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Evaluation of Ecological Indicators and LCA of the Innovative Integrated Plant

Life Cycle Analysis of the FFW process

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Summary

The overall aim of the FFW project is to obtain liquid (diesel) and gas (synthetic natural gas) fuels starting from olive and olive oil residues via synthetic processes, namely Fischer-Tropsch and methanation, both via gasification. In order to do so, a complex process needs to be undergone, and Work Package 6 was focused on the assessment of the environmental feasibility of the technology involved.

This Deliverable aims to present the Life Cycle Assessment (LCA) of the FFW processes. In this sense, the present study shows an idea of the overall impacts of the whole technology and a more detailed estimation of the environmental burdens of each process. This analysis was based on the simulations made in Work Package 4, the *Base case* and the *Case study* (D4.4).

The lessons learn from the LCA were explained and improvement possibilities were developed. To summarize, the chemical pre-treatment of the olives biomass has a highest contribution on the overall FFW system, especially the purification process and the step to produce hydrogen and carbon monoxide enriched. Some other processes showed significant contribution in more specific impacts categories: pomace residue drying (abiotic depletion, global warming and acidification), oxygen ASU process (almost all the eutrophication potential in the *Case study*), methane product upgrading process (eutrophication potential in the *Base case*) and hydrocracking (more than half of the acidification potential in the *Case study*).

The electricity consumption was the main contribution to the environmental impacts for almost all the processes; hence this resource consumption has to be the priority to reduce the environmental burdens of the system. The sources could also be selected in favour of renewable energy bases or according to the energetic mix of the countries. On that point, the Spanish mix seems to be the most optimal among the olive producing countries in Europe.

The FWW system produces a sufficient amount of diesel to cover national transport (500 km round trip) of the olive biomass from the cultivation field to the transformation plant. In the same line, a regional transportation (50 km round trip) consumed less than 10% of this production. In terms of environmental impacts, the transport step has a rather low contribution (less than 1% at regional scale).

Compared to other fuel production systems, the FFW presented rather higher impacts; however, results were in the range with other similar process (Fischer-Tropsch technologies).

According to this study, the energy balance of the system (energy content of the product, consumption and production of the processes) was self-sufficient, allowing covering the energetic needs for the olives agriculture and local transportation at 100% in the *Base case* and 86.7% in the *Case study*.

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1 Introduction

The overall aim of the FFW project is to use agricultural waste, mainly residues from olive farming and olive oil production, for the generation of ready-to-use fuels, namely synthetic natural gas (SNG) and diesel, which would be primarily used for energy production for oil manufacturing and as transportation fuel for olive farming.

Olive cultivation and especially olive oil production have a great economic importance in terms of production, as well as a high consumption in Mediterranean countries. The world olive production has been constantly rising over the ten past years despites the natural fluctuations of the threes production. In 2009, the virgin olive oil production reached 2 907 985 tons and three quarters of this production came from Europe, mainly Italy, Spain, Greece and Portugal (*Salomone et al., 2012*).

Olives' cultivation methods evolved in the past years, from a traditional plantation in small areas with trees planted in terrace and low-inputs requirements, to more intensive and modern plantations. This evolution has led to several negatives environmental effects, such as soil erosion, that reduces the soil productivity capacity, increasing the need for fertilizers and favoring their spreading thanks to water irrigation. In addition to the erosion issue that can lead to desertification, the intensive olive production has also developed the water consumption of the culture and problems of ground water production. Furthermore, as for others kind of culture, the quantity of residues from olive and olive oil production has been multiplied (*Beaufoy, 2001*).

The use of wastes and residues for fuels production would help to reduce the environmental impacts of the olive industry. The residues are usually land filled, reused for fertilizing purposes, burnt for energetic valorization or composted, but all of these disposal treatments present significant drawbacks, such as the high pollutant potential of alperujo or the greenhouse gas emissions generated by incineration. Vlyssides et al. (2004) estimated that the production of one kilogram of olive oil generates 0.5 kg of air emissions, 1.26 kg of solid wastes and 7.5 kg of wastewater containing 0.7 kg of COD (chemical oxygen demand) and 0.08 kg of phenolic compounds, which are extremely dangerous for the natural environment.

This report provides the evaluation of the environmental impacts of the innovative process developed during the FFW project, following the Life Cycle Assessment (LCA) methodology. The study gives an idea of the overall impacts of the technologies and tries to highlight potential improvements to reduce the environmental burdens.

After a brief introduction on the technologies used in the FFW process, Section 2 summarizes a literature review of LCA applied to "Biomass to Liquid" (BtL) technologies, bioenergy systems and similar applications to the FFW technologies. The LCA of the FFW system is presented in the 3rd part of the report. Firstly, the goal, scope and data inventory are defined. Then, the environmental impacts of the overall system are shown as well as the details for each elementary process. The transport, the energy balance and the water footprint are also assessed. The last section of this deliverable gives an overview of the legislations related to the project.

1.1 Transformation from biomass to biofuels

Amongst the renewable energies, one of the most important energy sources in the near future will be biomass. The third among the primary energy sources after coal and oil is the biomass, and specifically in Mediterranean countries, olive tree pruning residues represent an abundant source of energy biomass (*Cara et al., 2008; Spinelli et al., 2010*).

The FFW project overview includes different stages, which are included in Figure 1.

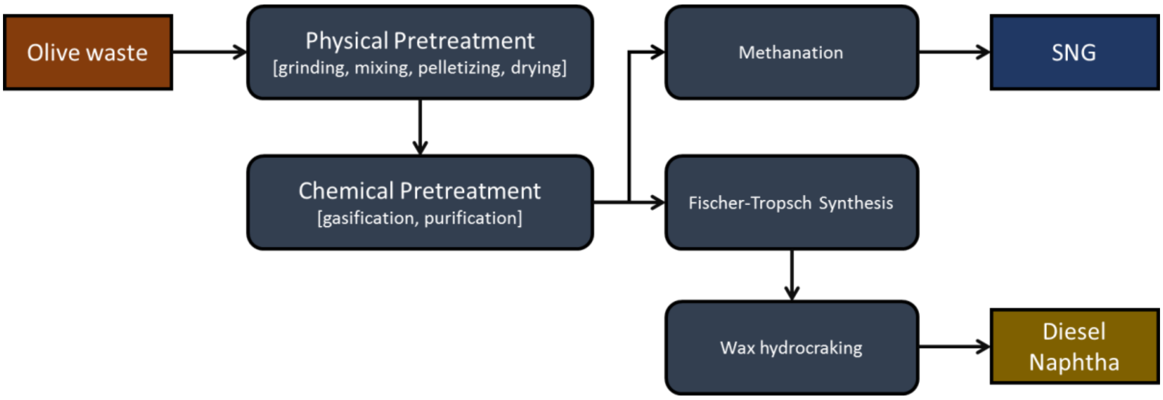

Figure 1. Schematics of the overall fuel production process.

There are two ways of extracting the oil: the traditional process, used for many centuries with only minor modifications, and centrifugation, which has been taken over by the olive oil industry in the last decades. There are two centrifugation systems, called three-phase and two-phase systems. In Spain, the most widely used process is the“2-phase”. In Italy and Greece the utilisation of “3-phase” methods is more common.

First generation (G1) biofuels have been developed to provide a substitute for fossil fuels in order to enhance energy independence and mitigate climate change. They mainly correspond to ethanol and biodiesel produced from conventional crops such as sugar cane, sugar beet, wheat, corn, rapeseed, sunflower, etc. Nevertheless, G1 biofuels have come up against sustainability issues (high environmental impacts of the feedstock growth, competition with food cultivations, etc.)(*UN-Energy, 2007*).

In order to be more efficient in terms of land use, food security, GHG emission reductions and other environmental aspects G2 Ethanol is obtained from the biochemical conversion of lignocellulosic biomass and synthetic diesel from biomass, also known as BtL (Biomass to Liquids) or biomass FT-diesel, is produced by the thermochemical conversion of lignocellulosic biomass. On the other hand, G3 biofuels from microalgae are produced using algal oil for biodiesel production from conventional transesterification (Fatty Acid Methyl Ester, FAME) or hydrotreated vegetable oil (HVO) (*European Biofuels Technology Platform, 2015*).

1.2 Fisher-Tropsch process

Liquid transportation hydrocarbon fuels and various other chemical products can be produced from syngas via the catalytic chemical process called Fischer-Tropsch (FT) synthesis, named after the original German inventors, Franz Fischer and Hans Tropsch in the 1920's (*Schulz, 1999*).

The Fischer-Tropsch process is a catalytic chemical reaction in which carbon monoxide (CO) and hydrogen (H_2) in the syngas are converted into hydrocarbons of various molecular weights according to the following equation:

$$(2n+1)\ H_2 + n\ CO \rightarrow C_n\, H_{(2n+2)} + n\ H_2O$$

Where n is an integer. Thus, for n=1, the reaction represents the formation of methane. The Fischer-Tropsch process conditions are usually chosen to maximize the formation of higher molecular weight hydrocarbon liquid fuels that are higher value products (*Kaneko et al., 2005*).

This process is different from the usual biodiesel production, since it does not require oil as an input and is a chemical, not biological, process: it allows the use of solid residues and, being a synthetic process, the length of the carbon chain can be optimised depending on the proposed use. In this case, diesel is the chosen liquid main product, but shorter or longer chains could be selected if needed, and the produced fuels are cleaner (*Kaneko et al., 2005*).

Figure 2 shows a simplified block flow diagram of a process incorporating FT synthesis.

The gasification stage consists of all the supporting process technologies of coal handling & feed preparation, heat recovery, syngas clean up and conditioning, water-gas-shift, etc. The clean syngas leaving the gasification process is sent onto the FT synthesis stage, where the clean shifted syngas is converted into primary products of wax, hydrocarbon condensate, tail gas, and reaction water. The wax is sent to an upgrading unit for hydrocracking in the presence of hydrogen, where it is chemically split into smaller molecular weight hydrocarbon liquids. A hydrogen recovery unit is used to extract the required quantity of hydrogen from the tail gas as shown, or alternatively from the feed syngas stream. The reaction products are fractionated into the final products of diesel, naphtha, and other light ends (*US National Energy Technology Laboratory www.netl.doe.gov*).

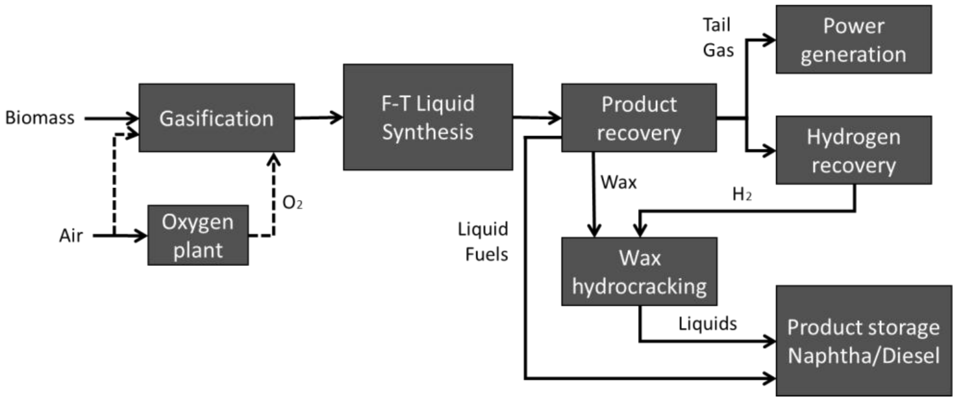

Figure 2 Simplified F-T Synthesis-based Production Scheme (*Source: www.netl.doe.gov*).

Gasification is a process that converts organic or fossil based carbonaceous materials into carbon monoxide, methane, hydrogen and carbon dioxide.

Syngas from biomass gasification consists mainly of CO, H_2, CH_4, CO_2 and H_2O, but also several unwanted impurities. Their total amount depends on feedstock qualities, gasifier type and reaction conditions. Furthermore, gasification in molten carbonates was investigated during the last years for clean production of CO and H_2 from biomass. For FT synthesis, a very high syngas quality is required, due to the high sensitiveness of the applied catalyst materials. Tar (all organic compounds with >78 amu) removal is possible by thermal and/or catalytic cracking as well as by physical removal. Thermal cracking requires temperatures higher than 1000°C. For physical removal, organic liquids like biodiesel, DME and others are used as absorbers; filters or charcoal are be used as adsorbents *(Kaneko et al., 2005*).

Depending on the requirements for the downstream process, gas cleaning can either be performed at high (>500°C) or low temperatures. High temperatures methods are cyclones, moving bed filters and ceramic filter candles, whereas scrubbers, fabric filters and wet electrostatic precipitators require temperatures below 250°C. But at low temperatures, tar condensation can occur and increase the maintenance performance of these devices (*Kaneko et al., 2005*).

In order to predict experimental results, mathematical models are developed to simulate the Fischer-Tropsch and associated processes.

2 LCA literature review

This chapter summarizes the literature review including reference values (qualitative and quantitative) of LCA studies applied to BtL (Biomass to Liquid) technologies, in order to establish a framework for further comparisons and applications to the FFW project.

There is abundant literature in regards to LCA applied to biodiesel production, among other multiple reasons, because of the several biomass types of feedstocks used for this aim. This statement does not mean that there is a lot of accurate, verifiable and comparable information. An important aspect that must be taken into account is the possible competition of the biomass feedstock with food supply; the European Commission has defined this aspect as relevant criteria. The most recent literature returns that factor and the FFW biomass source considered satisfies this requirement such as other newly used biomass feedstocks (microalgae, etc.).

One example of the attempt to quantify the environmental impact depending on the biomass feedstock used is the study from Clarens et al., (2010) (Table 1). This paper shows that Algae is an attractive source of biomass energy since it does not compete with food crops and have higher energy yields per area than terrestrial crops. In spite of these advantages, algae cultivation has not yet been compared with conventional crops from a life cycle perspective. In this work, the impacts associated with algae production were determined using a stochastic life cycle model and compared with switchgrass, canola, and corn farming. The results indicate that these conventional crops have lower environmental impacts than algae in energy and water uses and greenhouse gas emissions regardless of cultivation location. Only the total land use and the eutrophication potential do algae perform favorably.

Table 1. Five Life Cycle burdens for production of one functional unit of energy (317 GJ) for different biomass feedstocks (*Clarens et al., 2010*).

Feedstock	Land (ha)	Energy (MJ) x 10^4	GHG (kg CO_2eq) x 10^4	Water (m^3) x 10^4	Eutrophication (kg PO_4^- eq)
Algae	0.4 ± 0.05	30 ± 6.6	1.8 ± 0.58	12 ± 2.4	3.3 ± 0.86
Corn	1.3 ± 0.3	3.8 ± 0.35	-2.6 ± 0.09	0.82 ± 0.19	26 ± 5.4
Canola	2.0 ± 0.2	7.0 ± 0.83	-1.6 ± 0.10	1.0 ± 0.14	28 ± 5.8
Switchgrass	1.7 ± 0.4	2.9 ± 0.27	-2.4 ± 0.18	0.57 ± 0.21	6.1 ± 1.7

When the biomass type has already been analysed, there are other multiple aspects that determine the LCA outcomes. According to several literature reviews, life cycle GHG emission results for advanced biofuels vary significantly depending on various factors, such as: the assumptions made to describe the biomass production step (model used to estimate N_2O emissions and inclusion of direct and indirect land use change), the data used to describe the biomass conversion into biofuel (i.e. inventory phase) and the general LCA methodological choices (scope, system boundaries, functional unit, method used to account for coproducts impacts, etc.).

The use of different input data, functional units, allocation methods, reference systems and other assumptions complicates comparisons of LCA bioenergy studies. In addition, uncertainties and use of specific local factors for indirect effects (like land-use change and N-based soil emissions) may raise the range of the final results.

2.1 Life cycle assessment of bioenergy systems

Cherubini et al., (2011) performed a litterature review of the recent bioenergy LCA. Concerning the scope of the study, half of the papers (47) limited the assessment to GHG and energy balances without considering any possible contribution of bioenergy to other impact categories. This approach is usually supported by the evidence that mitigation of climate change and reduction of fossil fuel consumption are the main driving factors for worldwide bioenergy development. The remaining half of the papers performs an analysis which goes beyond GHG and energy balances, providing information on other impact categories or airborne emissions. Figure 3 shows the type of bioenergy products and biomass raw materials, which are assessed by the reviewed studies. Among transportation biofuels, there are a similar number of works evaluating 1st and 2nd generation biofuels, even if these latter are mainly at a pre-commercial stage (and their arrival in the market is predicted within the next 5–10 years). The majority of papers are focused on bioethanol and biodiesel production, which are the most common transportation biofuels produced today.

Also a relevant number of studies undertakes an assessment of synthetic biofuels like bio-methane, FT-diesel and others. Concerning studies evaluating the environmental performances of biomass for heat and power production, Figure 3 shows that their number is slightly lower than that for transportation biofuels. As shown in the upper part of Figure 3, the studies cover a wide spectrum of biomass raw materials. A broad distinction can be done between feedstocks, which come from dedicated crops (with occupancy of land and a possible competition with food and feed crops for available biomass and fertile land) and forest and the residues from agricultural, forestry and industrial activities, which can be available without upstream concerns. Lignocellulosic biomass is the most investigated type of feedstock, probably because this is the most abundant biomass resource in the world and is locally available in most of the countries (*Cherubini, 2011*).

Relatively few studies (9%) included in their impact assessment the land use category. This is an indicator particularly important for bioenergy systems based on dedicated crops or forest resources, since land use may lead to substantial impacts, particularly on biodiversity and on soil quality. The capital environmental importance of land use impacts contrasts with the lack of studies addressing this issue. This is particularly because there is no widely accepted methodology for including land use impacts in LCA, despite some recent efforts (*Dubreuil et al., 2007; Koellner et Scholz, 2008; Scholz, 2007*).

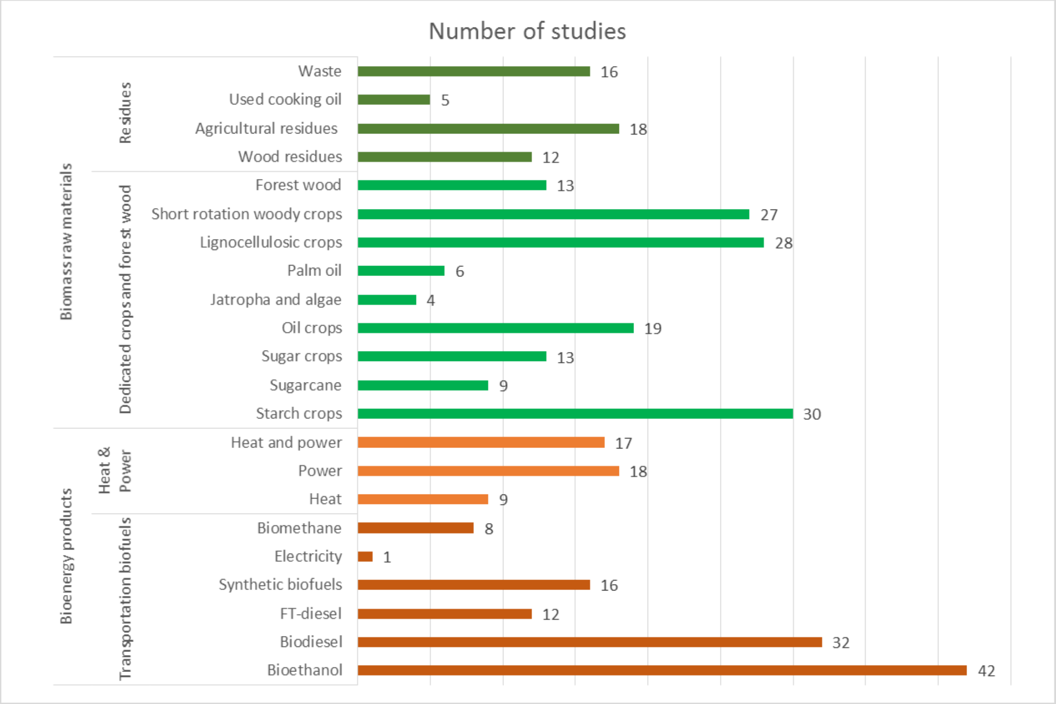

Figure 3. Type of bioenergy products and biomass raw materials covered by the reviewed studies (*Cherubini, 2011*).

GHG emissions are the most studied data in the LCA application to biofuels. Nevertheless and considering a different feedstock (vegetable oil and tallow), a correlation between different phases for the same impact category could be established. In the study from Niederl & Narodoslawsky (2004), it is shown that the GHG emissions are fragmented on the combustion phase (29.1%), on the process energy (20.7%), on chemicals (40.5%) and on the transport phase (17.8%). In the case of AP[1] and EP[2], almost the total impact (85.8% and 94.8% respectively) is caused by the combustion phase. The impact in biodiversity (ADP[3]) is caused mainly by process energy (67.1%) and transport (30.2%). From this study, is possible to correlate also the GWP impact and the rest of impact categories. This correlation is not physically correct, because different units cannot be compared, but it may be a reference in order to established orders of magnitude. It is also important that it should remain the technical parameters included in this LCA (feedstock, functional unit, impact categories, system boundaries, etc.).

- GWP (g CO2eq/MJ): 18.
- AP: **0.0117%** of the GWP (g CO_2eq/MJ) is AP impact in g SO_2eq/MJ.
- EP: **0.00183%** of the GWP (g CO_2eq/MJ) is EP impact in g PO_4eq/MJ.
- ADP: **0.00206%** of the GWP (g CO_2eq/MJ) is ADP impact in g Sbeq/MJ.

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[1] Acidification Potential.
[2] Eutrophication Potential.
[3] Abiotic Depletion Potential.

- POCP[4]: **0.00067%** of the GWP (g CO_2eq/MJ) is POCP impact in g ethylene eq/MJ.

2.1.1.1 Effects of agricultural residue removal.

There is an ongoing debate on the actual possibilities of crop residue removal from agricultural cropping systems for bioenergy production (*Lal, 2005; Wilhelm et al., 2004*).

Eighteen of the reviewed studies investigated the use of agricultural residues for bioenergy purposes, but most of them ignored the environmental impact induced by residue removal, except three studies. One of them assumed that 50% of the residues are left on the field to maintain soil organic carbon (SOC) levels (*Spatari et al., 2010*), while the others extended the investigation to other aspects, like the effects on grain yields, SOC, and Nitrogen cycle (*Cherubini and Ulgiati, 2010; Gabrielle & Gagnaire, 2008*).

2.1.1.2 Efficient biomass use: vehicle vs. stationary applications.

Since competition for biomass resources will be inevitable, it is important to make a selection of the best applications able to ensure the greatest GHG emission savings. One of the papers concludes that biomass use for electricity production enhances larger GHG savings, especially when compared to first generation biofuels (*Edwards et al., 2006*). Similarly, Greene (2004) suggests that bioelectricity ensures larger climate change mitigation benefits per ton of input biomass than transportation biofuels when coal electricity is displaced, but GHG savings become comparable between the two options when natural gas-derived electricity is replaced (*Greene, 2004*).

Another paper based on possible bioenergy uses of agricultural residues reveals that electricity production via direct firing or gasification save about three times the amount of GHG emissions saved by bioethanol and FT-diesel per unit of input biomass (coal electricity is assumed to be displaced) (*Searcy and Flynn, 2008*). Finally, two papers reveal that heating uses of biomass usually provide greater GHG savings per hectare than conventional biofuels and bioelectricity production systems (*Cherubini et al., 2009; Kaltschmitt et al., 1997*).

2.1.1.3 Recent trends and future challenges.

Concerning the LCA outcomes, the determination of the environmental performances is complex, and different combinations of feedstocks, conversion routes, fuels, end-use applications and methodological assumptions may lead to a wide range of results. In particular, different approaches are used to deal with the indirect effects, which have a large influence on final figures, and the way in which they should be estimated is still under discussion. The inclusion of these indirect effects in LCA represents the next research challenges for LCA practitioners. In fact, even though valuable improvements were achieved in determining the direct GHG emissions of bioenergy, a standard methodology for the indirect effects is still at a preliminary phase, and is needed further research

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[4] Photo-oxidant Creation Potential.

2.2 LCA literature related to FFW technologies

The literature review of the technologies similar to the FFW system allows to identify good practices in life cycle assessment of this kind of installation and to avoid inappropriate behaviors. The selection of the LCA study parameters and hypothesis was based on this literature review in order to stick to the mains objectives and specificity of the study. This overview also presented some references value to evaluate the environmental performances of the FFW system.

Regarding to the Mentel et al., (2013) presents the results of a literature review performed with a meta-regression analysis (MRA). It focuses on the estimates of advanced biofuel GHG emissions determined under a LCA approach. The mean GHG emissions of both second (G2) and third generation (G3) biofuels and the effects of factors influencing these estimates are identified. 47 LCA studies are included in the database, providing 593 estimates. Life cycle GHG emissions of G3 biofuels are statistically higher than those of Ethanol which, in turn, are higher than those of BtL.

G2 Ethanol is obtained from the biochemical conversion of lignocellulosic biomass and synthetic diesel from biomass and is produced by the thermochemical conversion of lignocellulosic biomass.

It has been decided to review only the literature of LCA studies assessing Global Warming impact indicators for the following reasons:

- To reduce global GHG emissions (in order to mitigate the climate change) is one of the most important objectives for developing biofuels.
- There is a significant literature about GHG emissions of advanced biofuel using the LCA approach.

Primary, study results remain difficult to compare because of differences in technical data or methodological choices. Consequently, it is quite challenging to attempt any summary and to form an accurate opinion on this topic using classical literature review methods. In particular, it seems hard to provide one GHG emission estimation appropriate for advanced biofuels. Therefore, there is a strong need for harmonization of LCA results.

Mentel et al. (2013) proposes an alternative summary to previous literature reviews methodology to describe and synthesize existing estimates of the LCA GHG emissions of advanced biofuels (Table 2).

Table 2. Harmonized emissions (g CO_2eq/MJ) (*Mentel et al., 2013*).

Harmonized GHG emissions			**95% Confidence interval**	
			Min	Max
Europe	G3	76.27	49.54	103.00
	G2 Ethanol	34.88	31.45	38.31
	G2 BtL	24.15	20.46	27.84
North America	G3	51.67	27.47	75.88
	G2 Ethanol	10.29	4.45	16.13
	G2 BtL	-0.44	-7.31	6.42
Simple predicted value	Mean	28.64	25.19	32.09

The results indicate a hierarchy between G3 and G2 biofuels: GHG emissions of G3 biofuels are statistically higher than those of Ethanol, which, in turn, are higher than those of BtL. Concerning G2 biofuels, the mass yield has a negative and non-linear effect for both Ethanol and BtL, whereas the type of process has a statistically significant effect only for BtL. The type of biomass pretreatment in the ethanol conversion process is probably not statistically significant because most of the Ethanol studies in this literature review use data from one single study. For each type of biofuel, a mean value of life cycle GHG emissions (expressed in g CO_2eq/MJ of biofuel) weighted by the influence of its main drivers and its corresponding Confidence intervals provided.

