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Report to
Biocarburantes de Castilla y Leon

on the case study
Biocarburantes de Castilla y Leon, Spain

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1 Introduction to the case study

BIOFIT Case Study: Retrofit of the first-generation ethanol production facility of Biocarburantes de Castilla y Leon to also produce second generation ethanol

The project partners, Biocarburantes de Castilla y Leon (BCyL) and CIEMAT will investigate two retrofitting case studies aiming to incorporate the production of advanced biofuels into the existing cereal-based first-generation ethanol production facility in Babilafuente, Spain. The first mid-term length case study will aim to produce 11,000 m^3/year of advanced bioethanol using feedstock listed in the Renewable Energy Directive Part A of Annex IX, and others industrial waste streams under evaluation by Spanish authorites to be included in this Annex. The second case study involves retrofitting the existing first-generation process to produce 19,000 m^3/year of advanced ethanol from unutilised components of the current feedstocks, thereby creating an integrated facility that produces both first-generation and advanced ethanol. The second case requires several modifications which will have a considerably longer duration and greater capital investment and expenditure than the retrofit of the first case.

2 Case study team (CST Leaders)

The case study will be conducted by the following partners:

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3 Confidentiality issues (CST Leaders)

This report will be shared among the partners in the case study team only. However, in the course of the project, this report will also be used as the basis for deliverable D3.3, which will be – although confidential – shared with all the BIOFIT project partners. Therefore, any information within this report which should not be distributed to a larger group than the case study team should be clearly marked with "remove before creating the deliverable".

As the BIOFIT project will publish the results of the case studies it is important to also define which parts of the information should be kept confidential within the BIOFIT project partners. Any such information within this report should be clearly marked with "do not distribute".

4 Case study description (CST Leaders)

4.1 The current situation

This section provides an overview of the *first-generation ethanol industry* and the description of the ethanol production facility of *Biocarburantes de Castilla y Leon (Babilafuente, Spain).*

Bioethanol is a liquid and clean biofuel that can replace gasoline or form different gasoline-ethanol blending. Currently, bioethanol is mainly produced from sugar and starch containing crops, such as sugar beet, grain and wheat (the so-called first generation ethanol or 1G ethanol), but it also can be produced from agricultural residues (straw, non-food lignocellulosic materials) and industrial waste, also known as advanced ethanol.

Ethanol blends up to 5-10% (E5, E10) can be used directly in cars produced since 2010, the current engines can use it without further modifications. Moreover, dedicated vehicles or flex fuel vehicles (FFVs) can use ethanol blends up to 65-85% (E65, E85). Therefore, FFVs can work with E85, petrol, or a mixture of these two fuels. The use of ethanol as fuel can achieve Green Houses Gases (GHG) savings of minimun 70% compared to petrol. Also, since the oxygen content of ethanol improves combustion, it has lower emissions of pollutants than fossil fuels, especially in petrol blends with high ethanol content[1].

In Spain, ethanol consumption reached 160.0 ktoe in 2018 (15% higher than the previous year), being the sixth country with the highest consumption in the European Union. This growth is attributed to the gradual increase in the rates of energy content for fuel blend regulated in Spain: 4.3% in 2016, 5% in 2017 and 6% in 2018. Regarding bioethanol production, Spain reached 261.9 ktoe in 2018, representing an increase of 38.3 % over the previous year. Such increase can be attributed to both a higher export volume and the growth in consumption[2].

Spain has three bioethanol facilities located in Galicia (Bioetanol Galicia S.A), Cartagena (Ecocarburantes Españoles) and Salamanca (Biocarburantes de Castilla y Leon S.A.) and they all are owned by Vertex Bioenergy., Vertex Bioenergy has a total production capacity of 780 million litres of ethanol (391.2 ktoe) including another facility placed in France. In addition to bioethanol, other valuable products such as animal feed (DDGS), electricity, captured CO_2 and corn oil are produced in some of those plants.

In this case study, different options for bioenergy retrofitting of the *Biocarburantes of Castilla y Leon* facility and its feasibility will be analysed. This plant is located in Babilafuente, Salamanca. Figure 1 shows a descriptive flow sheet of the current situation of the plant. This facility uses corn grain as raw material. In the plant, the raw material is first cleaned and milled.

