ruthenium in the ore), covered by plane.

Finally, in the study is considered an avoided production of 0.013 kWh of electricity that is produced from the process. In order to be consistent with the other processes that do not have any avoided production an exergy allocation has been performed. The electricity production has been converted from kWh to MJ, and the result is 0.0468 MJ.
The total exergy of the process is 1 MJ gas + 0.0468 MJ electricity = 1.0468. Thus, the values must be multiplied by (1/1.0468) which is 0.955.

The system boundaries are shown below:

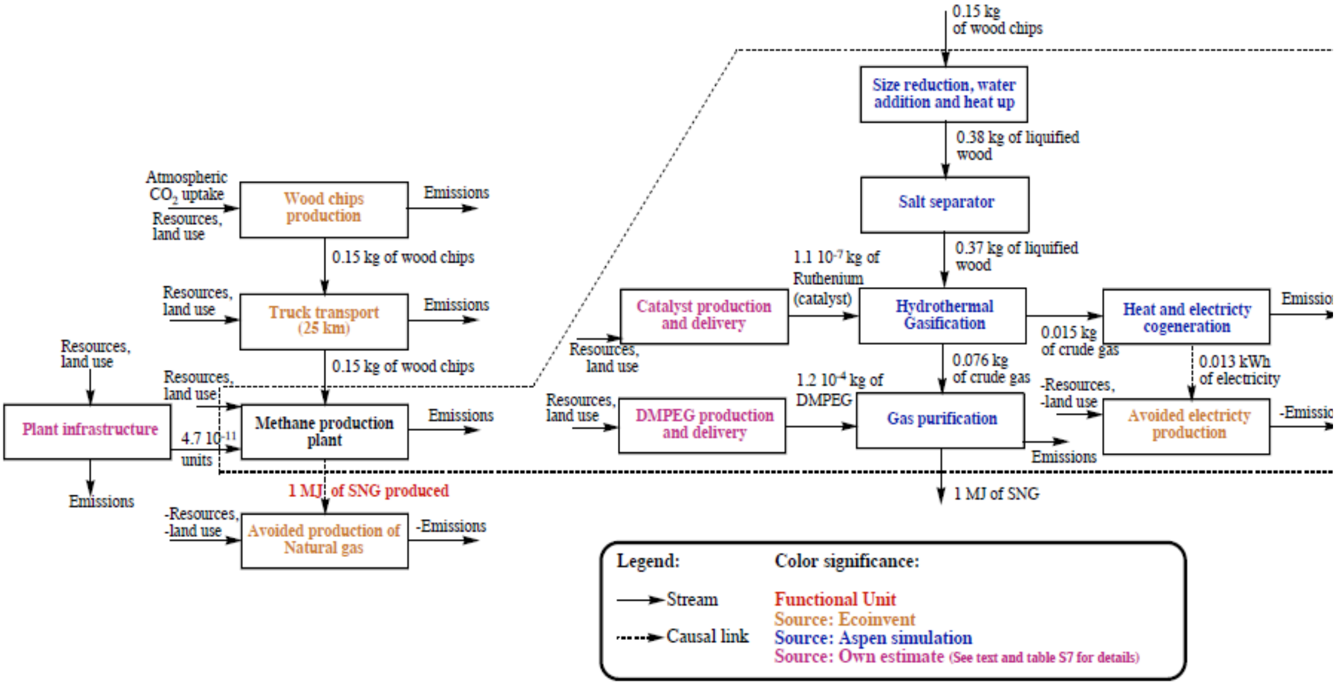


Image 3: Wood HTG system boundaries – Source:(Luterbacher et al., 2009)

The functional unit used by the author is 1MJ of SNG, according with the definition given above and is perfectly consistent with the FU chosen for this thesis.
The assumptions made for the optimized scenario are consistent to those made for the precedents processes.

Below is shown the table containing the LCI used for the baseline and optimized scenario:

Products	**Base**	**Optimized**	**Unit**	**Comment**
Methane from Wood HTG Base Case	1	1	MJ	
Resources				
Water, process, unspecified natural origin/kg	0.23*0.955	0.23*0.955*0.9	kg	For diluting the woodchips
Materials/fuels				
Methanol plant/GLO/I U	1.2853E-12*0.955	1.2853E-12*0.955*0.9	p	Proxy
Ruthenium	0.00000014*0.955	0.00000014*0.955*0.9	kg	Catalyst
DMPEG production and delivery	1.20E-4*0.955	1.20E-4*0.955*0.9	kg	Gas purification
Transport, lorry 20-28t, fleet average/CH S	0.0157*0.955	0	tkm	
Transport, freight, lorry 16-32 metric ton, EURO6 Alloc Rec, U	0	0.0141*0.955	tkm	
Waste wood chips, mixed, from industry, u=40%, at plant/CH U	0.00079*0.955	0.00079*0.955*0.9	m3	
Electricity/heat				
Heat, natural gas, at boiler modulating >100kW/RER U	0.0042*0.955	0.0042*0.955*0.9	MJ	
Emissions to air				
Hydrogen	3.94E-7*0.955	3.94E-7*0.955*0.5	kg	

Carbon monoxide, biogenic	8.01E-8*0.955	8.01E-8*0.955*0.5	kg	HTG
Carbon dioxide, biogenic	3.36E-3*0.955	3.36E-3*0.955*0.9	kg	HTG
Ethene	7.03E-13*0.955	7.03E-13*0.955*0.5	kg	
Ethane	1.41E-8*0.955	1.41E-8*0.955*0.5	kg	
Propane	6.36E-12*0.955	6.36E-12*0.955*0.5	kg	
Carbon dioxide, biogenic	5.71E-2*0.955	5.71E-2*0.955*0.9	kg	Gas Purification
Water	2.21E-6*0.955	2.21E-6*0.955*0.9	m3	
Emissions to water				
Ethene	1.19E-14*0.955	1.19E-14*0.955*0.9	kg	

Table 10: Wood HTG – LCI

4.4 Cogeneration Heat and Power Plant - LCI

This process is part of the ecoinvent v3.1 database. It refers to a cogeneration plant with a capacity of 6667 kW in Switzerland, installed in 2014.
Heat is the main product of this plant, and it follows the heat demand, while electricity is a co-product.
The electricity in this process is produced through an Organic Rankine Cycle (ORC) steam generator (Ecoinvent, 2014).

In this case the assumptions made for the optimized case are:

- Increase of the efficiency of the process by 10%;
- Reduction of the direct atmospheric emissions of the process by 50%;

Products	Base	Optimized	Unit	Comment
Electricity, high voltage (CH)| heat and power co-generation, wood chips, 6667 kW	1	1	MJ	
Materials/fuels				
Water, decarbonised, at user (GLO)| market for | Alloc Rec, U	0.0125	0.0125*0.9	kg	
Chemical, organic (GLO)| market for | Alloc Rec, U	9.303E-5	9.303E-5*0.9	kg	
Chlorine, gaseous| market for | Alloc Rec, U	5.216E-6	5.216E-6*0.9	kg	
Sodium chloride, powder (GLO)| market for | Alloc Rec, U	6.52E-5	6.520E-5*0.9	kg	
Lubricating oil (GLO)| market for | Alloc Rec, U	5.21E-5	5.21E-5*0.9	kg	
Ammonia, liquid | market for | Alloc Rec, U	1.304E-7	1.309E-7*0.9	kg	
Furnace, wood chips, with silo, 5000kW (GLO)| market for | Alloc Rec, U	8.282E-9	8.28E-9*0.9	p	
NOx retained, by selective catalytic reduction (GLO)| market for | Alloc Rec, U	0.00127	0.00127*0.9	kg	
Dust collector, electrostatic precipitator, for industrial use (GLO)| market for | Alloc Rec, U	8.28E-9	8.28E-9*0.9	p	
Heat and power co-generation unit, organic Rankine cycle, 1000kW electrical (GLO)| market for | Alloc Rec, U	8.282E-9	8.28E-9*0.9	p	
Wood chips, wet, measured as dry mass | market for | Alloc Rec, U	0.841	0.841*0.9	kg	
Emissions to air			See ecoinvent, too many to list	

Waste to treatment				
Wastewater, average (GLO)| market for | Alloc Rec, U	1.251E-5	1.251E-5*0.9	m3	
Municipal solid waste| market for | Alloc Rec, U	5.21E-5	5.21E-5*0.9	kg	
Wood ash mixture, pure (GLO)| market for | Alloc Rec, U	0.0084	0.0084*0.9	kg	
Waste mineral oil (GLO)| market for | Alloc Rec, U	5.216E-5	5.2167E-5*0.9	kg	

Table 11: Electricity from CHP – LCI

The LCI above is about the production of high voltage electricity from a wood cogeneration plant. To allow though, its use for powering an electric car, there is the need to convert it first to medium voltage electricity and the finally to low voltage electricity.

The LCIs of these conversions are going to be shown below:

Products	Base	Optimized	Unit
Electricity medium voltage wood cogeneration plant 6667 kwh	1	0	MJ
Electricity medium voltage wood cogeneration plant 6667 kwh Optimized	0	1	MJ
Materials/fuels			
Transmission network, electricity, medium voltage (CH)| construction | Alloc Rec, U	1.86E-08	1.86E-08	km
Sulfur hexafluoride, liquid | production | Alloc Rec, U	5.4E-08	5.4E-08	kg
Electricity/heat			
Electricity, high voltage (CH)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U	1.101024	0	kWh
Electricity, high voltage (CH)| heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 | Alloc Rec, U	0	1.101024	kWh
Emissions to air			
Sulfur hexafluoride	5.4E-08	5.4E-08	kg

Table 12: Conversion of cogeneration electricity from High to Medium Voltage - LCI

Products	Base	Optimized	Unit
Electricity low voltage wood cogeneration plant 6667 kwh	1	0	MJ
Electricity low voltage wood cogeneration plant 6667 kwh Optimized	0	1	MJ
Materials/fuels			
Distribution network, electricity, low voltage (CH)| construction | Alloc Rec, U	8.74E-08	8.74E-08	km
Sulfur hexafluoride, liquid| production | Alloc Rec, U	2.99E-09	2.99E-09	kg
Electricity/heat			
Electricity medium voltage wood cogeneration plant 6667 kwh	1.104	0	kWh
Electricity medium voltage wood cogeneration plant 6667 kwh Optimized	0	1.104	kWh
Emissions to air			
Sulfur hexafluoride	2.99E-09	2.99E-09	kg

Table 13:Conversion of cogeneration electricity from Medium to Low Voltage - LCI

4.5 Hydrogen From Wood Gasification – LCI

This process is modelled based entirely on the book (A. Wokaun, 2011). It considers the biomass gasification starting from waste wood chips from industry with 40% of humidity at 850°C and atmospheric pressure. After it the upgrading process used to convert the SNG produced into Hydrogen is the Steam Reforming (SR), the steam is used to enhance the hydrogen yield.
The Hydrogen made at the end of the upstream processes is at a pressure of 30 bar. For the further usage into a Fuel Cell vehicle this gas is compressed to 700 bar.

For the optimized case different operations have been carried on, as there are many processes involved in the production of the finished fuels. The modifications made are the following:

- Increase of the process efficiency of 10% applied to all the processes involved(i.e biomass gasification; SR; hydrogen compression);
- Transport is provided by a Euro 6 Lorry for the biomass gasification process;
- Electricity is assumed to come from Hydropower. The electricity used is a low voltage one, and the process is named "Electricity, low voltage, hydropower, 2030+, at grid CH/U" , which was created for the Thelma project (Stefan Hirschberg, 2016). This modification has been applied to both the biomass gasification process and the steam reforming one;
- The biomass gasification process optimized has been used in the SR process optimized as well;
- The hydrogen steam reforming process optimized has been used instead into the compression of the hydrogen process optimized;

The LCIs of all the processes accounted are shown below, considering both the base and the optimized cases:

Products	**Base**	**Optimized**	**Unit**
Syngas, from biomass gasification, 850°C, 1 bar, 2005/RER	1	1	MJ
Materials/fuels			
Wood chips, mixed, from industry, u=40%, at plant/RER U	0.000455	4.55E-4*0.9	m3
Rape methyl ester, at esterification plant/RER U	0.000121	1.205E-4*0.9	kg
Magnesium| production | Alloc Rec, U	0.000152	1.522E-4*0.9	kg
Iron scrap, sorted, pressed | sorting and pressing of iron scrap | Alloc Rec, U	0.000152	1.522E-4*0.9	kg
Lime, packed (CH)| lime production, milled, packed | Alloc Rec, U	0.000343	3.425E-4*0.9	kg
Charcoal (GLO)| production | Alloc Rec, U	0.000343	3.425E-4*0.9	kg
Zinc, primary, at regional storage/RER U	7.82E-06	7.82E-6*0.9	kg
Electricity, low voltage, at grid/CH U	0.002219	0	kWh
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	2.219E-3*0.9	kWh
Synthetic gas factory (CH)| construction | Alloc Rec, U	7.78E-11	7.78E-11*0.9	p

Tap water, at user/RER U	0.01194	1.194E-2*0.9	kg
Transport, freight, rail/RER U	0.0003	0.0003	tkm
Transport, lorry 3.5-20t, fleet average/CH S	0.00344	0	tkm
Transport, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	0	0.00344	tkm
Emissions to air			
Oxygen	0.00905	9.05E-3*0.5	Kg
Carbon dioxide, biogenic	0.0261	2.61E-2*0.9	Kg
Carbon monoxide, biogenic	3.34E-05	3.34E-5*0.5	Kg
Nitrogen oxides	1.92E-05	1.92E-5*0.5	Kg
Hydrocarbons, partly oxidized	3.66E-06	3.66E-6*0.5	Kg
Particulates, > 2.5 um, and < 10um	5.26E-07	5.26E-7*0.5	Kg
Waste to treatment			
Wood ash mixture, pure (CH)| treatment of, sanitary landfill | Alloc Rec, U	0.000386	3.86E-4*0.9	Kg
Inert waste, for final disposal (CH)| treatment of inert waste, inert material landfill | Alloc Rec, U	0.000825	8.25E-4*0.9	Kg

Table 14: Biomass gasification at 850°C - LCI

Products	**Base**	**Optimized**	**Unit**
H2, gaseous (30 bar), from steam reforming of biomass gas, at reforming plant, 2005/RER	1	0	MJ
H2, gaseous (30 bar), from steam reforming of biomass gas, at reforming plant, 2005/RER - Optimized	0	1	MJ
Materials/fuels			
Syngas, from biomass gasification, 850°C, 1 bar, 2005/RER	0.661	0	MJ
Syngas, from biomass gasification, 850°C, 1 bar, 2005/RER - Optimized	0	0.661	MJ
Steam, in chemical industry | production | Alloc Rec, U	0.044	0.044*0.9	kg
Liquid storage tank, chemicals, organics (CH)| production | Alloc Rec, U	1.64E-11	1.64E-11*0.9	p
Chemical factory, organics | construction | Alloc Rec, U	8.01E-12	8.01E-12*0.9	p
Electricity/heat			
Electricity, low voltage, at grid/CH U	0.068	0	kWh
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.068*0.9	kWh
Emissions to air			
Carbon dioxide, biogenic	0.12	0.12*0.9	kg

Table 15: Hydrogen from Steam Reforming - LCI

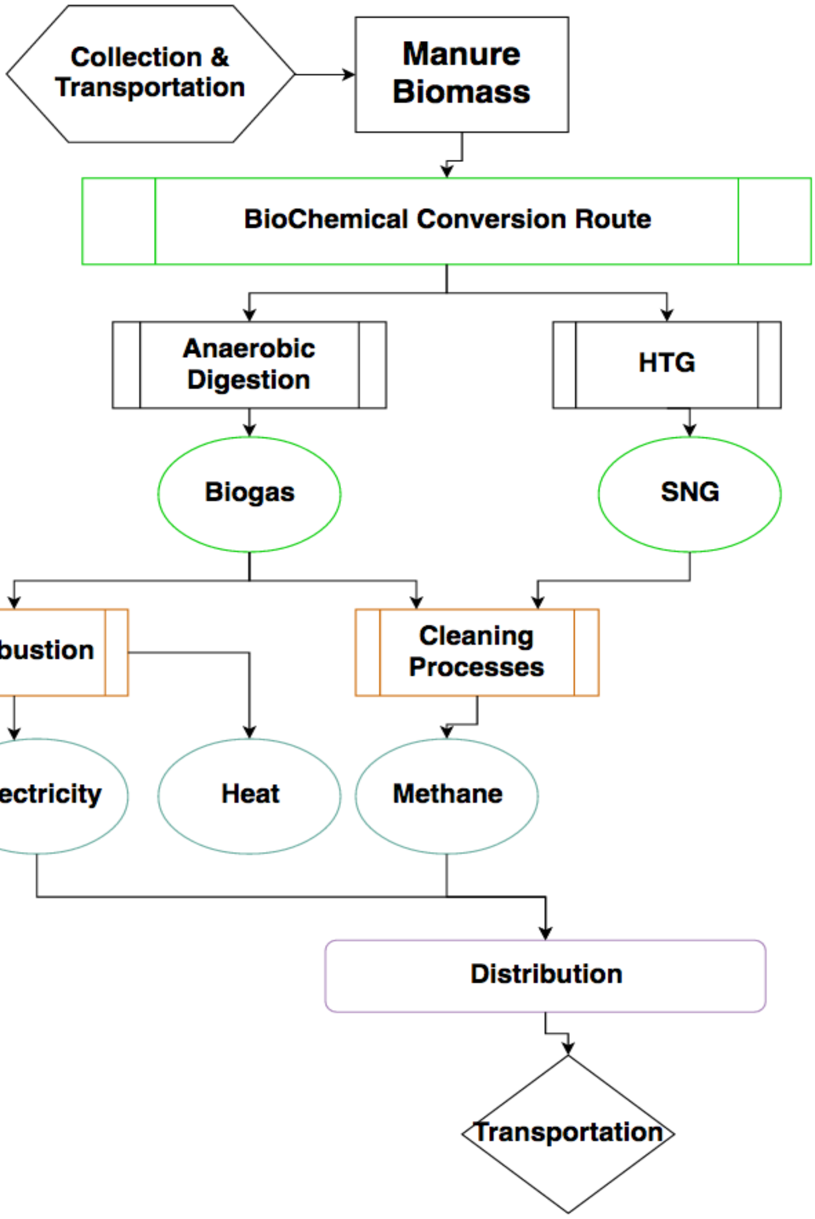
Products	**Base**	**Optimized**	**Unit**
Hydrogen, gaseous, from biomass gasification and SMR, 700 bar, 2005/RER U_Saverio	1	1	MJ
Materials/fuels			
hydrogen fuelling station, no static storage facility 2005/RER/I U	1.4E-09	1.4E-09*0.9	p
operation, hydrogen fuelling station 2005/RER U	0.185	0.185	hr
disposal, hydrogen fuelling station 2005/RER/I U	1.4E-09	1.4E-09*0.9	p
H2, gaseous (30 bar), from steam reforming of biomass gas, at reforming plant, 2005/RER	6.9E-05	0	MJ
H2, gaseous (30 bar), from steam reforming of biomass gas, at reforming plant, 2005/RER - Optimized	0	6.9E-05*0.9	MJ
Hydrogen compression, 30 to 700 bar, 2005	6.9E-05	6.9E-05*0.9	MJ

Table 16: Hydrogen compression to 700 bar – LCI

5. LCI of the Processes Using Manure Biomass

In this chapter the different pathways for processing manure biomass will be presented. All of these processes are taken from the ecoinvent database. The contribution from this thesis to these processes can be weighed in the optimized scenario analysis, where some of the assumptions made before in the method chapter are here therefore applied, and will be exactly explained in the following subchapters.

A flowchart explaining the pathways investigated is presented below:



Flowchart 2: Manure Biomass Pathways

5.1 Biogas Production and Methanation – LCI

This process considered is part of the ecoinvent database, and is completely documented in the report "Analyse de cycle de vie de la production centralisée et decentralisée de biogaz en exploitations agricoles" (Dauriat A., 2011) .

In this chapter the LCIs of the production of biogas from solid cattle manure and biowaste, and its upgrade to natural gas so that it can be used as a car's fuel will be briefly exposed. The plant considered is based on the study of several Swiss fermentation plants considering a lifetime of the plant of 20 years.

Below the system boundaries will be shown:

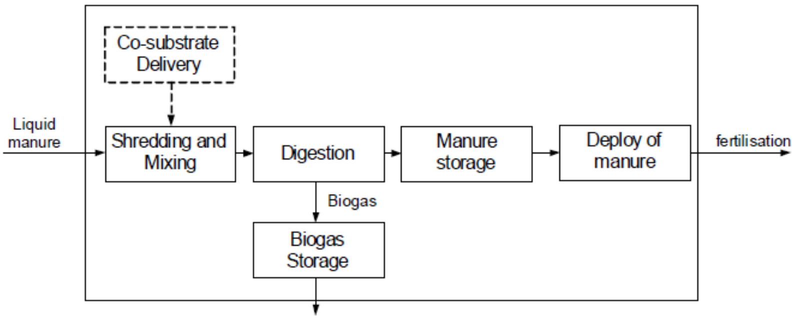


Figure 4: Biogas production boundaries – Source: (M. Spielmann, 2006)

The biogas composition from this process is so divided:

Compounds	Unit	Value
Methane	Vol %	67
Carbon Dioxide	Vol %	32.05
Methane	Kg/Nm^3	0.4
Carbon Dioxide	Kg/Nm^3	0.6
Total Carbon Content	Kg/Nm^3	0.5
Nitrogen	Vol %	0.7
Density	Kg/Nm^3	1.12
Lower Heating Value	MJ/Nm^3	24.04

Table 17: Biogas composition

The purification process of the Biogas (also known as biogas upgrade) has been taken from the ecoinvent report "Life Cycle Inventories of Bioenergy" chapter 13 ((M. Spielmann, 2006; Spiellmann, 2005), and the LCI used is the one present in the ecoinvent database. After this purification process the gas composition will be equal to that of natural gas, and for the purpose of the thesis will be considered for powering a mid-sized natural gas car.
For the production of the Bio methane the main operations to be carried out are:

- Removal of CO_2
- Removal of H_2S and Water (for corrosion problems they cause)

Among the different ways to remove those compounds (e.g. gas scrubbing, adsorption, membrane separation) in this process, the Pressure Swing Adsorption (PSA) process has been adopted, and the technical characteristics of it are taken from a typical Swiss plant: the Rütgers plant (2004). Below a flow chart explain the process will be shown:

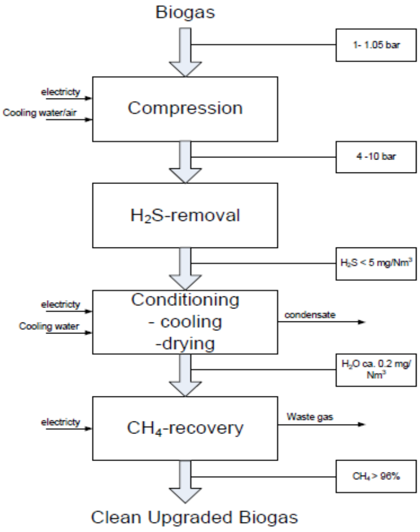


Image 5: Biogas cleaning and upgrading flowchart - Source:(M. Spielmann, 2006)

As for the other cases, many of the assumptions made for the optimized scenario are here applied.
The efficiency of the upgrading process of this process has been considered higher according to the papers written by (Alonso-Vicario et al., 2010; Cavenati, Grande, & Rodrigues, 2005). Cavenati et al. found out that a carbon molecular sieve (CH_4/CO_2=55/45, volume basis) at 303 K and 320 kPa can reach a methane purity higher than 96% and that the recovery rate can be of 75%. Alonso-Vicario et al. instead tested the CO_2 absorption capacity of natural zeolite respect to the synthetic one showing a double absorption capacity.

Furthermore, it is assumed that the methane yield from the anaerobic digestion plant can be improved considering different enhancements.

According to Prof. Urs Baier from ZHAW university we can state that: (Baier, 13.10.2016):

- Specific substrate treatment might allow doubling the biogas (i.e. the methane) yield on that specific substrate.
- Process control permits to enhance the efficiency of the whole plant, which is: more throughputs per volume or less volume for the same throughputs. It can be roughly estimated an increase of volumetric efficiency (volume gas produced per volume digester) of one third (30-35%) by applying advanced process control.
- Bioreactor design and operation including on-line analytics can have the same effect; to get more methane out of a substrate at a shorter residence time or with small fermenter volumes. This enhancement might lead to an increase in the efficiency between 20% and 400%, which is 20% more biogas in a given volume (or 20% less volume for an equal amount of biogas) up to the same amount

of biogas in a four-time smaller volume (though not four times more biogas which would be stoichiometrically impossible.

For an existing installation, it is possible to consider an increase of the methane produced by 40-65%.

It can be possible that the assumptions of Professor Baier are too optimistic and that the truth might resides among our base and optimized case.

In the light of these considerations our biogas production has been enhanced in the optimized case according with the suggestions of Prof. Baier, and the PSA step has been enhanced as well by a 10% accordingly to the aforementioned papers, and the assumptions made in sub-chapter 3.6, for the optimized scenario.

Hereby are the LCIs of the biogas production and subsequent upgrade respectively:

Products	**Base**	**Optimized**	**Unit**	**Comment**
Biogas (CH)| treatment of manure and biowaste by anaerobic digestion, from manure, liquid	1	1	m3	
Materials/fuels				
Manure, solid, cattle (GLO)| market for | Alloc Rec, U	38.93094	38.93*.5	kg	
Digester sludge (GLO)| digester sludge, Recycled Content cut-off | Alloc Rec, U	-86.6373	-86.6373*.5	kg	Linearly scaled
Anaerobic digestion plant, agriculture, with methane recovery (GLO)| market for | Alloc Rec, U	2.86E-07	2.86E-7*.70	p	
Glycerine (GLO)| market for | Alloc Rec, U	0.043213	0.043213*.5	kg	
Electricity/heat				
Heat, central or small-scale, other than natural gas (CH)| market for | Alloc Rec, U	3.47	3.47*0.7	MJ	
Electricity, low voltage (CH)| market for | Alloc Rec, U	0.158	0	kWh	
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.158*0.7	kWh	
Emissions to air				
Hydrogen sulfide	4.32E-05	4.32E-5*0.5	kg	
Ammonia	0.001693	0.001693*0.5	kg	
Dinitrogen monoxide	0.000108	0.000108*0.5	kg	
Carbon dioxide, biogenic	0.064411	0.064411*0.5	kg	
Methane, biogenic	0.055	0.055*0.5	kg	

Table 18: Biogas production from manure & biowaste –LCI

Products	**Base**	**Optimized**	**Unit**	**Comment**
Methane, 96% by volume (CH)| treatment of biogas, purification to methane 96 vol-% | Alloc Rec, U Saverio	1	1	MJ	
Materials/fuels				
Biogas (CH)| treatment of manure and biowaste by anaerobic digestion, from manure, liquid, cattle | Alloc Rec, U Base	0.043	0.043*0.9	m3	10% increase process efficiency
Chemical factory, organics (GLO)| market for | Alloc Rec, U	1.16E-11	4E-10*0.9	p	
Electricity/heat				
Electricity, low voltage, at grid/CH U	0.014	0	kWh	
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.014*0.9	kWh	

Emissions to air				
Sulfur dioxide	1.6E-05	1.6E-05*0.5	kg	
Carbon dioxide, biogenic	0.025	0.025*0.9	kg	
Hydrogen sulfide	1.01E-07	1.01E-07*0.5	kg	
Methane, biogenic	6.4E-4	6.4E-4*0.5	kg	

Table 19: Methane from manure biogas cleaning - LCI

5.2 Biogas Engine Co-generation – LCI

This process is about a small cogeneration plant based on the ecoinvent report “Life Cycle Inventories of Bioenergy” (M. Spielmann, 2006), but the operating data have been updated in 2014, and is possible to find it in the ecoinvent database. Respect to the original process instead of using as input of the process biogas from sewage and biowaste, it has been used the biogas produced from liquid cattle manure. The lower heating value of this biogas is assumed to be the same of the one stated in the ecoinvent database, and is equal to 22.73 MJ/Nm^3.
As it is a cogeneration plant there are two products, high voltage electricity and heat, thus an exergy allocation has been considered. Using this allocation method the electricity which is a higher form of energy will carry a heavier environmental burden respect to the heat.