Pressley et al. (2014) used LCA methodology to evaluate the conversion of U.S. municipal solid waste (MSW) to liquid transportation fuels via gasification and Fischer-Tropsch (FT). The model estimates the cumulative energy demand and global warming potential associated with the conversion of 1 ton of MSW. The model estimates that 1 ton of MSW entering the refuse-derived fuel (RDF) facility yields 123 L of gasoline, 57 L of diesel, 79 kg of other FT products, and 193 kWh (694.8 GJ) of gross electricity production. For each ton of MSW, the conversion process consumes 4.4 GJ of primary energy while creating fuels and electricity with a cumulative energy content of 10.8 GJ. The liquid fuels produced by gasification and FT processing resulted in a net GWP ranging from 267 to 144 kg CO_2eq per ton of MSW, including offsets for conventional electricity and fuel production. In this LCA study, the functional unit was 1 ton of mixed waste delivered to a sorting facility that mechanically sorts incoming MSW to produce a RDF suitable for a gasifier. The following processes are included within the system boundaries. The net GWP found in this system was 205 kg CO_2eq per ton of MSW, as is shown in Figure 4:

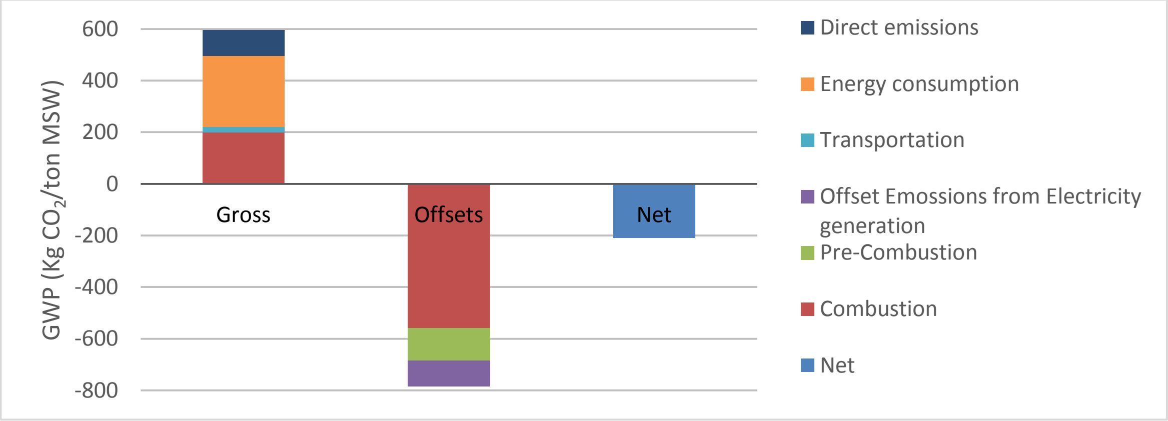

Figure 4. GWP for the MSW conversion processes and the offsets associated with conventional petroleum processing (*Pressley et al., 2014*).

From this study it is obtained a reference range values of **23 to 43 g CO_2eq/MJ** of biofuel generated. The modeled system in Pressley et al. (2014) produces 2.4 (10.8 GJ/4.4 GJ) times as much energy as it consumes.

According to Tonini & Astrup (2012), the impacts from FT-biodiesel were in the range of **65 to 88 g CO_2 eq/MJ** of fuel, depending on assumptions regarding benefits from biochar.

The impacts for AP (in m²) and EP (in g of N) associated with cultivation of willow for FT-biodiesel production (0.768 m^2 and 0.171 g N per MJ of biodiesel produced) was significantly lower than RME[5] (1.497 m^2 and 0.286 g N per MJ of biodiesel produced), due to the higher yield and reduced fertilizer use. This data is considering the cultivation process. FFW concept use waste and residues and therefore no cultivation, neither fertilization shall be considered in the LCA. The same issue occurs with land occupation: the impact of the FT-biodiesel (15.06 m^2/MJ) is 1.4 times lower than RME-biodiesel (20.68 m^2/MJ).

Niederl & Narodoslawsky (2004) presented a comparative LCA analysis of biodiesel made from used vegetable oil and tallow compared to fossil diesel. The functional unit applied was 1 MJ of combustion energy. This LCA study considers the provision of the product biodiesel from tallow (TME – tallow methyl ester) and biodiesel from used vegetable oil (UVO) from raw material extraction to the usage of the finished product (fuel combustion). The production of energy, raw materials and auxiliary materials is included as is the waste disposal and the treatment of liquid and gaseous emissions during all steps of the life cycle. The production and operation of the infrastructure needed in the provision of the function is excluded from the LCA as it has turned out to be of minor influence. The main impact found to climate change is due to process chemicals. The largest factor of the overall footprint (42.5%) comes from the combustion of biodiesel itself causing high emissions of nitrogen oxides. This is reflected in the problem oriented approach with the high contribution of combustion emissions to the acidification, eutrophication and photo-oxidant creation potential of 85.5 %, 94.8 % and 88.5 %, respectively. On the other hand, 22% of the total ecological footprint can be contributed to chemicals used during transesterification. For the provision of process energy and for transport the depletion of abiotic resources is the predominant impact category. In the case of biodiesel from used vegetable oil the ecological footprint is even shifted to a negative value from 4.8 m²a to -1.2 m²a per MJ combustion energy (*Niederl & Narodoslawsky, 2004*).

Börjesson et al. (2010) carried out and developed a life cycle assessments of biofuels produced and used in Sweden today. For this purpose, the functional unit used was the environmental impact per MJ of fuel. One advantage of this functional unit is that differences in fuel efficiency of different vehicles are also included and considered. The results regarding energy balance and climate benefit are additionally presented per hectare for fuels based on crops in order to reflect the area efficiency and land use. It is not possible to obtain data of exactly the same character for the various fuel systems since there are inherent differences in, for example, scale-size and number of units. In this paper the system boundaries were the length of the life cycle consists of the cultivation of the raw material (or alternatively the collection and handling of the waste product), the transportation of the raw material to the fuel plant, the production of the fuel and its end-use in vehicles (excluding the fuel distribution). However, the relevance of the energy input and emissions from the building of infrastructure for local biogas grids is assessed, for example, for linking production facilities to a common facility for upgrading. The transportation of sugar cane ethanol from Brazil to a Swedish port is included. Buildings and other infrastructure are not included.

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[5] Rapeseed methyl ester.

Souza & Seabra (2014) performed a stochastic evaluation of the environmental and economic implications of the integrated production of sugarcane bioethanol and soybean biodiesel, in comparison with the traditional sugarcane-to-ethanol process. The functional unit was defined as 1 MJ of ethanol and the system boundaries were: the fossil energy uses and the GHG emissions were evaluated in a cradle-to-gate approach, comprising the sugarcane cultivation up to ethanol processing. Fossil energy use is expressed by the ratio between the fossil energy invested to produce the biofuel, and the bioenergy produced. Over 30% of the life cycle burden associated with GHG emissions comes from the residues, including straw decomposition, vinasse, filter cake, boiler ash, soot and bagasse burning. Nitrogen use, which includes its production and use (direct and indirect emissions from the soil) is responsible for 27% of the total emissions in the traditional system, followed by limestone, which represents 12%. The biodiesel produced in the sugarcane–soybean integrated system is able to replace 38% of the diesel consumed in the sugarcane ethanol life cycle. For the GHG emissions, the Monte Carlo (MC) analysis indicates that the sugarcane–soybean integrated system can reduce the ethanol life cycle emissions from 23.4 to 22.9 g CO_2eq/MJ when compared to the traditional system. The emissions of N_2O from the managed soil, which include direct and indirect emissions, are responsible for 95% of the variance in the MC analysis.

Other works have studied similar approaches to Souza & Seabra (2014). A study reported that a switchgrass biorefinery system producing bioenergy, bioethanol and chemicals can save 79% of GHG emission and 80% of fossil energy, compared to the fossil reference system. For evaluate the environmental impact of the entire production chain of fuels made from biomass and used in Switzerland, Zah et al. (2007) carries on an LCA of various biofuels. The environmental LCA was done using two different methods: one was the Swiss method of ecological scarcity (Environmental Impact Points, UBP 06), which evaluates the difference between environmental impacts and legal limits. The other method is the European Eco-indicator 99, which quantifies the damage done to human health and ecosystems and choosing as functional unit a certain quantity of biogenic energy carrier (for instance, 1 kg of whey). Figure 5 provides a chart of how greenhouse gas emissions (GHG emissions) are distributed along various production chains for bioethanol, biodiesel, methanol and methane. The results showed that savings of up to 80% are possible as compared with fossil fuels depending on the biofuel and production path. However, there are large differences according to the production chain (*Zah et al., 2007*).

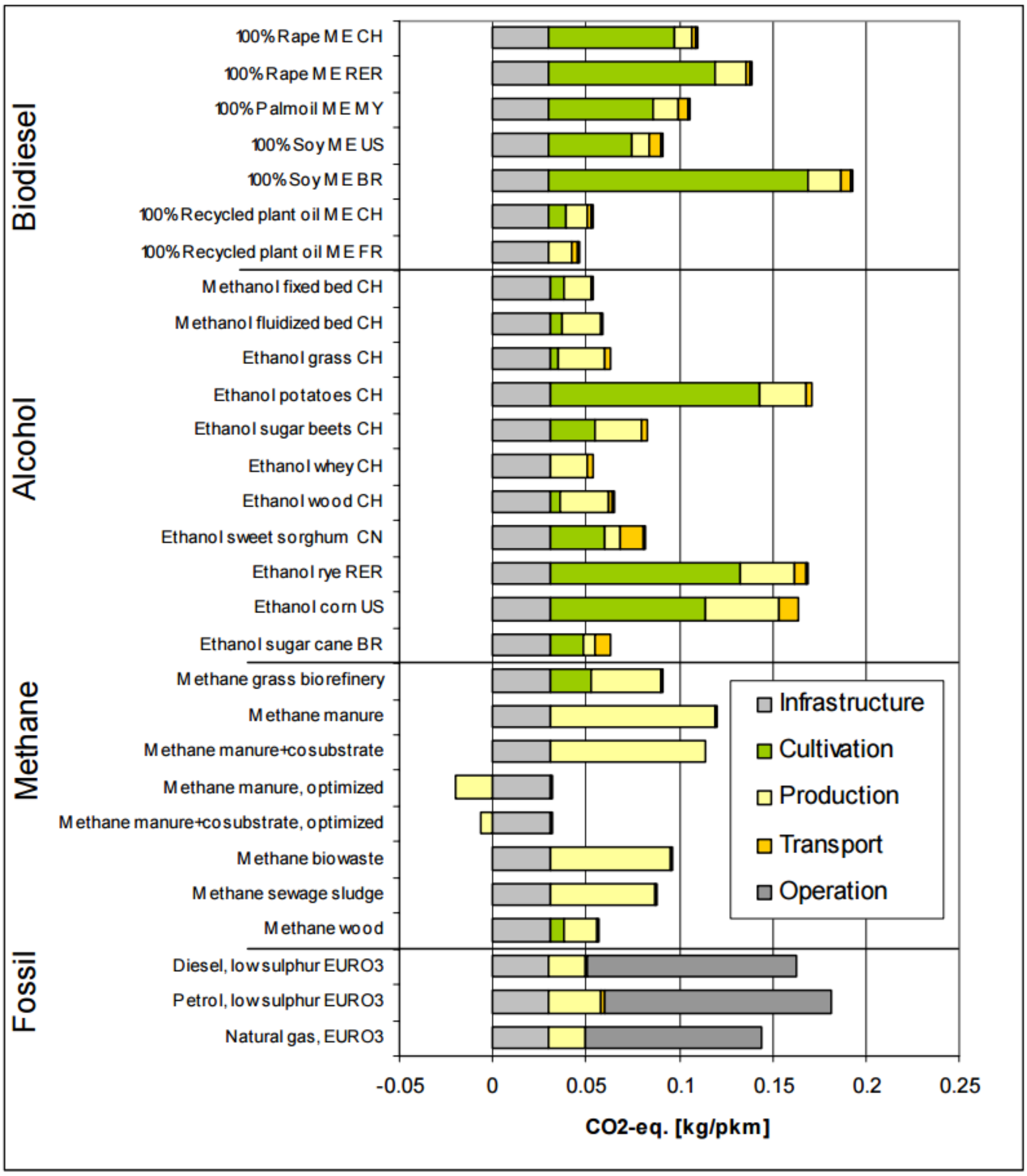


Figure 5. Comparison of the greenhouse gases emitted by biofuels in comparison to those emitted by fossil fuels (*Zah et al., 2007*).

Zhen (2013) uses the Life Cycle Assessment (LCA) to determine the environmental outcomes of biodiesel from waste cooking oil (WCO) in terms of global warming potential, life cycle energy efficiency (LCEE) and fossil energy ratio (FER) using the life cycle inventory. The finding of this study is the biodiesel production process is sustainable that compared to the fossil diesel process and exhaust tailpipe emission. The functional unit is the production of 1000 kg of biodiesel based on a process plant with a capacity of 45 ML biodiesel annually. The key data for the quantification of inputs (chemicals, water, electric and thermal energy demands, etc.) and outputs (products, by-products and wastes, etc.) in the process were derived from current literature in basis of simulator ASPEN Plus on biodiesel production from waste oil.

In terms of bio-oil production via fast pyrolysis, Peters et al. (2014) studied different alternatives of bio-oil use through LCA perspective. The goal of this study is to estimate and compare the environmental impacts that can be avoided by different uses of bio-oil from fast pyrolysis for bioenergy purposes. The functional unit was defined as 2.7 kg of “as-delivered” (50% moisture content) hybrid poplar biomass, i.e., 1 kg of bio-oil. The system boundaries included feedstock production, the production of all utilities (fuel, water, electricity, etc.), and all steps up to the end user. Required machinery, equipment, and buildings are not included in the assessment. Production is supposed to be located in Spain, and therefore, all secondary data (electricity mix, fossil fuel origin, domestic heat production, etc.) are specific for Spain as far as available. The cogeneration option shows the highest non-renewable energy saving potential, followed by co-combustion, decentralized biorefinery (BR-d), and integrated biorefinery (BR-i). The least favourable value is found for the BR-i option, although the values for the two biorefineries are similar. When comparing the BR-d and BR-i options, BR-i shows higher environmental impacts (or lower environmental benefits) in all categories except for ozone layer depletion potential. The two biorefinery options generally score worse than direct combustion.

The literature review revealed that second generation bio-diesel produced from Jatropha and algae indicated strong reduction in GHG emissions. Cherubini et al. (2011) also indicated that bio-diesel produced from residue and second generation raw material have larger GHG savings as against the first generation bio-diesel. Review studies indicated wide GHG emissions for bio-diesel, ranging from 15 to 170 g CO_2eq MJ. Reijnders & Huijbregts (2008) indicated high GHG intensity above 100 g CO_2eq MJ for biodiesel. It is mainly because of the high contribution from C and N_2O emissions from soil.

3 Life cycle Assessment of the FFW technologies

3.1 Goal and scope

The goal of this study is to assess the environmental impact of the FFW technologies for the production of synthetic natural gas, methane and biodiesel. The results of the study will highlight the more affecting stages of the overall system and identify the possible reduction of the environmental impacts.

The goal and scope of the study were previously stated in the *Deliverable 6.1 LCA scope and analyzed system boundaries*. The system boundaries were defined to follow a *gate-to-gate* approach: the main processes of the biodiesel and methane production are covered by the scope, from the transformation of the biomass into synthetic natural gas, and from the transformation of this SNG into final valuable products.

The impact assessment was focused on tree main areas: global warming, energy consumption and water use. Therefore, the selected impact categories were Global Warming Potential (GWP100), Abiotic depletion (fossil fuels), Fresh water aquatic ecotoxicity, Acidification and Eutrophication, following the CML-IA Baseline methodology by the software SimaPro 8.0.2.

The allocation definition was not determined in the previous report (D6.1). A part of the olive cultivation and the olive oil production impact could be allocated to the biomass used in the FFW processes. On the other hand, this biomass is considered as a residue from both olive cultivation and oil production. Olives' residues could be used as fertilizers or valorized by incineration. These applications were not chosen on purpose (the biomass is not produce for energetic combustion, for instance), thus it seem more logical to consider the biomass as an unevaluable residue (the economic value of the biomass is quite low compared to olive oil price).

For the fuel produced, several allocation system are possible. The more commonly used are the energetic content and the economy value (*Iribarren et al., 2013*). The economic option have several drawbacks: the prices are fluctuant daily, with huge fluctuation on a month or a year; there is a significant difference between the producer price and the consumer price due to taxes, margin and other parameters; information sources for prices often require unit conversion. As the energetic content of each product was determined in the Work Package 4, the energetic content allocation was chosen for this analysis.

The functional unit selected in the previous report was the unit of energy released by the combustion of the produced biofuels. As the data were provided for the treatment of one kilogram of biomass, the final results will be adapted to have the impacts of one mega-Joule of product (diesel, methane, naphtha).

In addition to the main analysis, the environmental impacts of the biomass transportation were assessed in the study in order to evaluate their contribution compared to the production impacts. By considering this transportation stage, the study can be extend to a *cradle-to-gate* approach, since the biomass was considered as a waste without dedicated impacts due to the cultivation.

3.2 Data collection and Life Cycle Inventory

The life cycle assessment was based on the simulations data provided by Exergy in the Work Packages 3, relative to "Chemical pretreatment technology" and WP4 on "Development of technological solutions for SNG-diesel production". In the same line, data calculate for the physical pretreatment of the biomass made in the Work Package 2 was considered.

As it was concluded in Deliverable 2.1, Italy is probably the most suitable location for the development of the FFW technologies for its high biomass production potential, its expertise in olive oil production and the availability of regional infrastructures for transportation. Therefore, the Life Cycle Inventory include specific Italian data as much as possible.

The EcoInvent database was preferred as much as possible to ensure a uniformity of the data and a rather good correspondence to the geographical context. However, a few information were not available in this database nor in other similar sources, then, the closest data were used. For instance, the waxes produced and used in the processes were simulated as "paraffin". The membrane feed used in the nitrogen removal process, made in polyaramide (aromatic polyamide) was simulated as simple polyamide fibers membrane.

For the steam generation, the distinction between the low, medium and high pressure was not possible with the available information. It was considered that the production of steam has higher impacts at high pressure. On another hand, it was tested in the software that the steam production has more impacts using heavy oil fuel as a heating source than using light oil fuel or natural gas. Therefore, the low pressure steam was simulated by steam produced by natural gas, the medium-pressure by light oil fuel and the high-pressure by heavy oil fuel.

Air emission such as off gas and purges were considered to be release directly to the atmosphere. The wastewater was treated in a classical urban wastewater treatment plant corresponding to a medium city.

3.3 Results and discussion

3.3.1 Assessment of the production system

In this section, the overall environmental impacts were evaluated for both the *Base case* and the *Case study*. The impacts were detailed in order to identify which are the highest elementary processes. The two cases were also compared.

3.3.1.1 Base case

The results of the Life Cycle Assessment of 1MJ of energy produced in the *Base case* are presented in the following table (Table 3).

Table 3. Environmental impacts of 1 MJ produced – *Base case.*

Impact category	**Abiotic depletion (fossil fuels)**	**Global warming (GWP100a)**	**Fresh water aquatic ecotox.**	**Acidification**	**Eutrophication**
Unit	*MJ*	*kg CO$_2$ eq*	*kg 1,4-DB eq*	*kg SO$_2$ eq*	*kg PO$_4$--- eq*
Grinding	4,011E-02	2,917E-03	5,196E-05	1,119E-05	8,435E-07
Mixing	2,006E-02	1,411E-03	2,598E-05	5,593E-06	4,218E-07
Pelletizing	5,014E-02	7,399E-03	6,495E-05	1,398E-05	1,054E-06
Pomace residue drying	8,925E-01	9,294E-02	1,156E-03	2,489E-04	1,877E-05
Pruning drying	3,009E-02	2,188E-03	3,897E-05	8,390E-06	6,326E-07
Biomass Gasification Gas	2,249E-05	-3,838E-04	-2,865E-06	-2,640E-05	-6,050E-07
Gas Purification	1,047E+00	1,325E-01	7,061E-02	3,498E-04	3,698E-04
WGS	2,217E-01	-6,824E-04	8,502E-05	5,598E-06	-9,761E-07
CO$_2$ removal - CO enriched	8,833E-02	1,404E-01	1,144E-04	2,463E-05	1,470E-03
Gas Compression	7,902E-02	-4,507E-03	9,856E-05	1,124E-05	-4,051E-07
N$_2$ removal – H$_2$ enriched	7,243E-04	4,061E-01	5,002E-04	1,326E-03	1,102E-02
Fischer-Tropsch	-1,109E-02	-1,480E-02	-2,044E-05	-1,887E-05	-3,315E-06
Naphtha FT Separation	2,579E-03	7,578E-06	2,962E-06	1,633E-06	1,771E-05
Diesel ATM FT Separation	2,839E-03	8,339E-06	3,259E-06	1,797E-06	1,949E-05
Diesel VAC FT Separation	1,532E-04	4,501E-07	1,759E-07	9,697E-08	1,052E-06
Naphtha hydrocracking	1,857E-04	3,068E-03	8,952E-06	1,070E-04	1,418E-06
Diesel hydrocracking	1,644E-04	2,717E-03	7,926E-06	9,470E-05	1,255E-06
Methanation	1,747E-03	-1,179E-02	-5,671E-06	-6,034E-05	-2,606E-06
Methane product (upgrading)	1,922E-02	1,784E-03	2,497E-05	5,771E-06	3,330E-02
Total	**2,486E+00**	**7,612E-01**	**7,276E-02**	**2,110E-03**	**4,621E-02**

As shown in Figure 6, the chemical pretreatment of the biomass is the main contribution to the abiotic depletion of fossil fuel (57.8%), global warming potential (88.5%), fresh water ecotoxicity (98.1%) and acidification (80.1%). The physical pretreatment of the biomass has contribution superior to 41% in abiotic depletion. It also have a significant contribution for global warming potential (14.0%) and acidification (13.7%). The production processes only has a high contribution on eutrophication (72.1%) and has a positive effect on global warming (-2.5%).

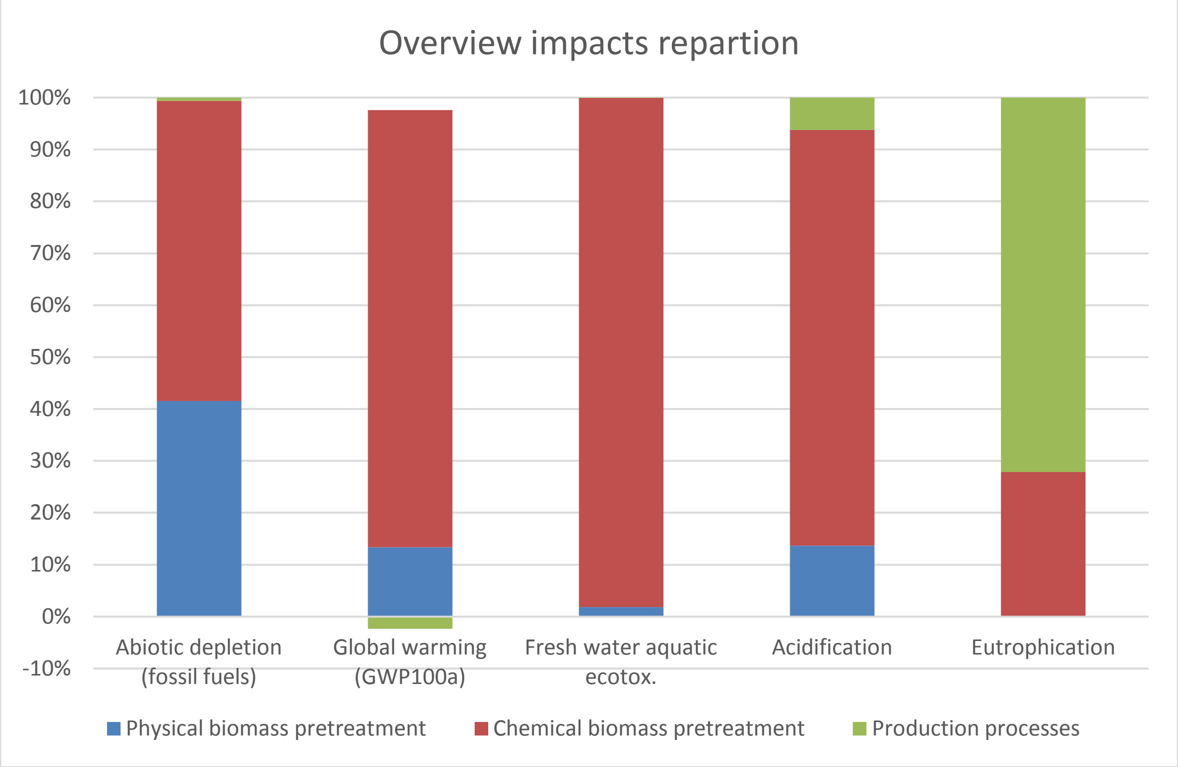


Figure 6. Overview impacts distribution – *Base case.*

Figure 7 provides more information about the contribution of each process on the physical pretreatment impacts. Pomace residue drying was the main contribution in all the impacts categories (between 86.4% and 87.0%), and mixing the lowest (between 1.3% and 1.9%). The other processes have similar contributions in almost all the impact categories.

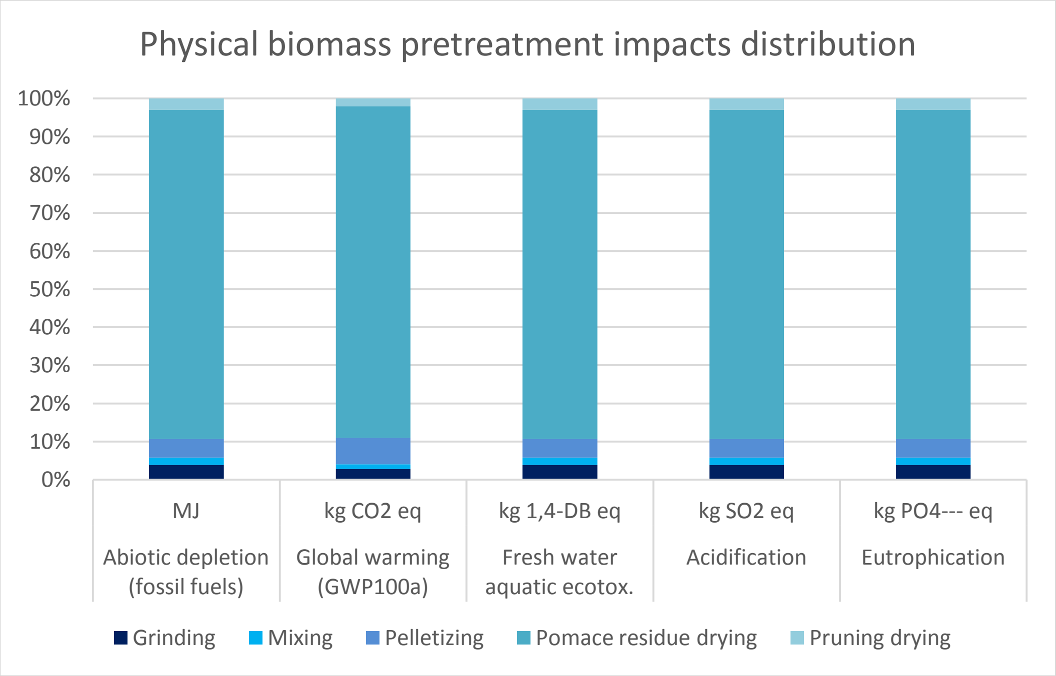


Figure 7. Physical pre-treatment impacts distribution – *Base case.*

The gas purification was the main contribution for abiotic depletion (72.9%) and fresh water ecotoxicity (98.9%). The contribution of this impact was lower for global warming (19.7%) and acidification (20.7%). Nitrogen removal was the most impacting process of the chemical pretreatment for global warming, acidification and eutrophication with a contribution of 60.3%, 78.4% and 85.7%, respectively (Figure 8).