[1] https://epure.org/about-ethanol/ethanol-benefits/

[2] https://www.eurobserv-er.org/biofuels-barometer-2019/

Then, it is mixed with water and heated with steam prior to enzyme addition. This process allows the conversion of starch polymer into free sugars. Subsequently, the produced sugars are fermented using *Saccharomyces cerevisiae as yeast* to obtain an ethanol-rich stream. The CO_2 produced in this process is also extracted and 30% is being captured for other uses, reducing the overall process emissions. After fermentation, the bioethanol-rich stream is subjected to distillation for obtaining high-purity bioethanol. The remaining stillage is treated and dried to obtain a protein-rich animal feed (DDGS, Distilled Dried Grains with Solubles). In order to fulfil the thermal energy demand of the process, this facility has 3 natural gas boilers producing the steam required for the plant, and a gas turbine where electricity is generated. The resulting hot gases derived from the gas turbine are then used to produce dry DDGS, while the electricity produced is sold to the grid.

The ethanol facility generates a number of wastewater streams that must be treated before recycle to the process or release to the environment. There are two water treatment units in the plant, one for water supply and wastewater streams from DDGS production, rectification and stillage evaporator, and another called wastewater treatment plant to pour into the river. The wastewater treatment plant is an extended aeration activated sludge treatment process.

Figure 1. Descriptive flow sheet of the current situation of Biocarburantes de Castilla y León (CONFIDENTIAL).

In 2019, *Biocarburantes de Castilla y León* facility processed 562,000 tonnes of corn grain, obtaining 241,670 m^3 of bioethanol, 142,000 tonnes of DDGS, 207,900 MWh of electricity and 172,788 tonnes of CO_2. Table 1 shows the quantities of the raw materials, products and energy requirements in this year.

Table 1. Raw materials, products quantities and energy requirements of *Biocarburantes de Castilla y Leon* facility in 2019 (CONFIDENTIAL).

4.2 Suggested retrofit

The European Renewable Energy Directive II (RED II) stablishes a minimum share of 14% of renewable energy from the energy consumed in road and rail transport by 2030. This includes minimum shares of 0.2% (2022), 1% (2025), and 3.5% (2030) for biogas and advanced biofuels, i.e., those obtained from lignocellulosic feedstocks, non-food crops or industrial waste and residual streams. Moreover, it limits food-based biofuels up to a maximum of 7%. Since biofuels are mainly produced from food crops today, this Directive supports the necessity of a transition from 1G biofuels to the production of advanced biofuels. In this sense, retrofitting could be a very good option to ease the transition from 1G to advanced biofuels without the necessity of building a new plant with full advanced technology.

In this case study, two scenarios of retrofit for Biocarburantes de Castilla y Leon facility have been defined. In the first one, an industrial rich-etanol waste, this feedstock is under evaluation to be considered twice its energy content in Spain, and wine alcohol, already validated as twice its energy content, have been considered for the production of 11,000 m3 per year of advanced bioethanol. This scenario presents low technical complexity, low CAPEX and, therefore, it could be quickly implemented. Figure 2 shows a descriptive flow sheet of the scenario 1.