The assumptions used for the optimized case are the following:

- Increase of the process efficiency by 10%;
- Reduction of the direct atmospheric emissions of the process by 50%;

The LCI is the following:

Products	**Base**	**Optimized**	**Unit**
Electricity, high voltage(CH)| heat and power co-generation, biogas, gas engine | Alloc Rec, U	1	1	kWh
Materials/fuels			
Heat and power co-generation unit, 160kW electrical, common components for heat+electricity (GLO)| market for | Alloc Rec, U	3.3E-08	3.3E-8*0.9	p
Heat and power co-generation unit, 160kW electrical, components for electricity only (GLO)| market for | Alloc Rec, U	3.3E-08	3.3E-8*0.9	p
Heat and power co-generation unit, 160kW electrical, components for heat only (GLO)| market for | Alloc Rec, U	3.3E-08	3.3E-8*0.9	p
Biogas (CH)| treatment of manure and biowaste by anaerobic digestion, from manure, liquid, cattle | Alloc Rec, U Base	0.29	0.29*0.9	m3
Lubricating oil (GLO)| market for | Alloc Rec, U	2.02E-4	2.02E-4*0.9	kg
Emission to air			
Platinum	4.7E-11	4.7E-11*0.5	kg
Dinitrogen monoxide	1.6E-05	1.6E-5*0.5	kg
Carbon monoxide, biogenic	3.2E-4	3.2E-4*0.5	kg
Carbon dioxide, biogenic	0.56	0.56*0.9	kg
Nitrogen oxides	1.01E-4	1.01E-4*0.5	kg

NMVOC, non-methane volatile organic compounds, unspecified origin	1.34E-05	1.34E-5*0.5	kg
Sulfur dioxide	1.4E-4	1.4E-4*0.5	kg
Methane, biogenic	1.5E-4	1.5E-4*0.5	kg
Waste to treatment			
Waste mineral oil (GLO)| market for | Alloc Rec, U	2.02E-4	2.02E-4*0.9	kg

As it has been stated in sub-chapter 4.4, also in this case the electricity produced, must be converted to low voltage before its use for powering an electric car. The LCI of these conversions are displayed below:

Products	Base	Optimized	Unit
Electricity medium voltage biogas engine	1	0	kWh
Electricity medium voltage biogas engine Optimized	0	1	kWh
Materials/fuels			
Transmission network, electricity, medium voltage (CH)| construction | Alloc Rec, U	1.86E-08	1.86E-08	km
Sulfur hexafluoride, liquid | production | Alloc Rec, U	5.4E-08	5.4E-08	kg
Electricity/heat			
Electricity, high voltage (CH)| heat and power co-generation, biogas, gas engine | Alloc Rec, U	1.101024	0	kWh
Electricity, high voltage (CH)| heat and power co-generation, biogas, gas engine | Alloc Rec, U Optimized	0	1.101024	kWh
Emissions to air			
Sulfur hexafluoride	5.4E-08	5.4E-08	kg

Table 20: Conversion from high to medium voltage biogas electricity - LCI

Products	Base	Optimized	Unit
Electricity low voltage biogas engine	1	0	kWh
	0	1	kWh
Materials/fuels			
Distribution network, electricity, low voltage (CH)| construction | Alloc Rec, U	8.74E-08	8.74E-08	km
Sulfur hexafluoride, liquid | production | Alloc Rec, U	2.99E-09	2.99E-09	kg
Electricity/heat			
Electricity medium voltage biogas engine	1.104	0	kWh
Electricity medium voltage biogas engine Optimized	0	1.104	
Emissions to air			
Sulfur hexafluoride	2.99E-09	2.99E-09	kg

Table 21: Conversion from medium to low voltage biogas electricity

5.3 Hydrothermal Gasification of Manure Biomass – LCI

This process has been based on the paper "Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Assessment" (Luterbacher et al., 2009). It has been included into this thesis because uses the Hydrothermal Gasification (HTG) process, that is believed to be one of the most promising one, especially when dealing with wet biomass, as the solvent used within the process is the water itself in its critical conditions or above them.

This means that there is no need to dry-up the biomass before processing it, avoiding using energy and heat for doing this intensive operation.

The assumptions made from the authors for the study of this large scale manure biomass plant (155 MW_{el} size) are the following:

- Two transport facilities are considered for collecting the biomass to the plant: freight train (for the long distance: 83 km) and tractor (to cover the short distance from the farm to the rail station: 5 km);
- The manure used for producing the biofuel is an avoided activity as the manure is not spread on the ground;
- If manure is not spread, the soil will need a fertilizer to replace it. But as the mineral fertilizer used to replace manure is 1.55 times more efficient, instead of replacing the exact quantity of minerals that are present in 1 kg of manure that is 312 g, just 113 g of mineral fertilizer are replaced, considering an efficiency of it of 100%.

Despite the assumptions carried on in the paper some of these assumptions have been neglected in this thesis in the effort carried on to harmonize the assumptions across various papers and data sources. As in the other processes concerning the production of biogas or methane, starting from manure, the assumption that the biomass converted to bio energy is not used for fertilizing the soil is not included, we avoid using it.
Not including this assumption though will make our results to be very different from those of the study on which our calculations are based on. Including the fertilizer production for not having spread the manure to the soil, would have heavily affected all the impact categories by us explored. This is because the contribution of this process would have not made possible to arrive to any conclusion, as all the other inputs and outputs included in the HTG process would have been obscured by the fertilizers produced.
Furthermore, in the process there is an over production of electricity from the burning of part of the methane produced. The amount of electricity that goes to the grid is $6.2 \cdot 10^{-3} kWh$ per MJ of methane produced, equal to 0.002232 MJ. The total output production is thus 1.002232 MJ. An exergy allocation of this electricity has been carried on, so that the other processes considered are fully comparable with this one. All the inputs and out puts of the process have been thus multiplied by (1/1.002232) = 0.997.

The process used is the same one used in the sub chapter 4.3, only the assumptions at the base of it, as the raw biomass is different, have been changed. The plant used is an approximation one, as no data are available for the structure, and again for cleaning the gas a physical absorption process is taken into account.

The system boundaries and the operations describing the process are shown underneath:

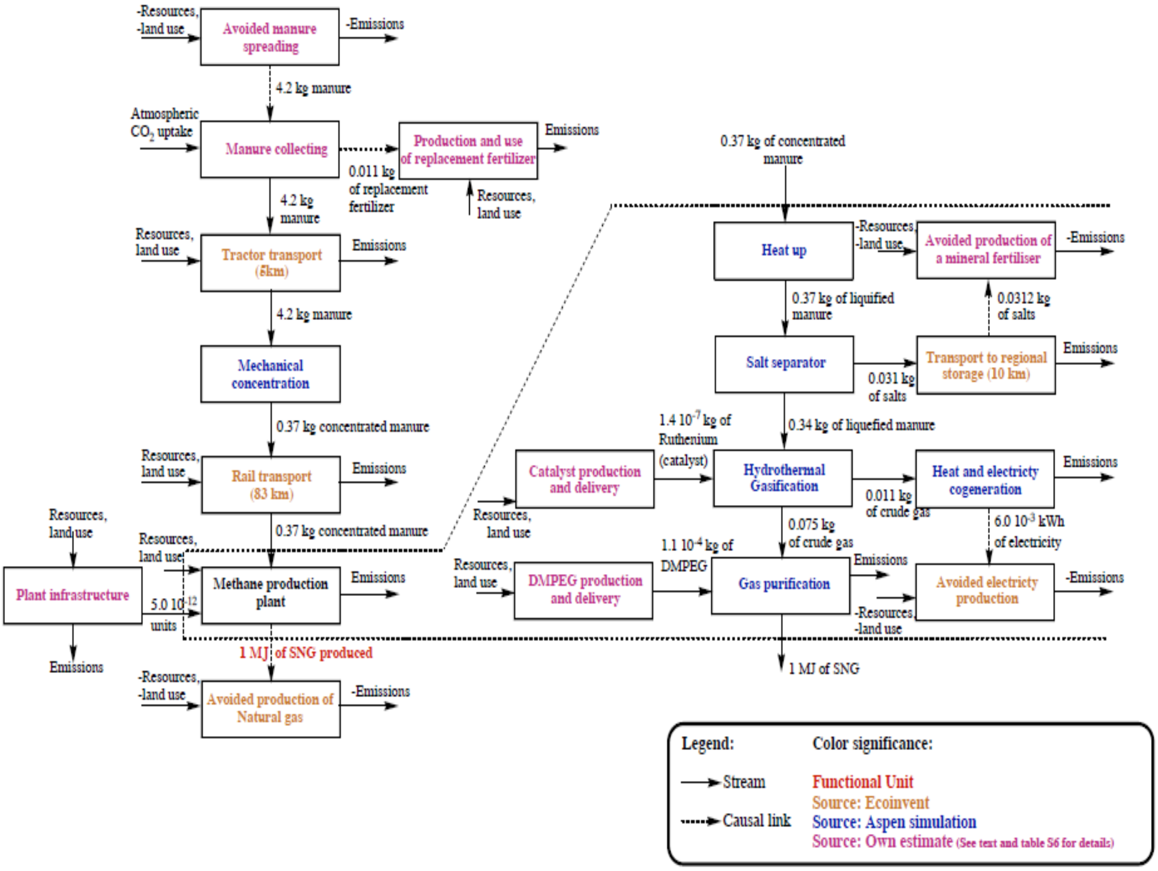


Image 6: Manure HTG system Boundaries - Source:(Luterbacher et al., 2009)

The purification of the gas has been done here as well using the PSA process.

In our optimized case the assumption accounted are:

- Increase of the efficiency of the process by 10%;
- Reduction of the direct atmospheric emissions of the process by 50%;
- Transport is provided by a Euro 6 Lorry;
- Electricity is assumed to come from Hydropower. The electricity used is a low voltage one, and the process is named “Electricity, low voltage, hydropower, 2030+, at grid CH/U” , which was created for the Thelma project (Stefan Hirschberg, 2016);

Below will be displayed the LCI of the process:

Products	Base	Optimized	Unit	Comment
Biomethane, manure HTG	1	1	MJ	
Resources				
Carbon dioxide, in air	5.46*0.997	4.914*0.997	kg	1.3kgCO$_2$ per kg manure dry mass
Materials/fuels				
Transport, lorry 3.5-20t, fleet average/CH S	0.0042*5*0.997	0	tkm	Proxy for the Tractor

Transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	0	0.00378*5*0.997	tkm	Proxy for the Tractor
Transport, freight, rail/CH U	0.0042*83*0.997	0.00378*83*0.997	tkm	Train
Methanol plant/GLO/I U	1.25E-11*0.997	1.25E-11*0.997	p	Proxy
Ruthenium	1.4E-7*0.997	1.4E-7*0.997*0.9	kg	
DMPEG production and delivery	1.10E-4*0.997	1.10E-4*0.997*0.9	kg	Gas purification – Physical Adsorption
Heat, natural gas, at boiler fan burner non-modulating <100kW/RER U	0.0031*0.997	0.0031*0.997*0.9	MJ	
Manure, solid, cattle (GLO)| market for | Alloc Rec, U	4.2*0.997	4.2*0.9*0.997	kg	
Emissions to air				
Hydrogen	6.6E-7*0.997	6.6E-7*0.997*0.5	kg	
Carbon monoxide, biogenic	1.59E-7*0.997	1.59E-7*0.997*0.5	kg	
Carbon dioxide, biogenic	5.63E-2*0.997	5.63E-2*0.997*0.9	kg	
Ethene	1.56E-12*0.997	1.56E-12*0.997*0.5	kg	
Ethane	1.28E-8*0.997	1.28E-8*0.997*0.5	kg	
Propane	5.66E-12*0.997	5.66E-12*0.997*0.5	kg	
Carbon dioxide, biogenic	5.2E-2*0.997	5.2E-2*0.997*0.9	kg	
Water	6.72E-7*0.997	6.72E-7*0.997*0.5	m3	
Emissions to water				
Ethene	2.66E-14*0.997	2.66E-14*0.997*0.5	kg	

The catalyst used in the process is Ruthenium that is not present in the ecoinvent database, that is why according to (Luterbacher et al., 2009) to calculate it the environmental load of the platinum groups metal (that is instead present in the ecoinvent inventory) has been used. The extraction of 1 kg of Ruthenium has been considered and it corresponds to the extraction of 0.008 kg of Rhodium, plus a distance of 15’000 km, to be accounted for the transportation from the South African mines (chosen instead of the Russian ones because of the higher presence of ruthenium in the ore), covered by plane.

6. LCI of Algae Processes

In this chapter the LCIs of all the processes investigated for the cultivation of the algae and to the production of the finished fuel are displayed. This section is included within this thesis for twofold reasons. The first is because this biomass represents the future as the potential within the algae is rich but as yet not fully exploited. The second one is because it is to believe that even if this technology is not yet ready for large-scale production, it is however true that with some improvements and further research this pathway would be the most promising one in the next generation. However the production of this biofuels will not be located in Switzerland, but in Italy because of the non-optimal weather conditions, there for in the following processes the Italian electricity average mix will be used. Also the transport of the finished fuel from Italy to Switzerland is considered and is done by train. The length of the trip is estimated to be 960 km (counting the distance from capital to capital).

Among the advantages represented by this renewable form of biomass we can consider:

- Biomass accumulation rate one order of magnitude superior compared to terrestrial crops per unit of land area (Richard, 2010);
- Higher photosynthetic efficiency, cultivation on non-arable or marginal land (Brown, Brown, Duan, & Savage, 2010)
- Extremely high oil yields, that is a desirable characteristic for producing biodiesel (Chisti, 2007);

Unfortunately despite these remarkable advantages compared to renewable biomass, algae production is still very expensive, and further researches must be done toward this subject, also disadvantages characterize their production.
Until today algae are cultivated and processed to achieve different high revenue products, usable in the pharmacy or alimentary sector, not for producing biofuels. This means that better cultivation and harvesting method must be discovered.
Furthermore the fertilizers used for the growth of the algae must be intensively recycled, as they can heavily impact the environment, while the biomass productivity and the oil yield must be improved.
For increasing the resilience of the algae from pathogens or predators hybridization and molecular modifications are required. Furthermore genetic modification can be a valid help for increasing the biomass and oil productivity.
Another interesting way to make advances for this technology is to co-locate it near to power plants, in order to exploit the exhaust flue or CO_2 gases as a source of nutrients, but also it is possible to conceive these plants close to wastewater plant or waste nutrients flows (Passell et al., 2013; Zhou et al., 2014) .
For the optimized scenario the processes investigated in this work we assume an increase in biomass productivity, the use of renewable electricity, an improvement in the process

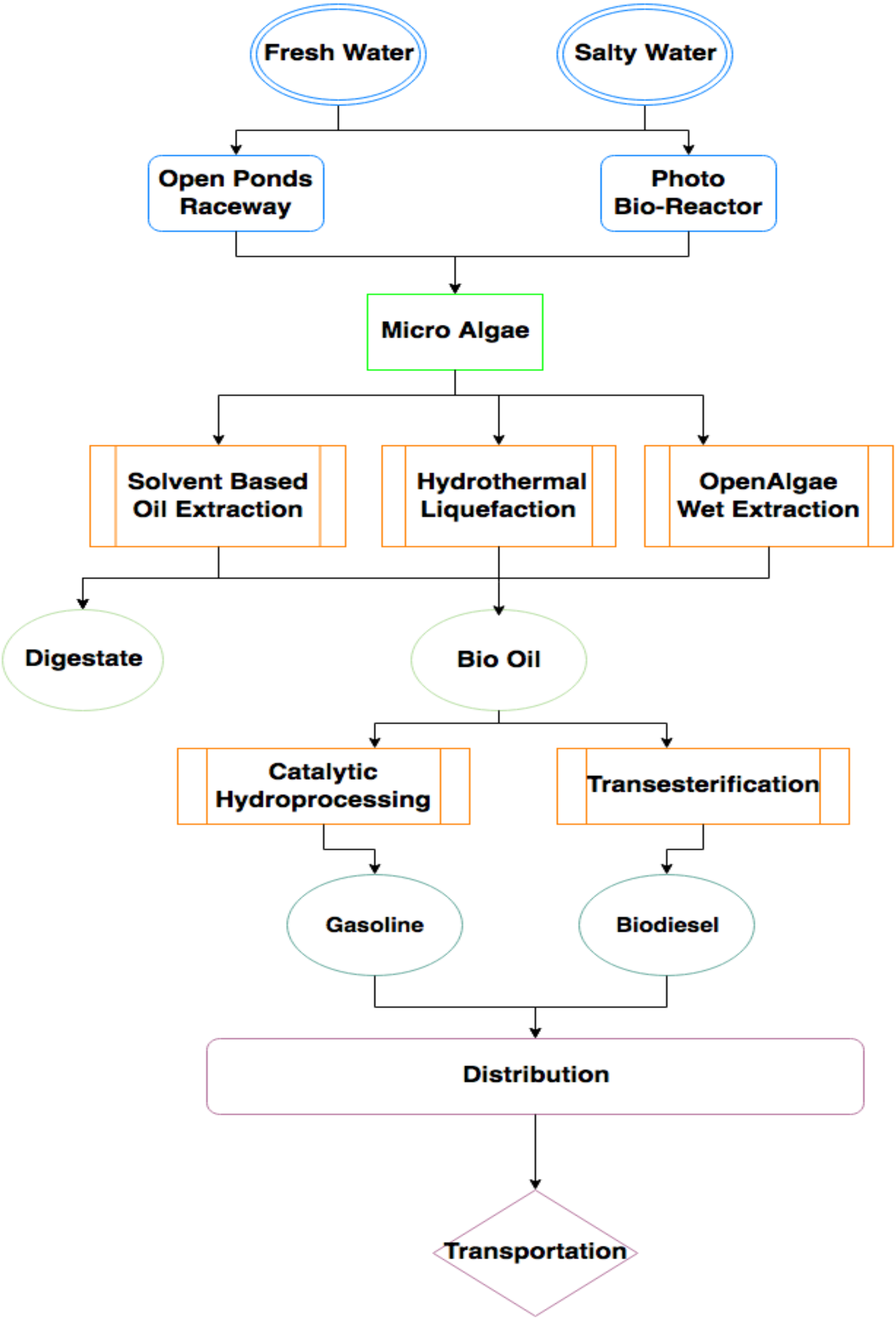
efficiency, and the co-location of the facility to a power plant, but specific details will be given case by case.

A summarizing table of all the processes investigated is hereby presented:

Cultivating System	**Algae Strain**	**Optimization**	**Biomass Productivity [g/m^2/d]**	**Oil Content [kg$_{oil}$/kg$_{db}$]**	**Extraction Method**	**Co-product**	**Fuel**
Open Pond Race (OPR)	*Nannochloris sp. and Nannochloropsis sp.*	No	3	0.24	Solvent Extraction (Hexane)	No	Diesel
Open Pond Race (OPR)	*Nannochloris sp. and Nannochloropsis sp.*	Yes	25	0.50	Solvent Extraction (Hexane)	No	Diesel
OPR + Photo Bio Reactor (PBR)	*Staurosira sp.*	No	19	0.31	Solvent Extraction (Hexane)	No	Gasoline
OPR + Photo Bio Reactor (PBR)	*Desmodemus sp.*	Yes	23	0.38	Hydro Thermal Liquefaction	No	Gasoline
OPR + Photo Bio Reactor (PBR)	*Desmodemus sp.*	Yes	23	0.38	Solvent extraction (Heptane)	Yes	Gasoline

Table 22: Algae pathways summarizing tables

A flowchart presenting the different pathways explored is presented below:



Flowchart 3: Algae Pathways

6.1 Biodiesel from Open Ponds Races

This chapter is about the cultivation of micro algae in an Open Ponds Race (OPR) and is modelled based on the paper of (Passell et al., 2013), whose work has been adapted for the purpose of the thesis to investigate the production of a biofuel from a large scale facility, because the original data used are of an existing plant of 0.1 ha scaled up to a 10 ha plant, using current commercial data.

In the scaling up different assumptions are made for increasing the current production, like higher production efficiency due to the bigger production facility and the progresses into the cultivation and harvesting method, together with a higher biomass productivity that goes from 3g/m^2/d to 25g/m^2/d. These are the values adopted for the base and optimized case, and they represent the current productivity of an existing commercial facility (at Sembiotic Inc. in Ashkelon, Israel) and the maximum productivity according with the literature range (Passell et al., 2013).

Image 7: Open Pond Races - Source: Wikipedia

The plant is co-located to a power plant that is the source of CO_2 and for every kg of biomass produced 2 kg of it are absorbed, as it will represent a source of carbon for the algae's growth. No transports or infrastructures are included, however for a greater thoroughness they have been added, using the data from the study of (Mu et al., 2014) and the assumption made in the previous chapter.

The algae strains used are *Nannochloris sp.* and *Nannochloropsis sp.* while the water used is waste sea water coming from the nearby power plant with a salinity of 35 g/L.

After the cultivation step the algae are centrifuged and reduced to a solution with 20% solids. The process used is a wet extraction method divided thus:

- Pretreatment
- Extraction
- Solvent recovery
- Oil separation

- Belt filter press
- Feed dryer

The solvent used is hexane, which is after recovered, even if a part of it is lost in the air as fugitive emissions. This solvent is required for extracting the oil contained in the algae. The last two steps are needed for the dewatering and drying of the remaining biomass.

The oil extracted is then further upgraded into a finished fuel (i.e. biodiesel) through a transesterification process. Even though this process is not present in the ecoinvent database, it has been adapted with the existing process of the transesterification of the soybean oil. For this reason, the original ecoinvent process has been updated for the purpose of this thesis, and so instead of considering the esterification plant in the United States (US) we consider it in the center of Italy. A distance of 960 km (i.e. distance from Rome to Bern) is covered by train. Then for the regional distribution of the finished fuel we maintain the assumptions of the ecoinvent process considering a distance of 150 km by road covered by a lorry, and a distance of 100 km covered by train.

The electricity mix used is the Italian average one at grid, as it has been said in the introduction chapter that Switzerland is not a suitable area for the cultivation of Algae, while the southern parts of Europe or northern parts of Africa can be a good compromise between the weather conditions and the distance for transporting the finished fuel.

Within the wet extraction process two co-products are produced together with the algae oil, low value lipids (Hydrocarbons) and the residual biomass (oilcake). The allocation of the impacts of the co-products is made considering the energy content of them.

The energy allocation percentages used in the study of (Passell et al., 2013) are the following:

Co-product	Percentage Allocation
Crude algae-oil	42%
Hydrocarbons	28%
Oilcake	30%

Table 23: Energy based allocation ratios per kg crude algae oil – Source:(Passell et al., 2013)

An energy allocation considering the crude algae-oil has thus been performed. The coproducts can be used in different ways, like animal feeding, or they can be used in the pharmacy and alimentary sector, having a high revenue value.

In the optimized case according to (Passell et al., 2013) these are the improvements made:

- The paddlewheels (that are used for continuously mixing the OPR and allowing the spread of the nutrients substances), scale from 7.5 kW in the 1000 m^2 facility to 5.8 kW for each of them in the 10 ha one (i.e. 50 paddlewheel for every pond sized 2000m^2);

- Water pump and blower energy scale linearly;
- Algae productivity increases from 3 $g/m^2/d$ to 25 $g/m^2/d$;
- 4 centrifuges at 4 kW are required to reduce water volume in the bigger facility;
- Higher oil content: from 0.24 kg oil/ kg dry algae biomass to 0.5 kg oil/ kg dry algae biomass;
- Renewable source of energy: for being consistent with the other optimized cases explored we use the same electricity, which is the low voltage hydropower one, created for the Thelma project (Stefan Hirschberg, 2016);
- In the transesterification process the transports on roads are provided by a EURO6 lorry and the atmospheric emissions have been reduced to 50%;

All these assumptions are valid only for the cultivation and harvesting processes, not for the oil extraction one.

Algae cultivation and oil extraction are counted in the same LCI dataset as it was performed originally by the work of (Passell et al., 2013). The values for the cultivation step are accounted per kg^{-1} dry biomass:

Products	**Base**	**Optimized**	**Unit**	**Comment**
Algae Oil OPR Baseline Case (3g/m2/d)	1	1	kg	
Resources				
Water, process, unspecified natural origin/m3	0.706	0.706	m3	Added to contrast the water evaporation and to mantain salinity to specific level
Carbon dioxide, in air	2	2	kg	From the co-located power plant as a source of C
Electricity/Heat				
Electricity, low voltage, production IT, at grid/IT U	12.676	0	kWh	Paddle wheels
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.582		Paddle wheels
Electricity, low voltage, production IT, at grid/IT U	5.07	0	kWh	Flue gas blower
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	30.121		Flue gas blower
Electricity, low voltage, production IT, at grid/IT U	1.408	0	kWh	Water pump
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.167		Water pump
Electricity, low voltage, production IT, at grid/IT U	2.86	0	kWh	Algae inoculant prep (florescent light)
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.17		Algae inoculant prep (florescent light)
Electricity, low voltage, production IT, at grid/IT U	2.52	0	kWh	Algae inoculant prep (air conditioner)
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.15		Algae inoculant prep (air conditioner)
Electricity, low voltage, production IT, at grid/IT U	0.845	0	kWh	Harvesting pump
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.05		Harvesting pump
Electricity, low voltage, production IT, at grid/IT U	6.761	0	kWh	Centrifuge - Dewatering

Electricity, low voltage, hydropower, 2030+, at grid/CH	0	0.04		Centrifuge - Dewatering
Electricity, low voltage, at grid/IT U	0.089	0	kWh	SRS process (Oil Extraction) - electricity per kg oil
Electricity, low voltage, hydropower, 2030+, at grid/CH U	0	0.089		SRS process (Oil Extraction) - electricity per kg oil
Heat, natural gas, at industrial furnace >100kW/RER U	2.19	2.19	MJ	Energy used for the pretreatment and extraction of the oil per kg oil
Heat, natural gas, at industrial furnace >100kW/RER U	2.79	2.79	MJ	Energy input for recovering the hexane per kg oil
Heat, natural gas, at industrial furnace >100kW/RER U	0.805	0.805	MJ	Energy input for processing of the oil to separate the oil and other lipids
Electricity, low voltage, at grid/IT U	0.845	0.845	kWh	Electricity Belt Filter Press, used to dewaterthe biomass
Heat, natural gas, at industrial furnace >100kW/RER U	2.86	2.86	MJ	Feed Dryer- Electricity for drying the biomass
Materials/fuels				
Diammonium phosphate, as N, at regional storehouse/RER U	0.11	0.11	Kg	Fertilizer – the quantity is fixed per g of algae biomass
Diammonium phosphate, as P2O5, at regional storehouse/RER U	0.019	0.019	kg	Fertilizer – the quantity is fixed per g of algae biomass
Polyethylene, linear low density, granulate| production | Alloc Rec, U	0.003	3.01E-05	kg	Infrastructure
Steel, unalloyed (GLO)| market for | Alloc Rec, U	0.00177	1.75E-05	kg	Infrastructure
Concrete, normal (GLO)| market for | Alloc Rec, U	5.49E-06	5.43E-08	m3	Infrastructure
Hexane (GLO)| market for | Alloc Rec, U	0.139	0.139	kg	Solvent used
Chemical, organic (GLO)| market for | Alloc Rec, U	0.034	0.034	kg	Proxy - Unknown organic used in the process
Emissions to air				
Water	0.706	70.578	m3	Evaporation
Hexane	0.002	0.002	kg	Fugitive emissions in the extraction process of the oil
Waste to treatment				
Wastewater from vegetable oil refinery (GLO)| treatment of | Alloc Rec, U	7.331	7.331	l	Proxy – wastewater from the oil extraction process

Table 24: Algae cultivation and oil extraction – LCI

The LCI of the transesterification process of the algae oil in the base and optimized case is instead the following:

Products	Base	Optimized	Unit
Biodiesel from Esterification process	1	1	MJ
Materials/fuels			
Algae Oil OPR Baseline Case (3g/m2/d)	2.63E-02	0	kg
Algae Oil OPR Optimized (25g/m2/d)	0	2.63E-02	kg
Electricity, low voltage (IT)| market for | Alloc Rec, U	1.76E-04	0	kWh
Electricity, low voltage, hydro power, 2030+, at grid/CH U	0	0.0067	kWh
Light fuel oil, burned in boiler 100kW, non-modulating/CH U	1.63E-05	0.000621	MJ
Transport, freight train (IT)| processing | Alloc Rec, U	0.025	0.025	tkm
Transport, freight train (CH)| electricity | Alloc Rec, U	2.63E-03	2.63E-03	tkm
Transport, lorry 20-28t, fleet average/CH U	3.95E-03	0	tkm
Transport, freight, lorry 16-32 metric ton| Alloc Rec, U	0	3.95E-03	tkm
Regional distribution, oil products/RER/I U	6.89E-12	6.89E-12	p
Tap water, at user/CH U	1.8E-05	1.8E-05	kg
Emissions to air			
Heat, waste	6.34E-04	6.34E-04	MJ
BOD5, Biological Oxygen Demand	9.2E-5	9.2E-5*0.5	kg
COD, Chemical Oxygen Demand	9.2E-5	9.2E-5*E-5	kg
DOC, Dissolved Organic Carbon	1.13E-05	1.13E-05*0.5	kg
TOC, Total Organic Carbon	1.13E-05	1.13E-05*0.5	kg
Emissions to soil			
Oils, biogenic	1.32E-05	1.32E-05 *0.5	kg
Waste to treatment			
Disposal, separator sludge, 90% water, to hazardous waste incineration/CH U	4.41E-06	4.41E-06	kg
Disposal, municipal solid waste, 22.9% water, to sanitary landfill/CH U	1.64E-07	1.64E-07	kg
Treatment, rainwater mineral oil storage, to wastewater treatment, class 2/CH U	1.97E-06	1.97E-06	m3
Treatment, sewage, to wastewater treatment, class 2/CH U	1.81E-08	1.81E-08	m3

6.2 Gasoline from Algae 100 ha facility

In this chapter the cultivation of the algae in a 100 ha hybrid system facility (i.e. a part is made with Photobioreactors (PBRs) and the other one with OPRs) is carried out in order to exploit the maximum advantages provided by these two cultivation systems. The modelling is based on the paper written by (Beal et al., 2015). The system modelled by the authors is based on an original demonstration plant of 0.5 ha scaled up (i.e. Kona Demonstration Facility (KDF) now Cellana LLC). Two algae species were there cultivated: *Staurosira sp.* and *Desmodemus sp.*, with biomass productivity respectively of 19 g/m^2/d and 23 g/m^2/d, evaluated through the demonstration plant. This large-size facility is assumed to be near a power plant, to exploit its waste stream gases as a source of carbon, while the fertilizers are assumed to be bought.