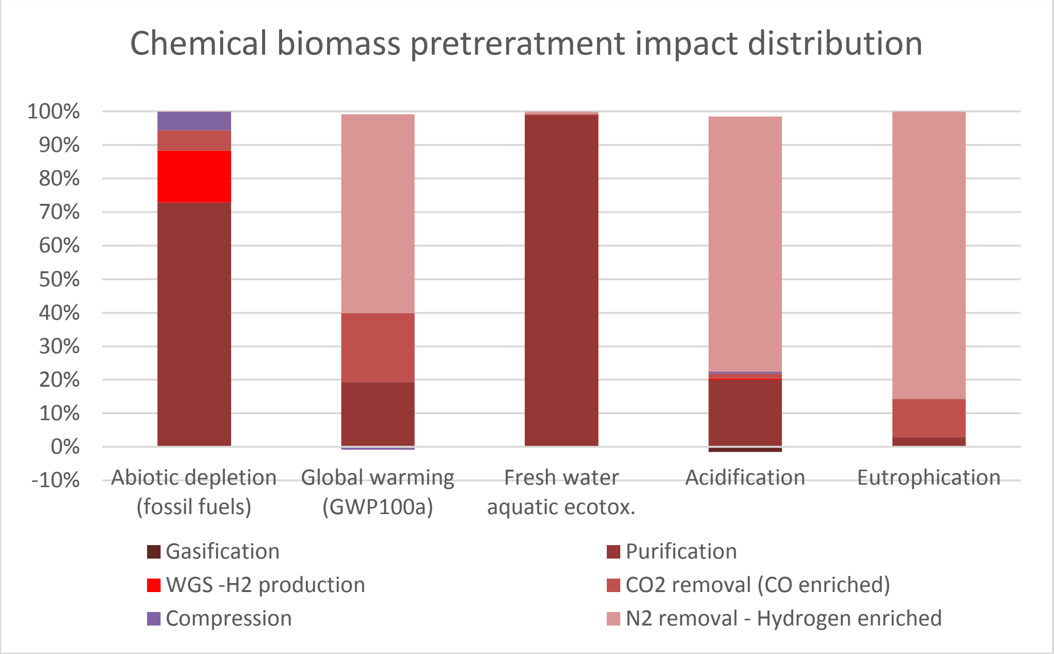


Figure 8. Chemical pre-treatment impacts distribution – *Base case.*

The methane upgrading process has the main contribution in abiotic depletion (50.6%), fresh water aquatic ecotoxicity (33.6%) and eutrophication (99.9%). For global warming, the highest contributions comes from the Fischer-Tropsch process (43.3%) and the methanation (34.5%). All the other processes presented a positive impact in this category. The main contribution for acidification were due to the hydrocracking process and its two products (36.9% for naphtha and 32.6% for diesel) (Figure 9).

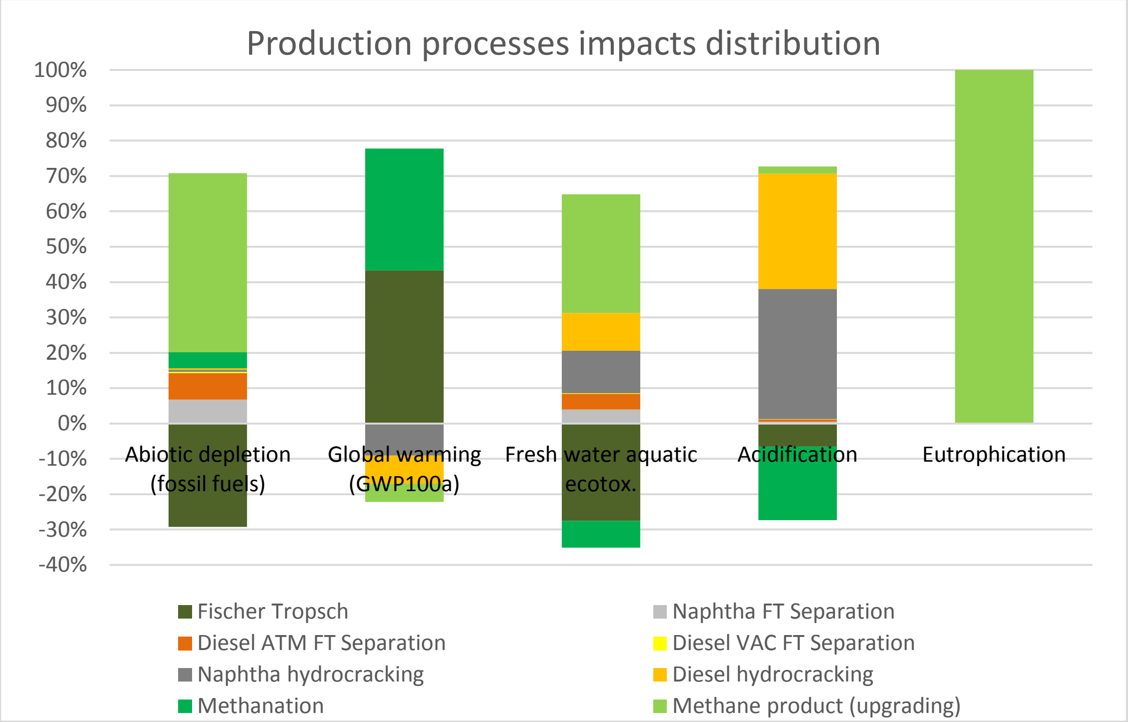


Figure 9. Production processes impacts distribution – *Base case.*

The contributions of each processes in the overall system impacts are reported in the Figure 10. It can be noticed that the purification process has a highest impact on fresh water aquatic ecotoxicity (97.0%) and on abiotic depletion of fossil fuels (42.1%). It also have a substantial contribution to global warming potential (17.4%) and acidification (16.6%). Pomace residue drying was the second main contribution in abiotic depletion potential (35.9%). Almost all the eutrophication potential was due to only two processes: nitrogen removal (23.8%) and methane upgrading (72.0%). The nitrogen removal was also the main contributor for global warming potential (53.3%) and acidification (62.8%).

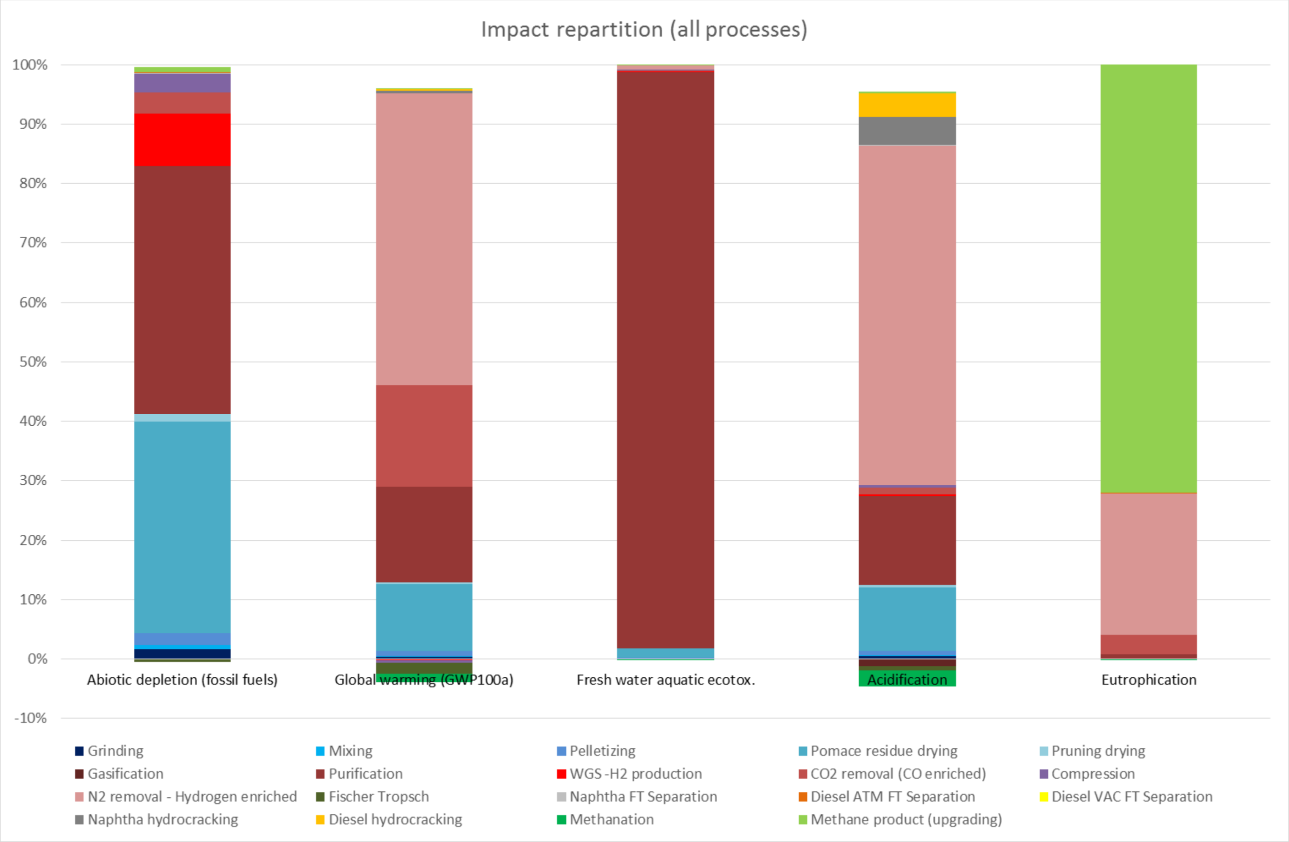


Figure 10. Detailed impacts distribution – *Base case.*

3.3.1.2 Case study

The results of the Life Cycle Assessment of 1 MJ of energy produced in the *Case study* are presented in the following table (Table 4).

Table 4. Impacts 1 MJ produced – *Case study.*

Impact category	**Abiotic depletion (fossil fuels)**	**Global warming (GWP100a)**	**Fresh water aquatic ecotox.**	**Acidification**	**Eutrophication**
Unit	*MJ*	*kg CO_2 eq*	*kg 1,4-DB eq*	*kg SO_2 eq*	*kg PO_4--- eq*
Grinding	4,141E-02	3,011E-03	5,364E-05	1,155E-05	8,708E-07
Mixing	2,071E-02	1,457E-03	2,682E-05	5,774E-06	4,354E-07
Pelletizing	5,177E-02	7,639E-03	6,705E-05	1,444E-05	1,089E-06
Pomace residue drying	9,214E-01	9,595E-02	1,194E-03	2,570E-04	1,938E-05
Pruning drying	3,106E-02	2,258E-03	4,023E-05	8,661E-06	6,531E-07
Oxigen ASU	4,322E-01	2,295E-02	5,588E-04	1,142E-04	7,530E-02
Gasification	6,160E-02	3,745E-03	3,440E-05	-1,053E-05	1,938E-07
Purification	7,788E-01	7,955E-02	3,753E-02	2,419E-04	1,994E-04
WGS - H_2 production	6,496E-01	-1,880E-02	2,254E-04	-7,136E-06	-7,066E-06
CO_2 removal - CO enriched	1,249E-01	1,098E-01	1,619E-04	3,485E-05	3,491E-05

CO_2 removal - Hydrogen enriched	6,162E-03	5,415E-03	7,983E-06	1,719E-06	1,722E-06
Compression	6,010E-02	-4,537E-04	7,610E-05	1,177E-05	3,097E-07
Fischer-Tropsch	-8,570E-03	-1,679E-02	-1,765E-05	-2,023E-05	-3,551E-06
Naphtha FT Separation	2,836E-03	3,099E-05	3,276E-06	1,802E-06	7,949E-06
Diesel ATM Separation	2,697E-03	2,947E-05	3,116E-06	1,714E-06	7,559E-06
Diesel VAC FT Separation	1,436E-04	1,569E-06	1,659E-07	9,128E-08	4,025E-07
Naphtha hydrocracking	1,968E-04	1,373E-02	3,914E-05	4,714E-04	6,286E-06
Diesel hydrocracking	1,687E-04	1,176E-02	3,354E-05	4,040E-04	5,387E-06
Methanation	2,430E-03	-1,300E-02	-6,891E-06	-7,714E-05	-3,207E-06
Methane product (upgrading)	1,810E-02	1,680E-03	2,351E-05	5,435E-06	3,136E-02
Total	**5,982E+00**	**6,593E-01**	**4,369E-02**	**2,258E-03**	**1,070E-01**

As shown in Figure 11, the chemical pretreatment of the biomass is the main contribution to the abiotic depletion of fossil fuel (66.4%), to global warming potential (65.5%), to fresh water ecotoxicity (96.4%) and to eutrophication (99.9%). The physical pretreatment of the biomass has significant contributions for abiotic depletion (33.9%), global warming potential (35.8%) and acidification (20.3%). The production processes only has the main contribution on acidification (53.4%).

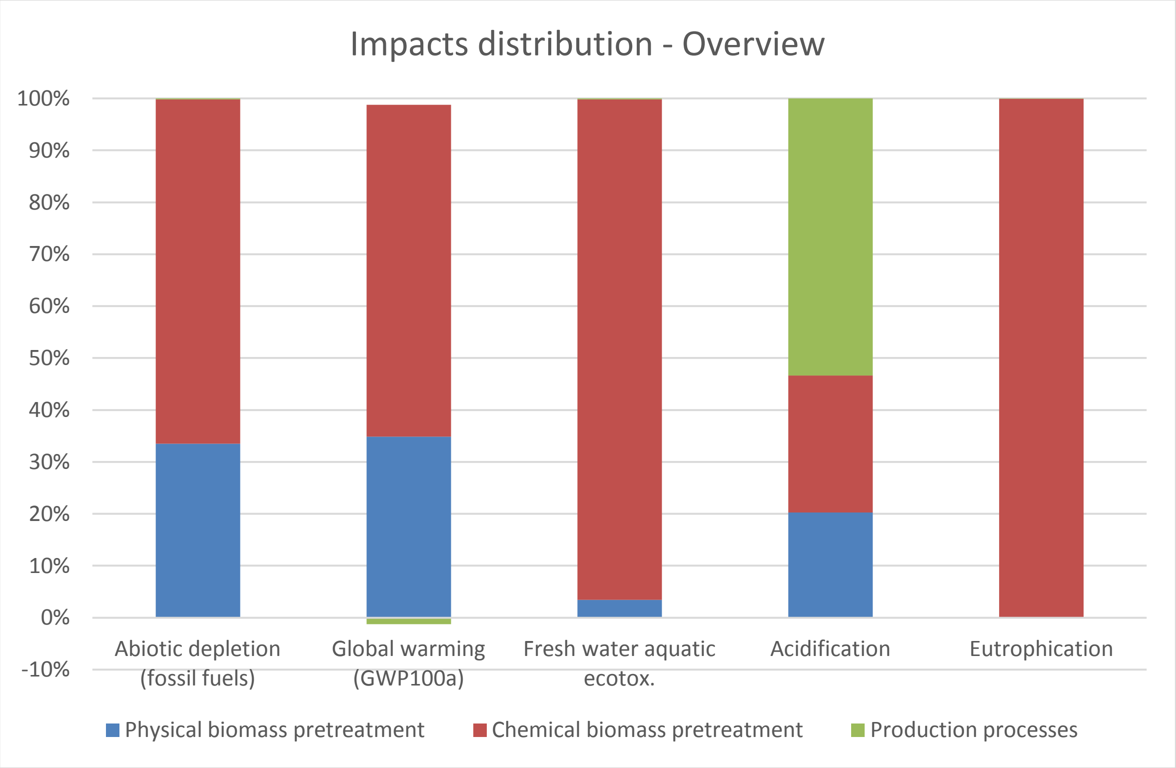


Figure 11. Overview impacts distribution – *Case study.*

The detailed impact distribution of the physical pretreatments' contributions were the same found in the *Case study* and in the *Base case* (See Figure 7).

The purification process was the main contributor to the acidification potential (62.5%), the fresh water aquatic ecotoxicity (97.2%) and the abiotic depletion of fossil fuel (36.9%). This process also have a significant impact on global warming potential (39.3%), such as the

CO_2 removal process (54.3% for CO enriched and 2.7% for H_2 enriched). Eutrophication potential was mainly due to the ASU oxygen production (99.7%), which also have significant impacts in abiotic depletion (20.5%), global warming (11.4%) and acidification potential (29.5%). WGS – H_2 production showed a rather high impact on abiotic depletion (30.7%), however, it also has a positive effect on global warming (-9.3%) and on acidification (-1.9%) (Figure 12).

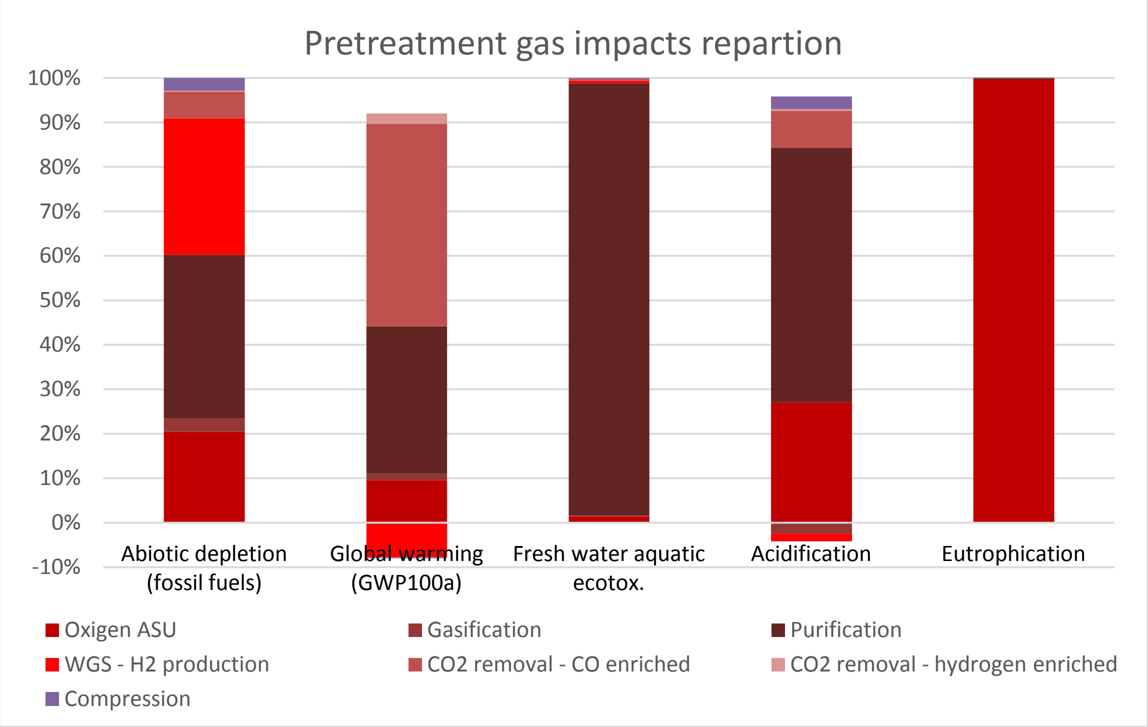


Figure 12. Chemical pre-treatment impacts distribution – *Case study.*

The Fischer-Tropsch process has a positive effect on the overall system, excepted on global warming potential (30.2%). On the contrary, hydrocracking and the FT separation have a positive impact only on global warming, with a more noteworthy contribution from the hydrocracking process. The methanation process has a substantial contribution on abiotic depletion (11.1%) and on global warming potential (23.4%). The methane upgrading process showed a significant impact on the abiotic depletion of fossil fuels (22.2%) (Figure 13).

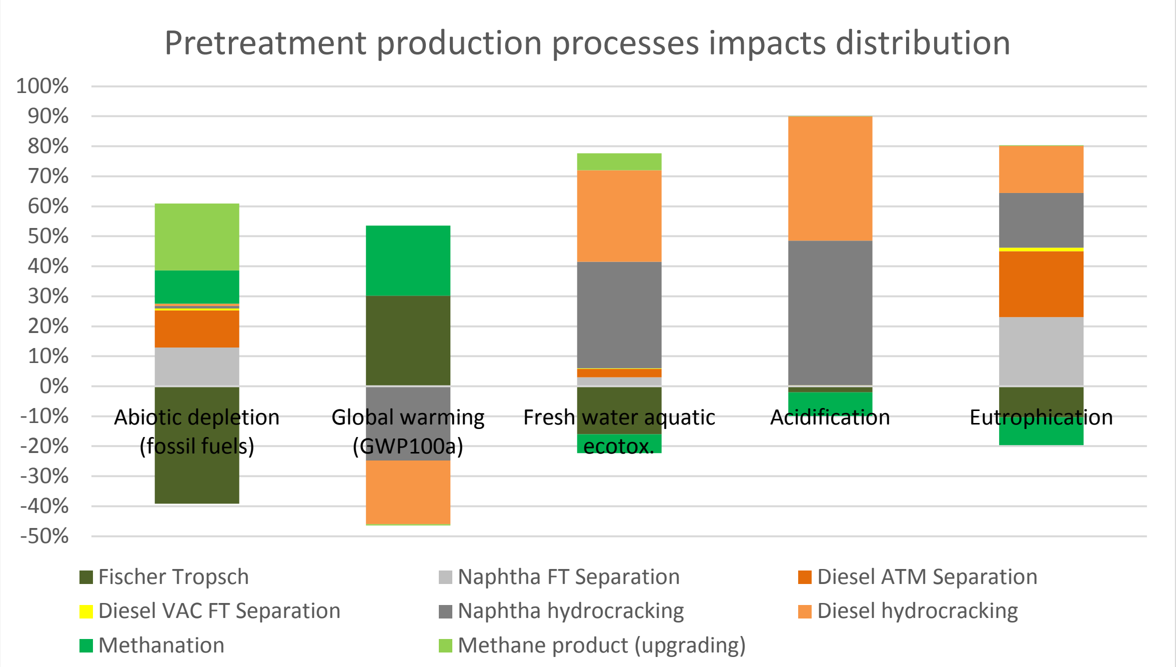


Figure 13. Production processes impacts distribution – *Case study.*

The contributions of each process in the overall system impacts are reported in Figure 14. It can be seen that the purification process has a major impact on fresh water aquatic ecotoxicity (93.7%). It also presented a significant contribution on abiotic depletion (24.5%) and global warming potential (25.8%). Almost all the eutrophication potential was due to Oxygen ASU process (99.6%). Hydrocracking has a significant contribution to the acidification potential (about 60%) and pomace residue drying showed a major contribution on abiotic depletion (28.9%) and global warming potential (31.1%).

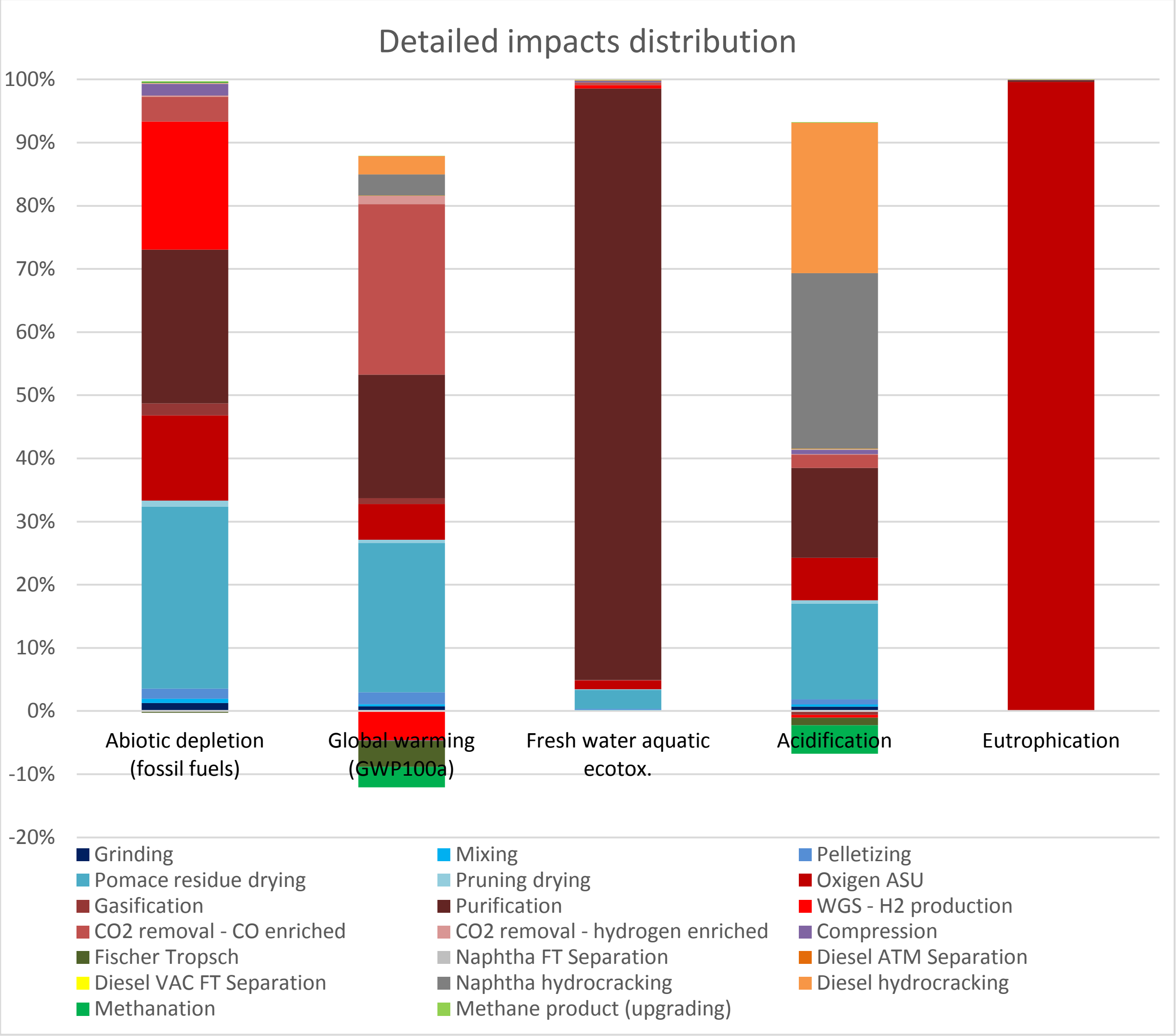


Figure 14. Detailed impacts distribution – *Case study.*

3.3.1.2 Comparison

Table 5 presents the impacts of the production of 1 MJ of energy in the both cases analyzed. As showed in the Figure 15, the *Base case* has higher impacts for global warming (59%), fresh water aquatic ecotoxicity (45%) and acidification (30%). The eutrophication potential was 39% higher for the *Case study* and the abiotic depletion was also slightly higher (22%).