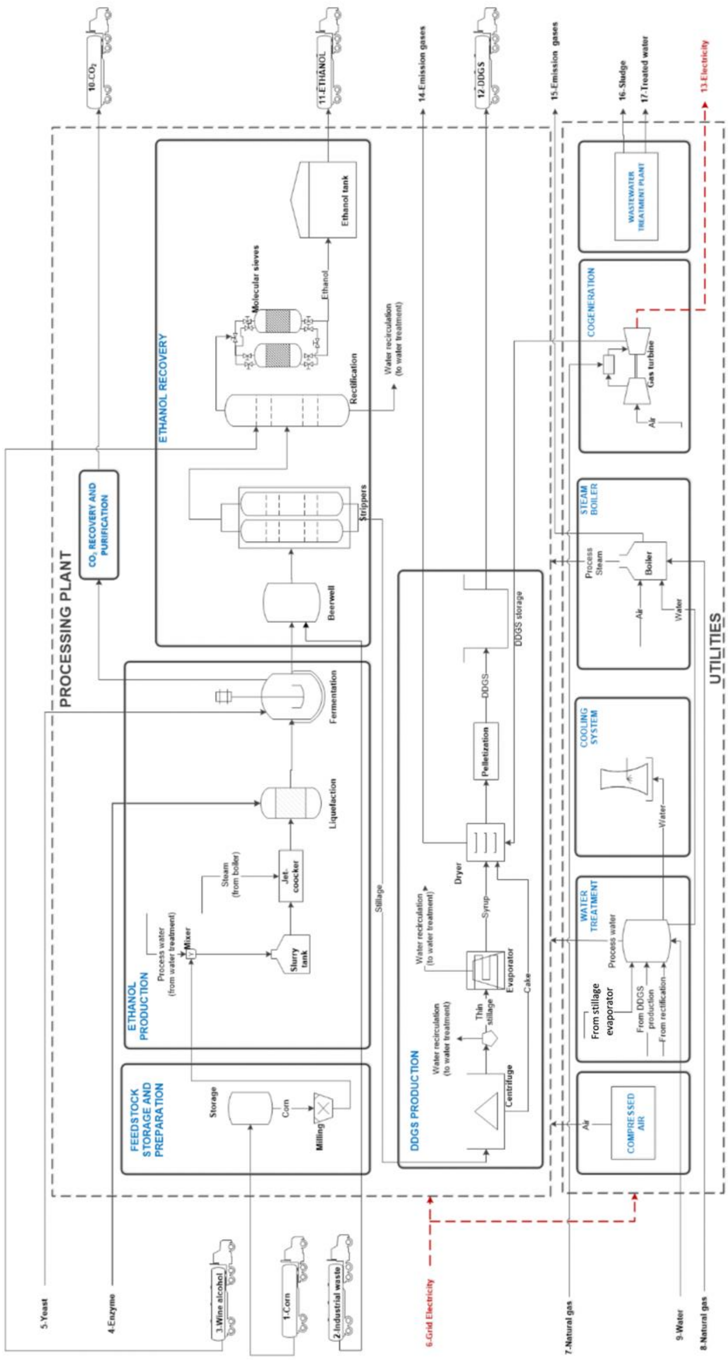


Figure 2. Descriptive flow sheet of the retrofit of Biocarburantes de Castilla y León facility (Scenario 1).

Table 2 shows the quantities of the raw materials, products and energy requirements of the plant in the retrofit Scenario 1.

Table 2. Raw materials, products quantities and energy requirements of retrofit (Scenario 1) (CONFIDENTIAL).

In the second scenario, in addition to obtain 11,000 m^3 of ethanol per year from industrial rich-ethanol waste and wine alcohol (Scenario 1), 19,000 m^3 per year of advanced ethanol are also produced from corn stover, therefore, it is an integrated facility that produces both 1G and advanced ethanol. The Scenario 2 will require several plant modifications and will have a considerably longer duration and greater CAPEX than the retrofit of the Scenario 1.

Figure 3 shows a descriptive flow sheet of the Scenario 2. In this scenario, corn stover is subjected to a pre-treatment process in a steam explosion unit obtaining two streams: a water insoluble solid fraction (WIS) containing mainly glucose and lignin, and a liquid fraction (pre-hydrolysate) consisting mainly of xylose. The WIS fraction undergoes a presaccharification and simultaneous saccharification and fermentation process (PSSF) producing a bioethanol-rich stream. In the latter, *Saccharomyces cerevisiae* is used as yeast as in the production of 1G bioethanol. The bioethanol-rich stream is concentrated to about 50% in a distillation column (beer column). The remaining stillage and the pre-hydrolysate are then mixed together with the first-generation in order to produce animal feed. On the other hand, the bioethanol stream is sent to the distillation area of the first-generation plant where it is purified to about 99.9%. Table 3 shows the quantities of the raw materials, products and energy requirements of the Scenario 2.