Two images are presented below to show the reader how a PBR looks like and how is designed the system facility:

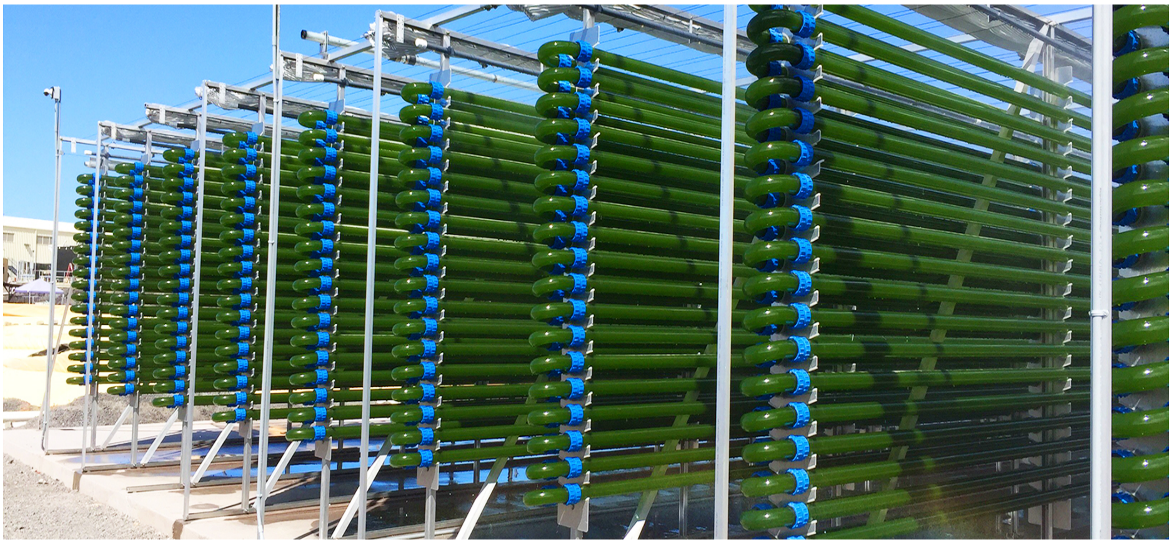


Image 8: Photobioreactor

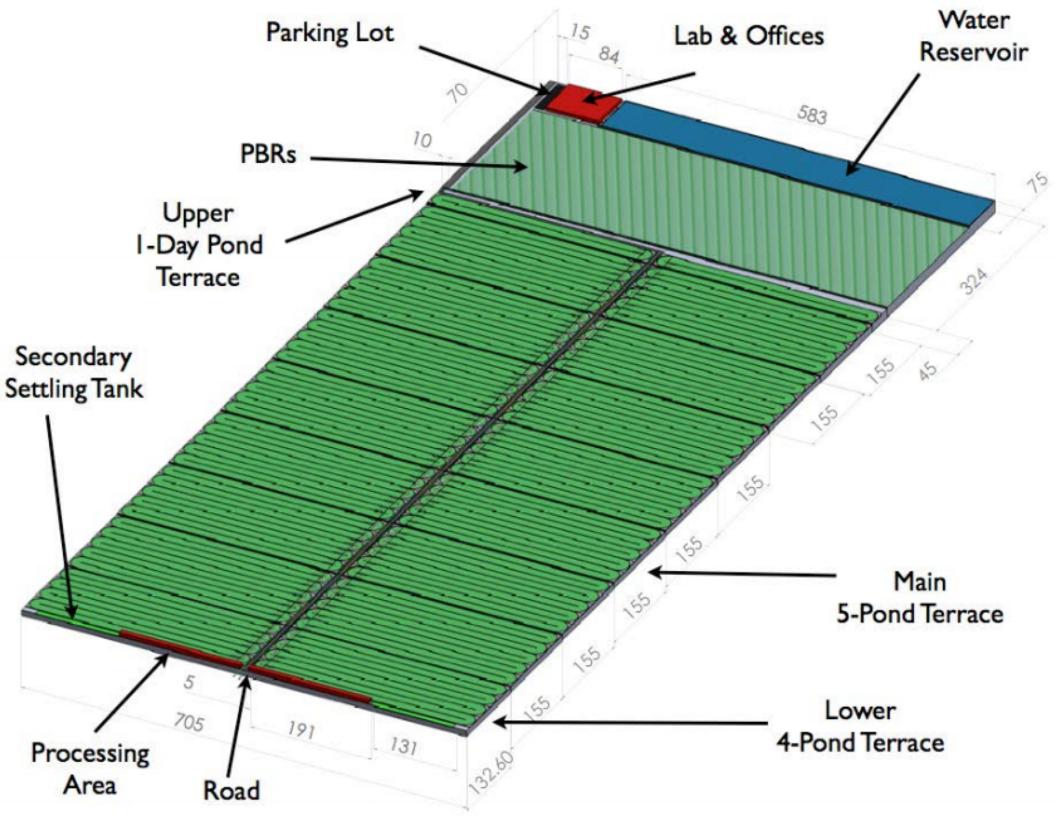


Image 9: System facility - Source:(Beal et al., 2015)

Many processes are explored within the study of (Beal et al., 2015), but those on which we are going to concentrate are three:

1. A process using the current technologies for cultivation and harvesting, adopting a solvent for the oil extraction;
2. A process with enhanced harvesting and cultivating processes and the oil extraction method is based on the hydrothermal liquefaction (HTL);
3. A process equal to the second one except for the oil extraction method that is based on a process named Openalgae. In this one electromagnetics forces are used for splitting the algae's cells allowing an easier recovery of the oil extracted.

The second and third processes are already considered optimized by the authors of the paper and each of these processes is carried on in the same large-size system facility of 100ha Even if these processes represent the target processes for the authors, it has to be said that a base case of them has been analyzed as well by the authors themselves. But as the purpose of this thesis is to show an optimized version of the current processes, we assumed as well that their target processes are our optimized ones.

The facility is already designed as a well enhanced one, considering at least the structure facility, but many assumptions have been taken for developing it:

- High productivity yields;

- Co-location with a waste CO_2 stream;
- Gravity enhanced volume transfers;
- Airlift pond circulation;
- Efficient conversion/extraction mode;
- Renewable energy;
- Lifetime: 30 years;

In the original work the functional unit is 1ha so their data have been adapted to the functional unit of the thesis that is 1 MJ. Besides the facility takes place in the US or in the Hawaii, while for being consistent with the previous process investigated in chapter 6.1, we still assume that our facility takes place in the center of Italy, and according to that the same transport distances are considered (i.e. transport of the finished fuel from Italy to Switzerland by train, and regional distribution performed with trains and lorries).
The fuel production in the paper is assumed as a coproduct, and with the Openalgae process is also considered a co-production of animal feed, replaced with two processes available in the ecoinvent database: soybean meal and corn maze.

6.1.1 Wet Solvent Extraction

This process according to (Beal et al., 2015) is based on the current technologies for harvesting and processing the biomass produced (e.g. paddlewheel for circulating the biomass continuously, the use of a centrifuge for concentrating it or the use of a ring dryier for drying the algae), even if it is known that are not efficient. The pond has to be mixed in this case for 24h. The algae strain considered is *Staurosira sp.* with productivity, as mentioned above, of 19 $g/m^2/d$ and an oil yield of 0.31 kg oil/ kg dry algae biomass.

Before processing the algae produced they must be thickened to a solution of 90% solids. This is performed through the centrifugation step and the ring drier. After these operations the algae are ready to be processed, in order to extract their oil content. A direct solvent extraction using hexane as solvent is used. Through this extraction process the 50% of lipids contained into the algae is collected as a biocrude. For calculating this qiuantity we can refer to the following equation:

$$M \cdot L_c \cdot RR = 0.155 \cdot M = B_r$$

Where:

- M: total mass output [Mton/day]
- L_c: Lipid content = 0.31
- RR: recovery rate = 0.5
- B_r: Biocrude recovered [Mton/day]

According to (Beal et al., 2015) in the operation 1% of the solvent is lost and 0.005g of phosphoric acid is needed per g of biocrude recovered. The biomass that remains after the oil recovery is all considered as animal feed.

Respect to the original paper we consider two source of electricity to power the different operations: the Swiss average mix, in order to have the same comparison mix with the other processes investigated through the thesis, and the Italian average one, as it is assumed that the cultivation will take place abroad from Switzerland, precisely in the center of Italy.
This process constitutes for us as well as our base case.
Another modification provided to the original paper is that the animal feed co-products are energy allocated considering the bio-crude produced:

Co-products	**LHV [MJ/kg]**	**Energy Allocation**
Gasoline	44.4	0.34
Soybean meal	19.7	0.50
Corn grain	18.7	0.16

Table 25: Gasoline energy allocation direct solvent extraction process

The fuel that we are going to consider is gasoline, because in the paper it is assumed that this fuel is replaced as its production is avoided.

The LCI of this base case process is shown beneath considering as electricity the Italian average one, but in the results section also the Swiss average mix is going to be showed:

Products	Base	Unit	Comment
Gasoline Solvent Extraction	1	MJ	Is based on the production of 0.025 kg of gasoline
Resources			
Occupation, water bodies, artificial	0.287	m2a	
Occupation, industrial area	0.0546	m2a	
Materials/fuels			
Ammonia, liquid| ammonia production, steam reforming, liquid | Alloc Rec, U	0.00317	kg	Fertilizer
Phosphate fertiliser, as P2O5 (GLO)| market for | Alloc Rec, U	0.000237	kg	Fertilizer
Packaging film, low density polyethylene (GLO)| market for | Alloc Rec, U	0.01396	kg	Infrastructure
Polyvinylchloride, bulk polymerised (Morero, Groppelli, & Campanella)| polyvinylchloride production, bulk polymerisation | Alloc Rec, U	4.98E-06	kg	Infrastructure
Transport, lorry 20-28t, fleet average/CH U	2.25E-5*150	tkm	Regional distribution
Hexane (GLO)| market for | Alloc Rec, U	0.000374	kg	Solvent
Phosphoric acid, fertiliser grade, without water, in 70% solution state (GLO)| market for | Alloc Def, U	4.63E-05	kg	Compound needed in the oil extraction
Transport, freight train (CH)| electricity | Alloc Rec, U	2.25E-5*100	tkm	Regional distribution
Transport, freight train (IT)| processing | Alloc Rec, U	2.25E-5*960	tkm	Transport from Italy by train

Electricity/heat			
Electricity, low voltage, at grid/IT U	0.255	kWh	Total electricity required per MJ of gasoline produced
Heat, natural gas, at boiler modulating >100kW/RER U	0.5437	MJ	Total heat required for the production of 1 MJ of gasoline
Emissions to air			
Hexane	0.000374	kg	Solvent loss
Final waste flows			
Polyethylene waste	0.01396	kg	Disposal of infrastructure
Polyvinyl chloride waste	4.98E-06	kg	Disposal of infrastructure

Table 26: Hexane solvent extraction process - LCI

6.2.2 Hydrothermal Liquefaction process (HTL) Optimized Case - LCI

One of the processes carried out in the study of (Beal et al., 2015) is the Hydrothermal Liquefaction process, and it is based on the one developed at Pacific Northwest National Lab (PNNL) (Zhu, Albrecht, Elliott, Hallen, & Jones, 2013). The hydrothermal processing is an approach used for exploiting the high moisture content of the algae, as it takes place using water at elevated temperatures and pressures, and within these conditions the algae cells will break down to form bio-oil and gases (Brown et al., 2010). This process represent a target case already in the original paper, thus we consider it our optimized case, including then all the assumptions exposed in chapter 6.

The design of the facility has not changed for this case, but in respect to the baseline process analyzed in the sub-chapter 6.2.1 the algae strain used is *Desmodemus sp.* with a biomass productivity of 23 g/m^2/day and an oil yield of 0.38 kg oil/ kg dry algae biomass. Furthermore the processes used for processing the algae are considered more effective than the ones seen before (e.g. airlift pond circulation instead of the paddlewheels, filter press instead of the centrifugation). The circulation time of the open ponds is now reduced to 12h from the 24h of the base case. The electricity to be used should be renewable and coming from a wind power plant, but for being consistent with the other optimized processes of the thesis the electricity will be again the low voltage hydropower one created for the Thelma project (Stefan Hirschberg, 2016).
The transports by road for the regional distribution of the finished fuel in Switzerland, compared to the base case process are provided by a EURO 6 lorry. The reduction of the atmospheric emissions by 50% is here as well done, and is based on the base case of the same process, even if we are not going to show the data concerning it.

To perform this process in the original paper is assumed that the heat and the electricity required are provided by an onsite combined heat and power plant (CHP). The lipid recovery from the biomass is assumed to be the 50% of all the biomass produced and is converted into biocrude. We can now express the biocrude recovery in this way:

$$M \cdot RR = B_r$$

Where:

- M: total mass output [Mton/day]
- RR: recovery rate = 0.5
- B_r: Biocrude recovered [Mton/day]

This way of assuming the lipid recovery is based on the assumptions made in the original paper by (Beal et al., 2015), and we are simply agreeing with their assumptions.

This process does not consider any co-production, but considers only the production of gasoline starting from algae, thus no energy allocation has been used in it. Furthermore the emissions of the CHP plant are part of the LCI of (Beal et al., 2015).

Hereafter the LCI of the process is presented:

Products	**Optimized**	**Unit**	**Comment**
Gasoline_HTL Optimized	1	MJ	Is based on the production of 0.025 kg of gasoline
Resources			
Occupation, water bodies, artificial	0.00583	m2a	
Occupation, industrial area	0.00111	m2a	
Materials/fuels			
Ammonia, liquid (Morero et al.)| ammonia production, steam reforming, liquid | Alloc Rec, U	0.00546	kg	Fertilizer
Phosphate fertiliser, as P2O5 (Morero et al.)| diammonium phosphate production | Alloc Rec, U	1.82E-05	kg	Fertilizer
Packaging film, low density polyethylene (GLO)| market for | Alloc Rec, U	0.001255	kg	Infrastructure
Polyvinylchloride, bulk polymerised (GLO)| market for | Alloc Rec, U	4.49E-06	kg	Infrastructure
Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U	2.25E-5*150	tkm	Regional distribution
Transport, freight train (CH)| electricity | Alloc Rec, U	2.25E-5*100	tkm	Regional distribution
Transport, freight train (IT)| processing | Alloc Rec, U	2.25E-5*960	tkm	Transport by train from IT to CH
Electricity/heat			
Electricity, low voltage, hydro power, 2030+, at grid/CH U	0.0237	kWh	Overall electricity required per MJ produced
Heat, natural gas, at boiler modulating >100kW/RER U	0.0168	MJ	Overall heat required per MJ produced
Emissions to air			

Nitrogen oxides	1.379E-6*0.5	kg	CHP emissions
Carbon monoxide, biogenic	4.41-6*0.5	kg	CHP emissions
Methane, biogenic	2.117E-6*0.5	kg	CHP emissions
NMVOC	1.748E-7*0.5	kg	CHP emissions
Sulfur dioxide	1.763E-6*0.5	kg	CHP emissions
Dinitrogen monoxide	12.33E-7*0.5	kg	CHP emissions
Final waste flows			
Polyethylene waste	0.001255	kg	Infrastructure Disposal
Polyvinyl chloride waste	4.49E-06	kg	Infrastructure Disposal

Table 27: Gasoline from HTL process - LCI

6.2.3 OpenAlgae Process (Wet Extraction) Optimized - LCI

This process is equal to the previous one analyzed in sub-chapter 6.2.2, and differs from it only because of the oil extraction method used. The method now used is a wet extraction method developed by (H. Thomas, 2014) named Openalgae.

The process is based on 4 main steps: grow of the algae, concentration, separation and oil recover. The oil recovered is then upgraded according to (Beal et al., 2015) into gasoline, as it is a co-product of the process.

The Openalgae process should allow for less energy consumption because the separation stage is effected using electro-magnetic forces to break down the cells. After the recovery of the oil, the remaining biomass can be used as a possible animal feedstock, with an extra added value because rich in Omega-3, so economically valuable.

Also, the water used for cultivation, can be cleaned after the oil recovery and sent back to the cultivation step.

Considering that, as in the first process investigated in sub-chapter 6.2.1, there are co-products out of the process (i.e. animal feed substituted by the soybean meal and corn grain processes from the ecoinvent database), again an energy allocation is performed as it is shown below:

Co-products	LHV [MJ/kg]	Energy Allocation
Gasoline	44.4	0.49
Soybean meal	19.7	0.39
Corn grain	18.7	0.12

Table 28: Energy allocation Openalgae process

The values showed in Table 27 differ from those of table 24 because the biomass productivity and the oil yield now considered are different. This is because the algae strain now used is *Desmodemus sp.* with a biomass productivity of 23 g/m^2/d and an oil yield equal to 0.38 kg oil/ kg dry algae biomass. The main difference though, apart from the higher biomass productivity, is the recovery rate that is possible to achieve with the Openalgae process, that is equal to 75%, as it is shown below in the following equation:

$$M \cdot L_c \cdot RR = 0.285 \cdot M = B_r$$

Where:

- M: total mass output [Mton/day]
- L_c: Lipid content = 0.38
- RR: recovery rate = 0.75
- B_r: Biocrude recovered [Mton/day]

In the paper of (Beal et al., 2015) what remains after the oil recovery is all considered to be biomass used as animal feed. Another difference with the direct solvent extraction process seen in sub-chapter 6.2.1 is that the solvent used is heptane, and not hexane, as assumed by the authors.
Again as for the previous process investigated, the target process of the paper of (Beal et al., 2015) is our optimized one.

The LCI of the gasoline produced with the Openalgae process, considering the energy allocation, is shown below:

Products	**Optimized**	**Unit**	**Comment**
Gasoline Openalgae Process Optimized	1	MJ	Is based on the production of 0.025 kg of gasoline
Resources			
Occupation, water bodies, artificial	0.00502	m2a	
Occupation, industrial area	0.00095	m2a	
Materials/fuels			
Ammonia, liquid (Morero et al.)| ammonia production, steam reforming, liquid | Alloc Rec, U	0.00268	kg	
Phosphate fertiliser, as P2O5 (Morero et al.)| diammonium phosphate production | Alloc Rec, U	0.0002	kg	
Packaging film, low density polyethylene (Morero et al.)| production | Alloc Rec, U	0.001081	kg	
Polyvinylchloride, bulk polymerised (Morero et al.)| polyvinylchloride production, bulk polymerisation | Alloc Rec, U	3.86E-06	kg	
Transport, freight, lorry 16-32 metric ton, EURO6 (Morero et al.)| transport, freight, lorry 16-32 metric ton, EURO6 | Alloc Rec, U	2.25E-5*150	tkm	
Heptane (GLO)| market for | Alloc Rec, U	8.36E-07	kg	
Transport, freight train (CH)| electricity | Alloc Rec, U	2.25E-5*100	tkm	
Transport, freight train (IT)| processing | Alloc Rec, U	2.25E-5*960	tkm	
Electricity/heat			
Electricity, low voltage, hydro power, 2030+, at grid/CH U	0.0298	kWh	
Heat, natural gas, at industrial furnace >100kW/RER S	0.0117	MJ	
Emissions to air			
Heptane			

Final waste flows			
Polyethylene waste	0.001081	kg	
Polyvinyl chloride waste	3.86E-06	kg	

Table 29: Gasoline from Openalgae process - LCI

6.2.4 Gasoline Processes Comparison

As the processes analyzed in the subchapters 6.2.1-6.2.3 are basically modelled in the same large scale facility, it has been thought that could be interesting to the reader to show the LCIs of the three of them all together, so that is possible to assist the differences among them:

Products	**Base**	**Optimized - HTL**	**Optimized – Openalgae Proc.**	**Unit**	**Comment**
Gasoline_HTL Optimized	1	1	1	MJ	Is based on the production of 0.025 kg of gasoline
Resources					
Occupation, water bodies, artificial	0.287	0.00583	0.00502	m2a	
Occupation, industrial area	0.0546	0.00111	0.00095	m2a	
Materials/fuels					
Ammonia, liquid| ammonia production, steam reforming, liquid | Alloc Rec, U	0.00317	0.00546	0.00268	kg	Fertilizer
Phosphate fertiliser, as P2O5 | diammonium phosphate production | Alloc Rec, U	0.000237	1.82E-05	0.0002	kg	Fertilizer
Packaging film, low density polyethylene (GLO)| market for | Alloc Rec, U	0.01396	0.001255	0.001081	kg	Infrastructure
Polyvinylchloride, bulk polymerised (GLO)| market for | Alloc Rec, U	4.98E-06	4.49E-06	3.86E-06	kg	Infrastructure
Transport, freight, lorry 16-32 metric ton, EURO6 (GLO)| market for | Alloc Rec, U	2.25E-5*150	2.25E-5*150	2.25E-5*150	tkm	Regional distribution
Hexane	0.000374	0	0	Kg	Solvent
Heptane	0	0	8.36E-07	kg	Solvent
Phosphoric Acid	4.63E-05	0	0	kg	Compound needed for biocrude recovery
Transport, freight train (CH)| electricity | Alloc Rec, U	2.25E-5*100	2.25E-5*100	2.25E-5*960	tkm	Regional distribution
Transport, freight train (IT)| processing | Alloc Rec, U	2.25E-5*960	2.25E-5*960	2.25E-5*100	tkm	Transport by train from IT to CH
Electricity/heat					
Electricity, low voltage, hydro power, 2030+, at grid/CH U	0.255	0.0237	0.0298	kWh	Overall electricity required per MJ produced

Heat, natural gas, at boiler modulating >100kW/RER U	0.5437	0.0168	0.0117	MJ	Overall heat required per MJ produced
Emissions to air					
Hexane	0.000374	0	0	Kg	Solvent Loss
Heptane	0	0	8.36E-07	kg	Solvent Loss
Nitrogen oxides	0	1.379E-6*0.5	0	kg	CHP emissions
Carbon monoxide, biogenic	0	4.41-6*0.5	0	kg	CHP emissions
Methane, biogenic	0	2.117E-6*0.5	0	kg	CHP emissions
NMVOC	0	1.748E-7*0.5	0	kg	CHP emissions
Sulfur dioxide	0	1.763E-6*0.5	0	kg	CHP emissions
Dinitrogen monoxide	0	12.33E-7*0.5	0	kg	CHP emissions
Final waste flows					
Polyethylene waste	0.01396	0.001255	0.001081	kg	Infrastructure Disposal
Polyvinyl chloride waste	4.98E-06	4.49E-06	3.86E-06	kg	Infrastructure Disposal

Table 30: Gasoline from algae processes comparison - LCI

7. Life Cycle Impact Assessment & Results

Starting from a specific type of biomass (i.e. wood, manure and algae) the different biofuels will be compared in powering different cars covering one kilometer. Before doing that the quantified result per 1 MJ of fuel will be showed to the reader.
This is very important because in this way it is possible to show what is influencing directly the different impact categories.
Among the impact categories that have been investigated only four mid-point indicators will be shown in this chapter, because are considered the most effective in displaying the results to the reader. All the other results are going to be shown in an appendix section at the end of the thesis.

The mid-points chosen for this section are those explained in the subchapter 3.4:

- Global warming potential [kg CO_2 eq.];
- Freshwater eutrophication potential [kg P eq.];
- Particulate Matter Formation potential [kg PM10 eq.];
- Natural Land Transformation potential [m^2];

The data for all the vehicles have been taken from the Thelma project (Stefan Hirschberg, 2016), and their environmental impacts have been divided in these categories:

- Car: considering for the production, the maintenance and the disposal of the car;
- Road: impacts on the environment due to production and maintenance of the road;
- Fuel/Electricity supply: every car is powered by a certain amount of energy (MJ/km), which is supplied by the different types of biofuels investigated and then compared with fossil fuels, conventional biofuels (e.g. soybean ester), different electricity mix, and hydrogen produced from fossil sources;
- Emissions: they include the fuel dependent emissions, the regulated emissions, and the non-exhaust emissions. The difference between a car powered with a fossil fuel and one powered by a biofuel is that the emissions for the last have been considered biogenic. All the other emissions from combustion of fossil fuels by vehicles have been assumed to be the same for combustion of biofuels.

The amount of energy used by these different cars for covering one kilometer is:

Vehicle	Energy Used [MJ/km]
ICEV gasoline	2.7
ICEV diesel	2.4
ICEV CNG	2.8
BEV	0.9
FCEV	1.6

Table 31: Cars Power

To calculate the emissions due to burning biofuels, they were assumed to be the same as those from burning fossil fuels in the same car, with the exception of biogenic CO2, CO and CH4. This data came from project THELMA (Stefan Hirschberg, 2016).

7.1 Wood Pathways

7.1.1 Global Warming Potential

The biofuels produced with different pathways from the wood biomass are here compared. In the following chart the results of producing 1 MJ of fuel are displayed. Doing that it is possible to assess which are the main contributors in the different categories. It will also be possible to see the direct comparison between the current cases and the optimized ones.