Table 5. Impacts 1 MJ produced – *Base case* vs *Case study.*

Impact category	**Unit**	Base case	Case study
Abiotic depletion (fossil fuels)	MJ	2,486E+00	3,185E+00
Global warming (GWP100a)	kg CO_2 eq	7,612E-01	3,086E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	7,276E-02	4,004E-02
Acidification	kg SO_2 eq	2,110E-03	1,467E-03

Eutrophication	kg PO_4--- eq	4,621E-02	7,557E-02

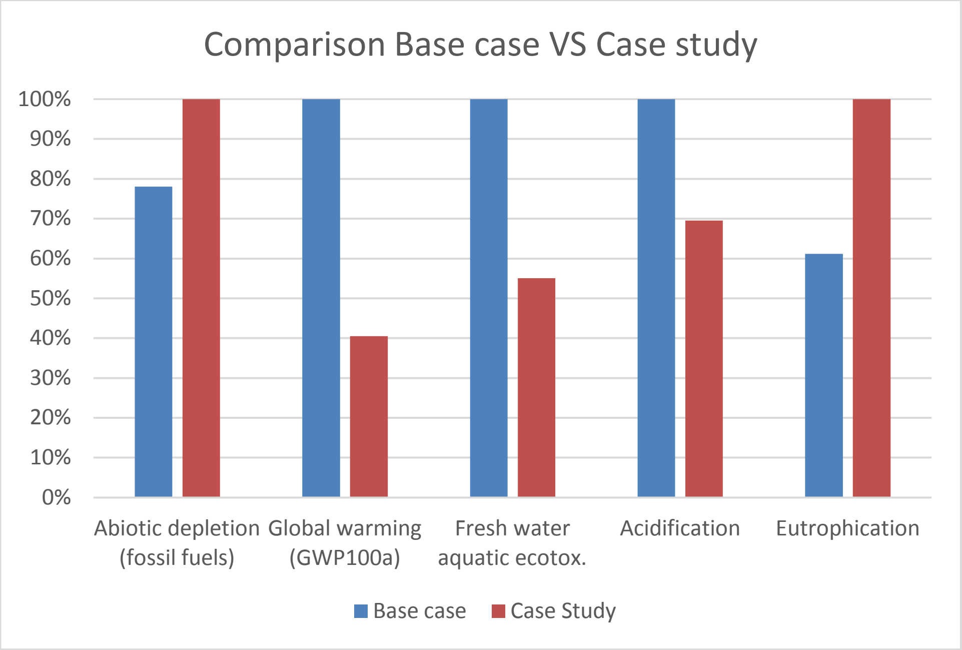
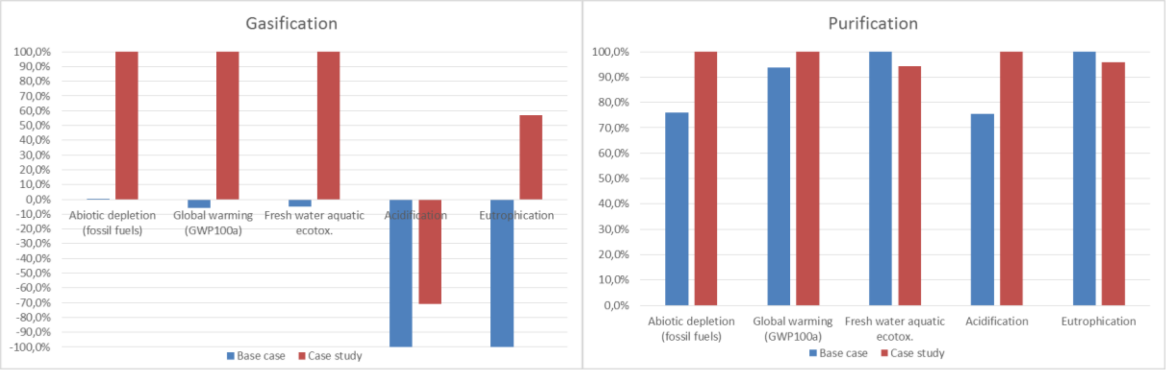


Figure 15. Comparison *Base case* vs *Case study.*

As the energetic production by kilogram of biomass consumed was similar in the two different case, it can be concluded that the environmental sustainability was slightly better for the *Case study* system.

If the *Base case* processes were compared with the same processes in the *Case study* (Figure 16), it can be noticed that in general, the changes made in the *Case study* allow to improve the environmental performances of the processes, especially for WGS, Fischer-Tropch process, methanation and methane upgrading. For a few processes, the *Case study* was not favorable in terms of environmental impacts (gasification, hydrocracking).



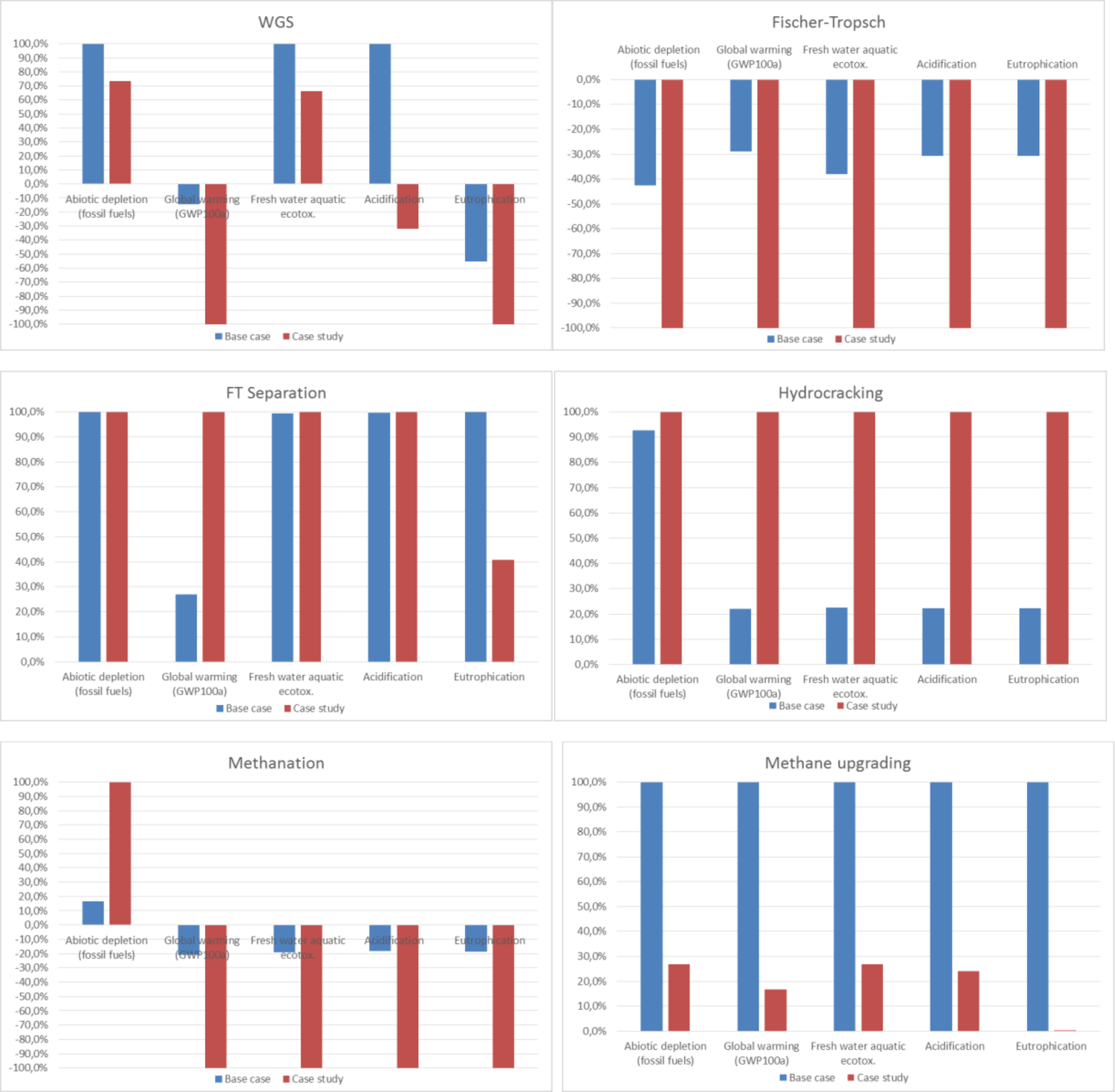


Figure 16. Comparison processes *Base case* vs *Case study.*

3.3.2 Assessment of the elementary processes

This section aims to highlight the materials, energies or emissions responsible of the main environmental impacts of each elementary process. Identification of these key elements will offer some tracks to improve the processes and reduce their impacts.

3.3.2.1 Base case

The environmental impacts of pomace residues drying were mainly due to the electricity consumed by the process and the process emissions, that shows impact only on the global warming potential (33.5%) (Figure 17).

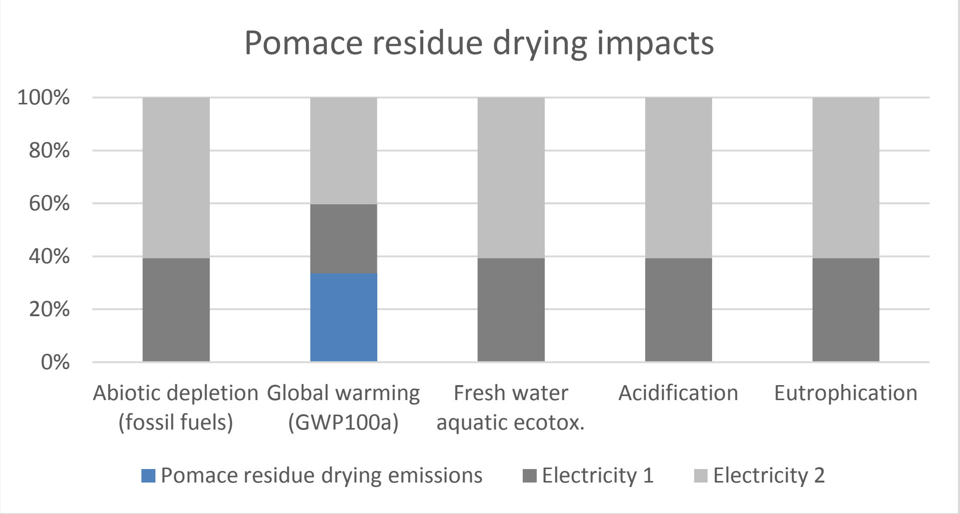


Figure 17. Impacts distribution of pomace residue drying.

The electricity consumption was the main contribution for all the impacts categories. The process emissions have a low contribution (about 5%) for the global warming potential (Figure 18).

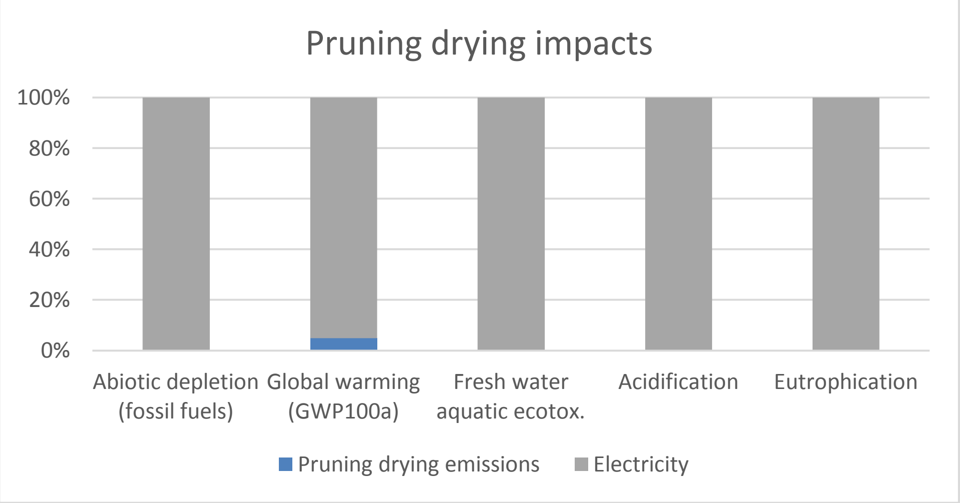


Figure 18. Impacts distribution of pruning drying.

The grinding impacts were mainly due to the electricity consumption of the process (100% in 4 out of 5 categories). For global warming potential, the process emissions have a low contribution (about 5%) (Figure 19).

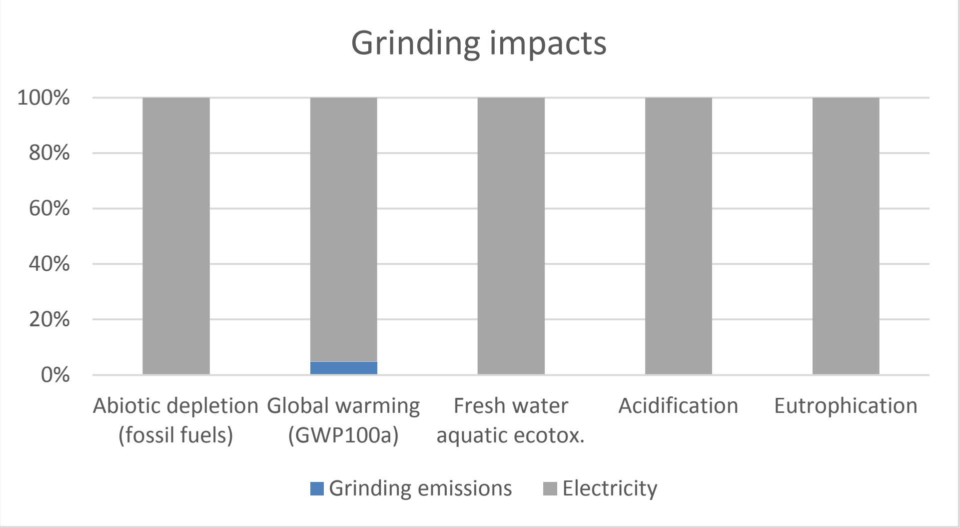


Figure 19. Impacts distribution of grinding.

Figure 20 shows that the mixing impacts were almost totally due to the electricity consumption. Emissions showed a low contribution for global warming potential (1.7%).

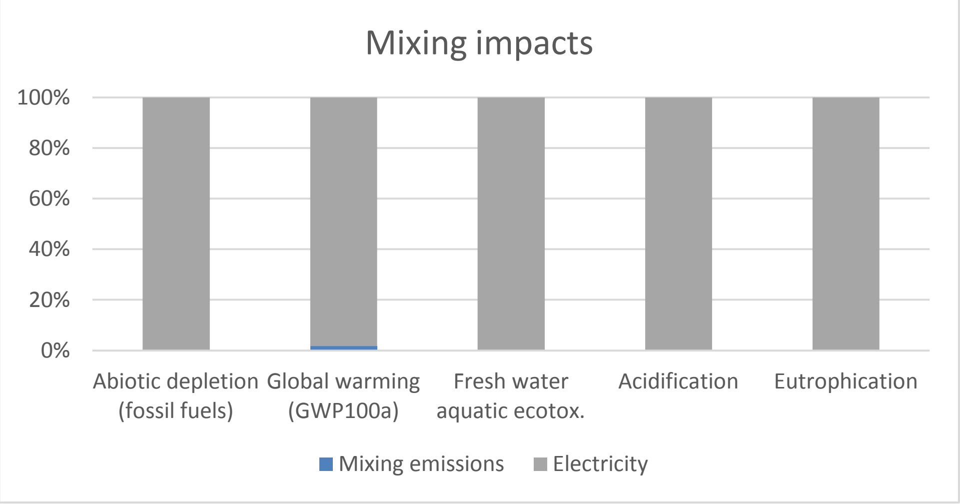


Figure 20. Impacts distribution of mixing.

As it was stated previously, pelletizing process has a significant contribution in the overall process to produce diesel, naphtha and methane, especially in term of abiotic depletion, global warming potential and acidification. Pelletizing impacts were mainly due to the electricity consumption. The process emissions were only responsible of 46.9% of the global warming potential (Figure 21).

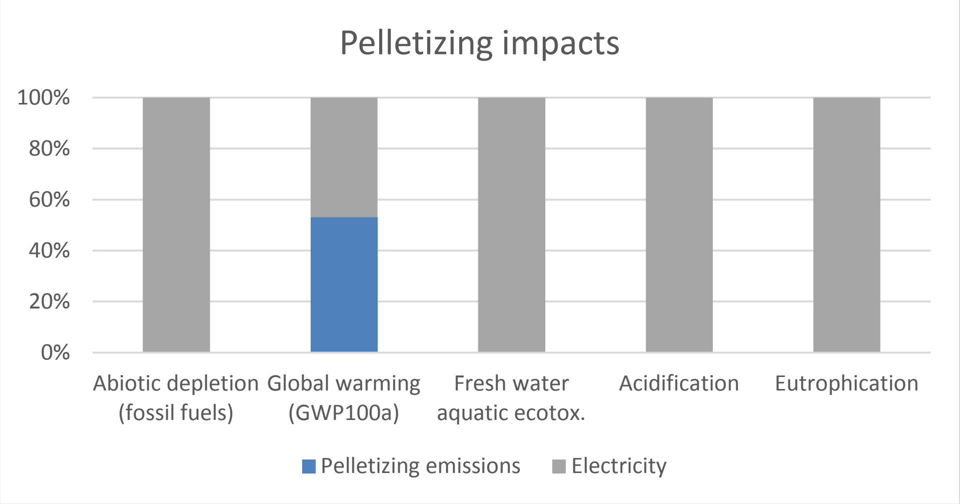


Figure 21. Impacts distribution of pelletizing.

Electricity consumed by the blower has a significant negative contribution in all the impact categories, especially in abiotic depletion of fossil fuel (90.5%). Heaters and the air heater also have negative impacts particularly on the global warming potential. The steam produced by the reactor heat and the cooler allows reducing the impacts of the process (Figure 22).

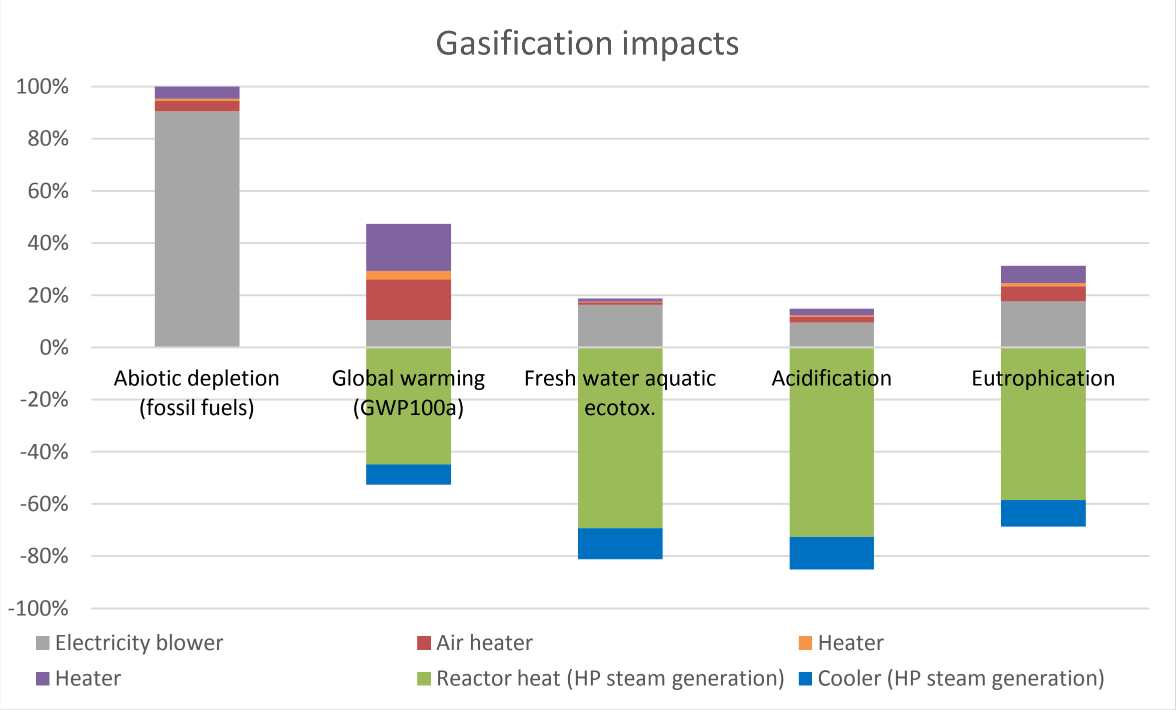


Figure 22. Impacts distribution of gasification – *Base case.*

Figure 23 shows that the consumption of oil has the main contribution to the purification impacts on fresh water aquatic ecotoxicity, acidification potential and eutrophication. It also has a substantial contribution on abiotic depletion (21.5%) and global warming potential (19.3%). The waste oil has also a negative impact on the process, especially on global warming potential (35.3%). The electricity consumed by the two blower and the tar removal compressor has a higher contribution on abiotic depletion, global warming and acidification. The positive effects of the steam generation by the cooler does not compensate enough the others contributions that make the purification process one of the most affecting the overall process.

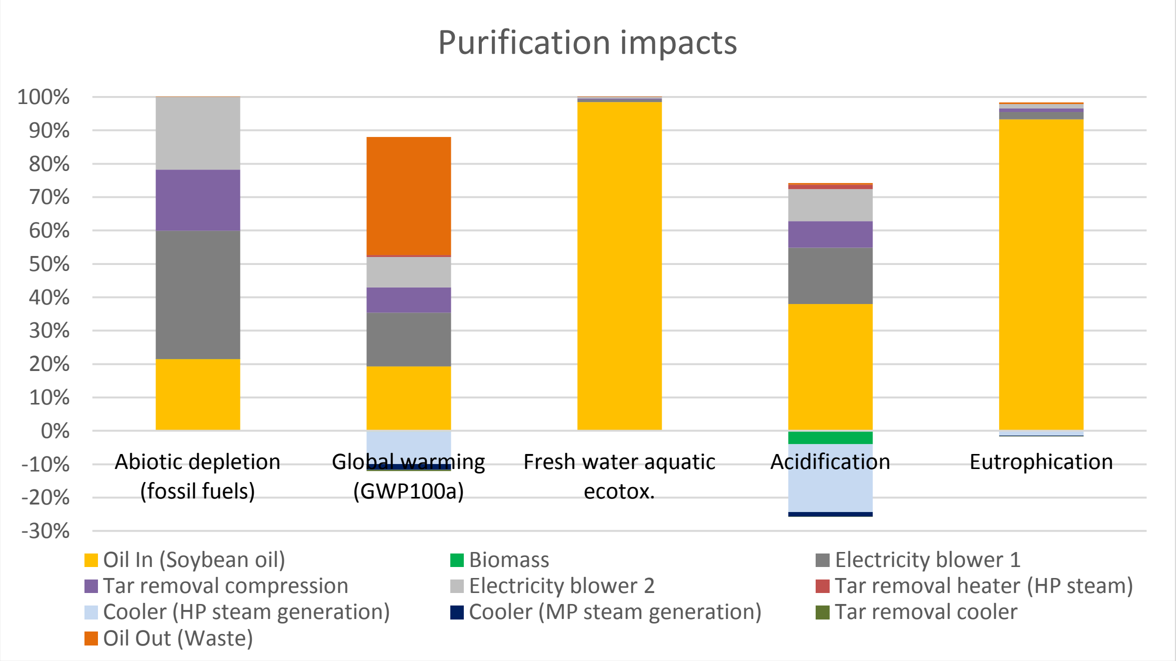


Figure 23. Impacts distribution of purification – *Base case.*

The steam used for the WGS process and the electricity consumed by the blower have the main contribution in almost all the impacts categories, especially on abiotic depletion and fresh water aquatic ecotoxicity. The two cooler that generate MP steam reduce significantly the process impacts, such as the two other cooler to a lesser extent (Figure 24).

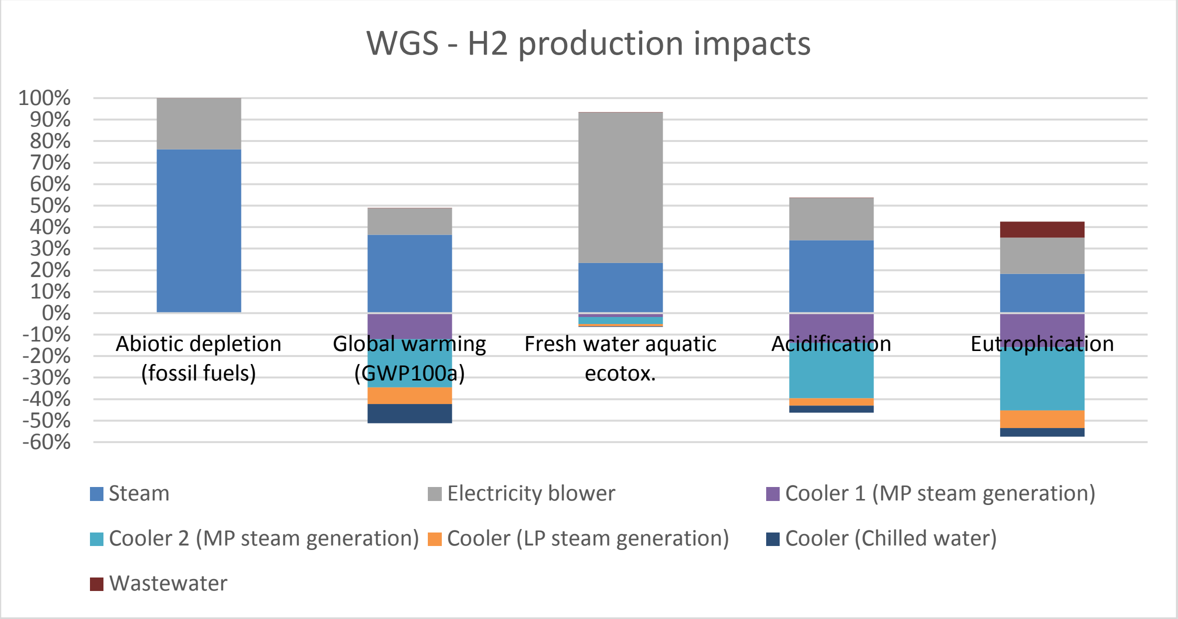


Figure 24. Impacts distribution of hydrogen production (WGS) – *Base case.*

Figure 25 shows clearly the three main contributions to the CO_2 removal process: the gas emissions cause more than 95% of the global warming and eutrophication potential. Abiotic depletion, fresh water aquatic ecotoxicity and acidification were represented by the electricity consumed by the pump (about 75%) and reboiler (about 25%).

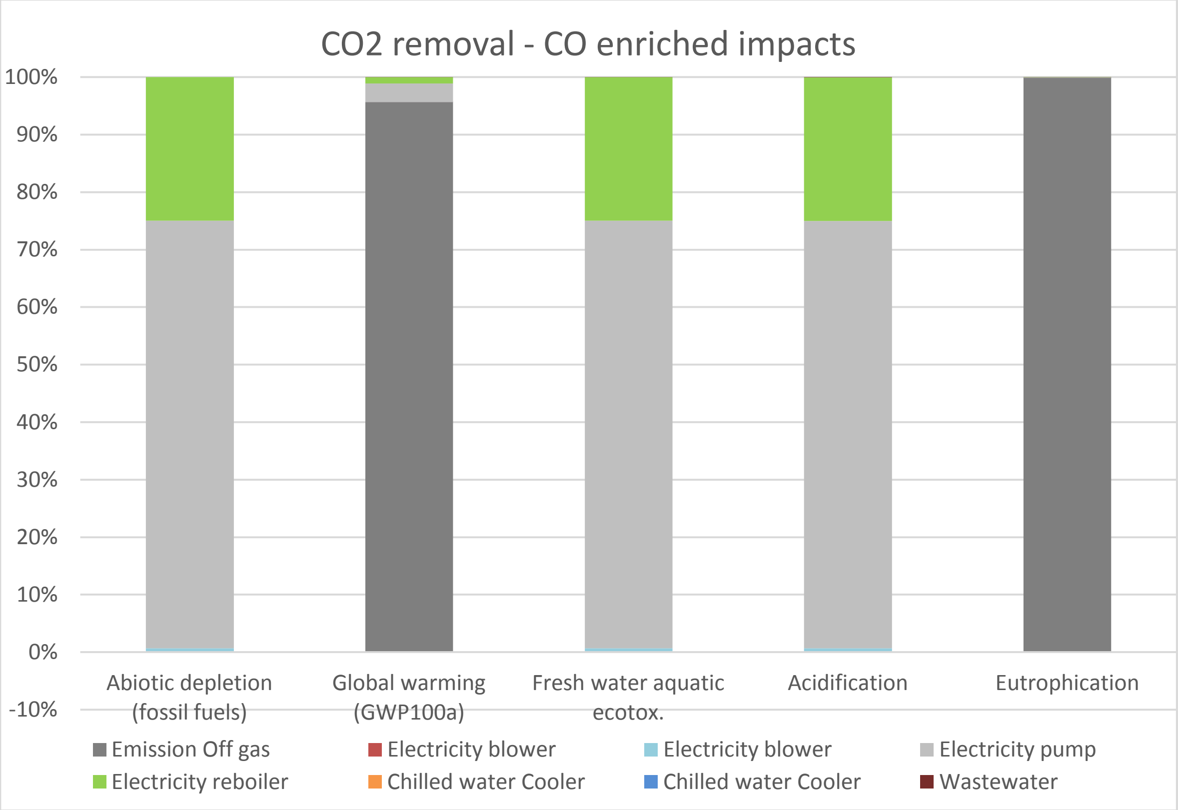


Figure 25. Impacts distribution of CO_2 removal – *Base case.*

The gas compression has a general positive impact on global warming potential and eutrophication due to the generation of LP steam and chilled water by the three coolers. The electricity consumed by the blower was the main contributor in the three other impact categories (Figure 26).