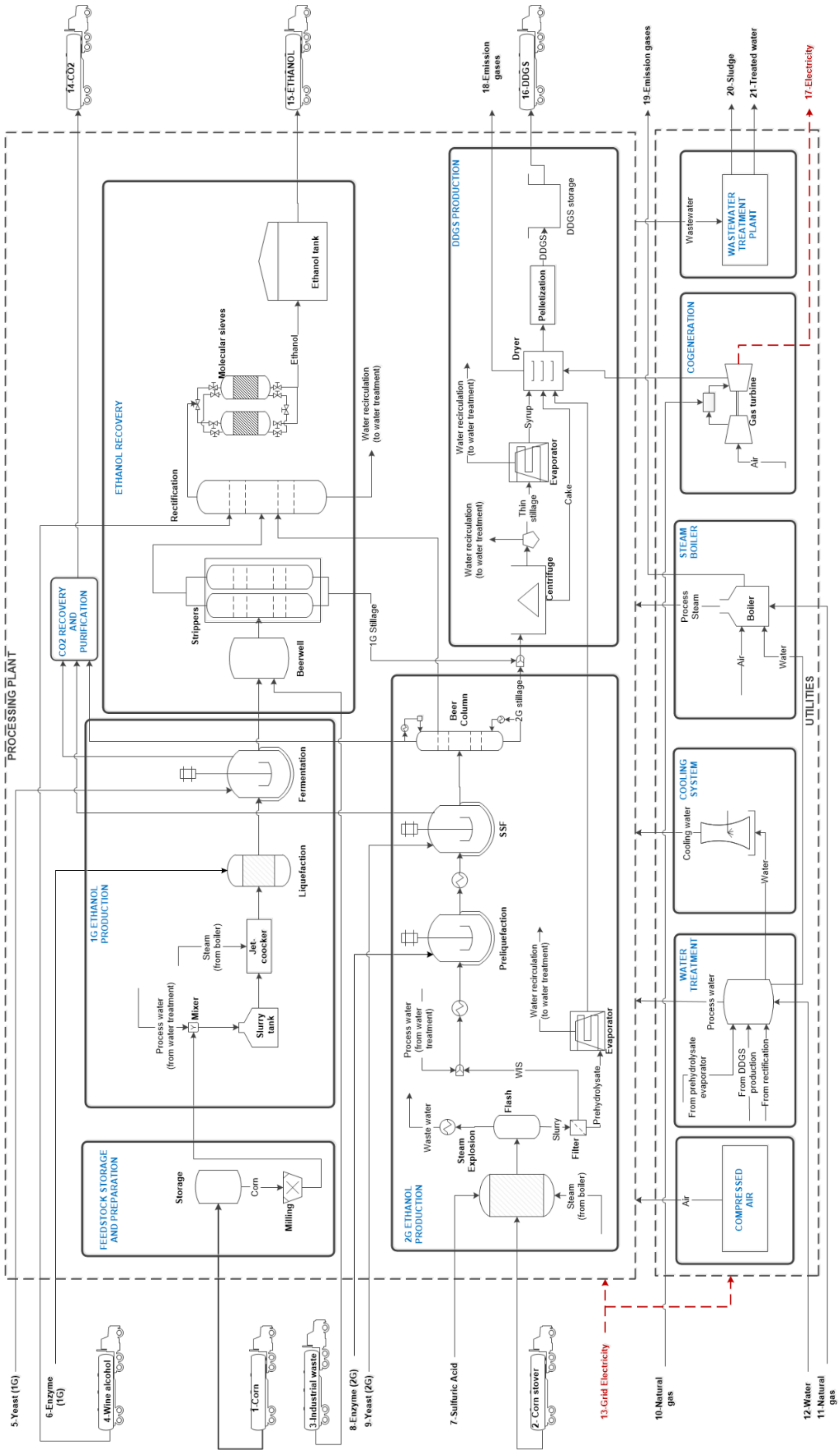


Figure 3. Descriptive flow sheet of the retrofit of Biocarburantes de Castilla y León facility (Scenario 2).

Table 3. Raw materials, products quantities and energy requirements of retrofit (Scenario 2) (CONFIDENTIAL).

4.3 Alternative to the retrofit

In this case study, a Second-Generation facility with a production of advanced bioethanol of 30.000 m3/year from corn stover has been defined as alternative to the retrofit of the first-generation facility. Figure 4 shows the descriptive flow sheet of the plant considered.

In the processing plant, a pre-treatment step of corn stover is carried out in a steam explosion unit. Pre-treated corn stover is subsequently split into a water insoluble solids (WIS) fraction, containing mainly glucose and lignin, and a liquid fraction (prehydrolysate), consisting mainly of xylose and biomass degradation compounds. Prehydrolysate fraction is subjected to a vacuum evaporation process to achieve a xylose concentration of about 80 g L^{-1} and then undergoes a detoxification step by over liming. Afterwards, detoxified prehydrolysate is fermented in order to produce bioethanol. The WIS fraction is subjected a presaccharification and simultaneous saccharification and fermentation process (PSSF) for bioethanol production.

Afterwards the ethanol-rich streams are sent to the ethanol recovery area, which consists of two distillation columns. In the first one (beer column) ethanol is concentrated to about 50% and, in the second one (rectification column), it is concentrated until the azeotropic point (93%). The, the resulting stream is purified by means of molecular sieves to obtain an ethanol concentration of 99.5% (w/w).

The combined wastewater stream from steam explosion flash vapor, boiler blowdown, cooling tower blowdown and the pressed stillage are processed by anaerobic digestion and activated sludge treatment also called aerobic digestion. Anaerobic digestion produces a biogas stream that is fed to the combustor. Aerobic digestion produces a treated water that can be reused in the facility if then it is treated by reverse osmosis. The wastewater treatment plant generate a sludge that is dewated and burned in the combustor. Both lignin fraction and biogas are combusted in order to satisfy the thermal energy demand of the plant.