The categories examined in the following chart are:

- Direct emissions: emissions strictly related to the production of the fuel;
- Material inputs: all the inputs required for producing the biofuel like the raw biomass, the processing water, or the operational materials (e.g. silica sand for the fluidized bed reactors, or compound used for cleaning the raw biogas produced);
- Infrastructure: the plants, or the components needed for processing the biomass;
- Transport: the lorries or the trains used for carrying the raw biomass or the finished fuel;
- Catalyst: is an operational input but as it usually have big influence on most of the impact categories we prefer to show it separately;
- Electricity;
- Heat;
- Waste: includes all the wastes at the end of the processes, and can include the wastewater treatment, or the disposal of used minerals, or inert materials or ashes;

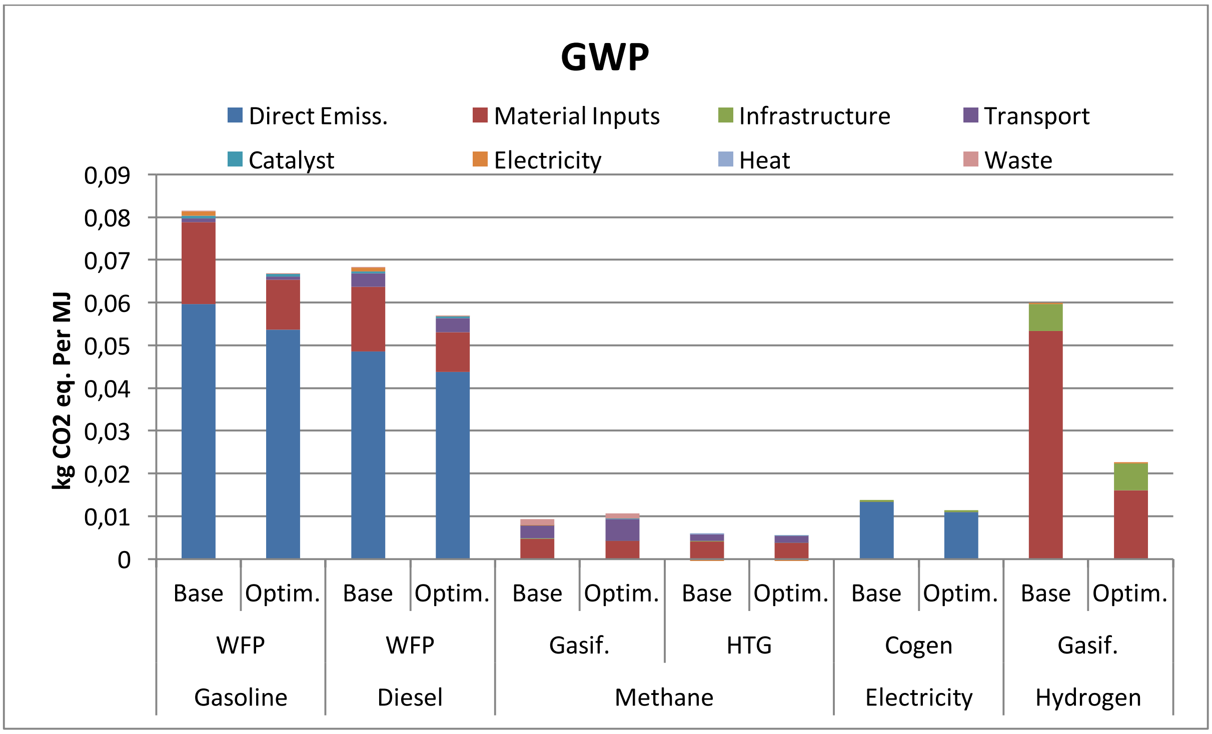


Chart 1: Wood pathways GWP results per MJ

As it possible to see the gasification pathway is so far the less contributing one. Even the conversion into electricity of the wood chips through a cogeneration plant represents a very good solution. For the other processes examined, we can assess how in the cases of the conversion of wood chips through the fast pyrolysis step into gasoline or diesel the main contribution comes from the direct emissions of the process. In the case of hydrogen production instead from the material inputs, which are represented mainly by the hydrogen produced starting from the gasification of the biomass.

Considering the fast pyrolysis, the main contributor is the bio-crude produced during the upstream process where the combustion of natural gas in the process affects badly this category, plus the transports freight used for the different operations (i.e. collecting the biomass, transporting the finished fuel). In considering the raw biomass, the chopping operations are the most contributing to the climate change because of the machines used that consume diesel fuel.

Considering instead the comparisons of the different fuels produced with the direct alternatives, we are going to show the results obtained in powering the different cars per one vehicle kilometer.

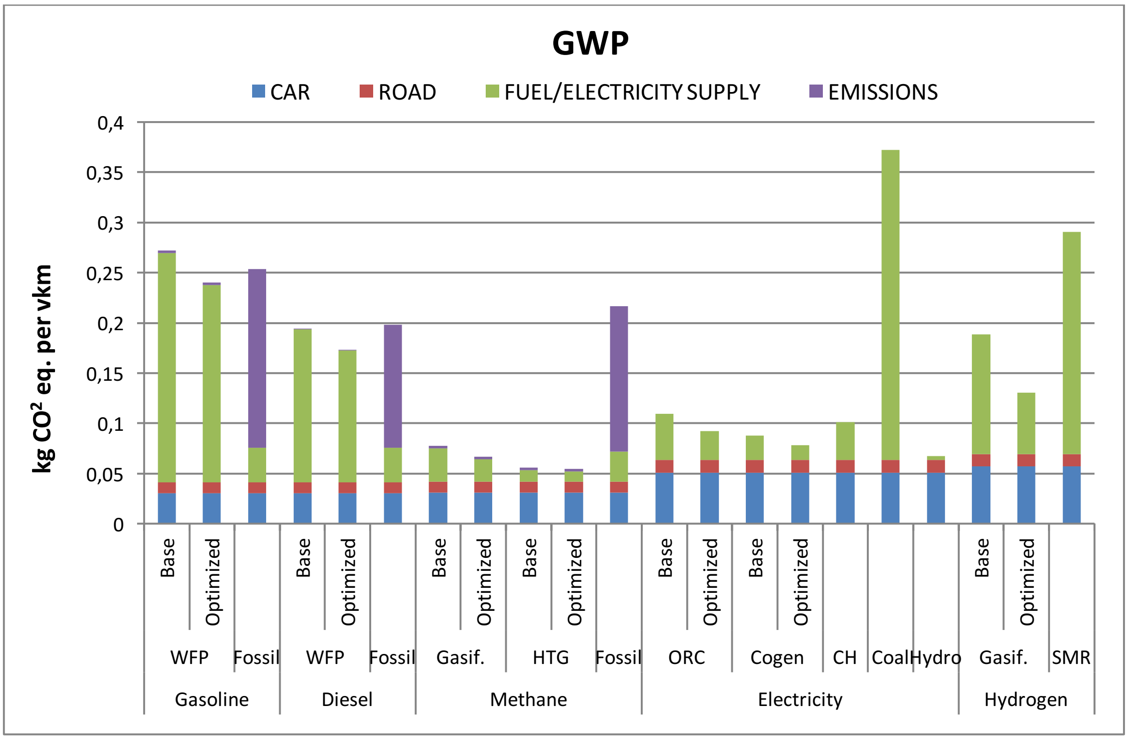


Chart 2: Wood pathways GWP results per vkm

A first important result coming from this chart is that, considering the Global Warming Potential, the best way to exploit wood biomass for powering a vehicle is mainly to gasify it and then upgrade the SNG produced into methane.
Also considering the Swiss average electricity mix, burning the wood into a cogeneration plant may represent a good way for using this biomass feedstock to power a car.

Some other considerations though arise from this chart. One of them is that the Pyrolysis process is not the most effective way to exploit the biomass for producing a fuel, at least not nowadays; GWP impacts are similar to using fossil fuels. Improvements of this technology in the future though, may lead to more interesting results.

Another consideration coming out from this chart is that hydrogen produced starting from woody biomass represents a promising pathway for producing it, as compared with the fossil way to do it is already competitive and might become much better with the improvements supposed by this work.

7.1.2 Fresh Water Eutrophication Potential

The following chart is about the impact resulting in this specific category from the production of 1 MJ of fuels, in the different pathways.

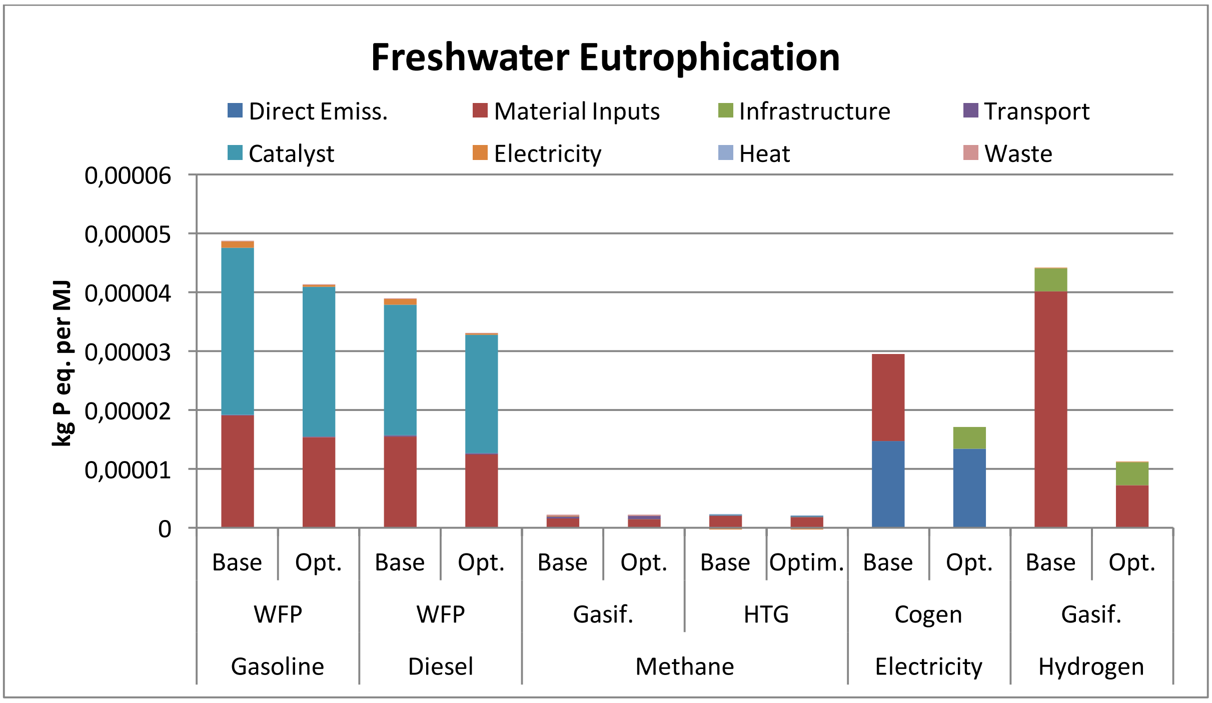


Chart 3: Wood pathways Freshwater eutrophication results per MJ

As the in the chart seen in the GWP category once again the fuels produced from the fast pyrolysis process together with the hydrogen produced from the biomass gasification process are those performing poorly. Although in this case the major contributions come from the catalysts used and the material inputs.
The catalyst has such a big contribution because of the mining operation involved in the production of one of its component the Molybdenum.

Considering instead the hydrogen process what is affecting this category is the electricity required for its production and compression to 700 bars. The reason to that is the combustion of lignite for producing the electricity, and the disposal of the spoil from lignite mining are highly influencing this category. The mining spoils include many hazardous compounds emitted to the water, where the main ones in terms of quantity are for example among the others: Sulfate, Silicon, Potassium, Magnesium and Sodium.

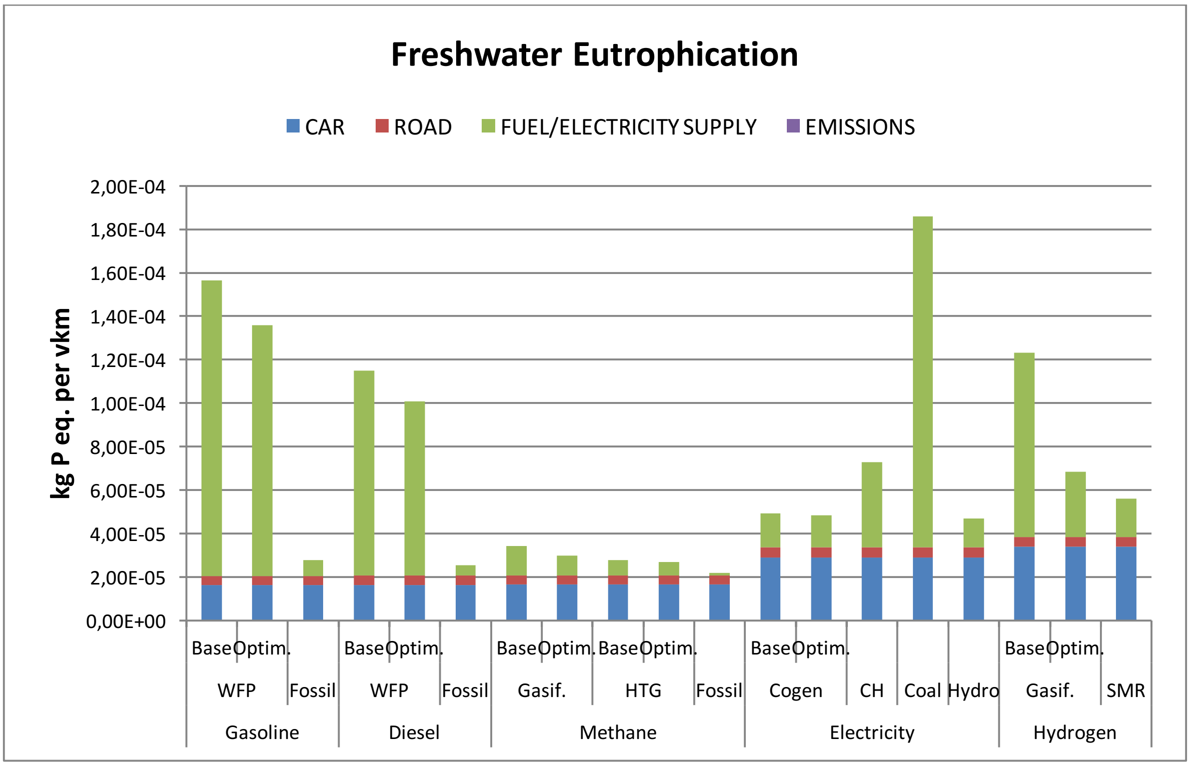


Chart 4: Wood pathways Freshwater eutrophication results per vkm

Even from the this chart that assesses the impacts of the different fuels per vkm the pyrolysis process and the hydrogen production are those that perform poorly.

Nevertheless, the other pathways explored shows good performances in this impact category, and their contribution is not that much if compared with the road and car categories. So as stated for the global warming potential category the conversion of the wood biomass into methane or into electricity are again the best ways for exploiting this source.

7.1.3 Particulate Matter Formation Potential

We are going now to show the results for this particular mid-point indicator that is a usual one used when assessing the environmental impacts of transportation units.
We will show first the chart indicating the impact of the production of 1 MJ of fuels, so it will be possible to assess in the specific what is really contributing in this impact category.

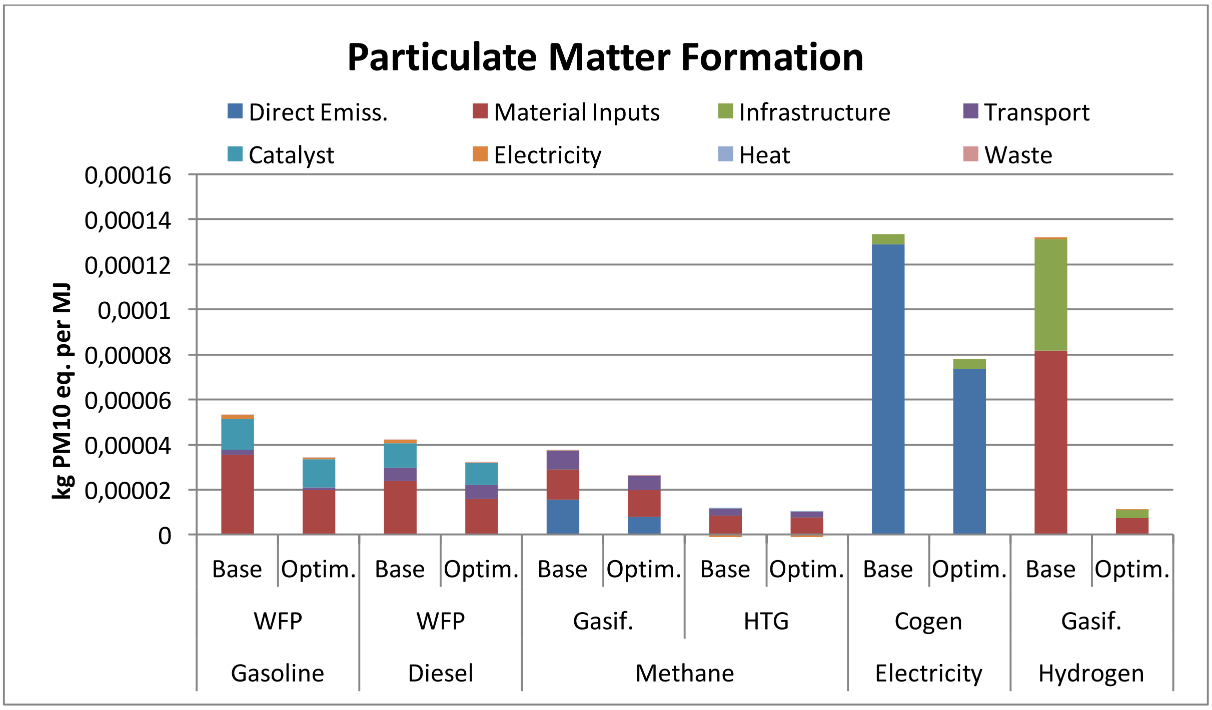


Chart 5: Wood pathways Particulate Matter Formation results per MJ

In every pathway is possible to assess how the material inputs are the most important contribution. For the electricity produced in the cogeneration plant this is indirectly seeable because a conversion from high to low voltage has been performed.
This is because of the processing of the wood chips (e.g. harvesting and chipping operations) and their transport to the plant. And their influence is very important and present in every process, as they constitute the starting biomass.
Only for the hydrogen process we can attribute the results obtained to other factors:

- the syngas produced from the biomass gasification, because of the magnesium used as bed material in the gasification process;
- the steam used in the steam reforming process, to enhance the hydrogen yield;
- The chemical plant and the distribution infrastructures included in the process;
- The electricity used for processing and compressing the hydrogen to 700 bar;

After having evaluated which are the main contributors in this impact category, we are going to show in the following chart the impacts related to the use of these fuels for powering different vehicles per a vkm. Like in the other cases the biofuels investigated will be directly compared with their direct alternatives.

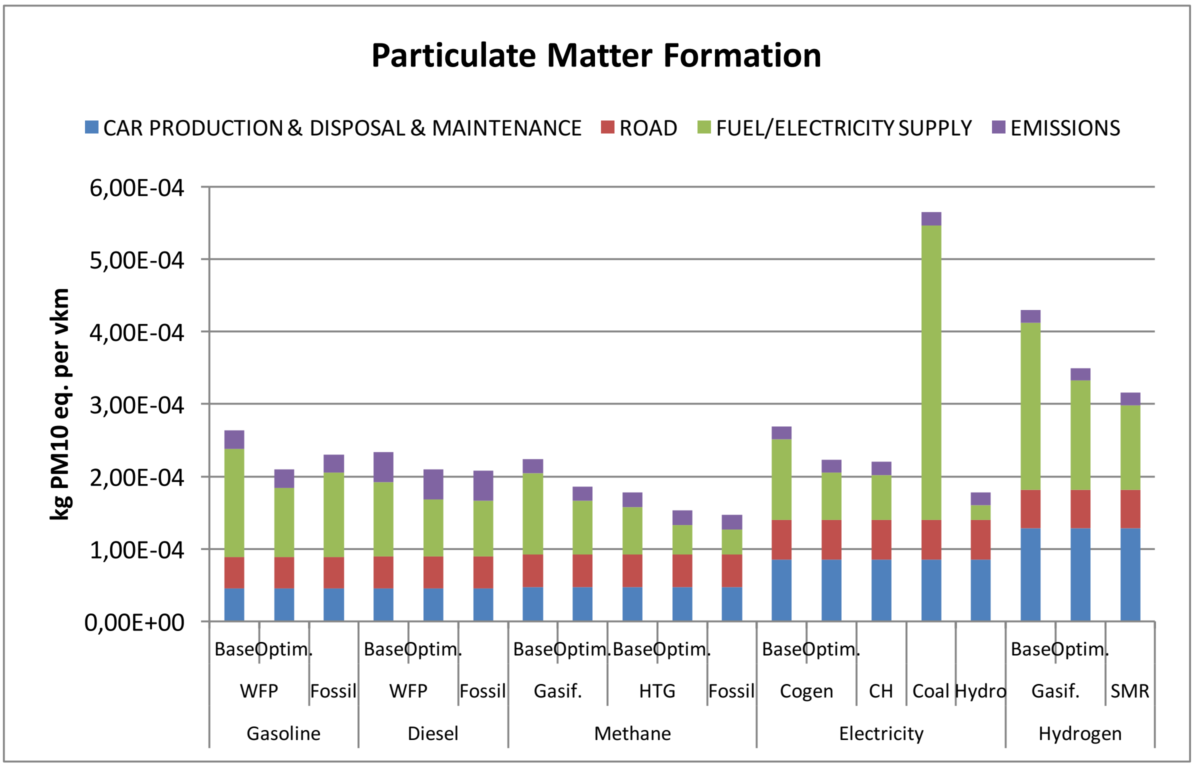


Chart 6: Wood pathways Particulate Matter Formation results per vkm

Regarding this mid-point category, the biofuels compared to the conventional fuels don’t perform much better, but still face the same issues that are present when is necessary to burn a substance to exploit its energy content.

The two processes that show a slightly worst performance if compared with their counterparts are the baseline case of the cogeneration plant and the hydrogen produced starting from the gasification of the biomass.

7.1.4 Natural Land Transformation Potential

The last category we are going to show regarding the wood pathways is the natural land transformation one. It assesses how the biofuel production is responsible in changing the pre-existent ecosystem and environment.

Firstly, the chart showing the results for the production of 1 MJ will be displayed, as it was done in the previouses sub-chapters.

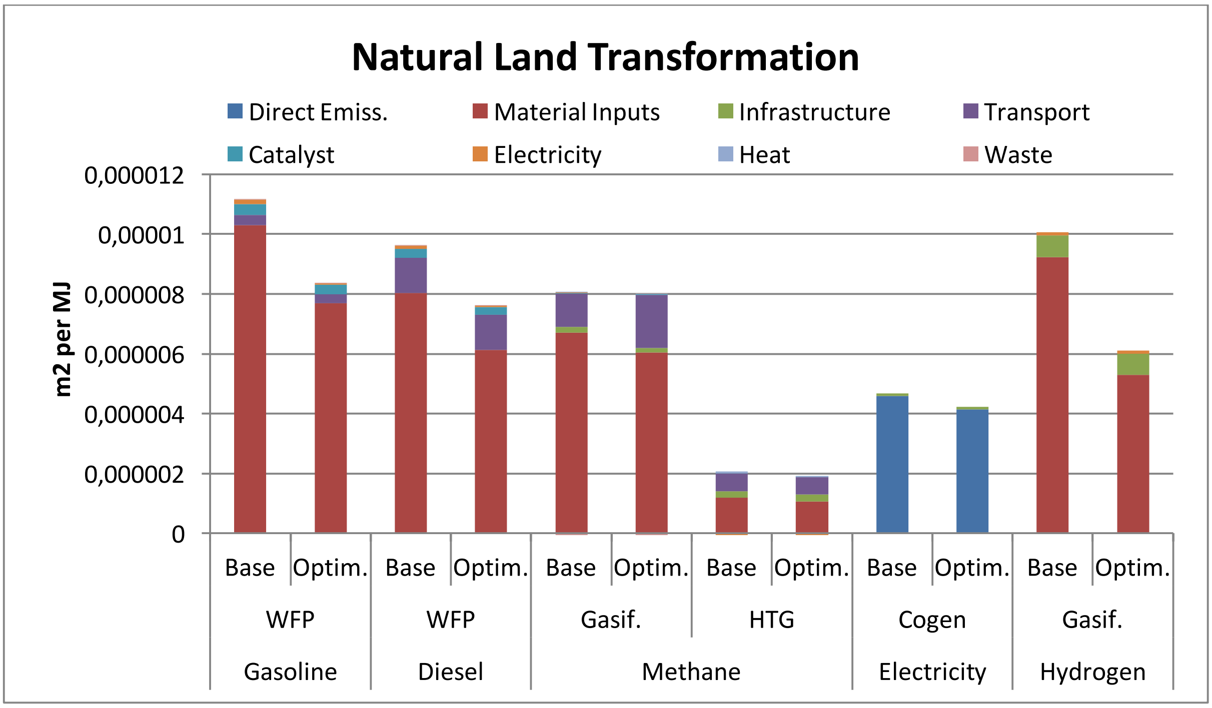


Chart 7: Wood pathways Natural Land transformation results per MJ

As it was possible to expect, like in the other categories, the material inputs, so the operations for processing the wood chips used in the different pathways are the main contributors to this impact. As explained before for the cogeneration process, this is indirectly seeable from this chart, as it actually shows the conversion from high to low voltage of the electricity produced.

Hereafter instead, the chart showing the results for this category of the different fuels covering one vkm is presented:

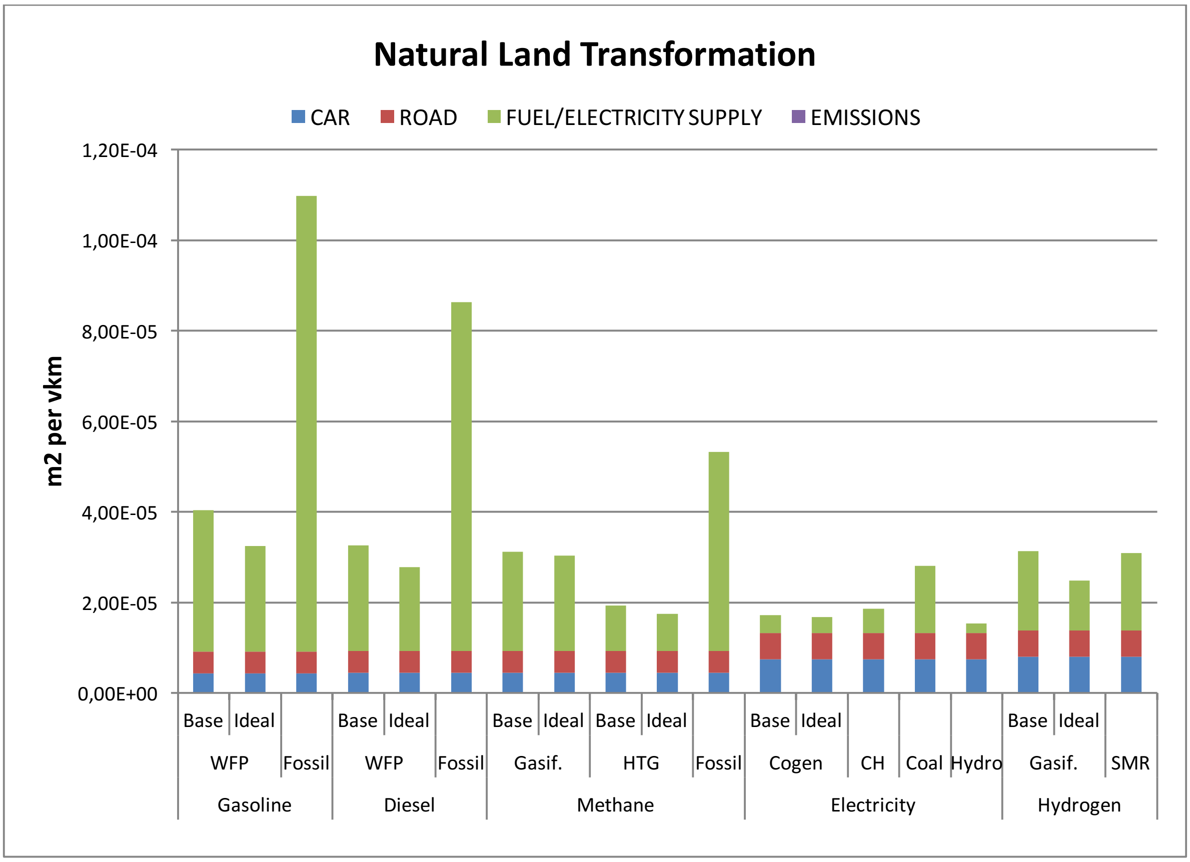


Chart 8: Wood pathways Natural Land Transformation results per vkm

For this impact category it is possible to assess how the biofuels produced have always higher performances compared to the fossil fuels.

The fossil fuels perform poorly in this specific category the extraction operations of the petrol or of the natural gas from the underground, highly modify the original environment and ecosystem.