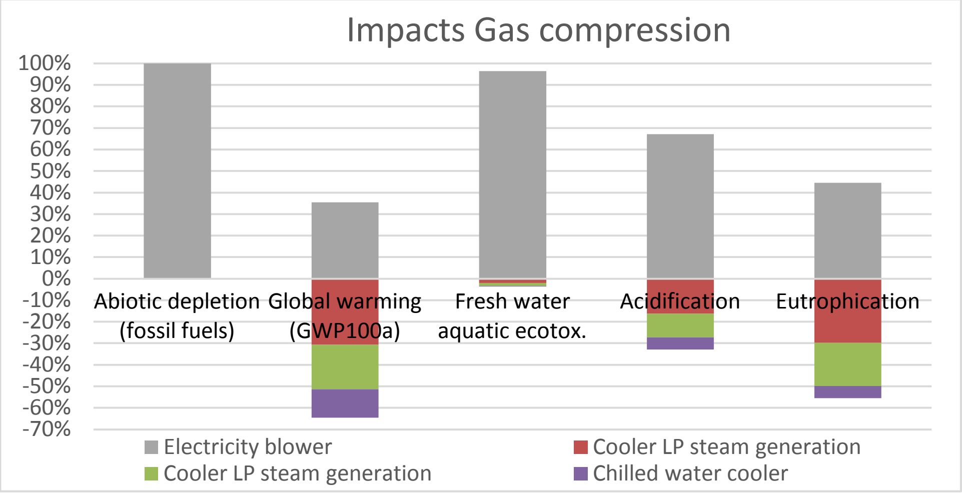


Figure 26. Impacts distribution of compression – *Base case.*

On the other hand, Nitrogen removal has a significant impact on the global warming potential, acidification and eutrophication potential of the overall production system. As presented in Figure 27, global warming potential, fresh water ecotoxicity and acidification were almost totally represented by the membrane feed step. The eutrophication potential was caused by the process emissions, while the electricity consumed by the blower was the main contribution to abiotic deletion of the fossil fuel.

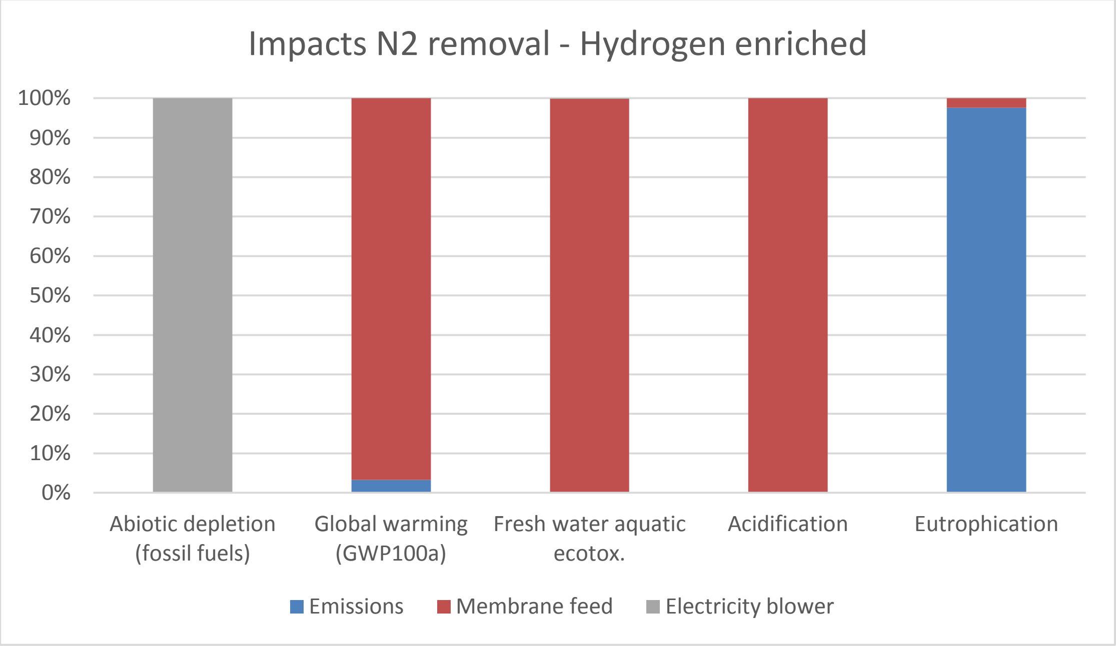


Figure 27. Impacts distribution of N_2 removal – *Base case.*

The Fischer-Tropsch process has a positive environmental impact on the overall process. Wastewater treatment was the only output that have a negative impact and it was significant only for eutrophication potential (6.2%). The electricity produced by the expander offers the main reduction of the abiotic depletion of fossil fuel (-100%) and fresh water aquatic ecotoxicity (-70.3%). The LP steam produce by the cooler and overall by the reactor heat allows the main reduction for the three other impact categories (Figure 28).

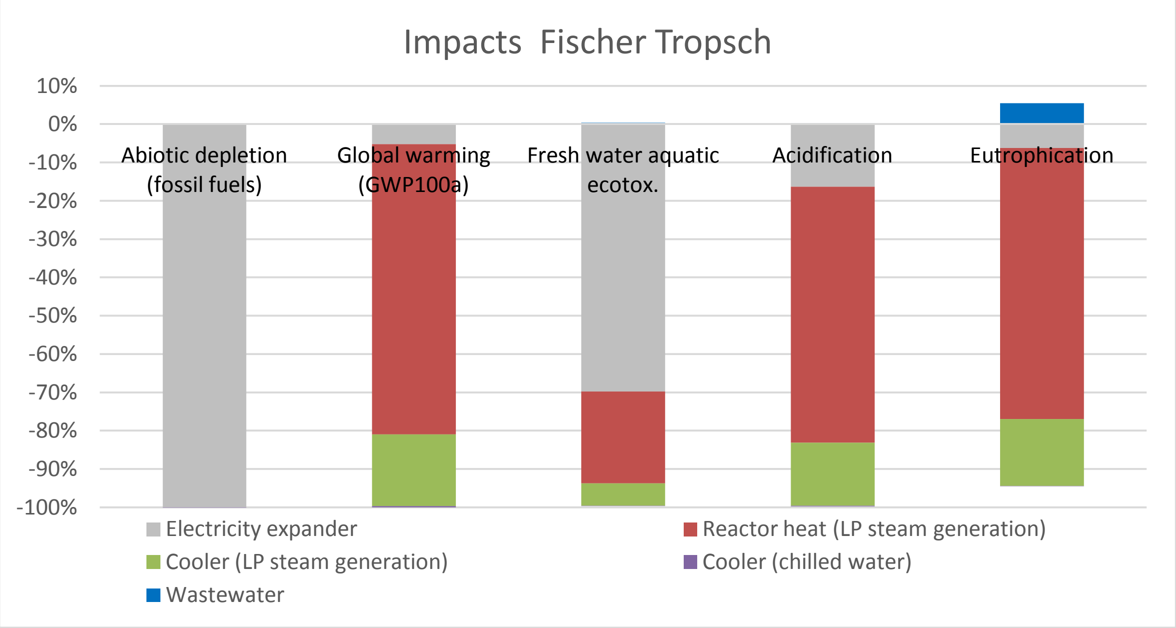


Figure 28. Impacts distribution of Fischer-Tropsch process – *Base case.*

The wastewater treatment was the main contributor to the fresh water aquatic ecotoxicity (75.5%) and the acidification potential (59.7%) of the Fischer-Tropsch separation process. It also showed a significant contribution on eutrophication (38.0%) and global warming potential (12.3%). The steam used in the process has the high impact on abiotic depletion of fossil fuel (76.0%), while the off gas emission causes 61.6% of the eutrophication potential. The positive effect of the chilled water produced by the condenser ATM allows to almost compensate the global warming potential of the wastewater, blower, steam, reboiler vacuum and off gas emission together (Figure 29).

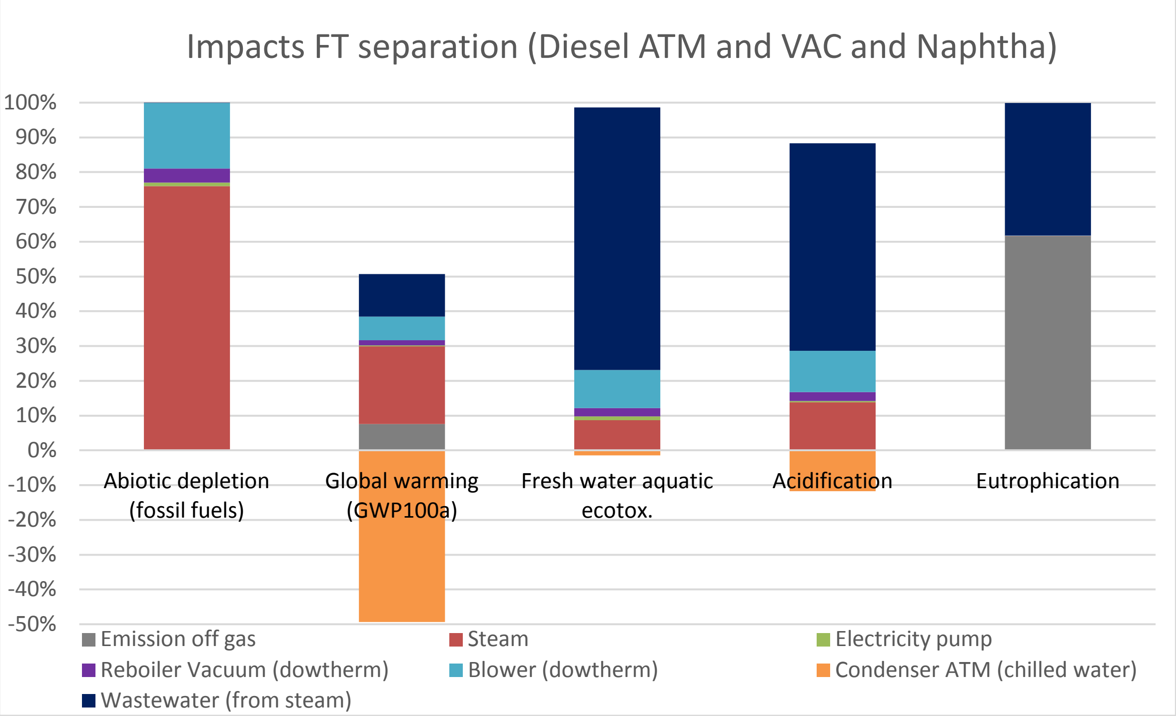


Figure 29. Impacts distribution of Fischer-Tropsch separation – *Base case.*

Figure 30 shows that the preheater was the main contribution to the abiotic depletion of the hydrocracking process. Heater was the main contribution of all the other impacts categories and the LP steam generated by the cooler compensate slightly these impacts (between -9.9% to -43.9%).

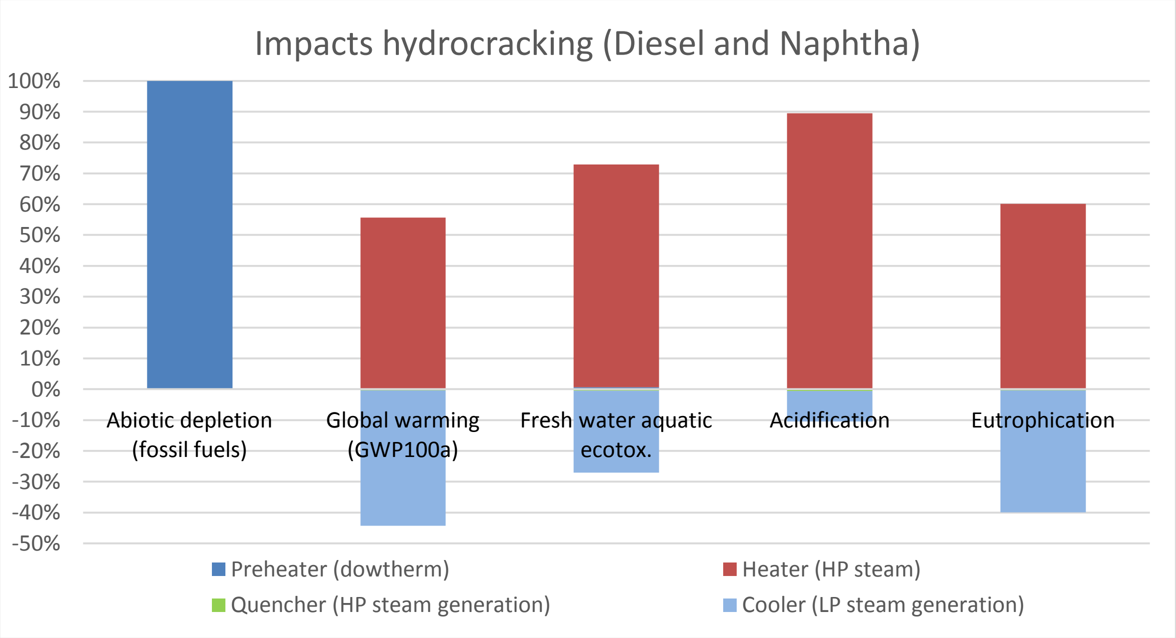


Figure 30. Impacts distribution of hydrocracking – *Base case.*

Methanation process represented a reduction of the environmental impacts in the overall systems, and for all the impacts categories, except for abiotic depletion of fossil fuel. For this category, the electricity consumed by the blower was responsible of 99.5% of the methanation impacts. The main impacts reductions were due to the HP steam generated by the Coolers 1 and 2. Cooler 3 and the vessel showed a lower contribution (Figure 31).

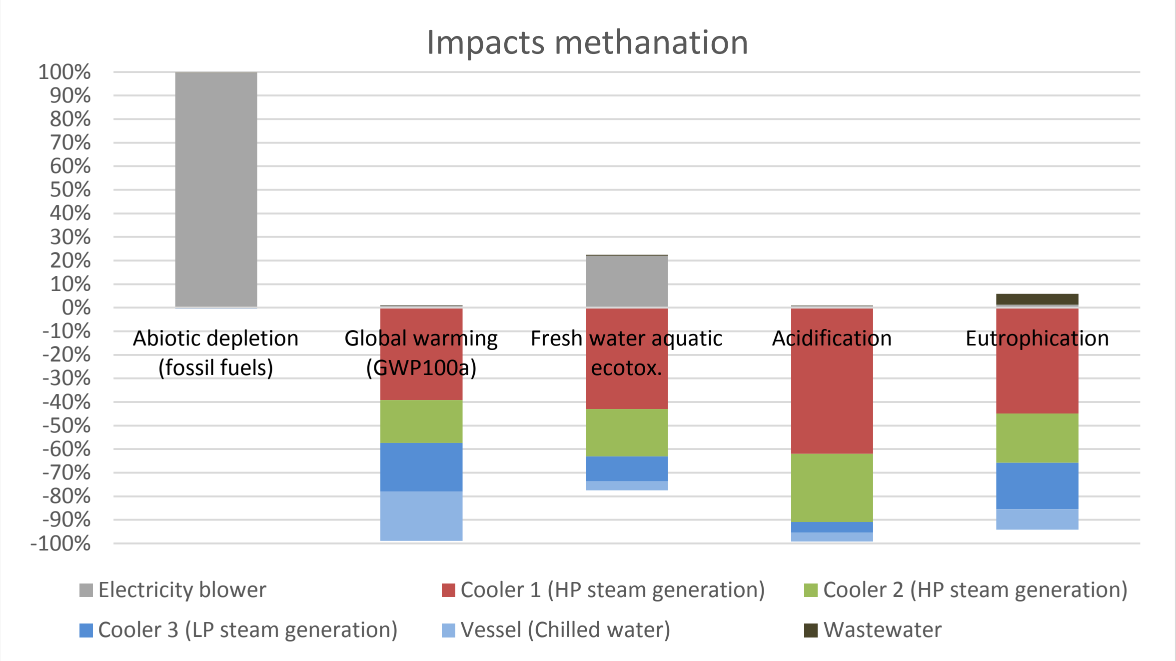


Figure 31. Impacts distribution of methanation – *Base case.*

Methane upgrading process was the main contribution of the eutrophication potential of the full process. Figure 32 shows that this impact was mainly due to the emission of nitrogen. For the rest impact categories, the electricity consumed by the blower 1 contribute to more than 70% of the impacts, while a lower part was due to the cooler.

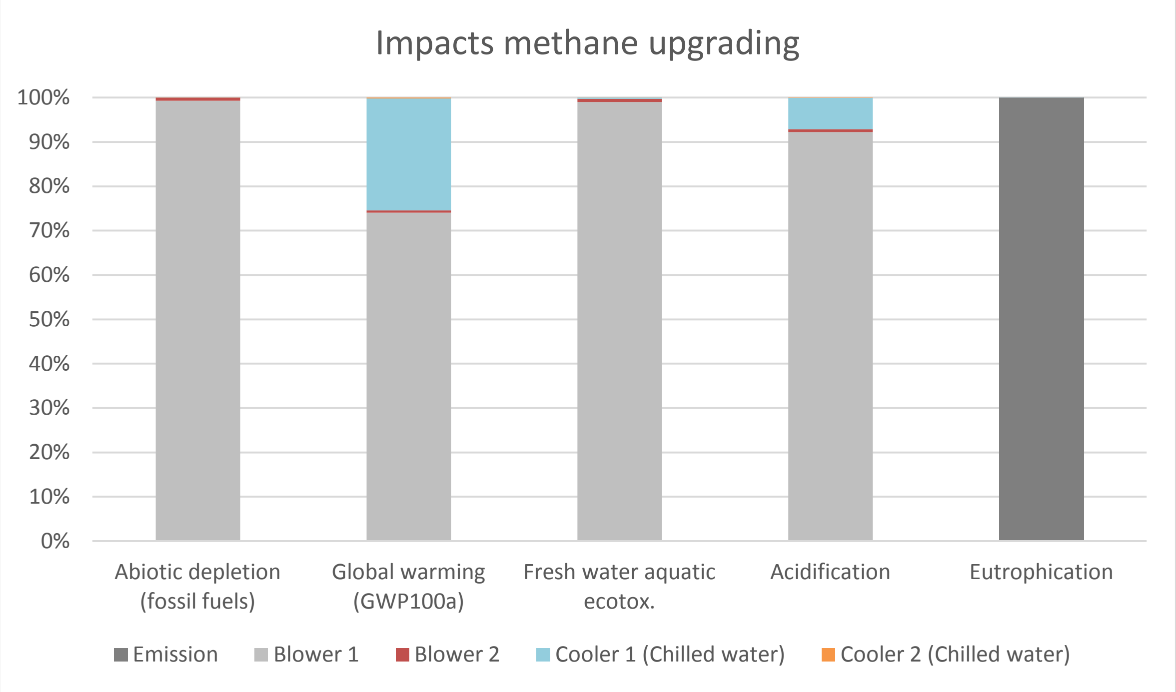


Figure 32. Impacts distribution of methane upgrading – *Base case.*

3.3.2.2 Case study

The physical pretreatment was the same for both cases and the impacts distribution was already presented in this document. For this reason, only the rest of the system processes will be presented for the *Case Study* scenario.

The electricity consumed by the blower was the main contribution of the ASU process. The only exception was for the eutrophication potential, which almost totally was represented by the process emissions, mainly nitrogen (Figure 33).

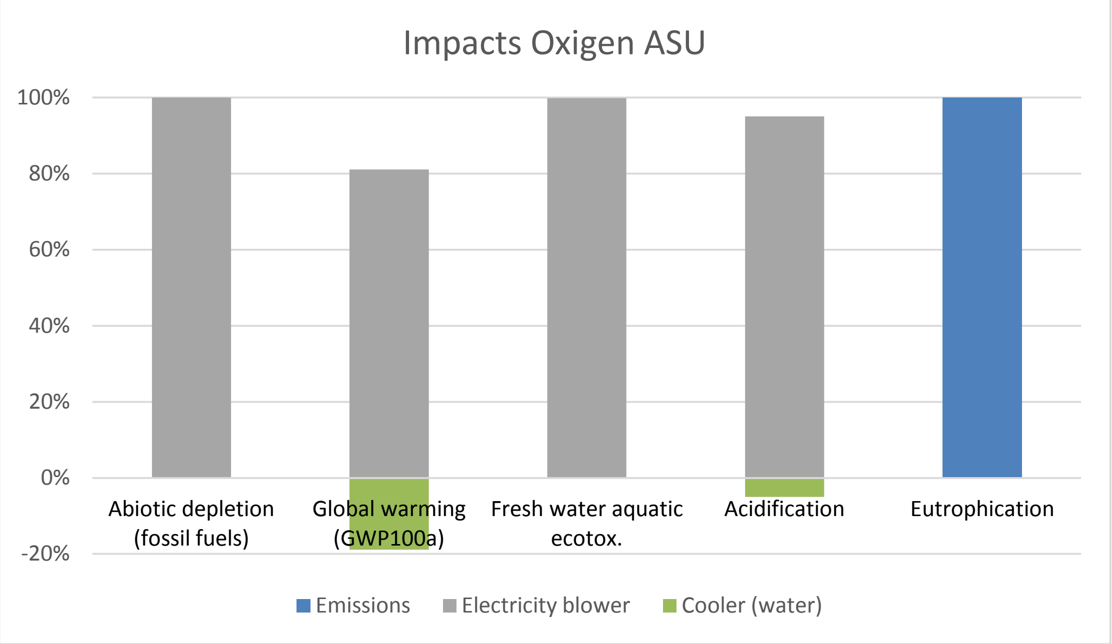


Figure 33. Impacts distribution of ASU – *Case study*.

The steam used showed a significant negative contribution in all the impact categories, especially in abiotic depletion of fossil fuel (almost 100%). Blower, heaters and the air heater also have negative impacts, particularly on the global warming potential. The steam produced by the reactor heat and the cooler allows reducing the impacts of this process (Figure 34).

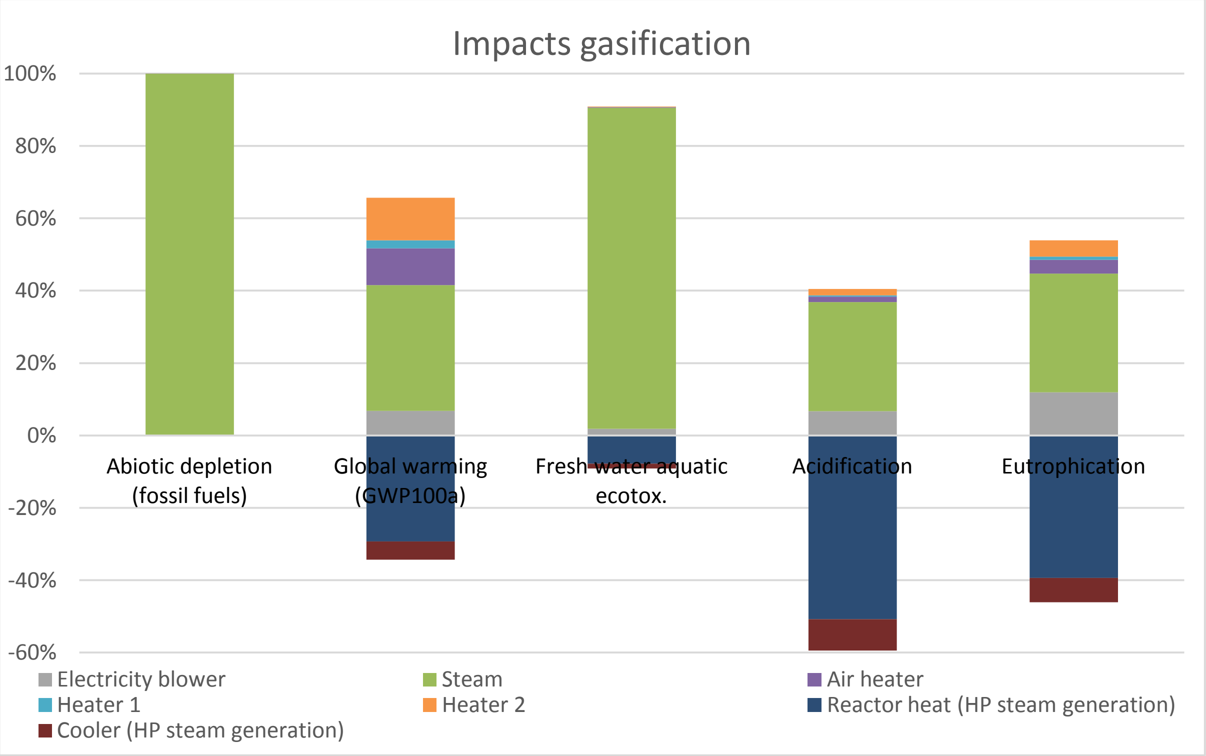


Figure 34. Impacts distribution of gasification – *Case study*.

Figure 35 shows that the consumption of oil was the main contributor to the purification impacts on fresh water aquatic ecotoxicity (97.7%), acidification potential (27.7%) and eutrophication (89.9%). It also has a substantial contribution on abiotic depletion and global warming potential (about 15%). The waste oil presented also a negative impact on global warming potential of the process (26.4%). The electricity consumed by the two blower and the tar removal compressor had a major contribution on abiotic depletion, global warming and acidification. The positive effects of the steam generation by the cooler do not compensate enough the other contributions that make the purification process one of the most relevant in terms of environmental impact on the overall system.

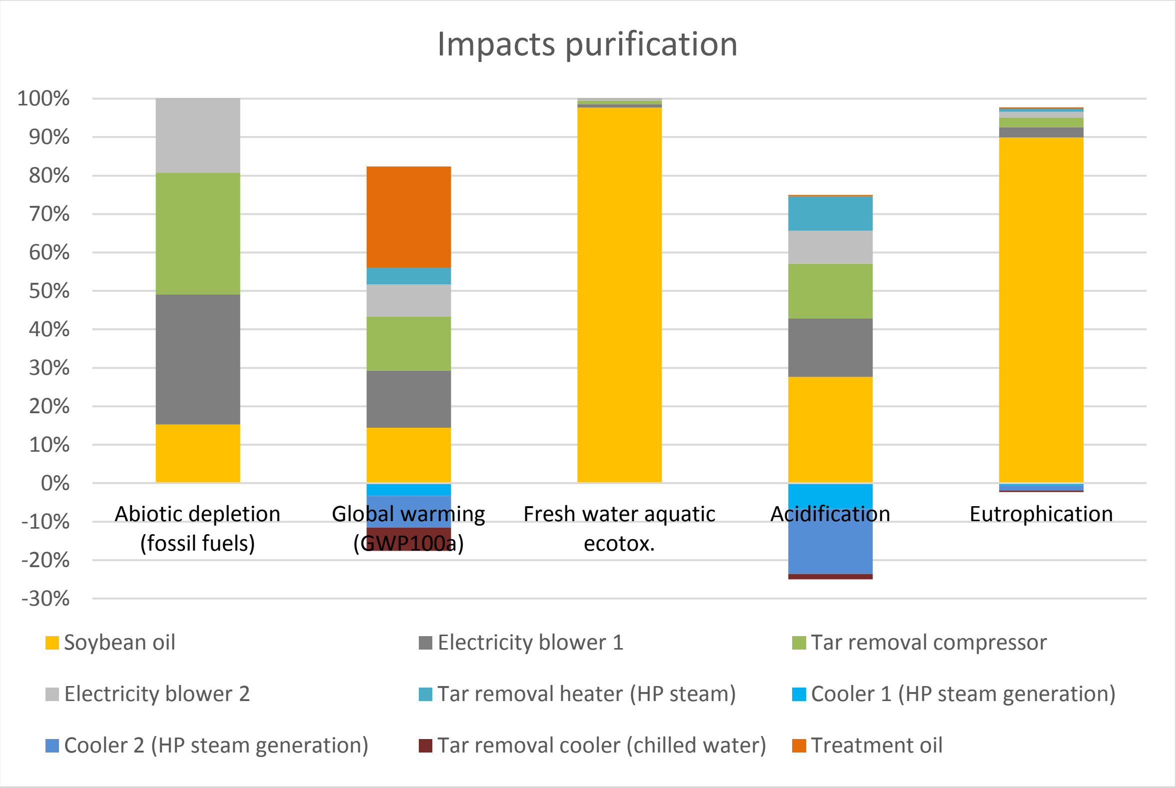


Figure 35. Impacts distribution of purification – *Case study.*

The steam used for the WGS process and the electricity consumed by the blower showed the highest contribution in almost all the impacts categories, especially on abiotic depletion and fresh water aquatic ecotoxicity. The four coolers reduce the environmental impacts of the process, especially the cooler 2 and the cooler that produce LP steam (Figure 36).