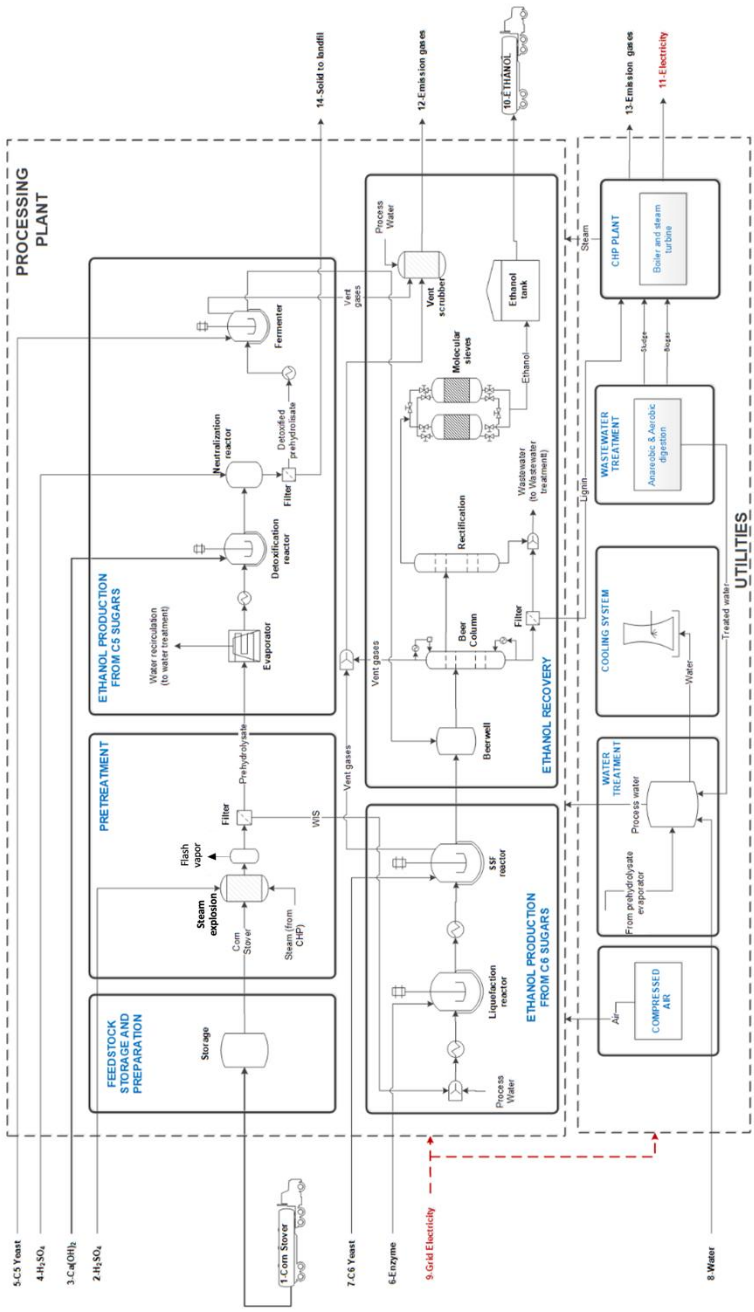


Figure 4. Descriptive flow sheet of the alternative case.

The quantities of the raw materials, products and energy requirements in the alternative case are shown in Table 4.

Table 4. Raw materials and products quantities and energy requirements of alternative case.

INPUTS	VALUE
Corn stover (tonne/year)	114,351
Sulfuric acid (tonne/year)	1,544
Calcium hidroxide (tonne/year)	1,426
Sulfuric acid (tonne/year)	15
C5 yeast (tonne/year)	230
Enzyme (tonne/year)	7,051
C6 yeast (tonne/year)	284
Water (tonne/year)	288,638
Grid Electricity (MWh/year)	38,515
Utility-Cooling water (m^3/year)	26,715,622
OUTPUTS	**VALUE**
Products	
Ethanol (m^3/year)	30,000
Electricity (MWh/year)	57,520
Emissions to the air	
Emission gases from fermenters (tonne/year)	23,112
CO_2	22,713
Water	399
Emission gases from boiler (tonne/year)	586,701
CO_2	114,260
NO_2	3,998
O_2	22,686
N_2	373,561
Water	72,198
Waste to treatment	
Solid to landfil (tonne/year)	2,461

5 Supply Chain (BE2020)

In the case study of BCyL, the focus lies on the market of bioethanol instead of the raw material supply chain. Therefore, this chapter contains only a short summary of the feedstock changes due to the suggested retrofits.

The biofuel, which is currently produced by BCyL is first-generation bioethanol. In order to partly produce second generation bioethanol (advanced bioethanol), two cases for retrofitting are considered. The description of the current situation, Case A and Case B can be found in the project description chapter.

The difference between first-generation and advanced bioethanol is the feedstock used. Due to the food vs. fuel debate and concerns over GHG emissions from indirect land use change, the EU is interested in reducing edible raw materials for energy generation. Therefore, the Renewable Energy Directive II (RED II) lists feedstocks, which are not in competition with food, for example lignocellulosic material, in Annex IX Part A. If bioethanol is produced with these listed (advanced) feedstocks, it is considered as second-generation or advanced bioethanol.