7.2 Manure Pathways

The same considerations made at the start of chapter 7.1 are here still valid, what differs now is the source of biomass examined, which is the manure produced in Switzerland.
The biofuels investigated come from different processes, like the biomass gasification and its subsequent cleaning, starting from the anaerobic digestion of it. We have also studied the hydrothermal gasification process, for producing methane and the production of electricity from the combustion of the manure biogas.
These biofuels, are then compared with fossil methane or with electricity coming from the Swiss average mix, the European one, a renewable source of electricity (i.e. hydropower) or a fossil one (i.e. natural gas).

7.2.1 Global Warming Potential

The first chart we are going to show will expose the results obtained for producing 1 MJ of fuel from manure biomass.

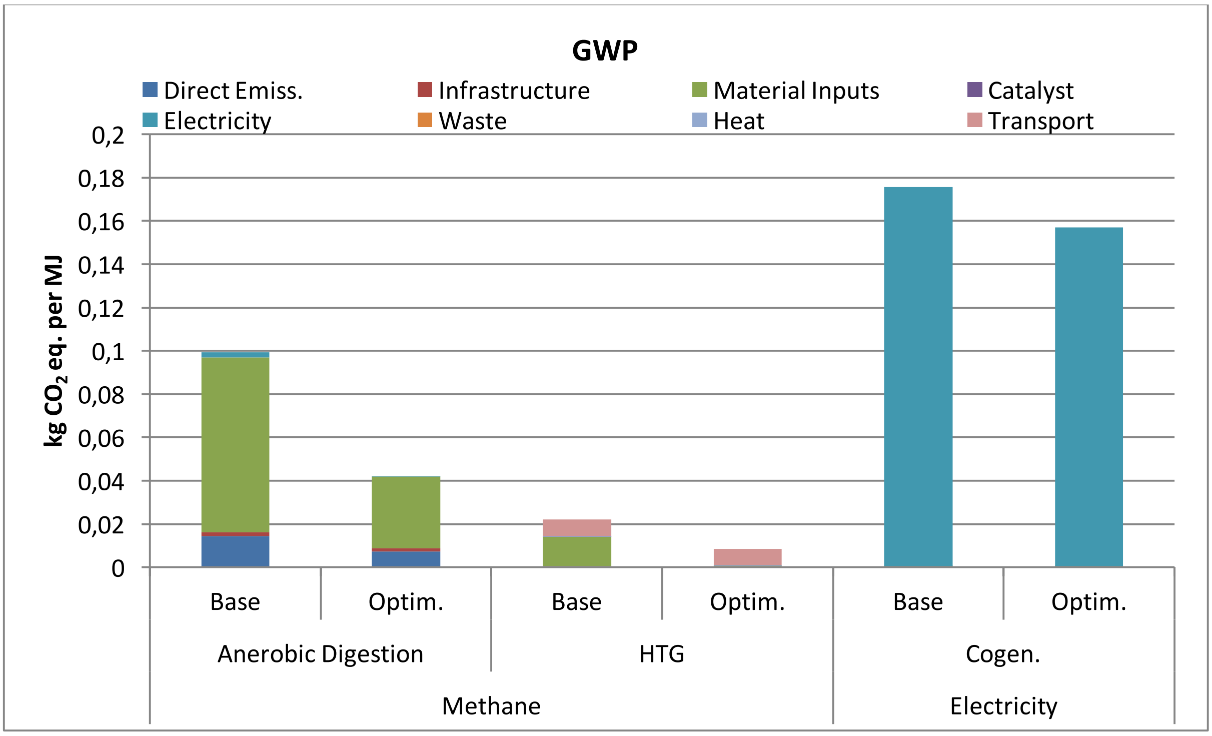


Chart 9: Manure pathways GWP results per MJ

What is highly affecting this impact category are the material inputs to the different processes. To be more specific the biogas used in the upgrading facility, for converting it to methane, and the one burned for producing electricity in a cogeneration plant. The main reason to that is because of the methane leakages from the anaerobical digestion plant. Unfortunately, methane has a huge impact on the climate change, because its effect is 25 times bigger than the one of the CO_2 itself. That is why the HTG process performs much better compared to the anaerobic digestion process of the manure, just because avoids the anaerobic digestion step.

The chart related instead to the resulting impacts of the different processes analyzed in covering one vkm with the different vehicles is the following:

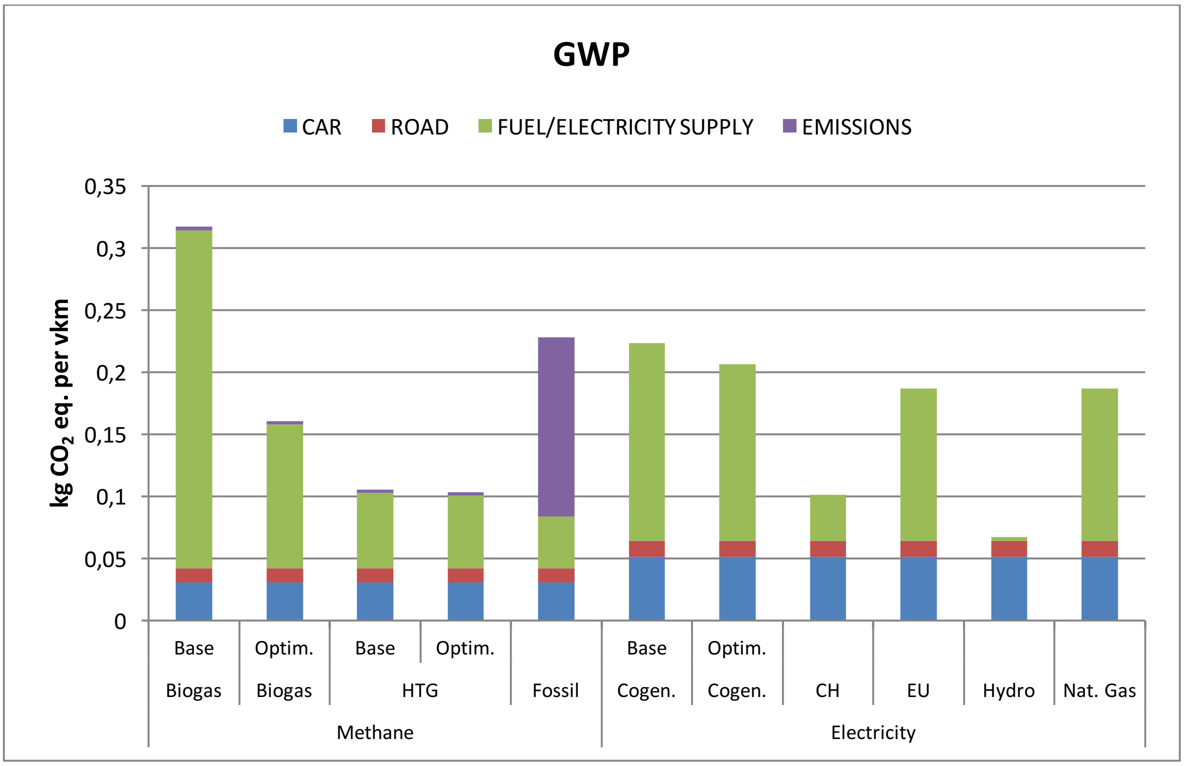


Chart 10: Manure pathways - GWP results per vkm

Knowing that the biogas production is heavily influencing this category is possible to see how nowadays this conversion process performs much worse than the direct counterparts. In fact only the reduction of the methane leakages may lead the anaerobical digestion step a way to exploit this biomass as it is stated by our optimized case for producing methane. Considering the electricity produced in the cogeneration plant, the poor performances are associated to the direct emissions of the process.

The HTG process instead avoiding the anaerobic digestion step avoids these leakages and shows greater results.

7.2.2 Freshwater Eutrophication Potential

The chart evaluating the impact results for the production of 1 MJ of fuel in the Freshwater Eutrophication potential is here after showed:

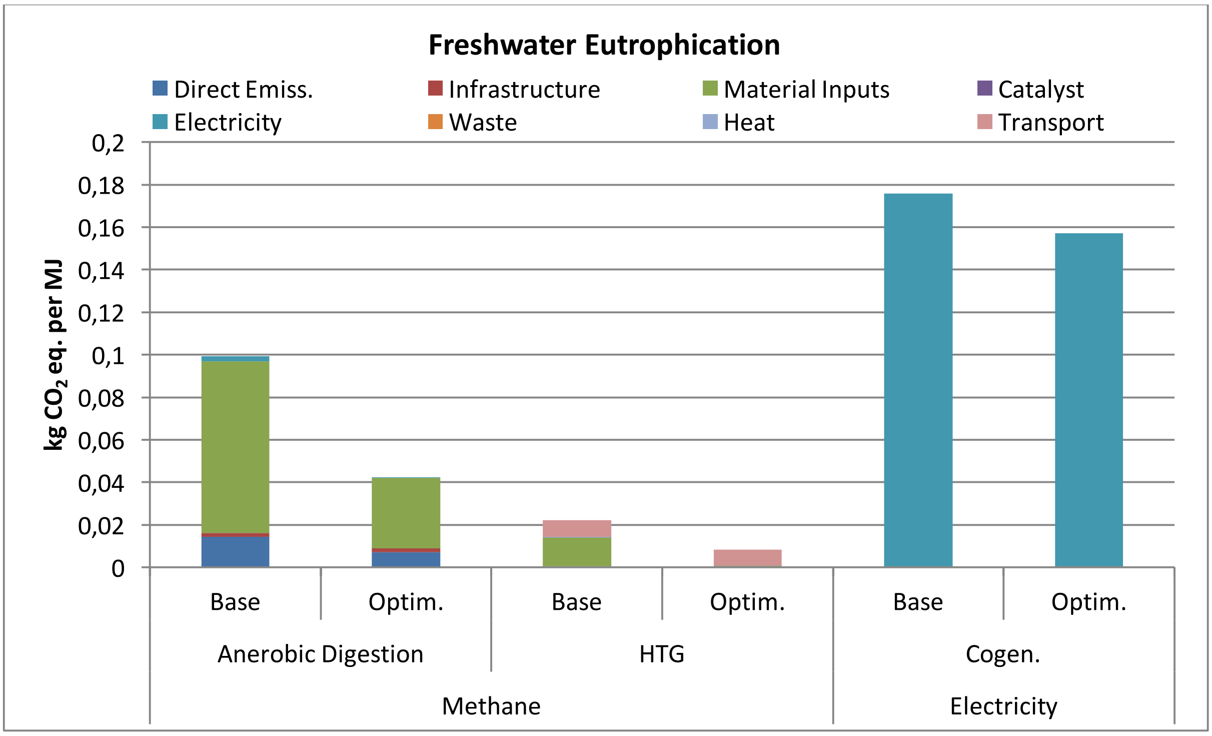


Chart 11: Manure pathways - Freshwater eutrophication potential results per MJ

From this chart is possible to evaluate, which is the main contributor in this category. Once again, it is possible to assess how for the methane produced starting from the anaerobic digestion of the biomass the material inputs are the main responsible. With the material inputs we mean the biogas used in the upgrading plant from which the methane is obtained. As for the methane path, the same considerations can be made for the biogas burned for producing electricity in the cogeneration plant.

The biogas is severely affecting this category for these manifold reasons:

- The manure input and its transportation (these are included in the biogas production);
- The anaerobic digestion plant, because of the materials used for its construction (e.g. copper, reinforced steel);
- The glycerin used as a co-substrate, as its production comes from the esterification plants of soybean and rape oil respectively;
- The import of electricity from countries where coal and lignite are used for its production (i.e. the mining disposal in the specific), especially the lignite's mining operations are highly affecting this mid-point indicator;

Against these two pathways we can assess how the HTG process is even in this category well performing.

The following chart presented will compare how in this impact category, the different cars analyzed perform:

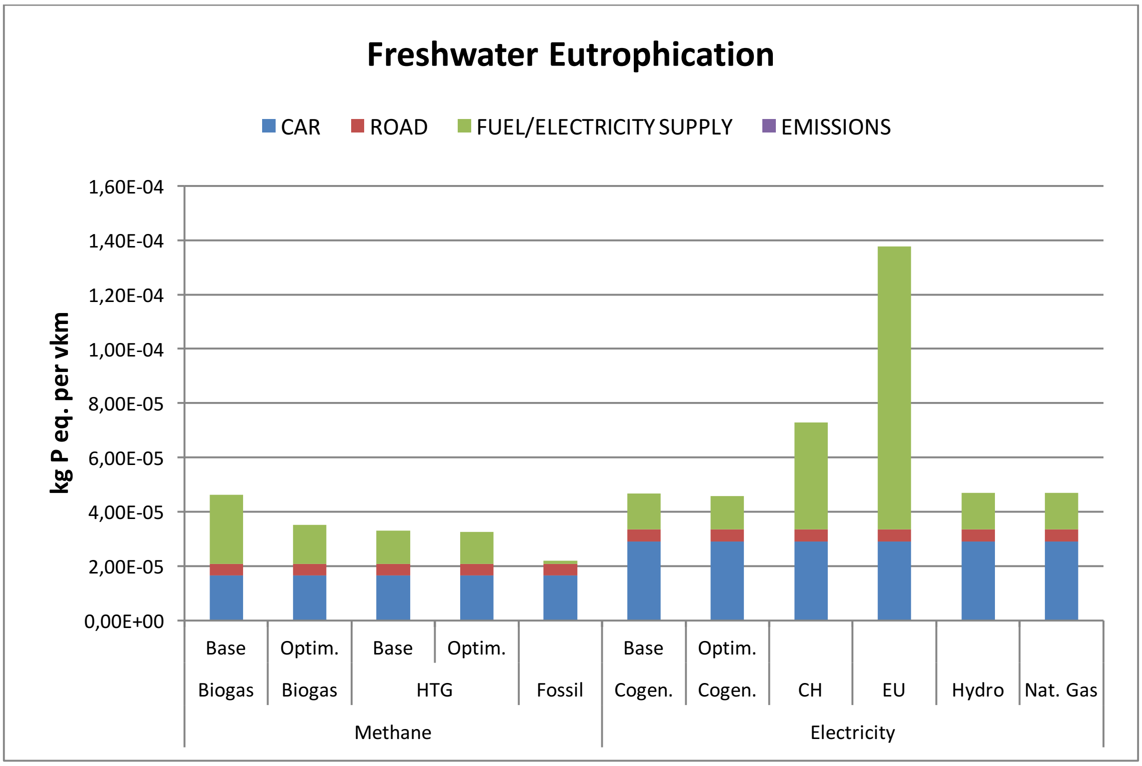


Chart 12: Manure pathways - Freshwater eutrophication potential results per vkm

Two important considerations come from this chart. The first is that compared to fossil methane the one produced starting from the biomass has worst performances. This is mainly due to the biogas itself used in the upgrading section, and to the catalyst needed in the HTG process.
The electricity pathway instead shows good performances in this category, compared with the others electricity sources.

An explanation on why the electricity pathway shows better results than the gasification one, is given by the amount of energy needed by the different cars as showed in Table 30.

7.2.3 Particulate Matter Formation Potential

The chart presenting the impacts related to the production of 1 MJ of fuel is the following for the particulate matter formation indicator:

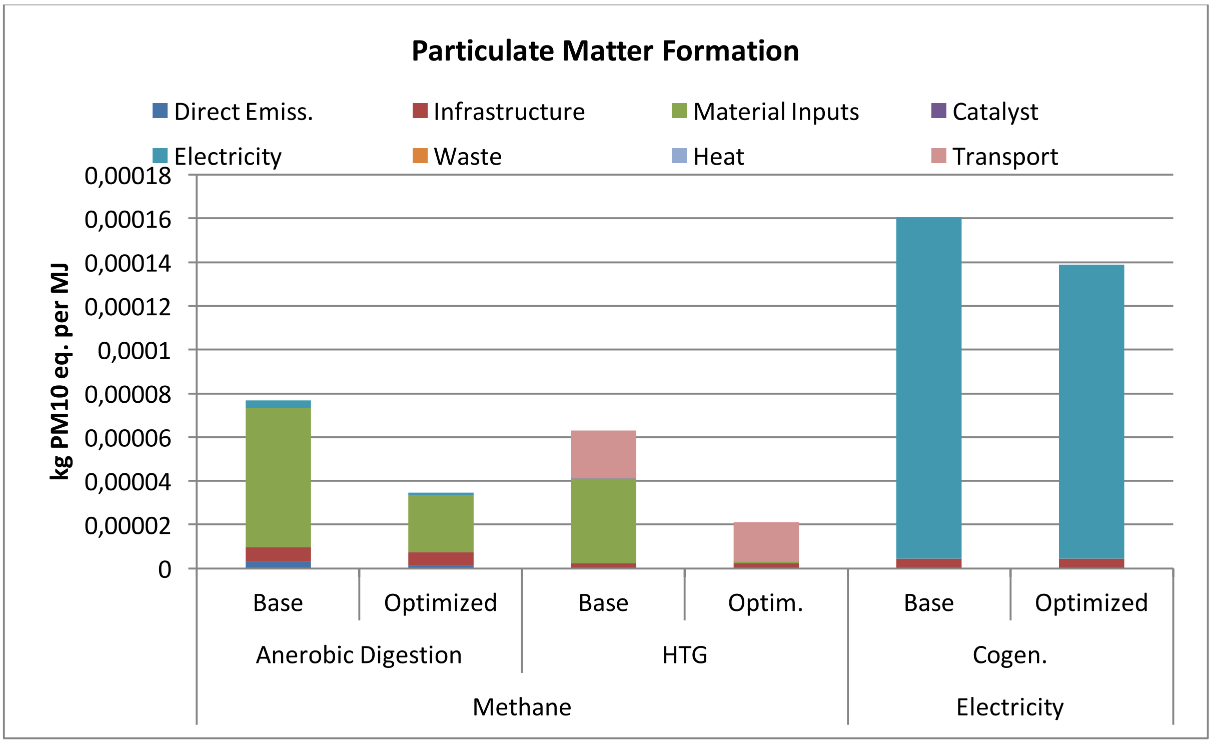


Chart 13: Manure pathways - PMF results per MJ

As it was stated in the previous subchapter the material inputs are again the main drivers in this specific impact category. To be more precise for the methane produced from the anaerobic digestion process the biogas is the main responsible, as it is in the electricity pathway. This is due to many reasons:

- The manure and its transportation
- The anaerobic digestion plant
- The glycerin from the esterification process of rape oil
- The heat required to maintain specific conditions in the anaerobic digestion process whose source is mainly light fuel oil

In the HTG process, the impacts mainly come from the manure itself and its transportation, as in the other two processes.

The chart comparing instead the resulting impacts from the different cars is the one below:

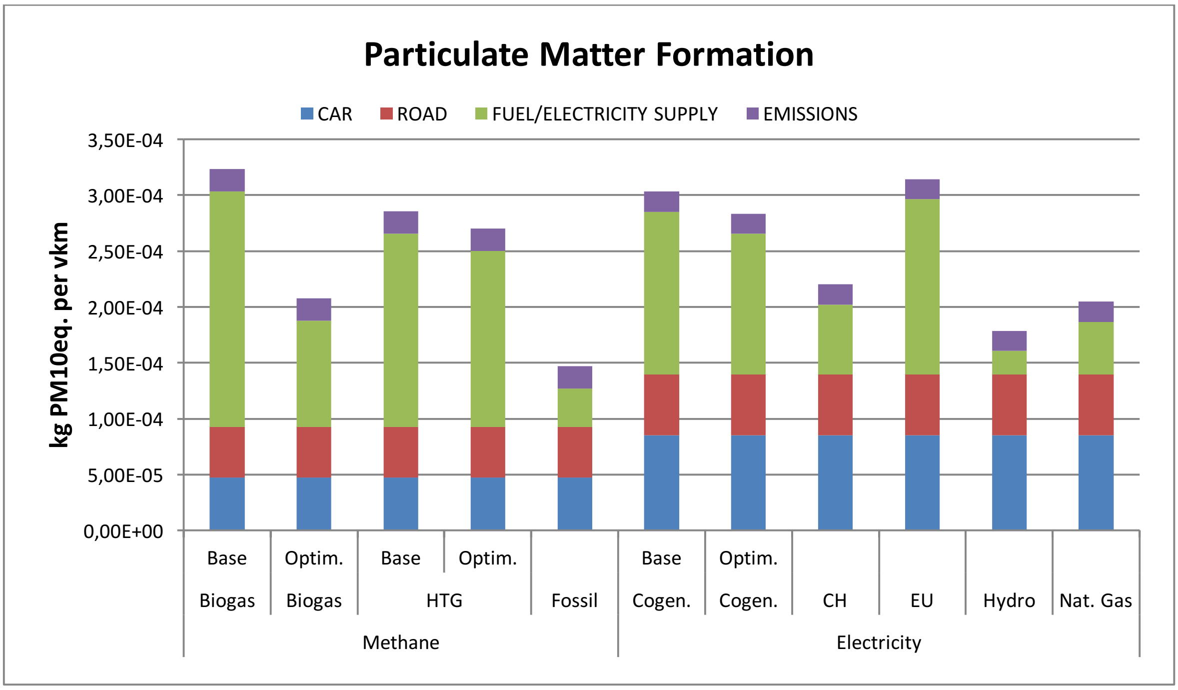


Chart 14: Manure pathways - PMF results per vkm

Regarding this category all the biofuels perform badly if compared with the fossil alternative or the electricity mix compared.

7.2.4 Natural Land Transformation Potential

Also for this category firstly we will show the specific contributors for this mid-point indicator in producing 1 MJ of fuel:

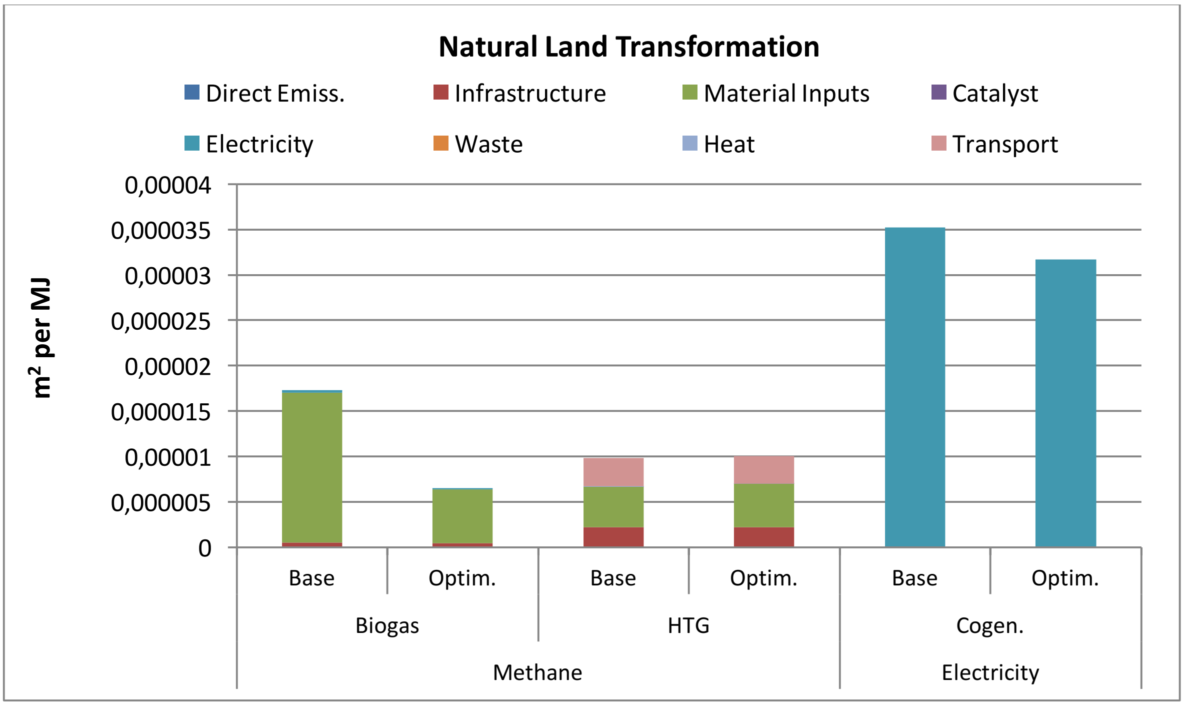
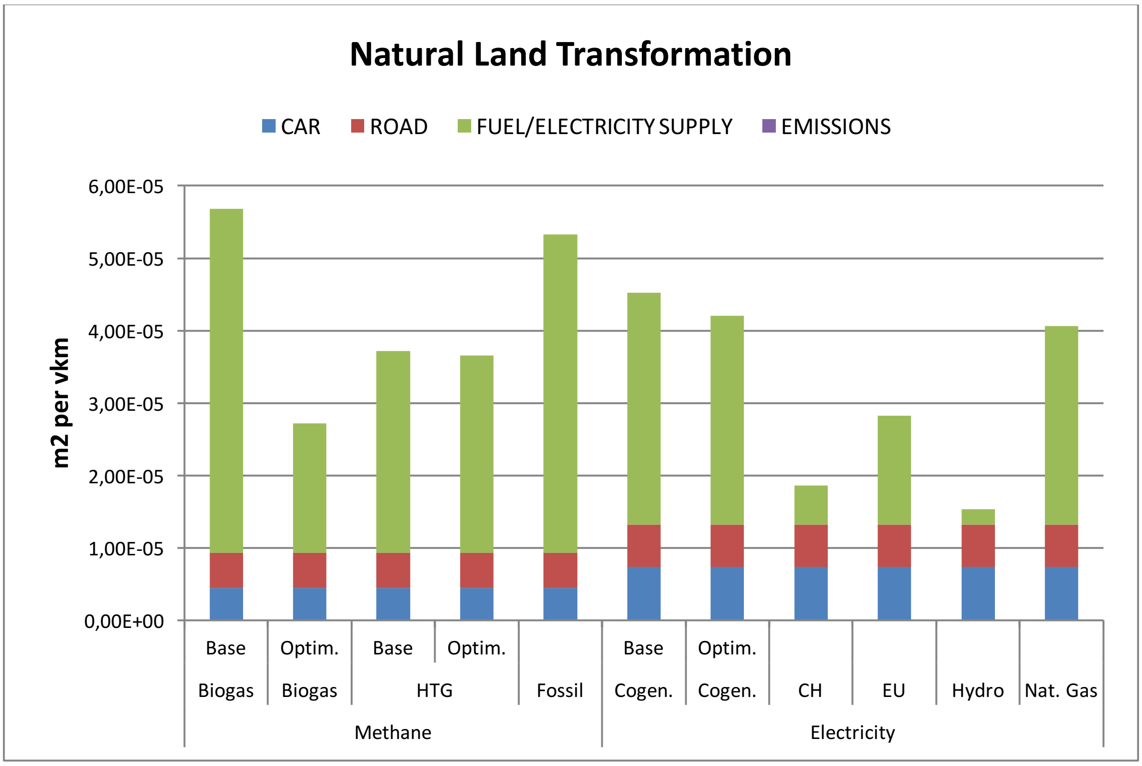


Chart 15: Manure Pathways - Natural Land Transformation Results per MJ

As in the other charts, when assessing which is the main driver, the biggest contribution in producing 1 MJ of fuel, comes from the material inputs (i.e. the biogas for the methane and electricity pathways, the manure for the HTG process).

Considering instead the different cars when covering one vehicle kilometer this is the resulting chart:



Regarding the current processes only the HTG process shows a good performance considering this impact category. The upgrading of the biogas process shows even greater performances when the process itself is optimized as assumed in chapter 5. Finally considering this mid-point indicator the electricity produced with the co-generative engine does not display any improvements even in the future.

In this category biofuels are found to have similar impacts if compared with the fossil alternatives or with the different electricity mix considered, and do not seem to present an advantage.