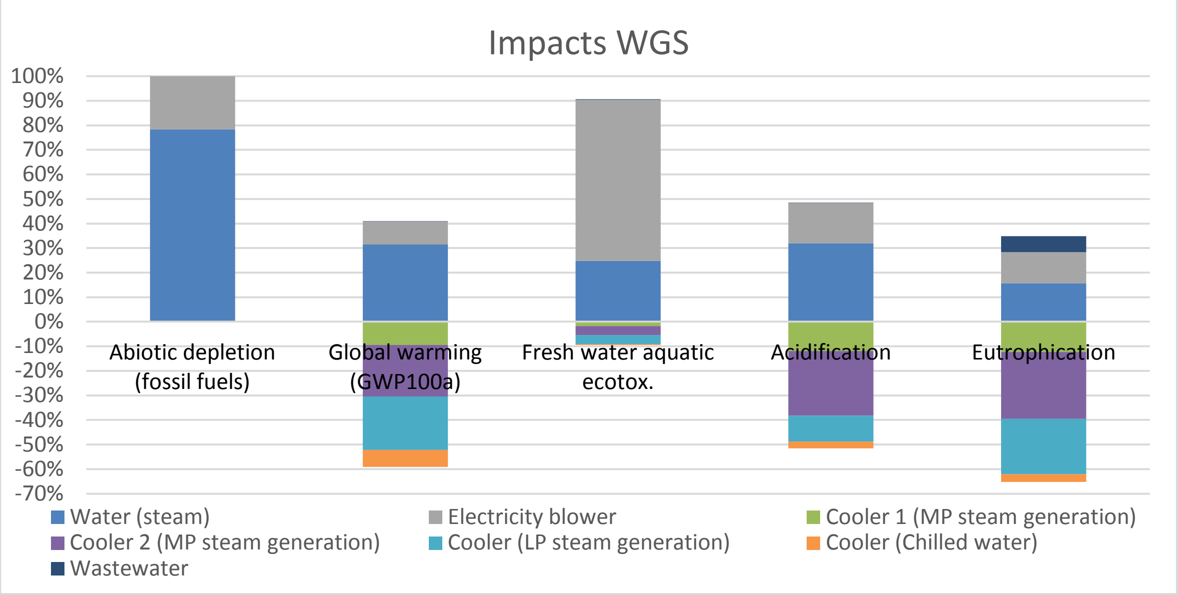


Figure 36. Impacts distribution of hydrogen production (WGS) – *Case study.*

In the *Case study*, both carbon monoxide enriched and hydrogen enriched were produced by the CO_2 removal process. The Figure 37 shows clearly the three main contributions to the CO_2 removal process: the gas emissions cause more than 90% of the global warming and eutrophication potential. Abiotic depletion, fresh water aquatic ecotoxicity and acidification were affected for the electricity consumed by the pump and reboiler on a similar basis (about 50%).

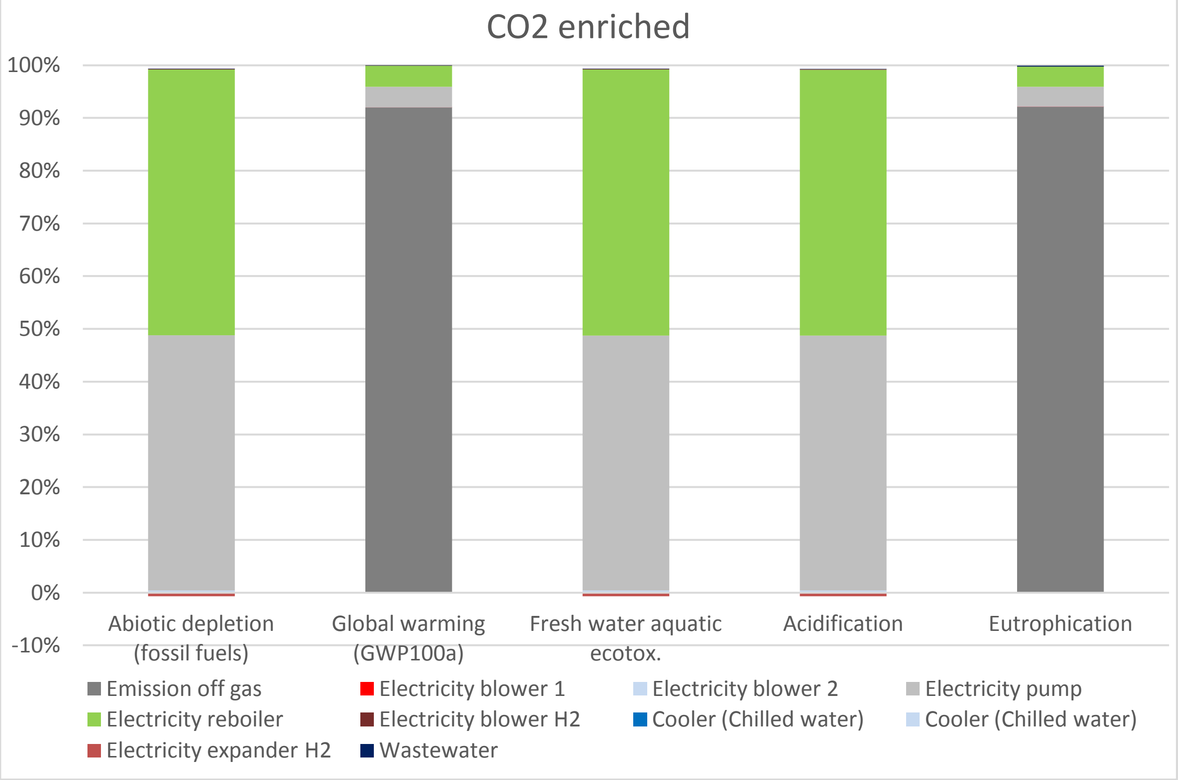


Figure 37. Impacts distribution of CO_2 removal – *Case study.*

The gas compression was reflected in a general positive impact on global warming potential, mainly due to the generation of LP steam and chilled water by the three coolers. The electricity consumed by the blower was the main contribution over the all impact categories (from 100.0% for abiotic depletion to 47.4% for global warming potential) (Figure 38).

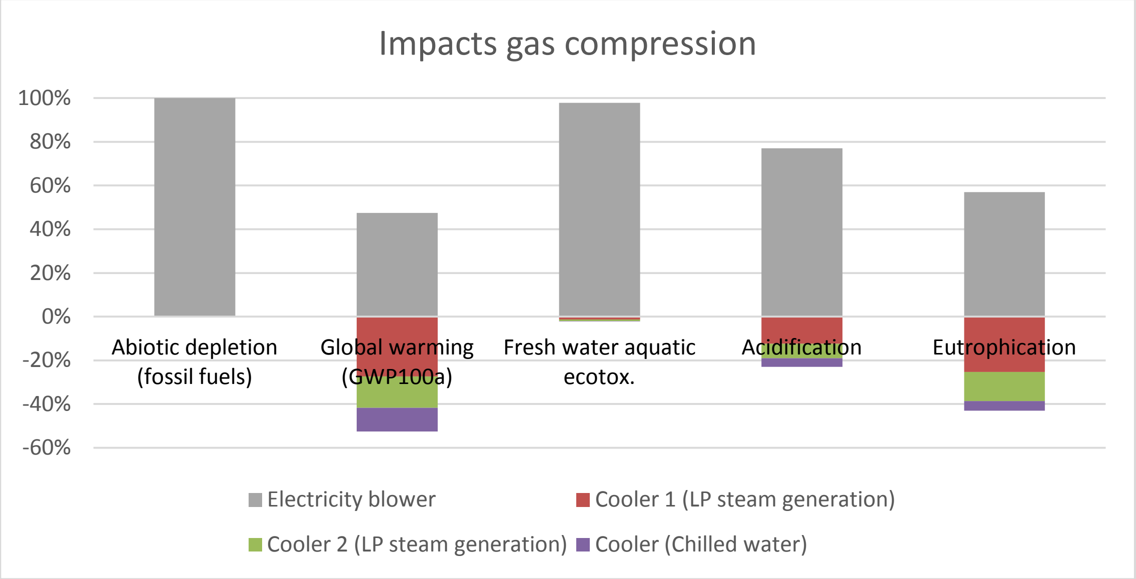


Figure 38. Impacts distribution of compression – *Case study.*

The Fischer-Tropsch process has a positive environmental impact on the overall system in all the analyzed categories. Wastewater treatment was the only output that showed a negative impact, and it was significant only for eutrophication (5.5%). The electricity produced by the expander offers the main reduction of the abiotic depletion of fossil fuel (-99.9%) and fresh water aquatic ecotoxicity (-62.9%). The LP steam produce by the reactor heat allows the main reduction for the three other impact categories (Figure 39).

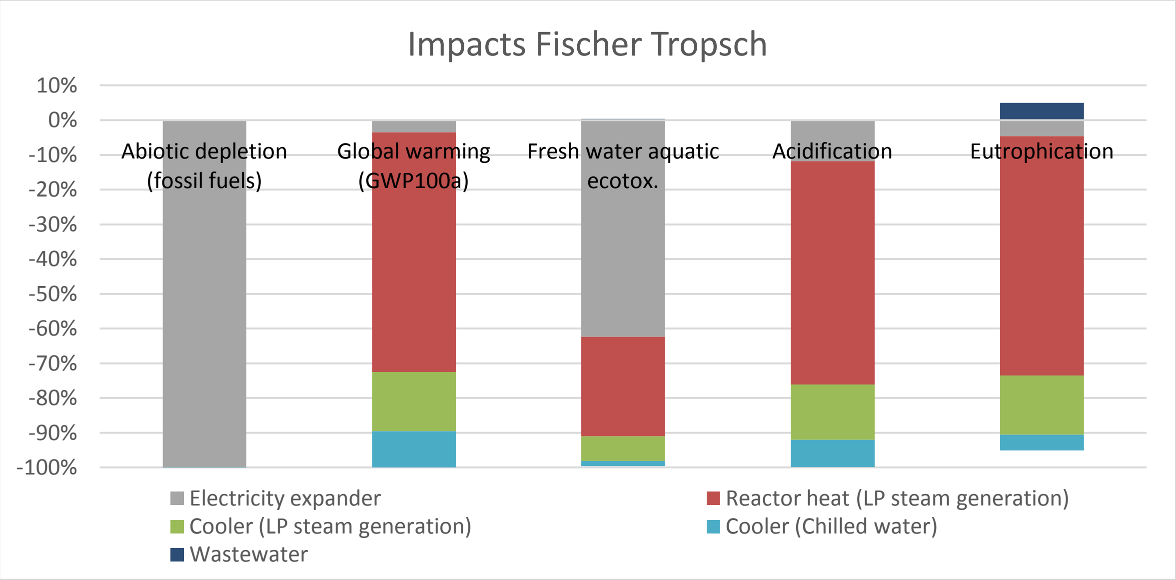


Figure 39. Impacts distribution of Fischer-Tropsch process – *Case study.*

The steam used in the process has the major impact on abiotic depletion of fossil fuel (77.0%) and have a significant contribution to global warming potential (21.8%). The wastewater treatment was the main contributor to the fresh water aquatic ecotoxicity (76.1%), acidification potential (60.3%) and eutrophication (93.9%) of the Fischer-Tropsch separation process. It also have a significant contribution on global warming potential (12.0%). The positive effect of the chilled water produced by the condenser ATM allows to almost compensate the global warming potential of the wastewater, heater, steam, reboiler vacuum and off gas emission together (Figure 40).

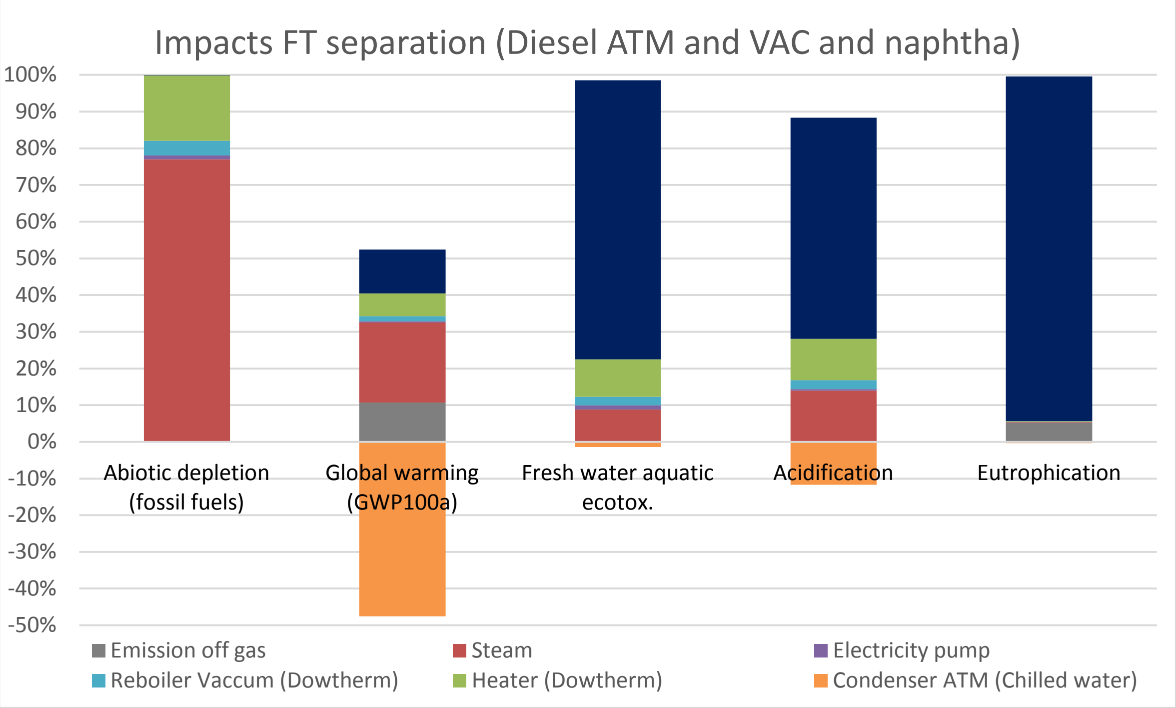


Figure 40. Impacts distribution of Fischer-Tropsch separation – *Case study.*

Figure 41 shows that the preheater was the main contribution to the abiotic depletion of the hydrocracking process. Heater was the main contribution of all the other impacts categories and the LP steam generated by the cooler slightly compensate these impacts (showing reductions between -9.9% to -44.1%).

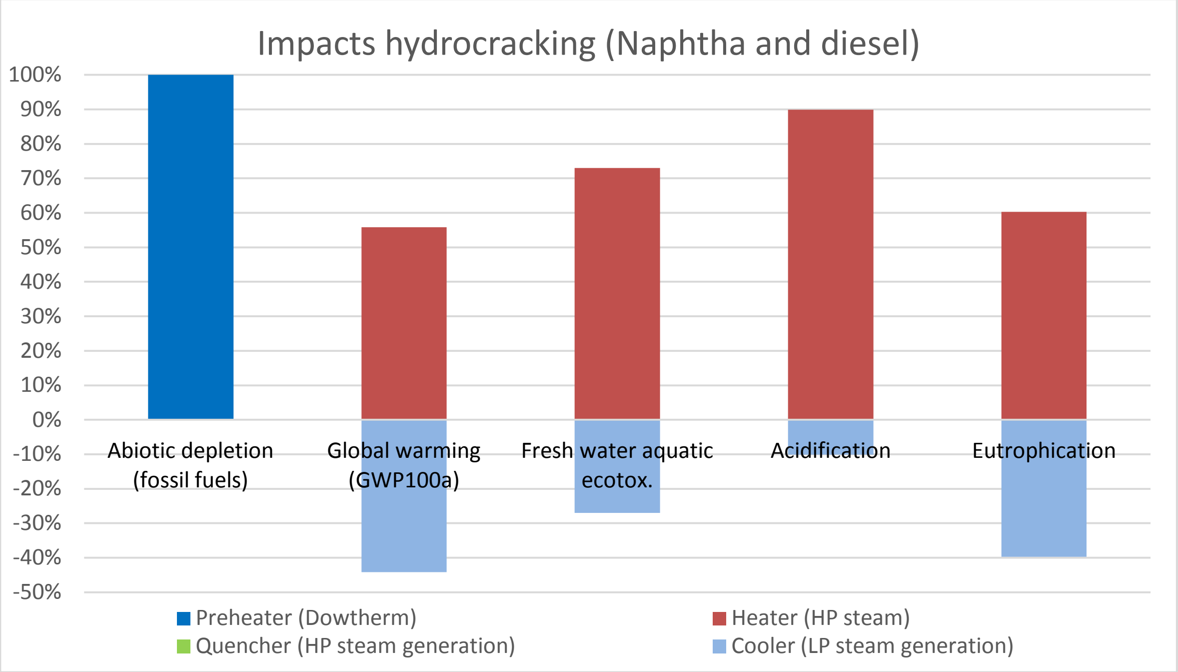


Figure 41. Impacts distribution of hydrocracking – *Case study.*

Methanation process was decreasing the environmental impacts of the overall process in all the impacts categories, excepted for abiotic depletion of fossil fuel. For this category, the electricity consumed by the blower was responsible of 99.8% of the methanation impacts. The main impacts reductions were due to the HP steam generated by the cooler and the product coolers (energy recovered). The vessel cooler have a lower contribution (-7%) (Figure 42).

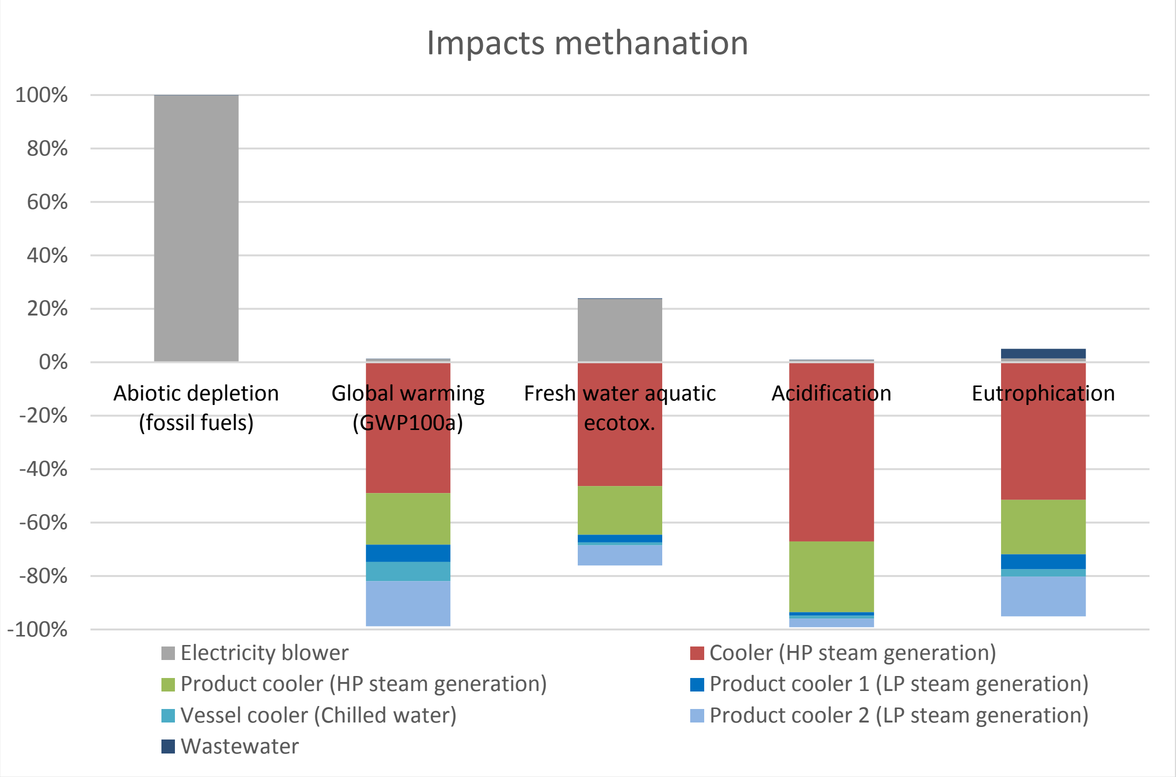


Figure 42. Impacts distribution of methanation – *Case study.*

As it can be seen in Figure 43, the impact of the methane upgrading process were mainly due to the electric consumption of the blower 1 in all the categories studied (more than 80%).

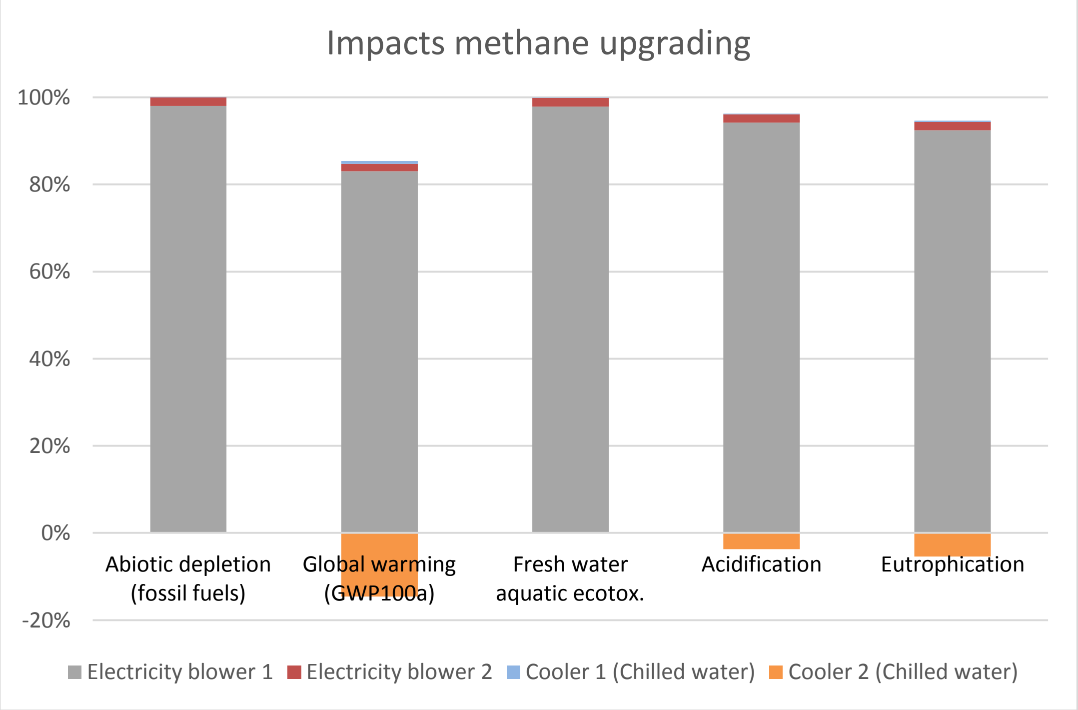


Figure 43. Impacts distribution of methane upgrading – *Case study.*

3.3.2.3 Main lessons learned

Analyzing the previous results, a few elements appears to be the key factor in the environmental impacts of the overall system. The electricity consumption represented a significant impact on almost all the elementary processes, especially for the pre-treatments (physical and chemical) and for the production of methane. Two leads have to be explored in order to reduce the environmental impacts of the electricity consumption. First, the consumption have to be reduce as much as possible. The up-scaling of the system can be a solution for that, such as a good sizing of the installations and a selection of efficient devices (pumps, blowers, etc.) with the adapted maintenance. The second possibility is to favor renewable energy sources. In the simulations, the Italian electricity mix was used for all the processes. This data represents the average electricity on the medium voltage grid in Italy, but it could be considered that the FFW plant will integrate renewable electricity (i.e. provided by solar panel or a small wind turbine).

In the simulation, emissions to air (off gas, purges) were not treated and released directly to the atmosphere. Even in small quantity, the gas released can have a high impact on the environment and should be captured. Furthermore, some products emitted could be used for energetic purpose for instance (methane, butane, ethane, etc.). The wastewater was treated in an urban water treatment plant. For the future installation, it is important to consider a more adapted treatment plant to eliminate properly the potential hydrocarbons residues. An urban water treatment plant usually includes pre-treatment devices to eliminate this kind of pollution, but it can be more specific.

In the purification process, the use and waste treatment of the oil potentially showed a high environmental impact. As the process was one of the most significant contributor in the overall system, this oil issue have to be considered carefully and alternatives have to be evaluated (i.e. other oil, recirculation, etc.). In a general way, the physical and chemical pretreatment have high environmental impacts compared to the production processes themselves. The performances of those processes were probably linked to the quality of the material used (the gas from the pretreatment). Therefore, to evaluate the effects of a lowest quality of syngas on the environmental impacts of the overall system it could be interesting in the future research.

3.3.3 *Transport assessment*

Due to logistical and practical reasons, it is not doable to transform the olive and oil residue into fuels directly where they are produced (cultivation field). The residue have to be transported, fact that affects a bit the interest of the overall FFW concept if the environmental impacts of the transport are too high or if this stage consumed more fuels than what is produced. These issues are evaluated in this section.

3.3.3.1 Fuel consumption

According to Martínez Blanco (2014), the average distance for the transportation of biomass are 10 to 25 km for local distance, 50 km for regional scale and 500 km for the national level. In a fuel production system, it is important to evaluate the consumption of fuel due to the system itself. In the FFW system, the biomass is hypothetically transported from the field to the factory where it is transformed into fuel. If the biomass transportation consumes more fuel than what the system produces, the process cannot be considered sustainable. For this assessment, the transport was supposed to be by 3.5 to 16 ton trucks or tractors consuming exclusively diesel. The truck consumption data were found in Martínez Gasol (2010) study. The return trip (from the factory to the field) was allocated to the transportation of biomass using a consumption value different from the full load consumption (Table 6).

Table 6. Parameters used for the transport study.

Parameters	**Base case**	**Case study**
Diesel produced (kg) / kg of biomass consumed	0.05146 kg	0.04737 kg
Diesel density (kg/L)	0.84	
Diesel produced (L) / kg of biomass consumed	0.06126 L	0.05639 L
Load capacity of the truck	12.5 ton	
Full consumption full load	77 L/100km	
Fuel consumption without load	63 L/100km	

For both case, the fuel consumed to transport the biomass from the field to the factory represent a small portion of the diesel produced at local scale (less than 5%). With a regional transport, 9 to 10% of the fuel produced is consumed on the road. For a longer distance (500 km) almost all the fuel produced is consumed during the transportation stage (91.4% in the *Base case*, 99.3% in the *Case study*) (Table 7 and 8).