Currently, BCyL produces 241,670 m^3/y (equal 241.7 million litres) first generation bioethanol. The amount of bioethanol produced is not affected by changing the feedstock. However, the share of advanced feedstock results in a share of advanced bioethanol (batch process).

Currently, 562,800t/y corn is processed to bioethanol. In Case A this amount would be decreased to 537,184t/y corn. Additionally, 20,000m^3/y industrial ethanol-containing waste and 9,680m^3/y wine alcohol would be processed. In Case B, the amount of corn would be further decreased to 492,937t/y and co-processed with 128,680t/y corn stover, 20,000m^3/y industrial ethanol-containing waste and 9,680m^3/y wine alcohol. (Table 5) The water content is estimated at: corn 14 wt.%, industrial waste 90 vol.% and wine alcohol 7 vol.%.

Table 5: Feedstock input

Feedstock	Current situation	Case A	Case B
Corn (t/y)	562,800	537,184	492,937
Industrial waste (m^3/y)	-	20,000	20,000
Wine alcohol (m^3/y)	-	9,680	9,680
Corn stover (t/y)	-	-	128,680

Wine alcohol (wine lees) and corn stover are considered as feedstocks for advanced biofuel production, according to RED II, Annex IX Part A. For the industrial ethanol-containing waste it is currently unclear, since it depends on national legislation that has not yet been published. The costs of the feedstocks are given in Table 6. The price of transport is already included.

Table 6: Feedstock costs (according to BCyL)

Feedstock	Value	Unit
Corn	200.0	€/t
Wine alcohol	670.0	€/m³
Industrial waste	17.0	€/m³
Corn stover	46.9	€/t

The total feedstock costs for each case are as follows, see Table 7.

Table 7: Total feedstock costs

Feedstock	Current situation	Case A	Case B
Corn	112,560,000	107,436,800	98,587,400
Industrial waste	0	340,000	340,000
Wine alcohol	0	6,485,600	6,485,600
Corn stover	0	0	6,035,092
Sum €/y	**112,560,000**	**114,262,314**	**111,448,093**

Castilla y León is the area with the highest corn production in Spain. Corn is mainly from León, Valladolid, Salamanca, Palencia and some from Extremadura and Andalusia. Currently, nearly all corn processed by BCyL is local and transported by truck. The main suppliers are located less than 5km from the plant. Sometimes, BCyL gets corn from Ukraine, Turkey, Brazil, Canada, etc., which is transported by ship to the ports in Aveiro or Gijón and reloaded to train.

6 Market assessment

This chapter provides an overview on the European fossil fuel, bioethanol and advanced bioethanol market, including production, consumption and trade. Additionally, policy framework, such as the blending mandates are addressed. Finally, expected market development and scenarios are described. The focus of the investigation lies on the markets of Spain, France and Portugal.

6.1 Market overview

6.1.1 EU petrol market

In 2017, fuel sales for road transport in the EU amounted to 270,668 million litres diesel and 103,766 million litres petrol. Whereas diesel sales are increasing, petrol sales are decreasing, except increasing sales from 2016 to 2017. The majority of petrol sold had an octane number of 95. (EEA, 2018) Petrol consumption is expected to decrease continuously until 2030 and stabilize afterwards. The share of diesel is expected to remain unchanged until 2030 and slightly decrease until 2050. (Capros, 2016)