7.3 Algae Pathways

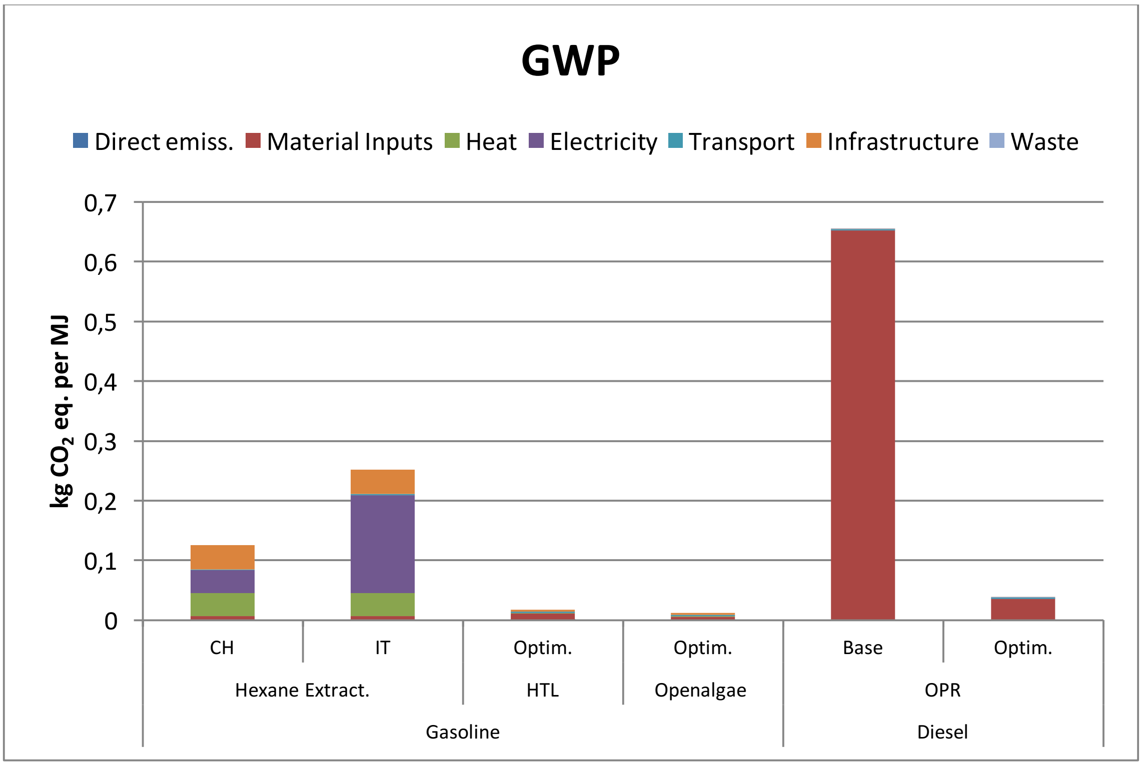
Finally, is the turn of the Algae production and exploitation for making biofuels. As stated before in the previous chapters this technology is not mature with the current knowledges, for the biofuel production, as we are going to assess in the next subchapters.

The biofuels produced from algae are gasoline and diesel, which are going to be compared with their fossil alternatives, and with two conventional biofuels (i.e. Soybean Methyl Ester and Palm Methyl Ester).

We are now considering two pathways for producing the algae, the Open Ponds Race and a hybrid system that includes Photo Bio Reactor (PBR) and OPR, as explained before in the 6.2 sub-chapter.

7.3.1 Global Warming Potential

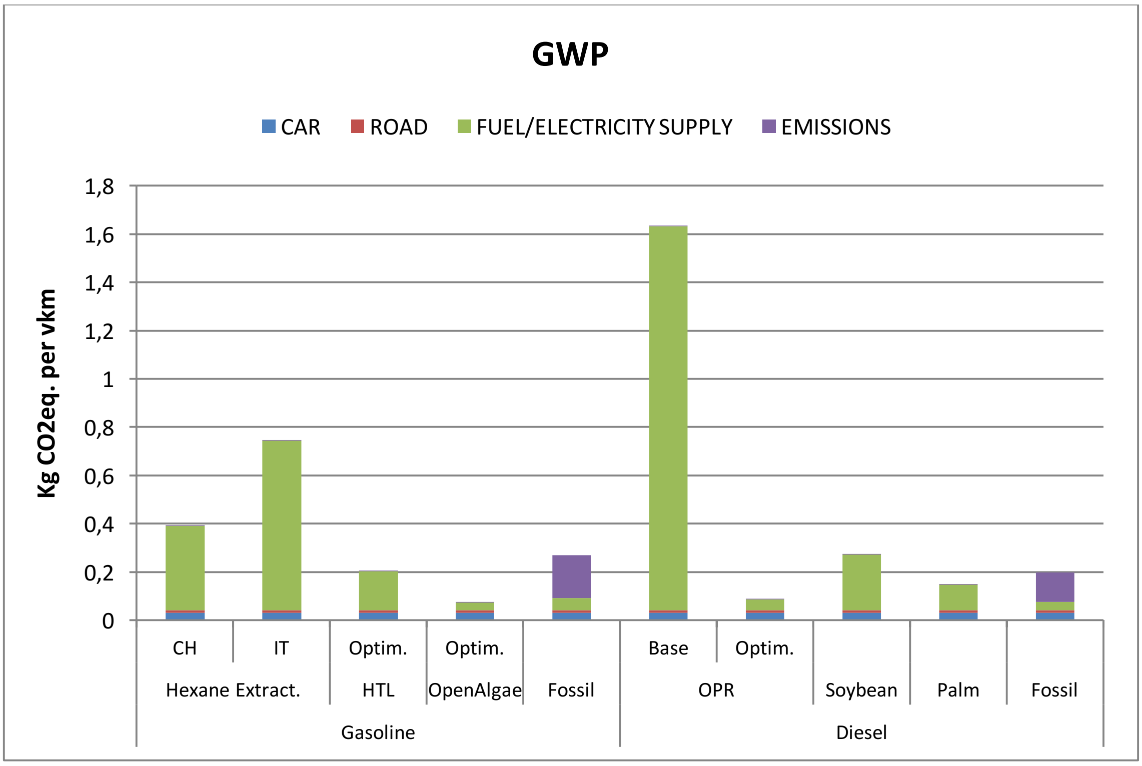
It is important to start showing the reader the main drivers for the climate change category when producing 1 MJ of fuel starting from algae cultivation:



The OPR base case process reveals that nowadays with the current market technologies, this fuel cannot compete with the conventional fossil or biofuels ones. From the chart is possible to state that the material inputs for the biodiesel produced in the OPR are the main responsible. This is indirectly true, because the material inputs considered here is the bio oil extracted from the algae cultivated. A big problem coming from this product is the high-energy demand required for both the cultivation and the extraction steps. The electricity and the heat required are indeed too intensive.

One statement though that is possible to make, is that the usage of an optimized facility and a cleaner source of energy, like the Swiss average one or a renewable one as explained in the previous chapters, already show how the potentiality of this technology can be right now very high and is strictly related to the processes and the technology used.

The chart showed below, compare instead the impacts for this category when the different cars are used:



The same considerations done for the previous chapter are also here applied.

7.3.2 Freshwater Eutrophication Potential

For the freshwater eutrophication potential we start showing the chart that compares the different impacts due to the production of 1 MJ of fuel. Secondly the chart where the different cars are compared in covering one vkm will follow:

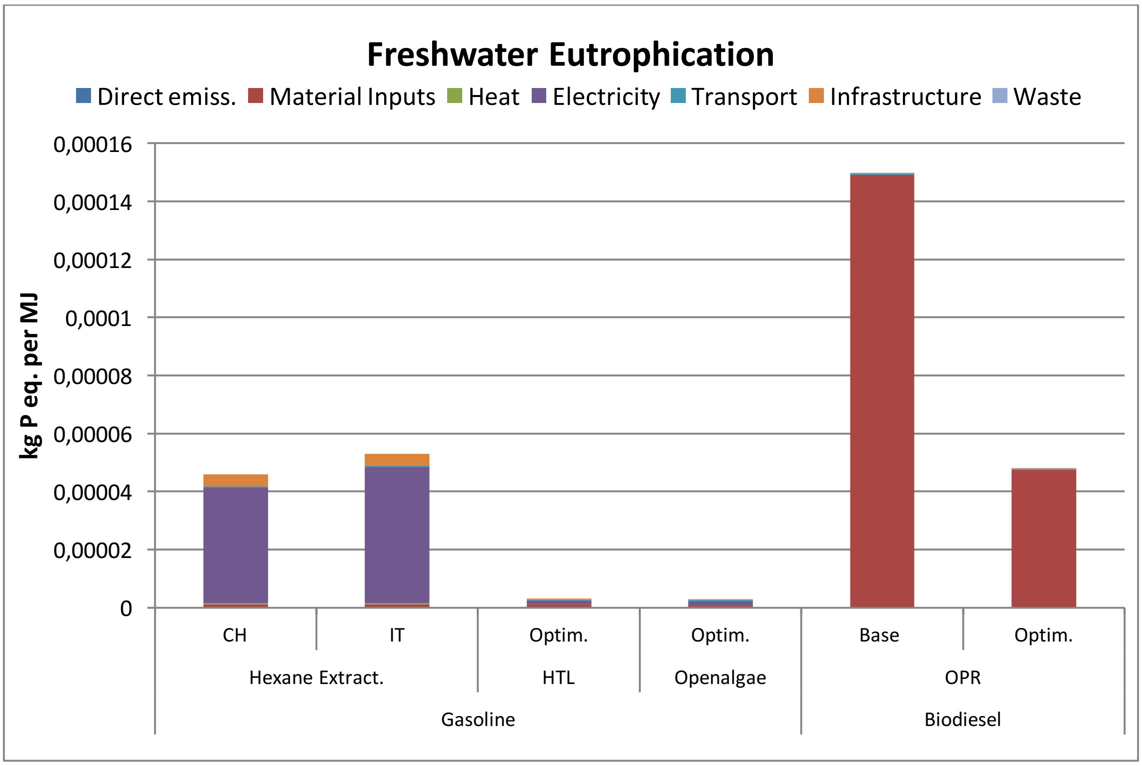


Chart 16: Algae Pathway - Freshwater Eutrophication Results per 1 MJ

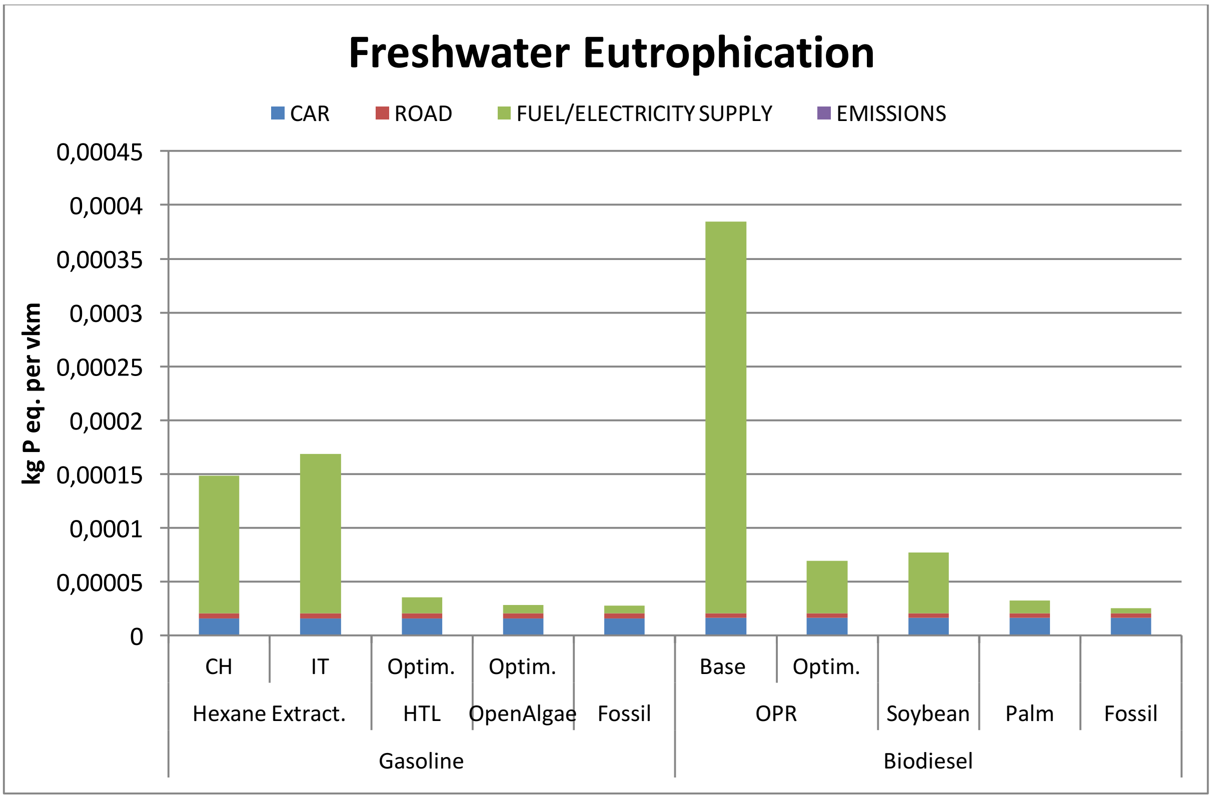


Chart 17: Algae Pathway - Freshwater Eutrophication Results per vkm

The main consideration regarding this impact category is that the biggest influence comes from the electricity used for processing and cultivating the algae. Only in the optimized cases when less energy is required we can see that this technology might represent a viable solution in replacing fossil fuels.

7.3.3 Particulate Matter Formation Potential

The first chart showed is the one that assesses the impacts from the production of 1 MJ of fuel:

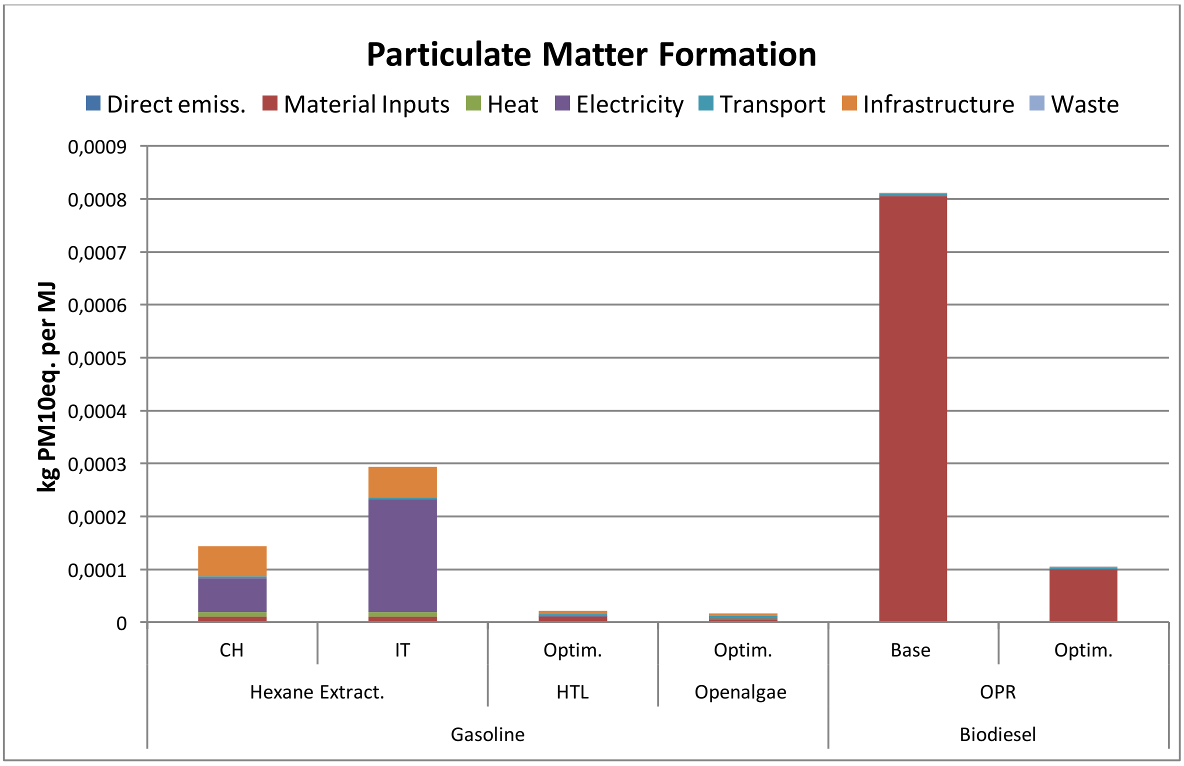


Chart 18: Algae Pathway – Particulate Matter Formation Results per 1 MJ

As for the other categories, the elevated energy demand is responsible of the poor performances of the base cases investigated.

The following chart is the one that compares the different cars powered by the different fuels investigated:

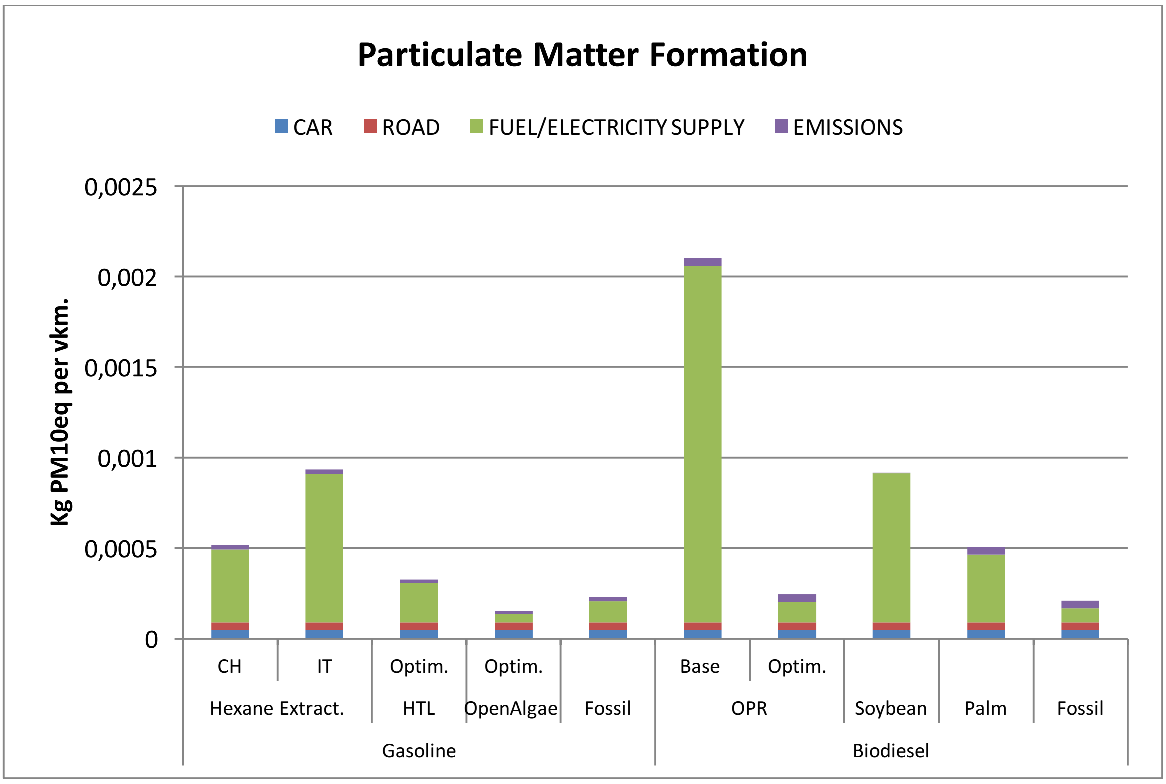


Chart 19: Algae Pathway - Freshwater Eutrophication Results per vkm

As in the previouses subchapters concerning the biofuels production from algae, the energy required is still the main environmental driver in the processes that consider the current available technologies. The optimization of the facility and the energy reduction must be among the actions that need to be undertaken.

7.3.4 Natural Land Transformation Potential

As in the other subchapter where this specific mid-point indicator is showed, we will first present a chart where we will compare the production of 1 MJ per the different fuels, and secondly we will show the comparison between the different cars covering one vkm.

When assessing which are the main contributors in the production of the fuel, as in the other mid-point indicators the energy required is the major one.

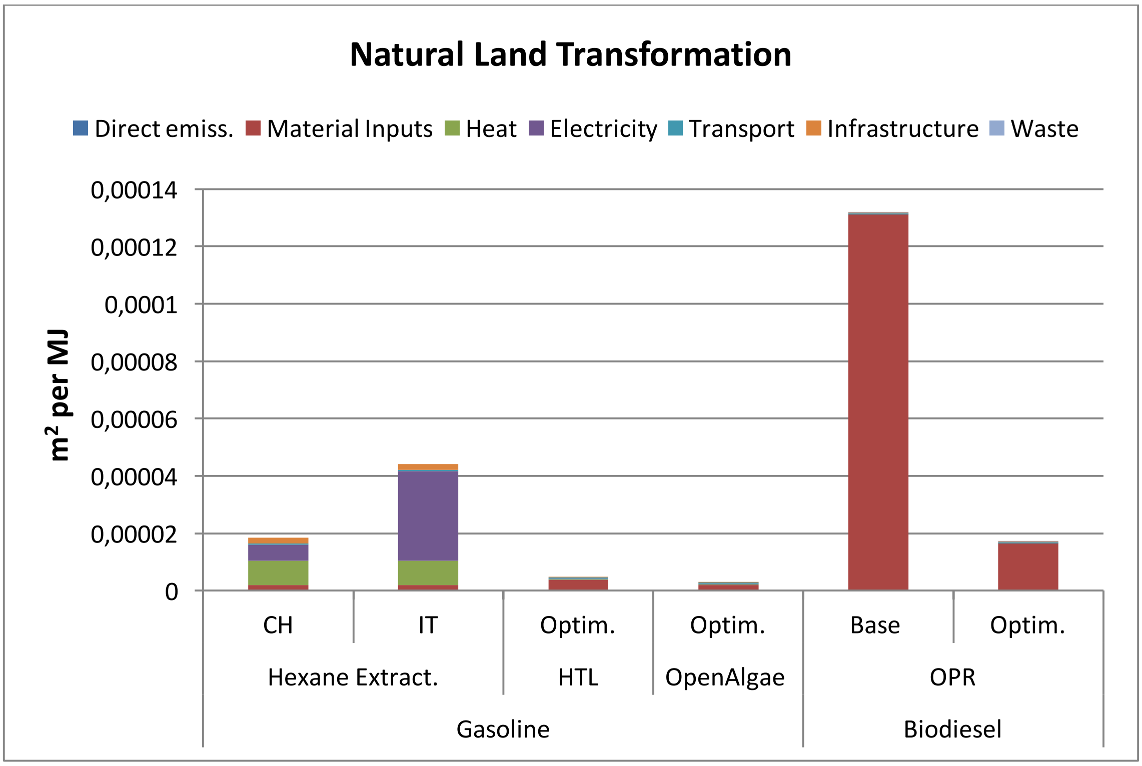


Chart 20:

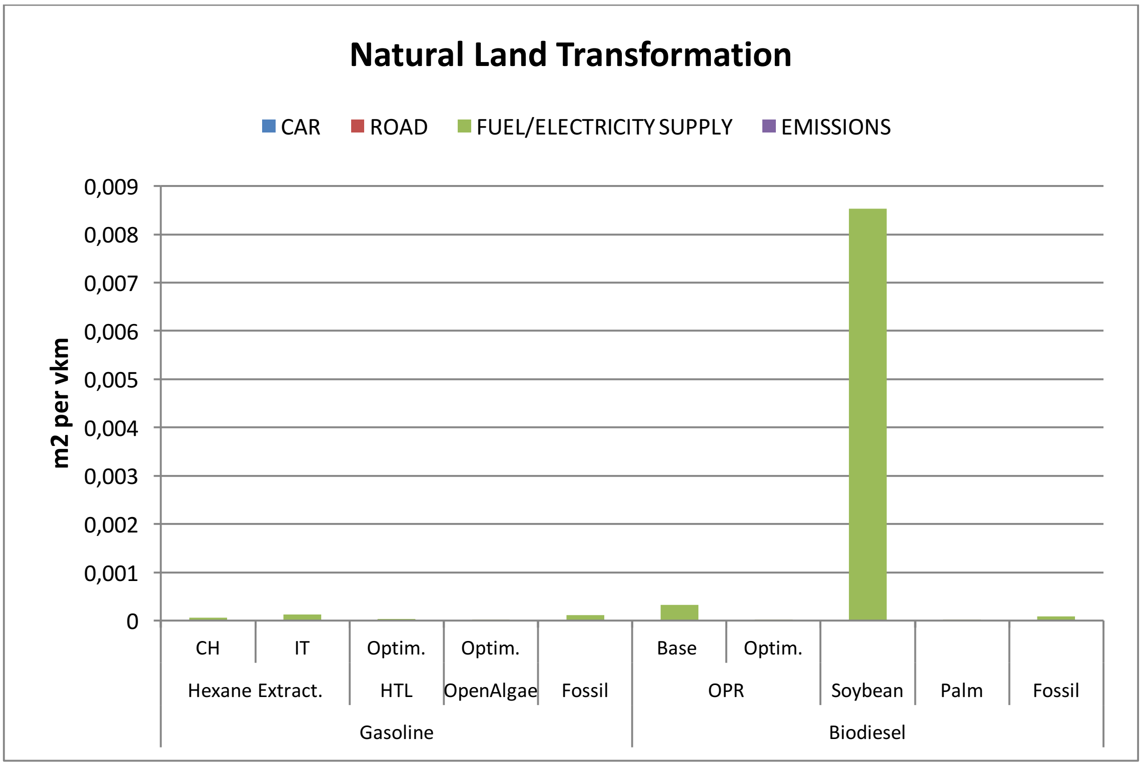


Chart 21:

When comparing instead the different cars covering one vkm, in this category the biodiesel coming from the soybean has a huge impact because of the cultivation of the soybean itself.

This practice affects heavily the existent ecosystem.
So, despite the premises even the algae that are so energy intensive perform better in regards to this specific category, if compared with this source of biomass.

8. Discussion

In this final chapter a comparison between this work and the available literature will be performed. Firstly, a comparison with a report made by EMPA that is the Swiss Federal Laboratories for Materials Science and Technology, on different biofuels produced in Switzerland will be done. Then a comparison with the results obtained in some others Life Cycle Assessments in the available literature will be accomplished.

8.1 Comparison with EMPA Study

One table is going to be shown below where the results per vkm from the EMPA report on biofuels (Mireille Faist Emmenegger, 2012) are compared with the results obtained within this work.

Some differences though in calculating climate change emissions in the EMPA report have been performed. The nitrogen emissions have been modelled differently compared to the ecoinvent v2.2 database as they have been harmonized and updated, based on the Agrammon model (www.agrammon.ch). Also, the emissions related to the land use change have been calculated differently, as in ecoinvent v2.2 only the emissions associated to the cutting of rain forest are considered for this category (Mireille Faist Emmenegger, 2012). Both nitrogen and land use change emissions are significant contributors to the global warming issue.

		EMPA	**This Study – Base Case**
Biofuel	**Process**	**GWP [kg CO_2 eq. per vkm]**	**GWP [kg CO_2 eq. per vkm]**
Methane, manure	**HTG**	9.2E-02	1.42E-01
Methane, manure	**Anaerobic digestion biogas**	-	2.72E-01
Methane, wood chips	**HTG**	7.0E-02	1.10E-01
Methane, wood chips	**SNG purification**	-	3.30E-02
Natural Gas		2.6E-01	2.28E-01
Diesel		2.7E-01	1.99E-01
Petrol		3.2E-01	2.69E-01

Table 32: Results comparison with EMPA report

The first consideration obtainable from this comparative table is that the results obtained by this study are higher considering the HTG processes, while are lower considering the fossil fuels used for comparison.

Stating that the actual data used for the calculations in the EMPA report are not available, some considerations about which could be the potential reasons on why there are differences in the results must be done.
It is possible that the inputs and the assumptions carried on in this thesis are different. For example in the HTG process of manure the suppositions of (Luterbacher et al., 2009) have been completely changed, in order to harmonize the results with the other processes, as explained in sub-chapter 5.3. Another difference is that the animal slurry used as input in this thesis is from the ecoinvent v3.01, while the one used in the EMPA report is from ecoinvent v2.2.

Even in the HTG process of wood, the biomass input used is different, because while in this study woodchips from industry waste with 40% of humidity have been utilized, in the EMPA report the biomass input is constituted by forestry and sawmills wastes. In this thesis, the woodchips used are the main contributor in the GWP category, as it has been stated in sub-chapter 7.1.1.

Furthermore the vehicles used in the EMPA report (Mireille Faist Emmenegger, 2012) are different from those used by this work, as the data for the cars are from the THELMA project (Stefan Hirschberg, 2016). To calculate the emissions factors of CO_2 in the EMPA report the Tremove database has been used (T&M-Leuven, 2007).