Table 7. Fuel consumed by the transport stage – *Base case.*

Distance field-factory (km)	**Fuel consumption (L/kg of biomass)**	**Percentage of diesel consumed for the biomass transport**
10 (local)	1,12E-03	1,83%
25 (local)	2,80E-03	4,57%
50 (regional)	5,60E-03	9,14%
500 (national)	5,60E-02	91,41%

Table 8. Fuel consumed by the transport stage – *Case study.*

Distance field-factory (km)	**Fuel consumption (L/kg of biomass)**	**Percentage of diesel consumed for the biomass transport**
10 (local)	1,12E-03	1,99%
25 (local)	2,80E-03	4,97%
50 (regional)	5,60E-03	9,93%
500 (national)	5,60E-02	99,31%

3.3.3.2 Impacts

For the *Base case*, the transport stage present a low contribution compared to the environmental impacts of the FFW system itself. For less than 50 km distance between the fields and the biomass transformation plant, the transport stage contribution does not exceed 1% in any of the impact category (Figure 44, 45 & 46). For 500 km (Figure 47), the global warming potential of the transportation step reach 1.55% of total impacts and 3.03% for the acidification potential.

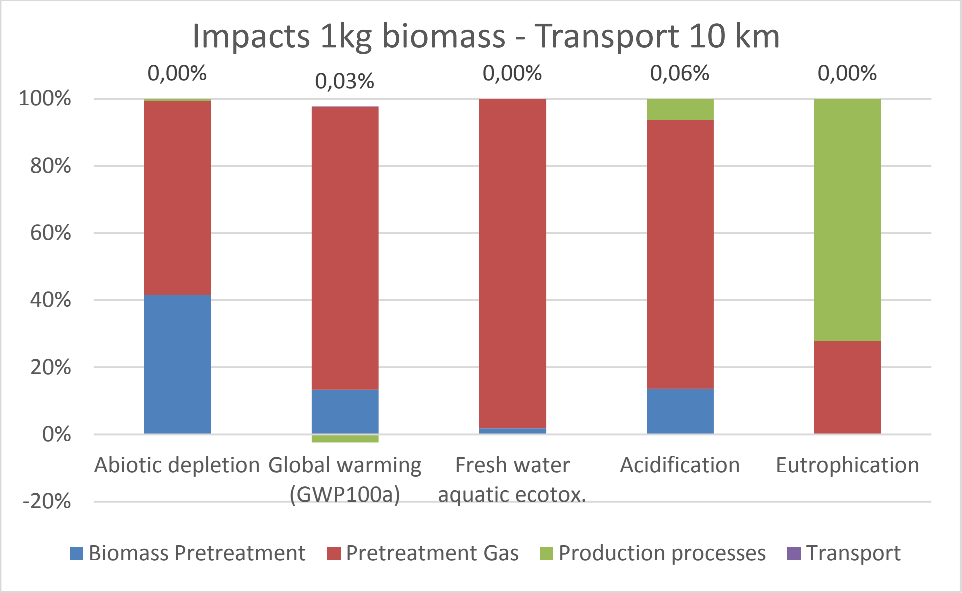


Figure 44. Impacts with transport 10 km – *Base case.*

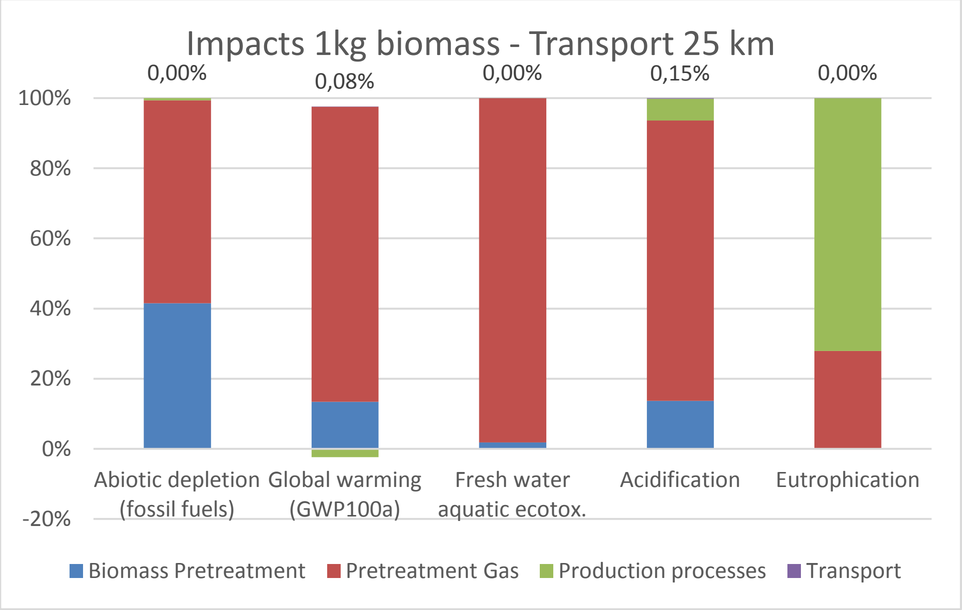


Figure 45. Impacts with transport 25 km – *Base case.*

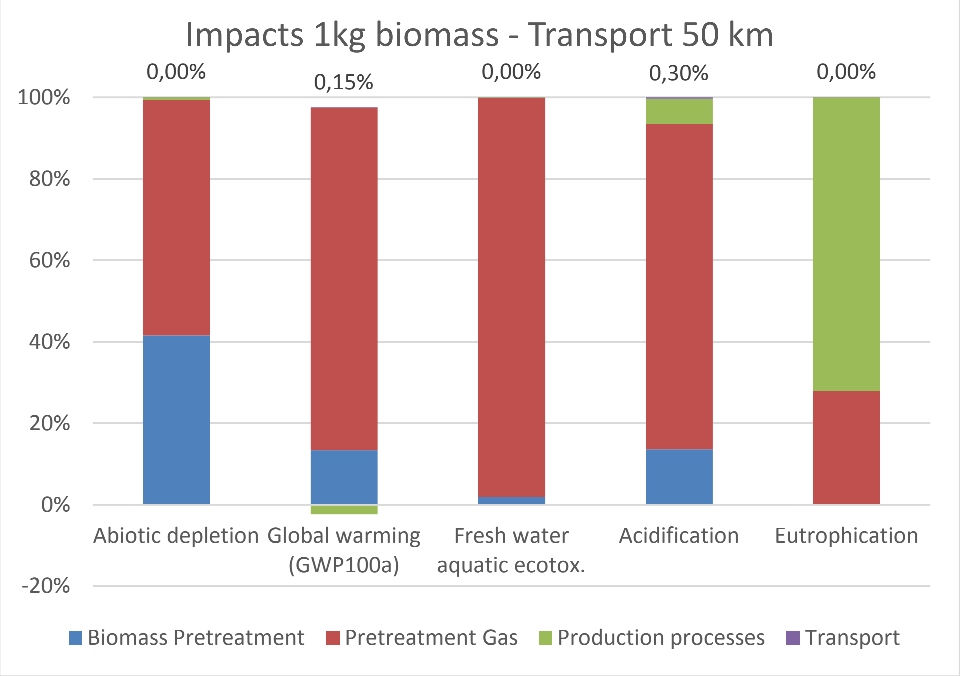


Figure 46. Impacts with transport 50 km – *Base case.*

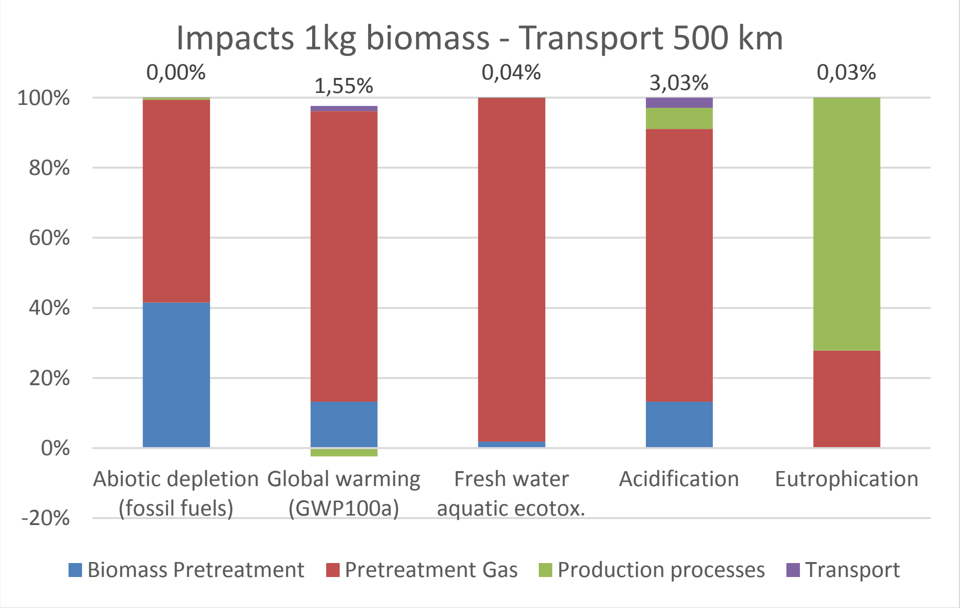


Figure 47. Impacts with transport 500 km – *Base case.*

The conclusions for the *Case study* were similar to the *Base case*: the transport contributions were negligible for local or regional transportation (Figure 48, 49 & 50) and it remains rather low for a national scale (maximum 4.50% for acidification potential) (Figure 51).

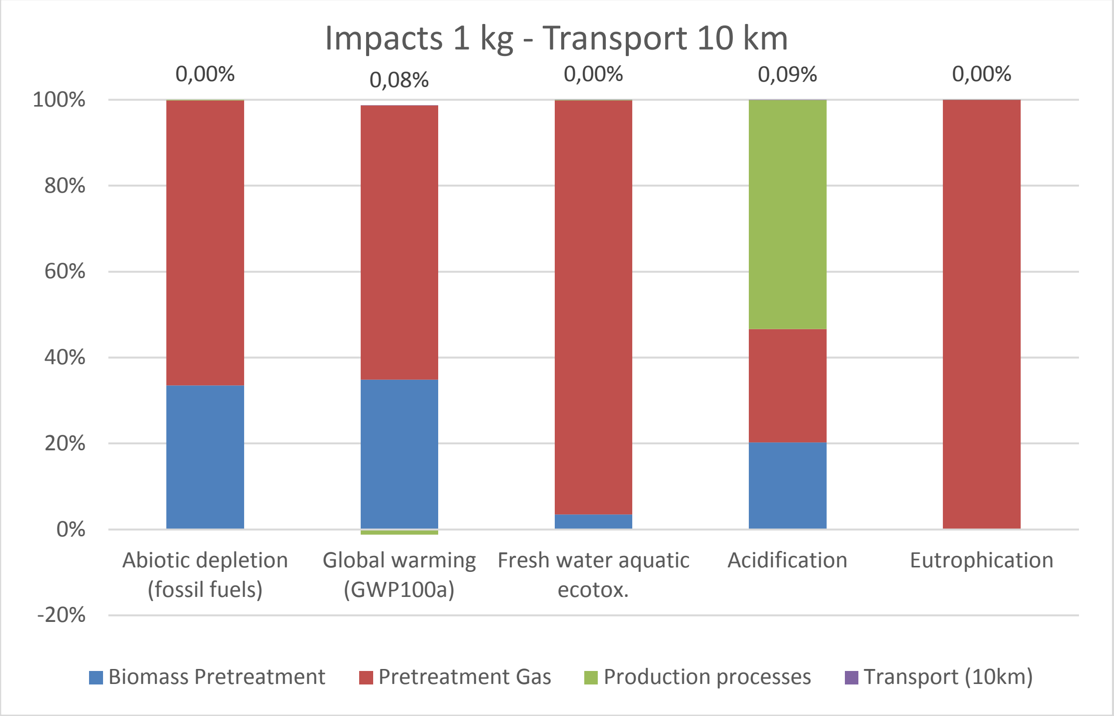


Figure 48. Impacts with transport 10 km – *Case study.*

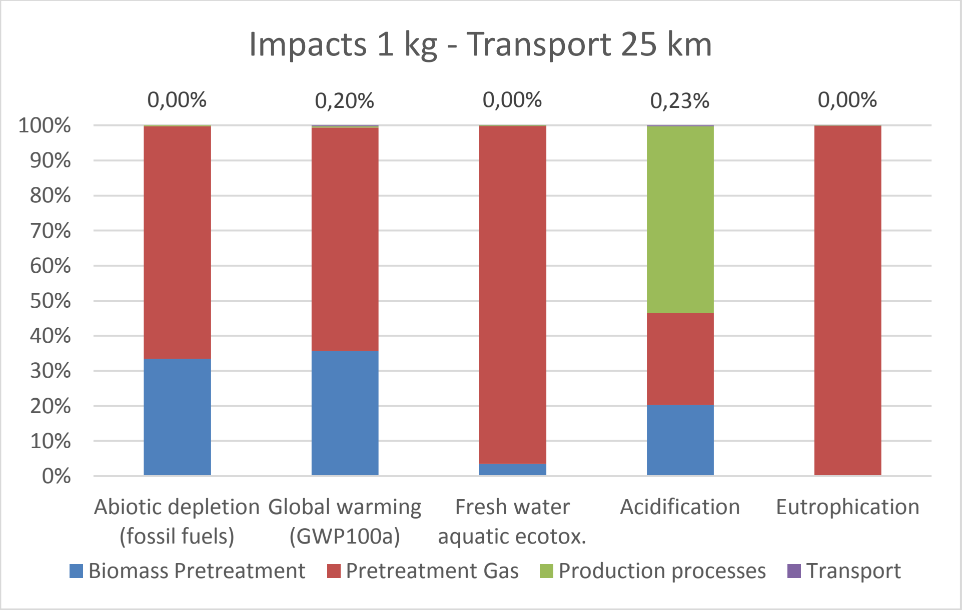


Figure 49. Impacts with transport 25 km – *Case study.*

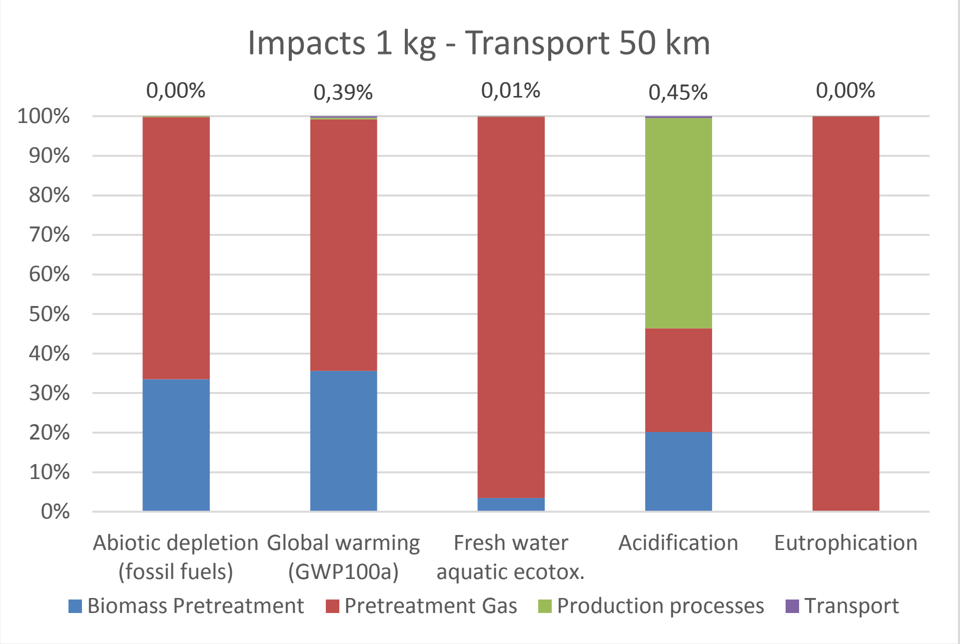


Figure 50. Impacts with transport 50 km – *Case study.*

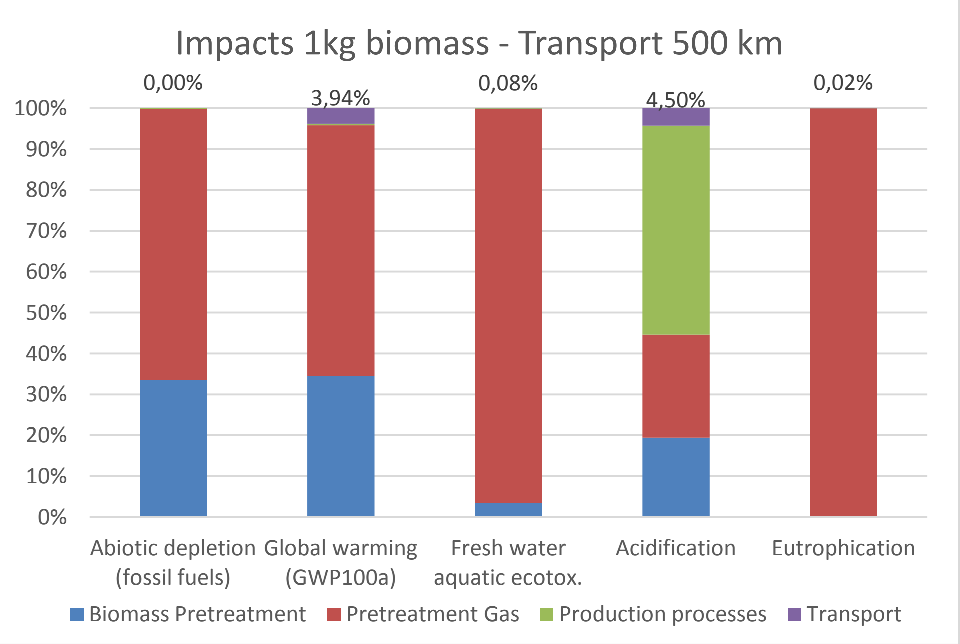


Figure 51. Impacts with transport 500 km – *Case study.*

3.3.4 *Energetic assessment of the process*

In this section, the energy balance of the system was evaluated. The aim was to verify if the overall system can be considered as self-sufficient.

3.3.4.1 Description of the production

The FFW system produces methane, tree different kinds of diesel and two kinds of naphtha. Those products have different energy content previously evaluated and presented in the Table 9.

Table 9. Energy content of the products.

Product	Process	Energy content (High Heating Value)
Diesel	Hydrocracking	36280 MJ/kg
Diesel ATM	Fischer-Tropsch Separation	32 582 MJ/kg
Diesel VAC	Fischer-Tropsch Separation	23 702 MJ/kg
Methane	Methanation	40364 MJ/kg
Naphtha	Fischer-Tropsch Separation	47844 MJ/kg
Naphtha	Hydrocracking	48135 MJ/kg

One MJ of energy produced was a combination of the six different products of the whole FFW system. For the *Base case*, the methane represents 62.4% of the energy produced, while the naphtha and diesels produce 17.9% and 19.6%, respectively (Table 10).

Table 10. Products for 1 MJ – *Base case.*

Product	Process	Quantity produced (kg)	HHV (kJ/kg)	Energy (kJ)	Ratio of the energy produced
Naphtha	FT separation	2,947E-03	47 844	140,99	14,1%
Diesel ATM	FT separation	4,761 E-03	32 582	155,14	15,5%
Diesel VAC	FT separation	3,529 E-04	23 702	8,36	0,8%
Naphtha	Hydrocracking	7,842 E-04	48 135	37,75	3,8%
Diesel	Hydrocracking	9,211 E-04	36 280	33,42	3,3%
Methane Product	Methanation	1,547 E-02	40 364	624,35	62,4%
Total				**1000**	

For the *Case study*, the methane represents 62.0% of the energy produced and the naphtha and the diesels produce 19.2% and 18.8%, respectively (Table 11).

Table 11. Products for 1 MJ – *Case study.*

Product	Process	Quantity produced (kg)	HHV (kJ/kg)	Energy (kJ)	Ratio of the energy produced
Naphtha	FT separation	3,245 E-03	47 844	155,25	15,5%
Diesel ATM	FT separation	4,530 E-03	32 582	147,60	14,8%
Diesel VAC	FT separation	3,329E-04	23 702	7,85	0,8%
Naphtha	Hydrocracking	7,703 E-04	48 135	37,08	3,7%
Diesel	Hydrocracking	8,723 E-04	36 280	31,78	3,2%
Methane Product	Methanation	1,457 E-02	40 364	620,43	62,0%
Total				**1000**	

3.3.4.2 Energetic consumption of the process

In addition to the energy content of the products (diesel, naphtha and methane), the energetic consumption of the process have to be evaluated. The sum of all the energetic consumption and production of each elementary processes shows that the physical pre-treatments consume energy while the production processes are producing. For the chemical pre-treatment, the energy balance was negative only for the *Case study* (more energy consumed than used). Regarding to the energetic content of the product, the system produce energy in both case (Table 12).

Table 12. Energy balance transformation of 1 kg of biomass.

	Base case	Case study
	kJ per kg of biomass	
Physical pretreatment	3708,0	3708,0
Chemical pretreatment	-1078,1	200,9
Production process	-2741,4	-3049,5
Products	-8526,0	-8258,6
Total	**-8637,5**	**-7399,2**

3.3.4.3 Cultivation and oil production

The energy required for the cultivation of olive tree and the production of olive oil has been assess in Özilgen et al. (2011) study. Considering chemical fertilizer use, agro chemical (pesticides) use, diesel oil consumed by trucks and tractor (for transport in the field and to the local market) and the energy consumed for the water irrigation, the total energy consumed to produce one ton of olives is 8533.2 MJ (247.0 MJ/ton for chemical fertilizers, 3317.0 MJ/ton for agro chemicals, 4908.8 MJ/ton for diesel-oil and 60.4 MJ/ton for irrigation water).

In the same study, the energy necessary to process one ton of olive into oil is estimated at 10 028.6 MJ. This energy includes the cultivation of olive, pre-treatment of olives (conveying, washing, crushing), the specific oil production processes (press, decanter, separation, pumping), oil conditioning (bottle filling, labelling, pasteurization, packaging) and the transportation of oil (550 km) (*Özilgen et al., 2011*).

In comparison, the energy produced in the system (pre-treatment included) and the energetic value of the fuels (diesel, naphtha and methane) together, compensate the energetic consumption to produce olive (agriculture to local market). For the *Case study*, 86.7% of the cultivation energetic needs are covered by the FFW system. In the *Base case*, more than 100% of the agriculture is covered, and in addition, a part (7.0%) of the oil production can be energized by the FFW system (Table 13).

Table 13. Energy balance transformation of 1 kg of biomass.

	Base case	**Case study**
	kJ per kg of biomass	
Total	-8637,5	-7399,2
Cultivation (from seed to market)	8533,2	
Cultivation consumption covered	101,2%	86,7%
Olive oil production (without agriculture)	1495,4	
Olive oil production covered	7,0%	0,0%

The production of fuel from the olive and olive oil residue is self-sufficient on an energetic point of view. As the system produces energy, it can also cover the fuel consumption of the transport of the biomass from the fields to the factory and at least a high percentage of the agriculture energetic needs.

3.3.5 Additional results

To complete the environmental impacts assessments, the water footprint and the cumulative energy demand of the system have be analyzed. The water footprint assessment allows evaluating more in detail the impact of the process on freshwater resources. Water footprint is a volumetric measure of water consumption and pollution used as an indicator of water use (*Aldaya et al., 2012*). The cumulative energy demand (CED) is an indicator of the depletion of energetic resources (*Huijbregt et al., 2010*) and by extension to the environmental impacts (global warming potential, etc.) and the efficiency of the process. A complementary study is also presented in this section to evaluate the relevance of the choice of Italy as the production location.

3.3.5.1 Water footprint

The water footprint of the two cases is presented in Figure 52. The water footprint was calculated with SimaPro 8.0.2 using the method “Hoekstra et al. (2012)”. The *Case study* water footprint (0.193 m^3) was slightly higher than the *Base case* (0.172 m^3). As shown in Figure 52, the physical biomass pretreatments showed a significant contribution (42.0%

for the *Base case* and 38.5% for the *Case study*). The purification process also presented a high contribution: 46.8% for the *Base case* and 30.0% for the *Case study*.

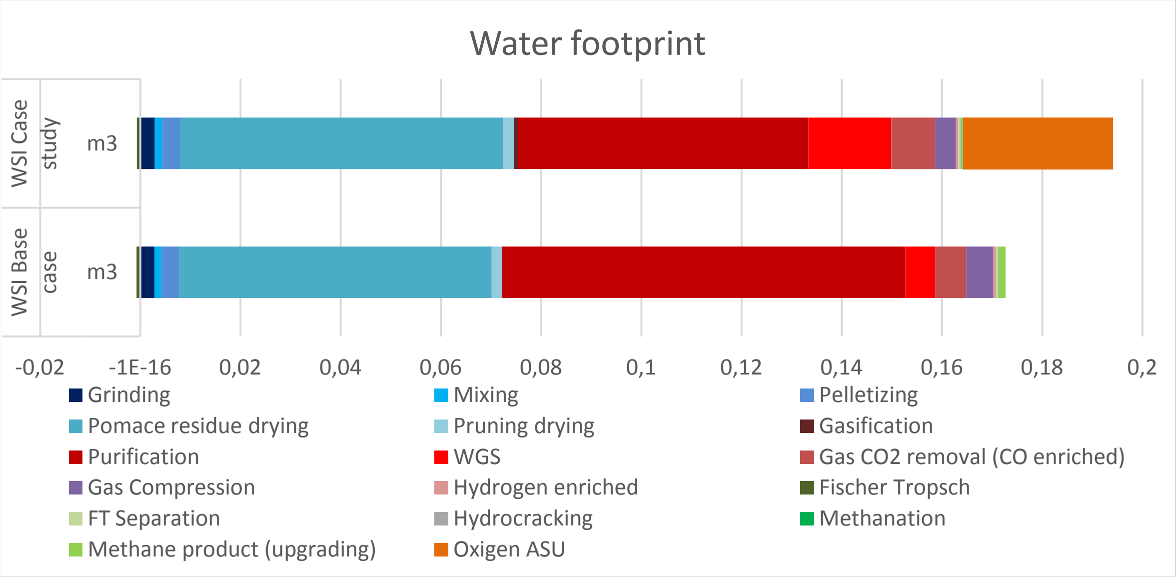


Figure 52. Water footprint per MJ produced.

According to Mekennen & Hoekstra (2011), the water footprint of biodiesel from oil palm, rapeseed and groundnuts is in the range between 0.15 and 0.2 m^3/MJ. Soybeans derived biodiesel consumes 0.343 m^3/MJ, 0.477 m^3/MJ for sunflowers, 0.547 m^3/MJ for seed cotton and 4.751 m^3/MJ for coconuts. Therefore, the FFW products have a water footprint similar to diesel from soybeans, which is in the average compared to other crops derived fuel. The water footprint of olive cultivation is not include in the calculation, as only the residues were used. Olives are mainly cultivated for olive oil production that have a 12.325 m^3/L water footprint. The biomass cultivation should have an addition of 0.650 to 0.687 m^3/MJ if the purpose is not only for olive and oil production.

3.3.5.2 Cumulative Energy Demand

The energy demanded to transform one kilogram of biomass is presented in Table 14. It can be noticed that the *Case study* consumes significantly lower energy than the *Base case*. The main energy demand for both case was the non-renewable energy based on fossil fuel. The balance between the energy consumed and the energy produced is positive in term of renewable energy from biomass (Figure 53).

Table 14. Cumulative Energy Demand (1 kg biomass).