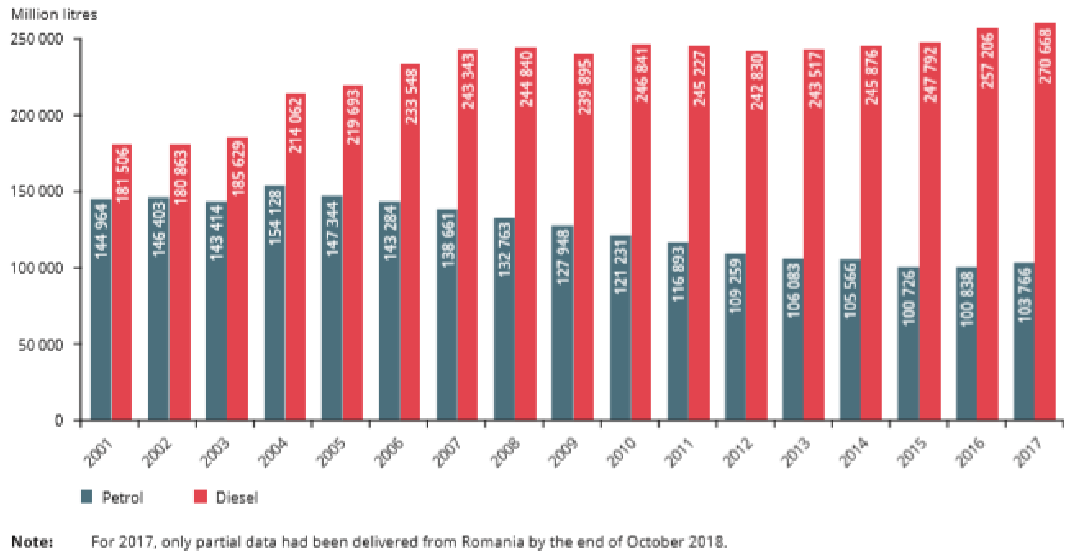


Figure 5: European diesel and petrol sales in 2017 in million litres (EEA, 2018)

87.8% of the petrol sold in 2017 in the EU contained bioethanol. 71.9% was sold as E5 blend, 15.7% as E10 blend and 0.1% as E85 blend. These numbers are shown in Figure 6. The European market share of E85 is comparably small.

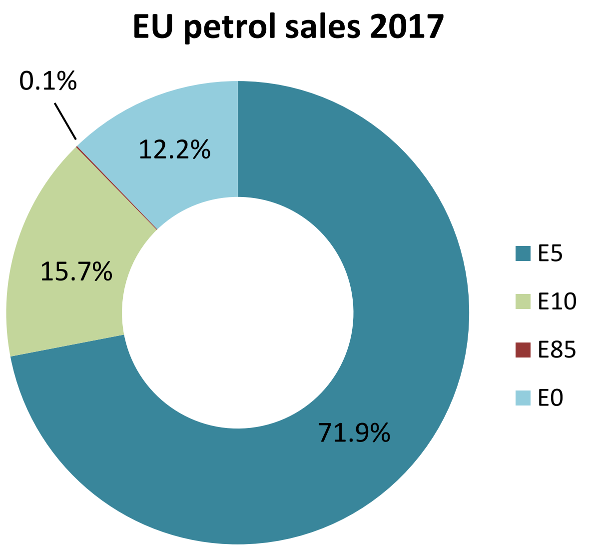


Figure 6: Petrol sales containing bio components (EEA, 2018)

In 2017, Spanish total petrol sales amounted to 6,467 million litres, all of it E5. In France total petrol sales amounted to 10,257 million litres, 60.45% of it E5, 38.40% E10 and 1.15% E85. France belongs to the countries with the highest share of E85. In Portugal total petrol sales amounted to 1,382 million litres, 92.3% E5 and 7.7% E10. (EEA, 2018)

6.1.2 EU bioethanol market

Production

The EU produced about 3.53 million tonnes (equal 4,446 million litres) of bioethanol in 2017. The production capacity is estimated to be about 7.07 million tonnes (equal 8,904 million litres). 81% of the produced bioethanol is used in the transport sector, 10% in industry (except food) and 9% for the food sector. In 2018 bioethanol production increased from about 1.7%, to 3.57 million tonnes (equal 4,496 million litres). One reason for that development was the overall increase in domestic consumption of petrol-type fuels, compared to diesel. (EurObserv'ER, 2019)

Figure 7 shows the development of first-generation bioethanol production and consumption in the EU from 2007 to 2018. One can see the formation of a market equilibrium, through an alignment of supply and demand. The share of bioethanol in petrol consumption is about 5% and remained unchanged over the last years. (Neumann, et al., 2019)