The EMPA report states that the energy consumptions of the cars are the following:

Fuel	**Energy Demand [MJ/km] – EMPA report**	**Energy Density – LHV [MJ/kg]**
Gasoline	2.86	42.9
Diesel	1.82	42.8
Methane	2.51	48.6

Table 33: Energy Demand per km - EMPA report

While the energy demands considered for this thesis are:

Fuel	**Energy Demand [MJ/km] – EMPA report**	**Energy Density – LHV [MJ/kg]**
Gasoline	2.8	44.4
Diesel	2.4	42.8
Methane	2.7	34.4

Table 34: Energy Demand per km - this thesis

LHVs of gasoline and diesel have been chosen like those according to the values chosen in the paper of (Iribarren et al., 2012), while the energy density of methane was chosen accordingly to the ecoinvent database.

As it is possible to state from table 31, the results obtained in the GWP category considering an average mid-sized car driving a kilometer, are always slightly better considering this thesis, even if the diesel car of the EMPA report consumes less energy. A possible reason is that the emissions standards used in the EMPA report are EURO3, while those used in this thesis are EURO5, which allow these improvements.

All of these differences might have led to the disparities in the results obtained.

8.2 Comparison with Other LCAs on Biofuels

A table comparing the results (in gCO_2 eq. per vkm) obtained in other LCAs and those from this thesis will be presented below:

Fuel	**Source**	**Cherubini** (1)	**EMPA** (2)	**This work - Base Case**	**Zah (2007)** (3)	**Weinberg-Kaltschmitt**(4)
Diesel	Fossil	185-220	260	**199**	288	-
Gasoline	Fossil	210-220	320	**269**	320	-
Natural Gas	Fossil	155-185	260	**228**	261	-
Bio-Methane	Manure - HTG	-	92	**142**	-	-
	Manure - AD	-	-	**272**	216	-
	Wood Gasific.	-	-	**78**	94	59
	Wood - HTG	-	70	**110**	-	-
Hydrogen	Wood Gasification	-	-	**180**	-	132.4
	SMR	-	-	**159**	-	-
Electricity	Woodchips-CHP	74	-	**75**	-	85

Table 35:Comparison with other LCAs

(1)(Cherubini et al., 2009); (2)(Mireille Faist Emmenegger, 2012); (3) (R. Zah, 2007);
(4) (Weinberg & Kaltschmitt, 2013)

From table 34 is possible to make some statements when comparing the biofuels modeled within this work and those from other studies.
Is necessary though to state that the actual data used in the different studies are not available.

Starting the comparison between conventional fossil fuels used as reference, it is possible to see how the values obtained by this work, based on the THELMA project (Stefan Hirschberg, 2016) are usually lower, and one possible explanation can be given by the fact that the cars investigated in this thesis have EURO5 emissions standards, while the others have EURO3 emissions standards. EU

Considering the methane produced through the hydrothermal gasification process the considerations made in the previous sub-chapters remain the same, while the methane produced starting from manure biogas has bigger emissions compared to the work of (3). It is possible that this is due to the use of different ecoinvent database (i.e. v2.2 and v3.01) respect to those used by (R. Zah, 2007) where ecoinvent database v1.3 was adopted. While the value regarding methane from wood gasification is in between the other two studies used for comparison. Also the electricity produced from a CHP plant has a value in between the other two works considered.

The results obtained for the production of 1 MJ of diesel or gasoline from the fast pyrolysis process from this thesis have not been compared with the original work, because the values obtained for the GWP category in (Iribarren et al., 2012) are negative, as they consider that the CO_2 is removed from the atmosphere thanks to the growing of the biomass.

In reference to the algae produced in the OPR and the upgrade of the oil extracted a comparative table between this work and the one of (Passell et al., 2013)(5) that considers the current commercial technology in a base and optimized case will be presented below.

Fuel		**Passell(5)**	**This Work**
Biodiesel	Biodiesel OPR-Base Case	2,88	1,63
	Biodiesel OPR-Optimized	0,18	0,04

Table 36: Biodiesel from algae cultivated in OPR comparison

As it is evident the biodiesel modeled in this thesis reached lower emissions value per MJ produced, even if the infrastructure has been added to the process. The reasons why these values are so different are manifold, but the main reason resides in the electricity used for processing the algae. In the work of (5) the electricity used is the American average mix in the base case and the German average mix in the optimized case. While in our base case process the electricity mix used is the Italian one, and in the optimized one is the Swiss hydropower electricity mix that is the cleanest source of energy implemented. It has been said that this is the main reason because as we have stated before in sub-chapter 7.3 the energy consumption in every stage is the most influencing one in every mid-point indicator analyzed. Another possible reason that can have contributed in achieving these values is that the transesterification process used for upgrading the bio-oil extracted from the algae is not the one used in the study of (5), which is based on the GREET data for converting soy oil into biodiesel. Furthermore, the transport distances considered in the transesterification process used have been modified in order to consider the distance between center of Italy and Switzerland.

9. Conclusions

In conclusion for this thesis work, we are going to assess which is the best environmental way of exploiting the available biomass for powering different mid-sized cars.

We are going now to compare all the biofuels produced in the current cases and in the optimized ones separately. This will allow us to suggest to the reader which can be an optimal environmental way to use the accessible resources.

Two charts for the GWP mid-point indicator are shown. The first one is presented for the current scenario, the second for the optimized one.

9.1 Current Scenario

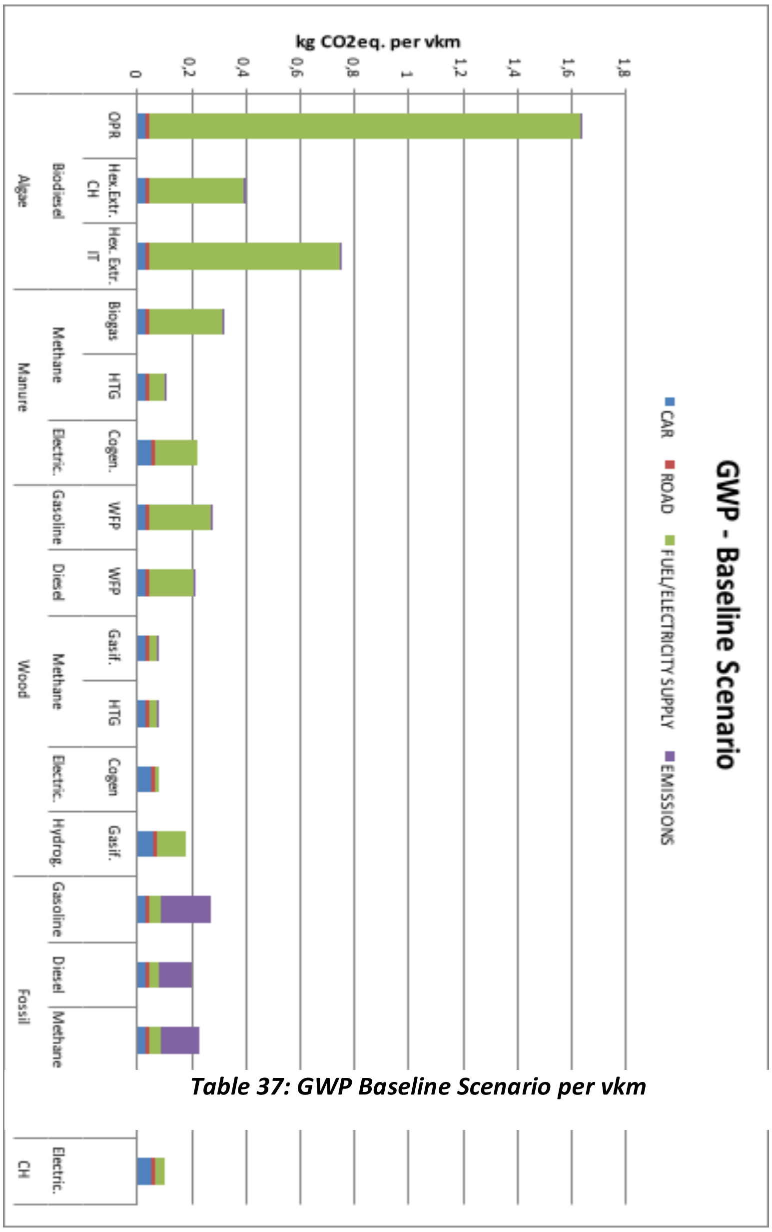


Table 37: GWP Baseline Scenario per vkm

Considering the current available technologies some conclusions can be suggested:

1. When wood biomass is available the best environmental way to convert it is to gasify it and subsequently upgrade it into methane or otherwise the wood chips can be burned and converted in electricity;
2. If manure biomass is available instead, its conversion into biogas and then methane or in electricity, nowadays do not shows good performances if compared to the fossil methane or the Swiss average electricity mix.
3. Hydrogen production through the biomass gasification stands as a really promising solution, if compared with the fossil based process.
4. The algae pathways nowadays is not a viable solution considering the climate change issues;

9.2 Optimized Scenario

The following chart will show the comparison between the different biofuels investigated in the optimized cases:

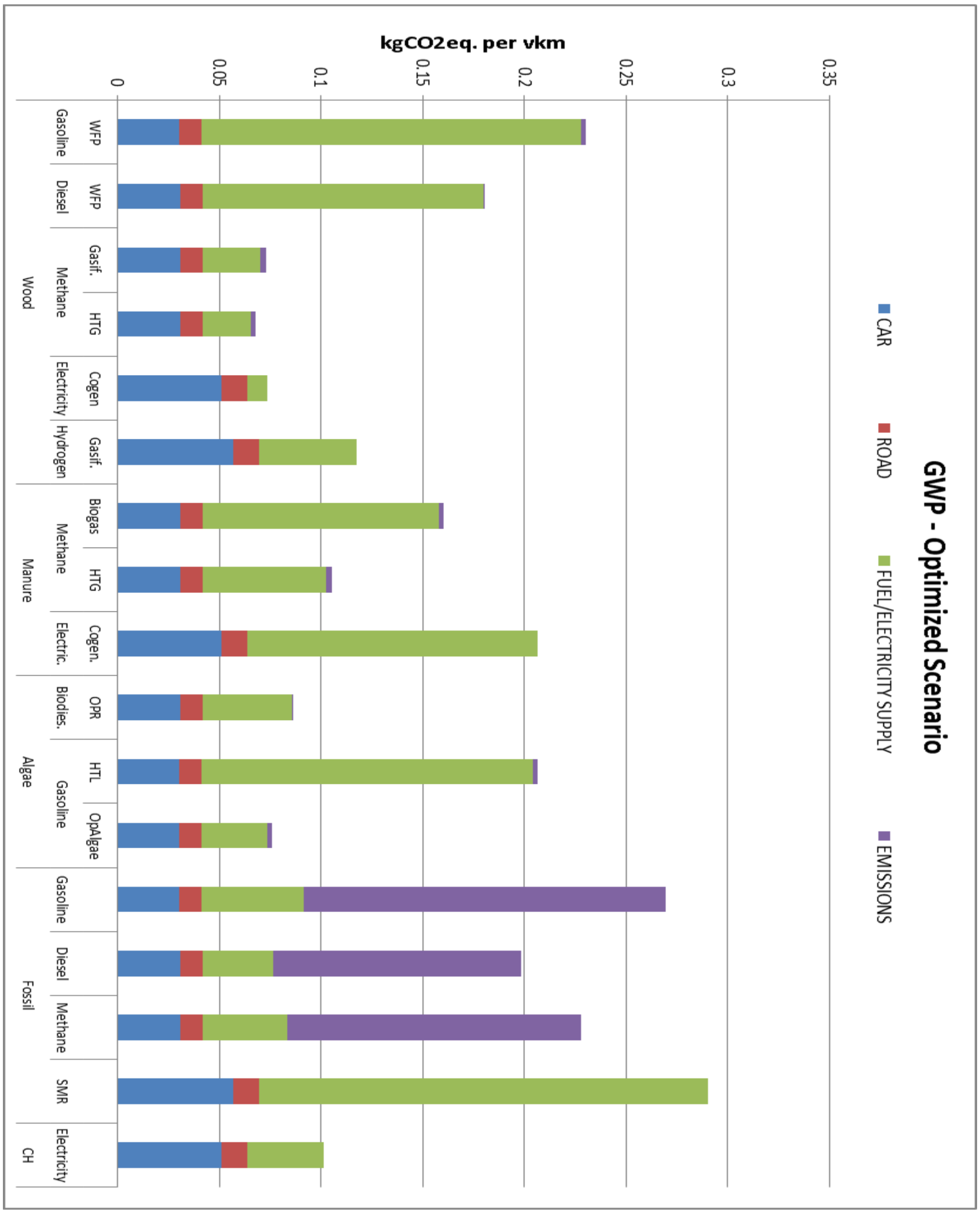


Table 38: GWP Optimized Scenario per vkm

The main conclusions from this chart are the following:

1. Wood biomass has the potentiality of being converted in methane, electricity or hydrogen, showing in every case great performances, if compared with the fossil alternatives or the Swiss energy mix;

2. The optimization phase assumed in our optimized scenario, shows how even the anaerobic digestion step may lead to good performances if comparing the bio-methane with the fossil one. The HTG process is still a good alternative, on which would be better deepen our technical knowledge;
3. Algae produced in an optimized facility, where a substantial cut has been performed on the energy demand and emissions, reveal to be a promising pathway if we consider the environmental side of it;

9.3 Final Conclusion

After presenting the charts comparing the different results obtaining in covering one kilometer by the different mid-sized cars is possible to state that this thesis has reached his goal to assess which is the best environmental way to exploit a specific source of biomass. The main conclusion is that if wood biomass is available the best environmental manner to exploit it is to gasify it or to burn it to produce electricity and heat in a cogeneration plant. Regarding manure biomass, which in Switzerland has a bigger potential than wood biomass, as it has been stated in sub-chapter 1.1, the problem is that nowadays, with the state of art technology, from an environmental point of view, the main process known namely the anaerobic digestion plant is not a good option. This is because the leakages of methane from the cover of the storage are highly affecting this process, so bigger efforts must be put in the research to find a solution for this issue.
Only the Hydrothermal Gasification process might represent a viable solution, because avoiding the anaerobic digestion step and so the methane leakages, better results in every category can be obtained.
Considering instead the cultivation of the algae, still many problems must be overcome, if this pathway wants to become a practicable one. The research must focus its attention on finding a way to make the cultivation step the least energy intensive possible.

What are the improvements though coming from this thesis to the scientific literature? First of all, it is a research that focuses only on the available biomass sources in Switzerland, assessing which could be the best environmental way to exploit them for producing biofuels. Knowing that all the studies used have been adapted to the Swiss situation, meaning that all the inputs, transport units, and energies are related to the Swiss contest. Even when the cultivation of algae and the upgrade of their oil has taken place in Italy for the more optimal weather conditions, the ecoinvent process for the transesterification of the oil extracted has been adapted to the Italian contest, and the transport distances have been considered from the center of Italy to Switzerland. In addition, for the algae cultivation step also the infrastructure has been implemented in the modeling to show more complete results.

Furthermore, the data used from the available studies were also harmonized in order to achieve the goal of this thesis, which is to compare different car powered by different fuels in covering one kilometer. This has been thought to be a good way to compare different biofuels, and to allow an easier comparison with other studies.

Considering instead a possible car driver, this thesis can help him decide which fuel would be the best environmental choice. In this way, he will be aware that if his concerns are towards the environment some choices will be better than others. Because of that for example if he is driving an electric car he would like to know that the electricity used for powering it, is coming from the combustion of wood biomass and not from the average Swiss mix.

The weaknesses instead of this thesis reside in not having performed any life cycle cost assessment of the different pathways explored. This is due to the lack of available time for exploring this matter, but is well known that an environmental assessment would gain much more strength if accompanied by an economic one. For the future, this is the direction where the research must go for completing this study, because if any of this biofuel is not economically convenient, even if the environmental results are really good, there is no actual way of producing biofuels starting from certain technologies that remain just promising.

Furthermore, the data used for the new processes (i.e. fast pyrolysis, HTG, algae cultivation and upgrade) have been taken from the available literature, but is possible that better data are available or can be produced.
Another weak point about the data used is that they are obtained not from existing facilities, on the contrary, they are obtained as well from assumptions and modeling of the different authors considered. In any case the results obtained even from theoretic models can give a first outlook on how a certain technology, or a certain process will perform, pointing out where are the areas on which is important to make some developments, but still the uncertainties persist.

10. Acknowledgements

I would like to start to thank my supervisor Brian Cox for his time, advices and precious help throughout this thesis. His support was fundamental for reaching my goals and finishing this work. Then my thanks go to Prof. Lorenzoni for letting me do this experience abroad from the University of Padova and for his support.

Thanks then to all my colleagues of the Technology Assessment Lab, especially Dr. Peter Burgherr the leader of the TA group, Anna Kalinina, Dr. Matteo Spada, Analy Castillo, Dhruv Pandya, Salvatore Greco and Rebecca Bishop. It was really nice to meet these people, and their help, but also their company during the lunch break and the commuting to and from PSI made me feel like I was at home.
Thanks also to Prof. Stephan Hirschberg for his help, and for the very interesting talks we had together.

A special thank must go to my family for its endless support in all my life, and as well in this occasion.

11. Appendix

In this section the results obtained for the production of 1 MJ in every mid-point indicator will be showed:

		Impacts per MJ								
Fuel	**Pathway**	**Climate Change (kg CO2 eq)**	**Ozone Depletion (kg CFC-11 eq)**	**Terrestrial acidification (kg SO2 eq)**	**Freshwater eutrophication (kg P eq)**	**Marine Eutrophication (kg N eq)**	**Human Toxicity(kg 1,4-DB eq)**	**Photochemical Oxidant Formation (kg NMVOC)**	**Particulate Matter Formation (kg**	**Terrestrial Ecotoxicity (kg 1,4-DB eq)**
Diesel	Algae Oil Esterification	6,55E-01	6,09E-08	2,75E-03	1,50E-04	9,45E-05	1,50E-01	1,77E-03	8,10E-04	2,82E-05
	Algae Oil Esterification Optimized	3,76E-02	5,76E-09	2,70E-04	4,78E-05	1,55E-05	1,03E-01	1,88E-04	1,04E-04	1,16E-05
	Wood Fast Pyrolysis	6,82E-02	3,34E-09	7,99E-05	3,89E-05	1,39E-05	4,69E-02	2,32E-04	4,20E-05	2,11E-05
	Wood Fast Pyrolysis - Optimized	5,68E-02	2,33E-09	5,74E-05	3,30E-05	1,17E-05	4,12E-02	1,93E-04	3,22E-05	1,89E-05
	Soybean methyl ester, at esterification plant, BR	9,54E-02	2,44E-09	3,51E-04	2,32E-05	5,16E-04	5,67E-03	6,36E-04	3,39E-04	2,95E-04
	Palm methyl ester, at esterification plant, MY	4,36E-02	1,81E-09	2,30E-04	4,92E-06	1,27E-04	6,45E-03	2,95E-04	1,53E-04	2,99E-03
	Diesel, low sulphur at regional storage	1,43E-02	1,34E-08	1,02E-04	2,02E-06	2,85E-06	2,23E-03	1,11E-04	3,14E-05	1,19E-06

Table 39: Diesel mid-point results per MJ

		Impacts per MJ								
Fuel	Pathway	Freshwater Ecotoxicity (kg 1.4-DB eq)	Marine Ecotoxicity (kg 1.4-DB eq)	Ionising radiation (kg U235 eq)	Agricultural Land Occupation	Urban Land Occupation (m2a)	Natural Land transformation (m2)	Water Depletion (m3)	Metal Depletion (kg Fe eq)	Fossil Depletion (kg oil eq)
Diesel	Algae Oil Esterification	3,07E-03	3,29E-03	1,70E-02	4,25E-03	1,86E-03	1,32E-04	2,02E-02	2,35E-02	2,02E-01
	Algae Oil Esterification Optimized	1,70E-03	1,82E-03	3,26E-03	1,77E-03	5,55E-04	1,70E-05	1,86E+00	3,25E-02	1,53E-02
	Wood Fast Pyrolysis	1,11E-03	1,02E-03	1,57E-02	4,67E-01	8,67E-03	9,64E-06	1,56E-04	8,65E-03	6,73E-03
	Wood Fast Pyrolysis - Optimized	9,72E-04	8,87E-04	1,07E-03	4,20E-01	7,78E-03	7,62E-06	4,56E-05	7,85E-03	4,61E-03
	Soybean methyl ester, at esterification plant, BR	2,25E-04	1,08E-04	2,02E-03	1,17E-01	4,54E-04	3,50E-03	1,58E-04	1,13E-03	6,65E-03
	Palm methyl ester, at esterification plant, MY	5,80E-04	1,51E-04	5,91E-03	4,07E-02	3,51E-04	4,25E-06	7,71E-03	1,39E-03	6,09E-03
	Diesel, low sulphur at regional storage	6,74E-05	7,04E-05	1,66E-03	5,01E-05	1,39E-04	3,17E-05	1,05E-04	3,22E-04	2,88E-02

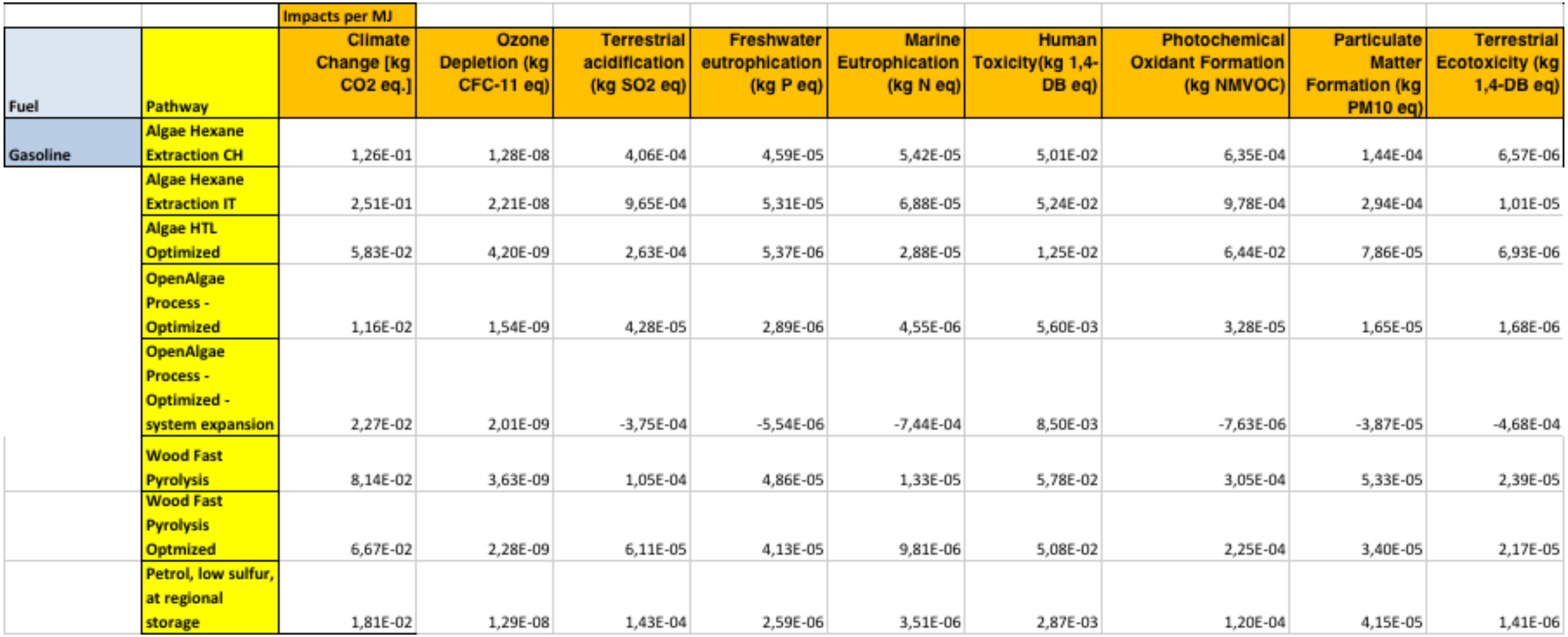
Table 40: Diesel mid-point results per MJ

		Impacts per MJ								
Fuel	**Pathway**	**Climate Change [kg CO2 eq.]**	**Ozone Depletion (kg CFC-11 eq)**	**Terrestrial acidification (kg SO2 eq)**	**Freshwater eutrophication (kg P eq)**	**Marine Eutrophication (kg N eq)**	**Human Toxicity(kg 1,4-DB eq)**	**Photochemical Oxidant Formation (kg NMVOC)**	**Particulate Matter Formation (kg PM10 eq)**	**Terrestrial Ecotoxicity (kg 1,4-DB eq)**
Bio-Methane	**Methane from Wood SNG**	1,20E-02	1,32E-09	1,03E-04	4,91E-06	1,63E-05	1,92E-02	1,51E-04	4,06E-05	6,56E-05
	Methane from WoodSNG Optimized	1,04E-02	1,24E-09	6,77E-05	3,24E-06	1,28E-05	1,86E-02	8,82E-05	2,68E-05	6,03E-05
	Purification Biogas - Manure	9,92E-02	5,16E-09	3,23E-04	9,23E-06	6,01E-05	1,38E-02	1,33E-04	7,68E-05	1,00E-04
	Purification Biogas - Manure - Optimized	4,22E-02	1,21E-09	1,46E-04	5,24E-06	2,79E-05	9,65E-03	4,85E-05	3,46E-05	4,79E-05
	HTG manure	2,21E-02	3,33E-09	1,23E-04	4,45E-06	6,61E-06	8,97E-03	1,68E-04	6,29E-05	7,24E-06
	HTG manure - Optmized	2,14E-02	3,28E-09	1,08E-04	4,27E-06	5,55E-06	9,52E-03	1,38E-04	5,73E-05	8,92E-06
	HTG wood	1,03E-02	1,44E-09	5,62E-05	2,54E-06	3,33E-06	2,30E-03	8,91E-05	2,38E-05	5,37E-07
	HTG wood - Optmized	8,51E-03	1,26E-09	3,07E-05	2,17E-06	1,55E-06	3,27E-03	3,45E-05	1,48E-05	3,51E-06
Natural Gas	**Natural gas, low pressure, at consumer/CH**	1,52E-02	1,12E-08	4,21E-05	4,21E-07	1,07E-06	5,45E-04	5,57E-05	1,25E-05	1,53E-07

Table 41: Methane mid-point results per MJ

		Impacts per MJ								
Fuel	Pathway	Freshwater Ecotoxicity (kg 1,4-DB eq)	Marine Ecotoxicity (kg 1,4-DB eq)	Ionising radiation (kg U235 eq)	Agricultural Land Occupation (m2a)	Urban Land Occupation (m2a)	Natural Land transformation (m2)	Water Depletion (m3)	Metal Depletion (kg Fe eq)	Fossil Depletion (kg oil eq)
Bio-Methane	Methane from Wood SNG	2,43E-04	2,27E-04	1,83E-02	7,11E-02	8,29E-04	7,96E-06	2,07E-04	8,91E-04	3,11E-03
	Methane from WoodSNG Optimized	2,42E-04	2,34E-04	1,37E-03	6,40E-02	8,71E-04	7,66E-06	7,43E-05	1,65E-03	2,82E-03
	Purification Biogas - Manure	6,87E-04	6,32E-04	1,90E-02	1,89E-02	6,68E-04	1,73E-05	2,31E-04	4,08E-03	8,65E-03
	Purification Biogas - Manure - Optimized	3,86E-04	3,66E-04	1,07E-03	9,02E-03	3,30E-04	6,50E-06	3,83E-05	3,25E-03	2,28E-03
	HTG manure	2,26E-04	2,61E-04	1,51E-02	4,31E-04	1,83E-03	1,01E-05	1,36E-04	3,70E-03	7,52E-03
	HTG manure - Optmized	2,32E-04	2,77E-04	1,50E-02	4,41E-04	1,90E-03	9,92E-06	1,24E-04	3,61E-03	7,27E-03
	HTG wood	6,35E-05	6,35E-05	2,08E-03	6,64E-05	1,39E-04	3,63E-06	2,91E-04	5,46E-04	3,64E-03
	HTG wood - Optmized	7,86E-05	9,59E-05	1,78E-03	1,00E-04	3,13E-04	2,99E-06	2,40E-04	4,35E-04	3,02E-03
Natural Gas	Natural gas, low pressure, at consumer/CH	1,26E-05	3,08E-05	2,09E-04	3,83E-05	3,68E-05	1,60E-05	1,34E-05	2,75E-04	2,58E-02