Impact category	Unit	Base case	Case study
Non renewable, fossil	MJ	65,17	14,23
Non-renewable, nuclear	MJ	9,01	2,73
Non-renewable, biomass	MJ	1,59E-08	6,04E-09
Renewable, biomass	MJ	-7,91E-04	-4,76E-03
Renewable, wind, solar,	MJ	3,22E-01	-1,07E-02
Renewable, water	MJ	7,74E-01	-1,34E-01
Total	MJ	**75,28**	**16,81**

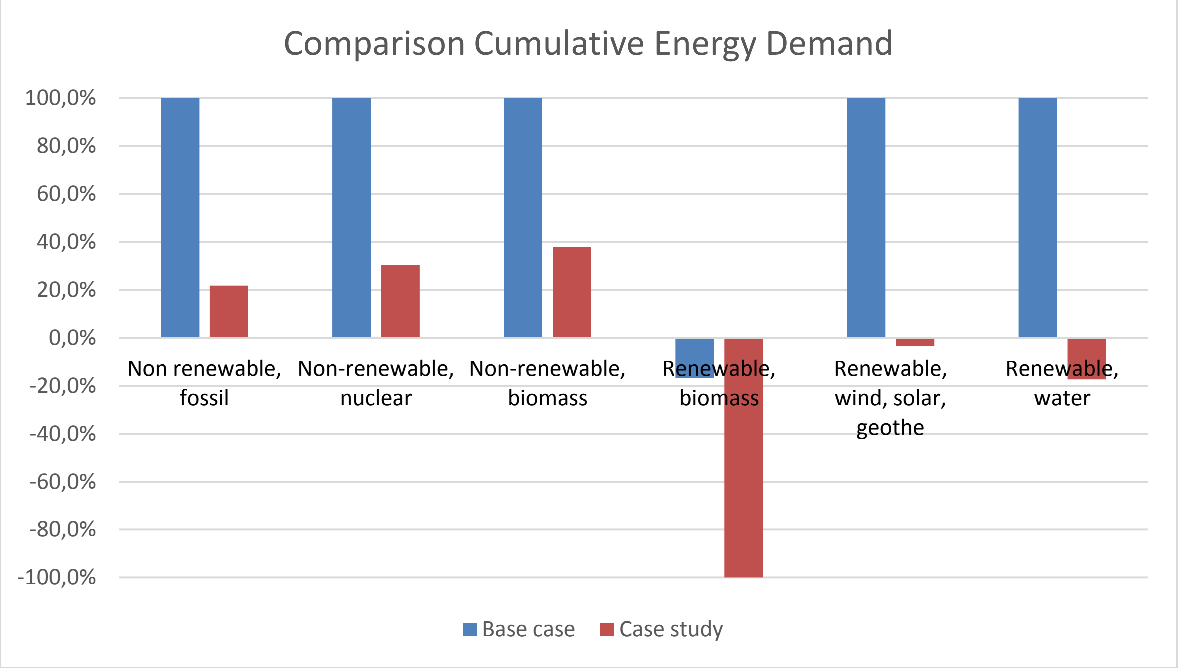


Figure 53. Cumulative Energy Demand comparison.

Figure 54 shows the distribution of the cumulative energy demand between the processes of the *Base case*. The nitrogen removal process to produce hydrogen enriched was the main energy consuming process in four energy categories (about 72% of non-renewable energy from fossil and nuclear, 98.5% of renewable energy from wind, solar and geothermic and 93.3% of renewable energy from water). The biomass-based non-renewable energy demand was mainly due to the purification process (53.7%) and the gasification on a lesser extend (12.2%). The gasification process also demand a significant amount of biomass-based renewable energy (14.3%), nevertheless, this number was widely compensate by the energetic production of WGS (-24.0%), compression (-18.8%) and methanation (-23.1%).

The chemical pretreatment was responsible of the highest part of the energy demand in all energy categories, excepted for biomass-based renewable energy. Production processes (Fischer-Tropsch, FT separation, hydrocracking, methanation and methane upgrading) showed a positive energy balance in almost all the energy categories.

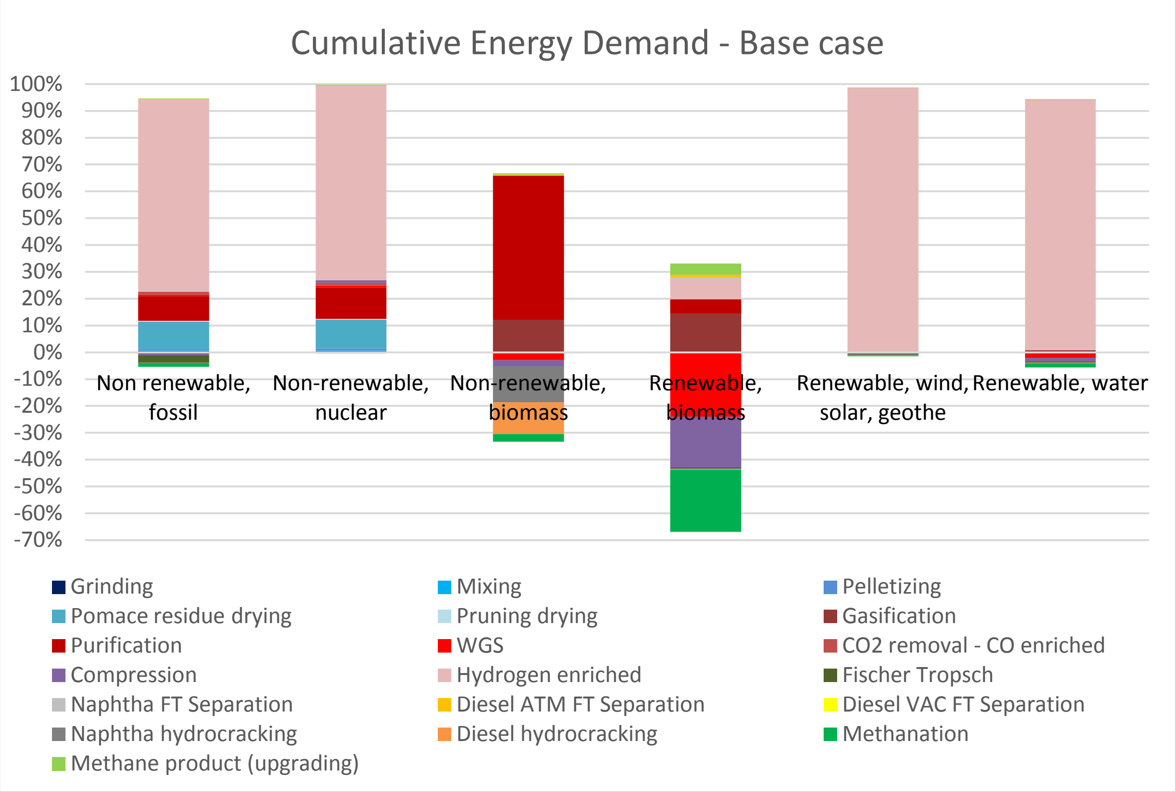


Figure 54. Cumulative Energy Demand – ***Base case.***

In the *Case study*, the main demand for non-renewable energies from fossil and nuclear sources comes from the pomace residue drying (32.0% and 34.9%, respectively). In this two categories, oxygen ASU and the purification process show also a rather significant demand. Gas purification was the main biomass-based non-renewable energy consuming process (38%), but presented a noteworthy negative demand of renewable energy and from water (-23.0%). Gas purification, WGS and oxygen ASU processes represented a substantial positive energy balance for renewable energy based on biomass (-25.8%, -26.8% and -26.3%, respectively). The cumulative demand of renewable wind, solar and geothermic energy was reduced by the WGS process (-27.8%) and by the hydrocracking (-21.9% for naphtha and -18.7% for diesel) (Figure 55).

The combination of the production processes showed a negative energy demand (as it produce energy) for all the energy categories. The physical pretreatments (grinding, mixing, pruning drying, pomace residue drying and pelletizing) had the main energy demand for fossil and nuclear non-renewable energies. The chemical pretreatment only presented a negative energy demand on non-renewable energy, but also a significant impact on non-renewable energies.

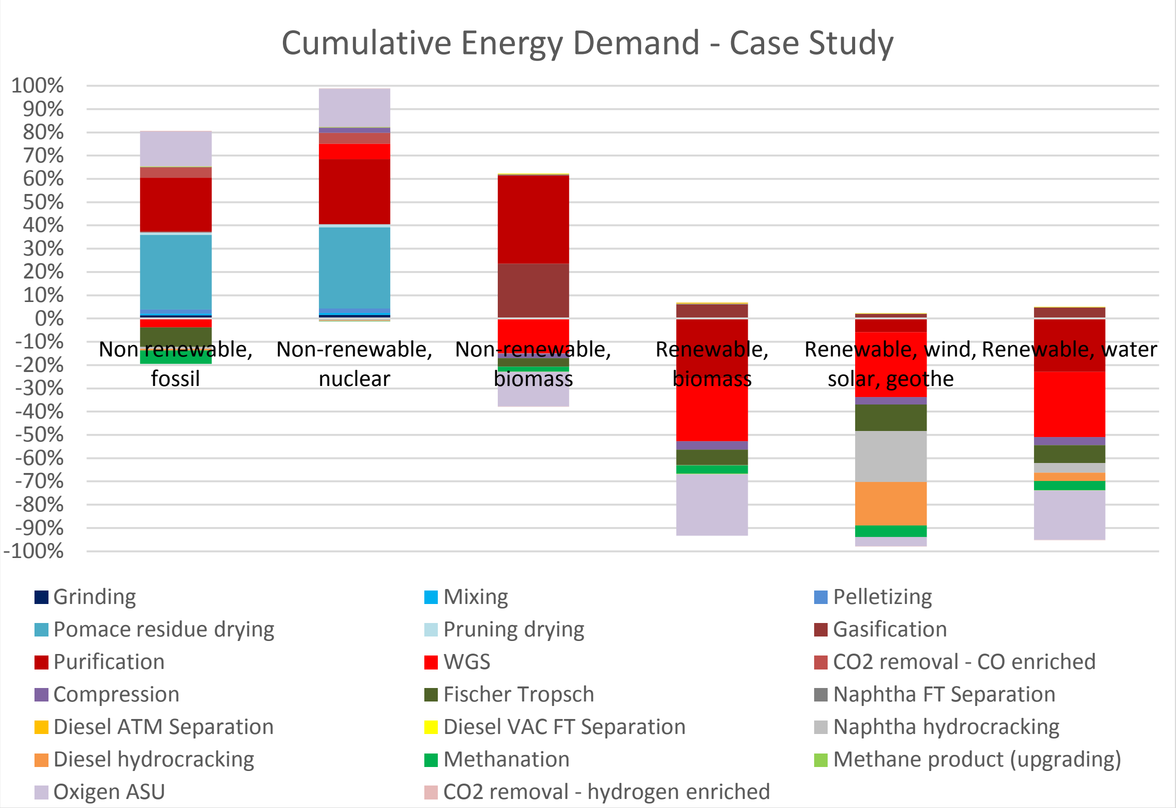


Figure 55. Cumulative Energy Demand – *Case study.*

3.3.5.3 Processes location

As stated previously in this report, Italy was chosen as the reference country for the life cycle assessment. The energetic consumption of the process was shown to be a determining element in the environmental impacts of the system. As this energetic consumption is geographically linked to the country, it is important to consider several production locations to select the most optimal. Among the olives producers country, Italy is second behind Spain but far ahead other Mediterranean countries (Greece, Portugal, etc.) (*D.6.1 Database on olive farming and olive industry in the Mediterranean Countries, 2014*).

Compared to the Italian scenario, the *Base case* production in Spain showed a significantly lower global warming potential (-65.9%), fresh water ecotoxicity (-48.8%) and acidification (-43,0%). However, the Spanish scenario presented a higher abiotic depletion (+5.6%) and eutrophication potential (+58.4%) (Table 15).

Table 15. Impacts comparison Italy vs Spain – 1 MJ produced – *Base case.*

		Italy	Spain	Difference
Abiotic depletion (fossil fuels)	MJ	2,486E+00	2,624E+00	5,6%
Global warming (GWP100a)	kg CO_2 eq	7,612E-01	2,597E-01	-65,9%
Fresh water aquatic ecotox.	kg 1,4-DB eq	7,276E-02	3,728E-02	-48,8%
Acidification	kg SO_2 eq	2,110E-03	1,203E-03	-43,0%
Eutrophication	kg PO_4--- eq	4,621E-02	7,319E-02	58,4%

For the *Case study* (Table 16), the Spanish scenario was the best option in almost all the impact categories; there was just a slight difference in eutrophication potential.

Table 16. Impacts comparison Italy vs Spain – 1 MJ produced – *Case study*.

		Italy	Spain	Difference
Abiotic depletion (fossil fuels)	MJ	3,185E+00	2,709E+00	-14,9%
Global warming (GWP100a)	kg CO_2 eq	3,086E-01	2,681E-01	-13,1%
Fresh water aquatic ecotox.	kg 1,4-DB eq	4,004E-02	3,848E-02	-3,9%
Acidification	kg SO_2 eq	1,467E-03	1,242E-03	-15,4%
Eutrophication	kg PO_4--- eq	7,557E-02	7,556E-02	0,0%

Despites the better impacts, the production in Spain has a water footprint indisputably higher than for the Italian scenario (more than +400% for both) (Table 17). Contrary to the Italian production, the water footprint required to transform one kilogram of biomass in Spain was superior to the water footprint of the olives production.

Table 17. Comparison Italy vs Spain – Water footprint.

		Base Case	Case Study
Italy	m^3/MJ	0,172	0,193
Spain	m^3/MJ	0,940	1,110
Difference		447,1%	474,0%

The global cumulative energy demand was lower in Spain than in Italy (-1.3% for the *Base case* and -7.6% for the *Case study*). In detail, for the *Base case* (Table 18), the cumulative energy demand was higher in Spain for non-renewable nuclear energy (35.9%), renewable energy from biomass (196.5%) and renewable energy from water (0.7%). For the *Case study* (Table 19), the Spanish scenario only showed a higher demand of non-renewable nuclear energy (136.9%).

Table 18. Comparison Italy vs Spain – Cumulative Energy Demand – *Base case.*

Impact category	Unit	Base case Italy	Base case Spain	Difference
Non renewable, fossil	MJ	6,517E+01	6,098E+01	-6,4%
Non-renewable, nuclear	MJ	9,013E+00	1,225E+01	35,9%
Non-renewable, biomass	MJ	1,594E-08	1,432E-08	-10,2%
Renewable, biomass	MJ	-7,906E-04	2,344E-03	196,5%
Renewable, wind, solar, geothe	MJ	3,219E-01	3,213E-01	-0,2%
Renewable, water	MJ	7,736E-01	7,793E-01	0,7%
Total	**MJ**	**7,528E+01**	**7,433E+01**	**-1,3%**

Table 19. Comparison Italy vs Spain – Cumulative Energy Demand – *Case study.*

Impact category	**Unit**	**Case study Italy**	**Case study Spain**	**Difference**
Non renewable, fossil	MJ	1,423E+01	9,188E+00	-35,4%
Non-renewable, nuclear	MJ	2,735E+00	6,478E+00	136,9%
Non-renewable, biomass	MJ	6,041E-09	4,420E-09	-26,8%
Renewable, biomass	MJ	-4,761E-03	-1,618E-03	-66,0%
Renewable, wind, solar, geothe	MJ	-1,067E-02	-1,020E-02	-4,4%
Renewable, water	MJ	-1,336E-01	-1,149E-01	-14,0%
Total	**MJ**	**1,681E+01**	**1,554E+01**	**-7,6%**

To conclude, the Spanish options seem to be quite interesting even if the water footprint is an important drawback. In addition to these impacts comparisons, others parameters should be included to select the optimal location, such as biomass quality and availability, infrastructure, legislation, among others.

3.3.5.4 Comparison with other fuels and biofuels

In the following section, the environmental impacts of some fuels and biofuels are provided. The aim of the FFW is not to compete with other fuels producers; nevertheless, putting in contrast these results with other finding in the literature will give a wider overview of the FFW process' performances.

Larson (2006) evaluates the greenhouse gas emissions of the total life cycle of some biofuels. The results range from 12.7 kg CO_2eq/GJ for wheat straw ethanol to 40.7 kg CO_2eq/GJ for rape methyl ester. In comparison, the results for the *Base case* and the *Case study* are 761.2 kg CO_2eq/GJ and 659.3 kg CO_2eq/GJ, respectively.

Hill et al. (2006) study shows the GHG emissions (as CO_2 eq) during production and combustion of biofuels and their conventional counterparts: 84.9 g CO_2eq/MJ for corn grain ethanol, 96.9 g CO_2eq/MJ for gasoline, 49.0 g CO_2eq/MJ for soybean biodiesel and 82.3 g CO_2eq/MJ for oil-based diesel.

On the other hand, Van Vliet et al. (2009) evaluate the carbon balance of diesel production plants; the study estimated the 8.6 g CO_2eq are emitted for each MJ of oil-based diesel produced and 3.59 g CO_2eq for each MJ of natural gas. The production process emissions for the FFW *Base case* were -96.7 g CO_2eq per MJ of diesel produced and -30.5 g CO_2eq per MJ of methane produced (similar to natural gas). However, emissions were much higher with the pretreatment (3865.8 and 1219.3 g CO_2eq per MJ of diesel and methane, respectively). In this paper, the authors compared 14 Fischer-Tropsch diesel production plants and the FFW FT process offers results similar to the optimal plants (*Van Vliet et al., 2009*).

Other reference values are presented in the Section 2 *LCA literature review.*

4 Legislation and regulation

4.1.1.1 Production of olives and oil

The olive and olive oil production are ruled by the Council Regulation 178/2002 laying down General Principles and Requirements of Food Law and the Council Regulation 2200/96 on the Common Organisation of the Market in Fruit and Vegetables and by others global European legislations affecting the food industry.

The Commission Regulation EEC n°183/93 defined the characteristics of olive oil and olive oil residues and described analysis methodologies. The Commission Regulation EEC n°796/2002 stated the same things for olive oil and olive-pomace oil.

4.1.1.2 Management of wastes and residues

In Greece, due to the lack of specific legislation and effective monitoring form local, regional and national authorities, the most common disposal methods are storage in evaporation lagoons, discharge into nearby water bodies and land application. In Italy, the management of olive mill wastewater (OMW) is ruled by the law N° 574 of 1996 and the Ministerial Degree of 6th July 2005 with the majority of the mill owners already conformed to them. The common practice is the separation of the wastewater from husk and use of wastewater for irrigation or just soil disposal while the husk is landfilled. In Spain, the wastes of the olive oil industry are mainly used for the production of heat and energy, or they are composted; however large amounts are still deposited in evaporation ponds (*PRODOSOL project, 2012*).

The global European policy about waste management is defined by the Waste Framework Directive 2009/98/EC which classify the treatments from the more advised one to those to be avoided: prevention (following the idea that the best waste is the one we avoid to produce), then reuse, followed by recycling, recovery (conversion in usable form or energetic valorisation), and finally, disposal. The transformation of olive and oil residues in the FFW process follows globally the main incentives of the Directive 2009/98/EC. This fundamental text is completed by more specific European legislation for preventing sewage sludge pollution when used as soil fertilizer (Directive 86/278/EEC), to regulate landfilling of wastes (Directive 1999/31/EC) or incineration (Directive 2000/76/EC), etc.

The difference between a by-product and a residue was also defined by the Directive 2009/98/EC. The by-product is a substance/object resulting from a production process the primary purpose of which is not the production of that element. Such a substance/object can be viewed as not being a waste if the following conditions are fulfilled:

- Further use of the substance/object is certain;
- The substance/object can be used directly without additional processing;
- The substance/object is produced as an integral part of the process;
- Further use is lawful; the substance/object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts.

With this definition, the residues used by the FFW process are not clearly stated as a waste, however, it can neither be totally considered as by-products. In some Member State Country, olive oil are specified as “minor hazardous waste” like in United-Kingdom though the EWC Decision 2002/532 especially because of the potential phenol content.

The wastewater from olive oil production has to follow the Urban Waste Water Treatment Directive 91/271/EEC which is a specific application of the Water Framework Directive 2000/60/EC and all the other associated legislation about water quality, pollutions, emissions limits, etc.

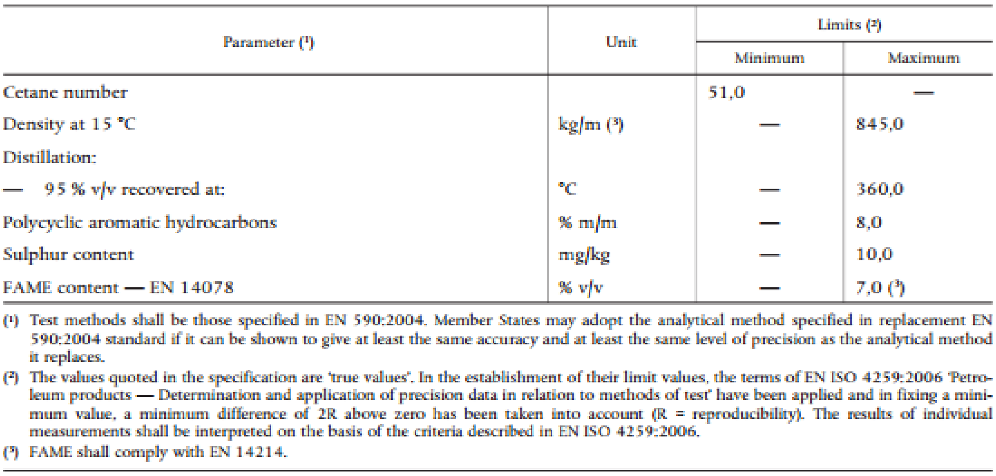
Similarly to water issue, the FFW process should enter under the Soil Framework Directive 2006/232 and the Directive on industrial emissions 2010/75/EU.

4.1.1.3 Fuel production

The general EU policy about biofuels development is based on three main objectives: the competiveness of European Union economy, the security of energy supply and environmental protection. Since 2003, the EC tries to promote the use of biofuel in that way and the Directive 2003/30/EC stipulate that each European country should replace 5.75% of the fossil fuels consumed in all transport by 2010. The target was not achieved in 2010 but the Directive 2003/30/EC was replaced by the Directive 2009/28/EC which rise the objective to 10% of biofuels by 2020.

The Directive 2009/30/EC defines the quality requirements for road fuel (Table 20). The text stated that the life cycle greenhouse gases of the fuels should be determined and communicated. A reduction target of these emissions is also included in the text with several steps since 2020. The methodology for calculating the greenhouse gas emissions and the energy balance of the fuel is described and a specific methodology is dedicated to biofuels (Article 7b). The greenhouse emissions saving by the use of biofuels shall be at least 35%. The production of biofuels should not interfere on natural ecosystem but this restriction did not concern the FFW process as agricultural residues are used as raw material.

Table 20. Environmental specifications for Market fuels to be used for vehicles Diesel-type (*Directive 2009/30/EC Annex II*).



Parameter (¹)	Unit	Limits (²)	
		Minimum	Maximum
Cetane number		51,0	—
Density at 15 °C	kg/m (³)	—	845,0
Distillation:			
— 95 % v/v recovered at:	°C	—	360,0
Polycyclic aromatic hydrocarbons	% m/m	—	8,0
Sulphur content	mg/kg	—	10,0
FAME content — EN 14078	% v/v	—	7,0 (³)

(¹) Test methods shall be those specified in EN 590:2004. Member States may adopt the analytical method specified in replacement EN 590:2004 standard if it can be shown to give at least the same accuracy and at least the same level of precision as the analytical method it replaces.

(²) The values quoted in the specification are 'true values'. In the establishment of their limit values, the terms of EN ISO 4259:2006 'Petroleum products — Determination and application of precision data in relation to methods of test' have been applied and in fixing a minimum value, a minimum difference of 2R above zero has been taken into account (R = reproducibility). The results of individual measurements shall be interpreted on the basis of the criteria described in EN ISO 4259:2006.

(³) FAME shall comply with EN 14214.

5 Conclusions

The overall environmental impacts of the FFW system were assessed in this report. The processes can be divided in three main groups: the physical pretreatments of the biomass, the chemical pretreatments and the production processes. The chemical pretreatment was the main contributor to the environmental impacts; more than 55% of the overall impacts were due to these processes for abiotic depletion of fossil fuels and global warming potential. Almost all the fresh water aquatic ecotoxicity (more than 98%) was caused by the chemical pretreatments of the biomass. It was also responsible of 80% of the acidification potential in the *Base case* and more than 99% of the eutrophication potential in the *Case study*. The main impact of the physical pretreatments of the biomass can be seen on the abiotic depletion of fossil fuels (more than 35%). The physical pretreatment also showed a significant contribution to global warming potential (14% for the *Base case* and 35% for the *Case study*) and to acidification potential (14% for the *Base case* and 20% for the *Case study*). The production process presented a slight positive effect on the global warming potential (about -2%), however, a high contribution to eutrophication potential (72%) in the *Base case* and to acidification potential (53%) in the *Case study* was also found.

Among the processes, it is possible to identify a few steps responsible for the main impacts. The purification process showed a significant contribution (over 16%) in all the impact categories analyzed, excepted for eutrophication potential. The contribution of this process was especially high (more than 90%) for fresh water aquatic ecotoxicity. The impacts of the purification process were mainly due to the use and waste treatment of oil and the electricity consumption. The processes to generate hydrogen enriched and carbon monoxide enriched presented a noteworthy contribution to the global warming potential (about 70% for the *Base case* and 35% for the *Case study*) and to acidification and eutrophication potentials for the *Base case* (63% and 24%, respectively). For these processes, the environmental impacts were mainly due to electricity consumption and the air emissions of the processes. Due to the release of nitrogen to the atmosphere, the Oxygen ASU step represents nearly the totality (99%) of the complete eutrophication potential of the *Case study* system. Pomace residue drying was the main impact contributor among the physical pretreatment processes. This process represented a significant contribution to abiotic depletion (about 30%), global warming potential (over 12%) and acidification potential (about 11%). The methane product upgrading was the highest contributor (72%) to eutrophication potential for the *Base case*, due to the high electricity consumption. In the *Case study*, the hydrocracking process showed a high contribution (about 50%), which was significantly lower in the *Base case* (less than 10%).

The *Case study*'s impacts were rather lower than the *Base case*, excepted for the abiotic depletion (about 20% higher) and the eutrophication potential, due to the oxygen ASU process. In general, the electricity consumption was responsible for the main part of the environmental impact. To improve the ecological performance of the FFW system, the electric consumption should be reduced as much as possible using less demanding devices or up-scaling the processes. As the environmental impacts of the electricity were dependent of its production, the location of the FFW plant has to be carefully chosen.

Indeed, the environmental burdens of each electric unit were linked to the energetic mix of the country of production. It could be interesting to supply the FFW plant with only renewable electricity; nevertheless, this is not feasible if the plant is linked to the national grid. Among the big olive producing countries (Spain, Italy, Greece and Portugal), Spain was the more interesting option in terms of electricity supply, as its environmental impacts are the lowest. Compared to Italy, the FFW approach will have lowest environmental impacts (about 10% reduction) or at least similar (for eutrophication potential); notwithstanding, the water footprint was about 450% higher in the Spanish scenario.

An initial idea of the FFW project was to produce fuel for the olive farming use and for the transportation of biomass produced. Considering only the diesel produced by the system, the transportation stage is comfortably covered: the biomass can be transported more than 500 kilometers (round trip of the truck) with the diesel produced. Regional (50 km) and local (25 km) transportation consume less than 10% and 5%, respectively. Compared to the environmental impacts of the FFW system, the transport step has a negligible contribution at local or regional level (less than 1%). The contribution remains quite low at national scale (under 5%).

With the energetic value of the products (diesel, naphtha and methane) and the energetic production of the process (pretreatments included), it was possible to cover the energetic requirements of the olives cultivation. For the *Base case*, more than 100% of the agriculture and transportation consumption was covered and a bit less for the *Case study* (86.7%). Therefore, the process can be considered as self-sufficient in terms of energy. Nonetheless, it is important to take into account the form of the energy: the majority of the energy produce by the processes is disseminated as heating energy (in steam or water) and this energy could be only used in the field after transformation.

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