Table 42: Methane mid-point results per MJ

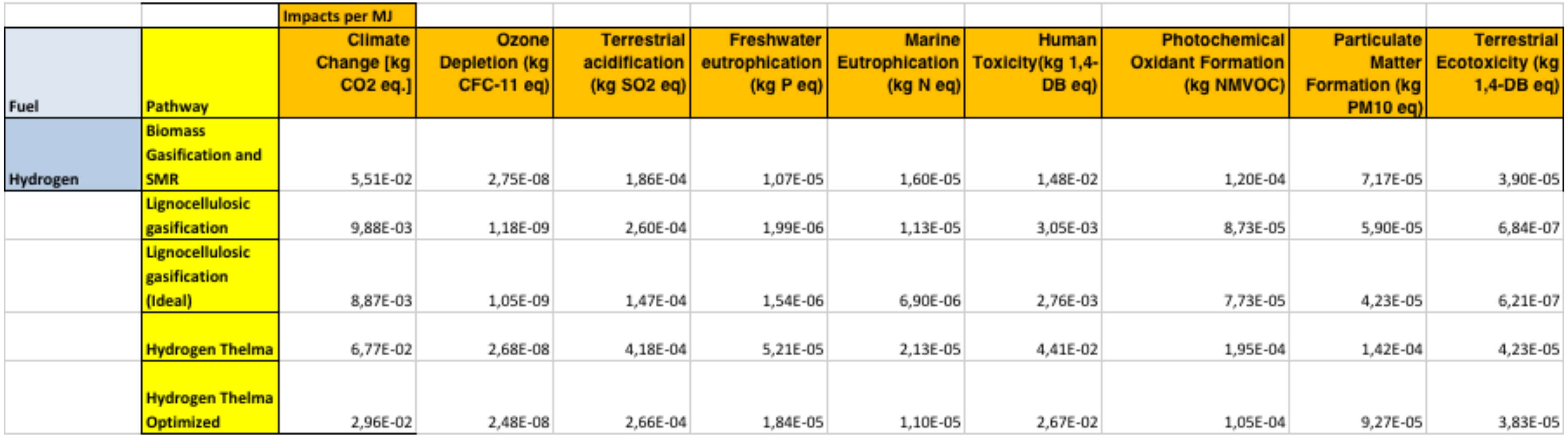


		Impacts per MJ								
Fuel	Pathway	Climate Change [kg CO2 eq.]	Ozone Depletion (kg CFC-11 eq)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine Eutrophication (kg N eq)	Human Toxicity(kg 1,4-DB eq)	Photochemical Oxidant Formation (kg NMVOC)	Particulate Matter Formation (kg PM10 eq)	Terrestrial Ecotoxicity (kg 1,4-DB eq)
Gasoline	Algae Hexane Extraction CH	1,26E-01	1,28E-08	4,06E-04	4,59E-05	5,42E-05	5,01E-02	6,35E-04	1,44E-04	6,57E-06
	Algae Hexane Extraction IT	2,51E-01	2,21E-08	9,65E-04	5,31E-05	6,88E-05	5,24E-02	9,78E-04	2,94E-04	1,01E-05
	Algae HTL Optimized	5,83E-02	4,20E-09	2,63E-04	5,37E-06	2,88E-05	1,25E-02	6,44E-02	7,86E-05	6,93E-06
	OpenAlgae Process - Optimized	1,16E-02	1,54E-09	4,28E-05	2,89E-06	4,55E-06	5,60E-03	3,28E-05	1,65E-05	1,68E-06
	OpenAlgae Process - Optimized - system expansion	2,27E-02	2,01E-09	-3,75E-04	-5,54E-06	-7,44E-04	8,50E-03	-7,63E-06	-3,87E-05	-4,68E-04
	Wood Fast Pyrolysis	8,14E-02	3,63E-09	1,05E-04	4,86E-05	1,33E-05	5,78E-02	3,05E-04	5,33E-05	2,39E-05
	Wood Fast Pyrolysis Optmized	6,67E-02	2,28E-09	6,11E-05	4,13E-05	9,81E-06	5,08E-02	2,25E-04	3,40E-05	2,17E-05
	Petrol, low sulfur, at regional storage	1,81E-02	1,29E-08	1,43E-04	2,59E-06	3,51E-06	2,87E-03	1,20E-04	4,15E-05	1,41E-06

Table 43: Gasoline mid-point results per MJ

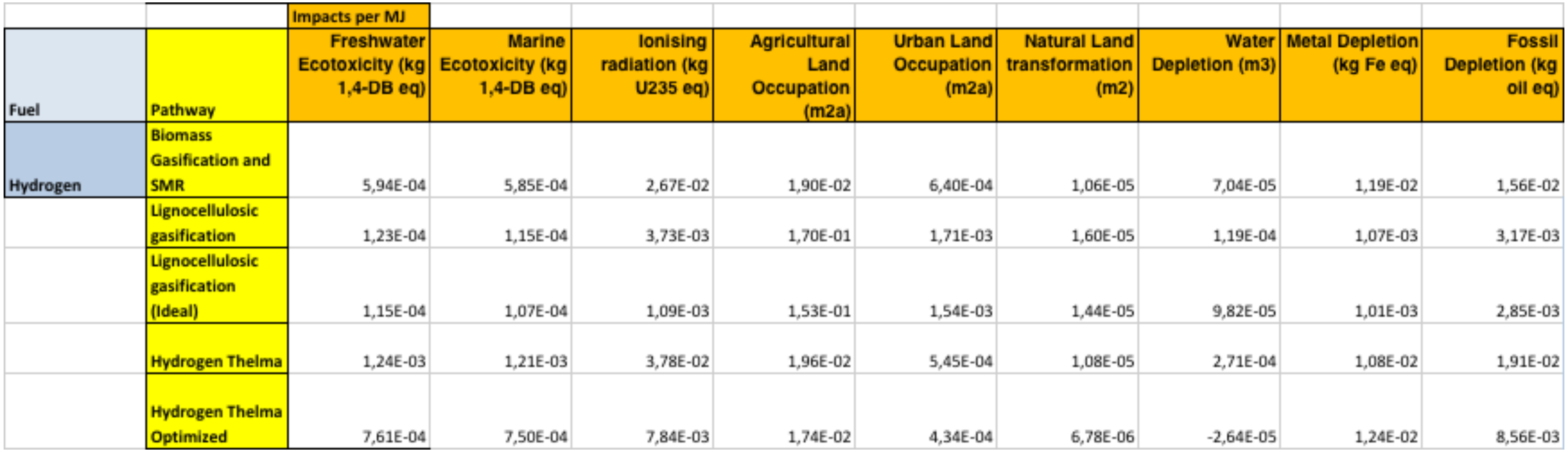
		Impacts per MJ								
Fuel	Pathway	Freshwater Ecotoxicity (kg 1,4-DB eq)	Marine Ecotoxicity (kg 1,4-DB eq)	Ionising radiation (kg U235 eq)	Agricultural Land Occupation (m2a)	Urban Land Occupation (m2a)	Natural Land transformation (m2)	Water Depletion (m3)	Metal Depletion (kg Fe eq)	Fossil Depletion (kg oil eq)
Gasoline	Algae Hexane Extraction CH	1,12E-03	1,11E-03	2,01E-01	4,41E-03	5,51E-02	1,84E-05	1,77E-03	7,94E-03	5,41E-02
	Algae Hexane Extraction IT	1,19E-03	1,22E-03	3,30E-02	4,60E-03	5,54E-02	4,41E-05	1,01E-03	7,63E-03	9,26E-02
	Algae HTL Optimized	3,89E-04	4,11E-04	2,33E-03	8,69E-04	1,37E-03	8,48E-06	2,96E-04	3,16E-03	1,13E-02
	OpenAlgae Process - Optimized	1,24E-04	1,31E-04	8,94E-04	4,32E-04	1,14E-03	3,00E-06	1,68E-04	1,61E-03	5,34E-03
	OpenAlgae Process - Optimized - system expansion	-1,75E-05	3,01E-04	-2,88E-03	-1,70E-01	-1,91E-03	-2,80E-06	-9,89E-04	2,67E-03	7,51E-03
	Wood Fast Pyrolysis	1,39E-03	1,25E-03	1,91E-02	5,76E-01	1,05E-02	1,12E-05	1,96E-04	1,09E-02	7,46E-03
	Wood Fast Pyrolysis Optmized	1,22E-03	1,09E-03	1,05E-03	5,18E-01	9,44E-03	8,37E-06	4,30E-05	9,86E-03	4,59E-03
	Petrol, low sulfur, at regional storage	8,13E-05	8,91E-05	2,08E-03	6,81E-05	1,64E-04	3,60E-05	1,13E-04	4,27E-04	3,02E-02

Table 44: Gasoline mid-point results per MJ



		Impacts per MJ								
Fuel	Pathway	Climate Change [kg CO2 eq.]	Ozone Depletion (kg CFC-11 eq)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine Eutrophication (kg N eq)	Human Toxicity(kg 1,4-DB eq)	Photochemical Oxidant Formation (kg NMVOC)	Particulate Matter Formation (kg PM10 eq)	Terrestrial Ecotoxicity (kg 1,4-DB eq)
Hydrogen	Biomass Gasification and SMR	5,51E-02	2,75E-08	1,86E-04	1,07E-05	1,60E-05	1,48E-02	1,20E-04	7,17E-05	3,90E-05
	Lignocellulosic gasification	9,88E-03	1,18E-09	2,60E-04	1,99E-06	1,13E-05	3,05E-03	8,73E-05	5,90E-05	6,84E-07
	Lignocellulosic gasification (Ideal)	8,87E-03	1,05E-09	1,47E-04	1,54E-06	6,90E-06	2,76E-03	7,73E-05	4,23E-05	6,21E-07
	Hydrogen Thelma	6,77E-02	2,68E-08	4,18E-04	5,21E-05	2,13E-05	4,41E-02	1,95E-04	1,42E-04	4,23E-05
	Hydrogen Thelma Optimized	2,96E-02	2,48E-08	2,66E-04	1,84E-05	1,10E-05	2,67E-02	1,05E-04	9,27E-05	3,83E-05

Table 45: Hydrogen mid-point results per MJ



		Impacts per MJ								
Fuel	Pathway	Freshwater Ecotoxicity (kg 1,4-DB eq)	Marine Ecotoxicity (kg 1,4-DB eq)	Ionising radiation (kg U235 eq)	Agricultural Land Occupation (m2a)	Urban Land Occupation (m2a)	Natural Land transformation (m2)	Water Depletion (m3)	Metal Depletion (kg Fe eq)	Fossil Depletion (kg oil eq)
Hydrogen	Biomass Gasification and SMR	5,94E-04	5,85E-04	2,67E-02	1,90E-02	6,40E-04	1,06E-05	7,04E-05	1,19E-02	1,56E-02
	Lignocellulosic gasification	1,23E-04	1,15E-04	3,73E-03	1,70E-01	1,71E-03	1,60E-05	1,19E-04	1,07E-03	3,17E-03
	Lignocellulosic gasification (Ideal)	1,15E-04	1,07E-04	1,09E-03	1,53E-01	1,54E-03	1,44E-05	9,82E-05	1,01E-03	2,85E-03
	Hydrogen Thelma	1,24E-03	1,21E-03	3,78E-02	1,96E-02	5,45E-04	1,08E-05	2,71E-04	1,08E-02	1,91E-02
	Hydrogen Thelma Optimized	7,61E-04	7,50E-04	7,84E-03	1,74E-02	4,34E-04	6,78E-06	-2,64E-05	1,24E-02	8,56E-03

Table 46: Hydrogen mid-point results per MJ

		Impacts per MJ								
Fuel	Pathway	Climate Change [kg CO2 eq.]	Ozone Depletion (kg CFC-11 eq)	Terrestrial acidification (kg SO2 eq)	Freshwater eutrophication (kg P eq)	Marine Eutrophication (kg N eq)	Human Toxicity(kg 1,4-DB eq)	Photochemical Oxidant Formation (kg NMVOC)	Particulate Matter Formation (kg PM10 eq)	Terrestrial Ecotoxicity (kg 1,4-DB eq)
Electricity	Electricity, at cogen 6667 kWth, wood	1,27E-02	2,38E-08	3,66E-04	1,74E-05	2,05E-05	2,99E-02	3,94E-04	1,23E-04	1,72E-05
	Electricity, at cogen 6667 kWth, wood, Optimized	1,05E-02	2,14E-08	2,10E-04	1,61E-05	1,22E-05	2,60E-02	2,34E-04	7,21E-05	1,29E-05
	Electricity, at cogen with biogas engine (Base Case)	1,76E-01	1,02E-08	6,89E-04	1,44E-05	1,27E-04	2,43E-02	2,92E-04	1,61E-04	2,11E-04
	Electricity, at cogen with biogas engine, (Best Case)	1,57E-01	9,19E-09	5,98E-04	1,35E-05	1,14E-04	2,29E-02	2,46E-04	1,39E-04	1,90E-04
	Electricity, low voltage, at grid-CH (Import+Production)	4,12E-02	5,50E-09	1,86E-04	4,34E-05	1,18E-05	4,67E-02	9,70E-05	6,90E-05	3,95E-06
	Electricity, low voltage, Hard Coal, at grid, CH	3,40E-01	1,87E-09	1,49E-03	1,68E-04	6,56E-05	1,32E-01	8,25E-04	4,49E-04	6,02E-06
	Electricity, low voltage, Hydropower, at grid, CH	3,72E-03	1,93E-10	5,88E-05	1,46E-05	3,82E-06	3,22E-02	2,10E-05	2,30E-05	3,13E-06
	Electricty, low voltage, Nuclear, at grid, CH	4,91E-03	9,84E-09	7,07E-05	1,46E-05	5,06E-06	3,31E-02	2,86E-05	2,40E-05	3,26E-06
	Electricity, low voltage, Wood combustion cogeneration plant, exergy alloc., at grid, CH	3,13E-02	1,00E-09	3,14E-04	1,91E-05	1,64E-05	5,70E-02	2,22E-04	1,00E-04	1,19E-05
	Electricity, low voltage, Natural Gas CC, at grid, CH	1,35E-01	1,93E-08	1,55E-04	1,47E-05	7,45E-06	3,26E-02	1,61E-04	5,19E-05	3,40E-06
	Electricity, low voltage, wind, at grid, CH	7,58E-03	4,38E-10	7,65E-05	1,78E-05	5,54E-06	3,72E-02	3,21E-05	3,24E-05	3,60E-06
	Electricity, low voltage, production mix, EU	1,35E-01	6,42E-09	5,37E-04	1,15E-04	3,44E-05	7,44E-02	2,82E-04	1,73E-04	2,92E-06

Table 47: Electricity mid-point results per MJ

		Impacts per MJ								
Fuel	Pathway	Freshwater Ecotoxicity (kg 1,4-DB eq)	Marine Ecotoxicity (kg 1,4-DB eq)	Ionising radiation (kg U235 eq)	Agricultural Land Occupation (m2a)	Urban Land Occupation (m2a)	Natural Land transformation (m2)	Water Depletion (m3)	Metal Depletion (kg Fe eq)	Fossil Depletion (kg oil eq)
Electricity	Electricity, at cogen 6667 kWth, wood	9,43E-04	9,15E-04	8,29E-04	4,82E-01	4,68E-03	4,31E-06	1,96E-05	4,55E-03	3,20E-03
	Electricity, at cogen 6667 kWth, wood, Optimized	8,65E-04	8,20E-04	7,51E-04	4,34E-01	4,22E-03	3,89E-06	1,84E-05	4,41E-03	2,89E-03
	Electricity, at cogen with biogas engine (Base Case)	1,05E-03	9,70E-04	1,61E-02	3,89E-02	1,29E-03	3,52E-05	3,65E-04	7,67E-03	1,66E-02
	Electricity, at cogen with biogas engine, (Best Case)	9,58E-04	8,90E-04	1,45E-02	3,50E-02	1,16E-03	3,17E-05	3,29E-04	7,22E-03	1,50E-02
	Electricity, low voltage, at grid-CH (Import+Production)	9,25E-04	9,39E-04	2,15E-01	9,40E-04	1,93E-04	5,89E-06	1,47E-03	7,34E-03	1,13E-02
	Electricity, low voltage, Hard Coal, at grid, CH	3,00E-03	2,96E-03	5,60E-03	7,64E-03	2,23E-03	1,63E-05	8,64E-04	1,07E-02	8,71E-02
	Electricity, low voltage, Hydropower, at grid, CH	5,12E-04	5,45E-04	3,70E-04	4,38E-04	1,13E-04	2,28E-06	4,12E-05	1,02E-02	6,83E-04
	Electricty, low voltage, Nuclear, at grid, CH	5,35E-04	5,68E-04	4,05E-01	5,53E-04	1,47E-04	1,08E-06	2,73E-03	1,14E-02	1,13E-03
	Electricity, low voltage, Wood combustion cogeneration plant, exergy alloc., at grid, CH	6,89E-04	7,62E-04	1,33E-03	5,35E-02	8,27E-04	8,33E-06	6,76E-05	1,07E-02	2,77E-03
	Electricity, low voltage, Natural Gas CC, at grid, CH	5,19E-04	5,84E-04	3,93E-04	4,58E-04	1,41E-04	3,01E-05	1,06E-03	1,03E-02	5,01E-02
	Electricity, low voltage, wind, at grid, CH	7,03E-04	7,39E-04	1,07E-03	5,21E-04	4,78E-04	1,00E-06	7,48E-05	1,60E-02	1,91E-03
	Electricity, low voltage, production mix, EU	1,79E-03	1,76E-03	1,05E-01	2,28E-03	4,55E-04	1,65E-05	1,08E-03	9,84E-04	3,72E-02

Table 48: Electricity mid-point results per MJ

12. References

A. Dauriat, E. G. (2006). *Synthetic Biofuels*. Retrieved from

A. Wokaun, W. (2011) *Transition to Hydrogen - Pathways Toward Clean Transportation*

.

Abhishek Chaudhary, Francesca Verones, Laura de Baan, Stephan Pfister, & Hellweg, S. (2014). Land stress: Potential species loss from land use (global; PSSRg). *11*.

Alonso-Vicario, A., Ochoa-Gómez, J. R., Gil-Río, S., Gómez-Jiménez-Aberasturi, O., Ramírez-López, C. A., Torrecilla-Soria, J., & Domínguez, A. (2010). Purification and upgrading of biogas by pressure swing adsorption on synthetic and natural zeolites. *Microporous and Mesoporous Materials, 134*(1–3), 100-107. doi:http://dx.doi.org/10.1016/j.micromeso.2010.05.014

Baier, p. U. (13.10.2016).

Beal, C. M., Gerber, L. N., Sills, D. L., Huntley, M. E., Machesky, S. C., Walsh, M. J., . . . Greene, C. H. (2015). Algal biofuel production for fuels and feed in a 100-ha facility: A comprehensive techno-economic analysis and life cycle assessment. *Algal Research, 10*, 266-279. doi:http://dx.doi.org/10.1016/j.algal.2015.04.017

BIOSWEET. (2016). Biomass for Swiss Energy Future Conference 2016.

Brown, Brown, T., Duan, P., & Savage, P. (2010). Hydrothermal Liquefaction and Gasification of Nannochloropsis sp. *Energy & fuels, 24*(6), 3639-3646.

Cavenati, S., Grande, C., & Rodrigues, A. (2005). Upgrade of Methane from Landfill Gas by Pressure Swing Adsorption. *Energy & fuels, 19*(6), 2545-2555.

Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G., Schlamadinger, B., & Woess-Gallasch, S. (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling, 53*(8), 434-447. doi:http://dx.doi.org/10.1016/j.resconrec.2009.03.013

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances, 25*(3), 294-306. doi:http://dx.doi.org/10.1016/j.biotechadv.2007.02.001

Dauriat A., G. G., Alig M, Scharfy D, Membrez Y, Bachmann N, Steiner R. (2011). Analyse de cycle de vie de la production centralisée et decentralisée de biogaz en exploitations agricoles.

E4tech. Comparison of wood combustion and gasification technologies in the context of the Swiss Energy Strategy 2050.

EC. (2006). Biofuels in the European Union - a vision for 2030 and beyond.

Ecoinvent. (2014). heat and power co-generation, wood chips, 6667 kW. https://v33.ecoquery.ecoinvent.org/Details/UPR/03713B24-7420-4550-88AC-E4AF5157E3D4/290C1F85-4CC4-4FA1-B0C8-2CB7F4276DCE.

EPA. (2016). Global Green House Gas Emissions Data. https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

Federal Department of the Environment, T., Energy and Communications DETEC, Swiss Federal Office of Energy SFOE. (2016). Energy Consumption in Switzerland 2015.

H. Thomas. (2014). OpenAlgae Wet Extraction. *C.M. Beal (Ed.)* (www.openalgae.com)*.*

IEA. (2008). Energy technology perspective - Scenario and strategies to 2050.

IEA. (2012). Energy Policies of IEA Countries - Switzerland. (Review).

IEA. (2015). CO2 EMISSIONS FROM FUEL COMBUSTION - Highlights.

Iribarren, D., Peters, J. F., & Dufour, J. (2012). Life cycle assessment of transportation fuels from biomass pyrolysis. *Fuel, 97*, 812-821. doi:http://dx.doi.org/10.1016/j.fuel.2012.02.053

ISO. (2006). The new international standards for life cycle assessment: ISO 14040 and ISO 14044.

Kahn Ribeiro, S., S. Kobayashi, M. Beuthe, J. Gasca, D. Greene, D. S. Lee, Y. Muromachi, P. J. Newton, S. Plotkin, D. Sperling, R. Wit,, & Zhou, P. J. (2007). Transport and its infrastructure. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)],*

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. .

Luterbacher, Luterbacher, J., Fröling, M., Vogel, F. d. r., Maréchal, F. o., & Tester, J. (2009). Hydrothermal Gasification of Waste Biomass: Process Design and Life Cycle Asessment. *Environmental science & technology, 43*(5), 1578-1583.

M. Spielmann, F. D., K. Schleiss, N. Jungbluth. (2006). *Biogas* Retrieved from

Mariluz Bagnoud-Velasquez, D. R., Francois Vuille, and Christian Ludwig. (2016). Opportunities for Switzerland to contribute to the production of algal biofuels: the hydrothermal pathway to bio-methane. *CHIMIA, 10*.

Mark A. J. Huijbregts, F. V., Ligia B. Azevedo, Abhishek Chaudhary, Nuno Cosme, Peter Fantke, Mark Goedkoop, Michael Hauschild, Alexis Laurent, Christopher L. Mutel, Stephan Pfister, Tommie Ponsioen, Zoran Steinmann, Rosalie van Zelm, Marisa Vieira, Stefanie Hellweg. (2014). LC-Impact v0.1.

Mark Goedkoop, R. H., Mark Huijbregts, An De Schryver, Jaap Struijs, and Rosalie van Zelm. (2013). ReCiPe 2008.

Mireille Faist Emmenegger, S. G. n., Jürgen Reinhard, Rainer Zah,Thomas Nemecek, Julian Schnetzer, Christian Bauer, Andrew Simons, Gabor Doka. (2012). *Harmonisation and extension of the bioenergy inventories and assessment*. Retrieved from

Morero, B., Groppelli, E., & Campanella, E. A. (2015). Life cycle assessment of biomethane use in Argentina. *Bioresource Technology, 182*, 208-216. doi:http://dx.doi.org/10.1016/j.biortech.2015.01.077

Mu, Mu, D., Min, M., Krohn, B., Mullins, K., Ruan, R., & Hill, J. (2014). Life Cycle Environmental Impacts of Wastewater-Based Algal Biofuels. *Environmental science & technology, 48*(19), 11696-11704.

N. Jungbluth, M. F. E., F.Dinkel, C. Stettler, G. Doka, M. Chudakoff, A. Dauriat, E. Gnansounou, M. Spielmann, J. Sutter, N. Kljun, M. Keller, K. Schleiss. (2007). *Life Cycle Inventories of Bioenergy* (17). Retrieved from Uster:

Passell, H., Dhaliwal, H., Reno, M., Wu, B., Ben Amotz, A., Ivry, E., . . . Ayer, N. (2013). Algae biodiesel life cycle assessment using current commercial data. *Journal of Environmental Management, 129*, 103-111. doi:http://dx.doi.org/10.1016/j.jenvman.2013.06.055

Prognos. (2012). Die energieperspektiven für die Schweiz bis 2050 - Energienachfrage und Elektrizitätsangebot in der Schweiz 2000 - 2050.

R. Zah, H. B., M. Gauch, R. Hischier, M. Lehmann, P. Wäger. (2007). LCA of energy products: environmental impact assessment of biofuels.

Richard, T. L. (2010). Challenges in Scaling Up Biofuels Infrastructure. *Science, 329*(5993), 793-796. doi:10.1126/science.1189139

SCCER-Mobility. Swiss Competence Center for Energy Research - Efficient Technologies and Systems for Mobility. http://www.sccer-mobility.ch/.

SimaPro. (2016). https://simapro.com/databases/ecoinvent/.

Snowden-Swan, L. J., Spies, K. A., Lee, G. J., & Zhu, Y. (2016). Life cycle greenhouse gas emissions analysis of catalysts for hydrotreating of fast pyrolysis bio-oil. *Biomass and Bioenergy, 86*, 136-145. doi:http://dx.doi.org/10.1016/j.biombioe.2016.01.019

Spiellmann, M. (2005). *Use and Upgrading of Biogas*. Retrieved from

Stefan Hirschberg, C. B., Brian Cox, Thomas Heck, Johannes Hofer, Warren Schenler, Andrew Simons, Andrea Del Duce, Hans-Jörg Althaus, Gil Georges,Thilo Krause, Marina González Vayá,Francesco Ciari, Rashid Waraich, Boris Jäggi,Alexander Stahel, Andreas Froemelt, Dominik Saner. (2016). Opportunities and challenges for electric mobility: an interdisciplinary assessment of passenger vehicles - Final report of the THELMA project in co-operation with the Swiss Competence Center for Energy Research “Efficient technologies and systems for mobility”.

Steubing, B., Zah, R., Waeger, P., & Ludwig, C. (2010). Bioenergy in Switzerland: Assessing the domestic sustainable biomass potential. *Renewable and Sustainable Energy Reviews, 14*(8), 2256-2265. doi:http://dx.doi.org/10.1016/j.rser.2010.03.036

Stoppato, A. (2013). LCA - Life Cycle Assessment A Brief Introduction.

Surendra, K. C., Takara, D., Hashimoto, A. G., & Khanal, S. K. (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews, 31*, 846-859. doi:http://dx.doi.org/10.1016/j.rser.2013.12.015

T&M-Leuven. (2007). TREMOVE v2.7b, Transport & Mobility Leuven. Brussels, European Commission.

Thees, B., Erni, Bowman, Lemm. (2017). Biomassepotenziale der Schweiz für die energetische Nutzung" (preliminary results, September 2016). *Final report SCCER-Biosweet*.

United States Environmental Protection Agency, O. o. A. a. R., & Office of Atmospheric Programs, C. C. D. (2014). Framework for Assessing Biogenic CO2 Emissions

from Stationary Sources

Weinberg, J., & Kaltschmitt, M. (2013). Life cycle assessment of mobility options using wood based fuels – Comparison of selected environmental effects and costs. *Bioresource Technology, 150*, 420-428. doi:http://dx.doi.org/10.1016/j.biortech.2013.08.093

www.agrammon.ch. www.agrammon.ch.

Zhou, W., Chen, P., Min, M., Ma, X., Wang, J., Griffith, R., . . . Ruan, R. (2014). Environment-enhancing algal biofuel production using wastewaters. *Renewable and Sustainable Energy Reviews, 36*, 256-269. doi:http://dx.doi.org/10.1016/j.rser.2014.04.073

Zhu, Y., Albrecht, K. O., Elliott, D. C., Hallen, R. T., & Jones, S. B. (2013). Development of hydrothermal liquefaction and upgrading technologies for lipid-extracted algae conversion to liquid fuels. *Algal Research, 2*(4), 455-464. doi:http://dx.doi.org/10.1016/j.algal.2013.07.003