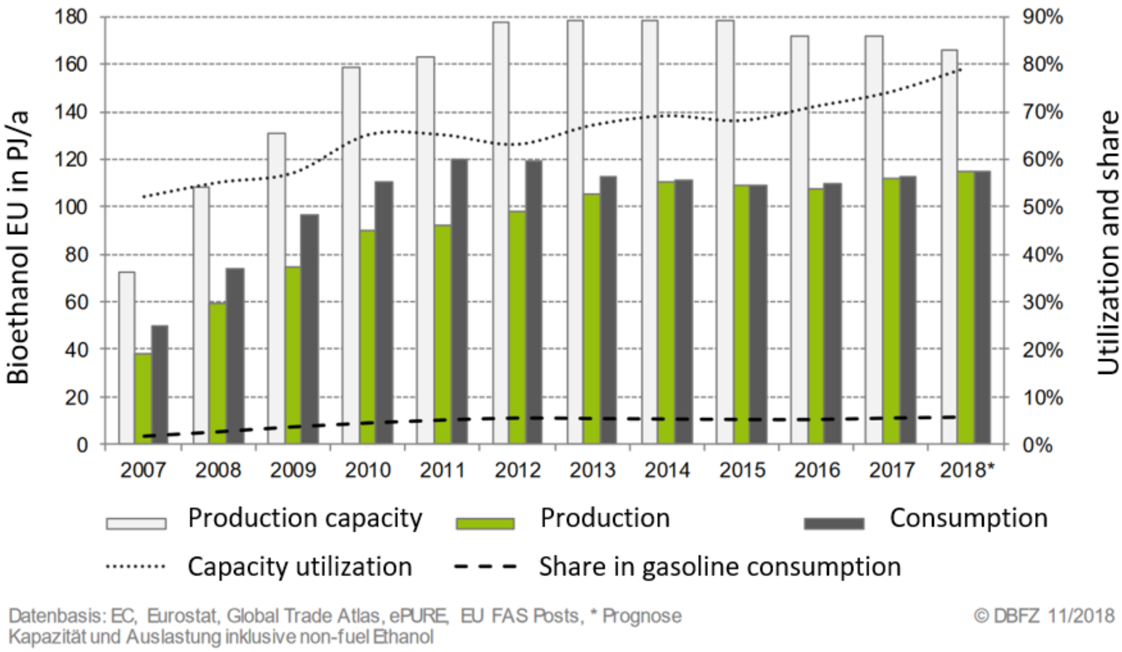


Figure 7: Development of bioethanol market (Neumann, et al., 2019)

More than 50% of bioethanol produced in the EU comes from Germany, France and the UK. Main European bioethanol production companies are listed in Table 8.

Table 8: Main bioethanol production companies in the EU in 2018 (EurObserv'ER, 2019)3

Company	Location of plants	Production (million litres)	Feedstocks
Tereos	France, Czech Republic, UK, Italy	1,200	Sugar juice, wheat
Crop Energies	Germany, Belgium, France, UK	967	Sugar juice, wheat, corn, triticale
Vertex	Spain, France	762	Corn
Vivergo	UK	420	Wheat
Cristal Union	France	320	Sugar juice, wheat
Agrana	Austria	250	Wheat, corn

In 2018, bioethanol production capacity in Spain amounted to 464 ktoe (equal 917 million litres), which remains unchanged for several years. (EUROSTAT, 2020) Capacity is provided by three bioethanol facilities, owned by Vertex Bioenergy. In Spain, first-generation bioethanol production in 2018 amounted to 522 million litres)[4]. This indicates a capacity utilization of about 57%.

France had a bioethanol production capacity of 1,092 ktoe (equal 2,158 million litres), which also remained on the same level for several years. (EUROSTAT, 2020) In 2016, bioethanol production amounted to 386 ktoe (equal 763 million litres) (Calderón, Gauthier, & Jossart, 2018), which indicates a capacity utilization of about 35%.

Currently, there is no bioethanol production in Portugal. (EUROSTAT, 2020)

<u>Consumption</u>

The consumption of biofuels in the European transport sector increased by 12.2% between 2017 and 2018 (in energy content). In 2018 the consumption reached about 17 Mtoe (equal 33,599 million litres) of biofuels, 81% of which were biodiesel, 17.9% bioethanol and 1.1% biogas. 13,906 ktoe (equal 27,484 million litres) were dedicated to the EU transport sector. (EurObserv'ER, 2019) The increase of biofuel consumption is mainly due to legal obligations and policy support (e.g. tax incentives). Price of fossil fuels is highly influencing the use of biofuels. In 2018 the crude oil price peaked at 76 USD per barrel. (EurObserv'ER, 2019) Currently, in 2020, the crude oil price is falling sharply due to the Covid-19 pandemic. This is resulting in an overall declining economic output and further it will likely result in lower biofuels consumption.

[3] https://www.cnmc.es/estadistica/estadistica-de-biocarburantes (Spanish only)

[4] https://www.cnmc.es/estadistica/estadistica-de-biocarburantes

Figure 8 shows the biofuel consumption in respective countries of the EU in 2018 by fuel type. Bioethanol consumption is shown in dark green. The consumption of bioethanol for transport amounted to 2,990.5 ktoe (equal 5,910 million litres) in the EU in 2018. Germany had the highest bioethanol consumption with 748.0 ktoe (equal 1,478 million litres), followed by France with 582.8 ktoe (equal 1,151 million litres), UK with 387.2 ktoe (equal 765 million litres), Poland with 172.8 ktoe (equal 342 million litres), the Netherlands with 169.7 ktoe (equal 335 million litres) and Spain with 153.8 ktoe (equal 304 million litres). Portugal had a bioethanol consumption of 7.6 ktoe (equal 15 million litres). (EurObserv'ER, 2019)

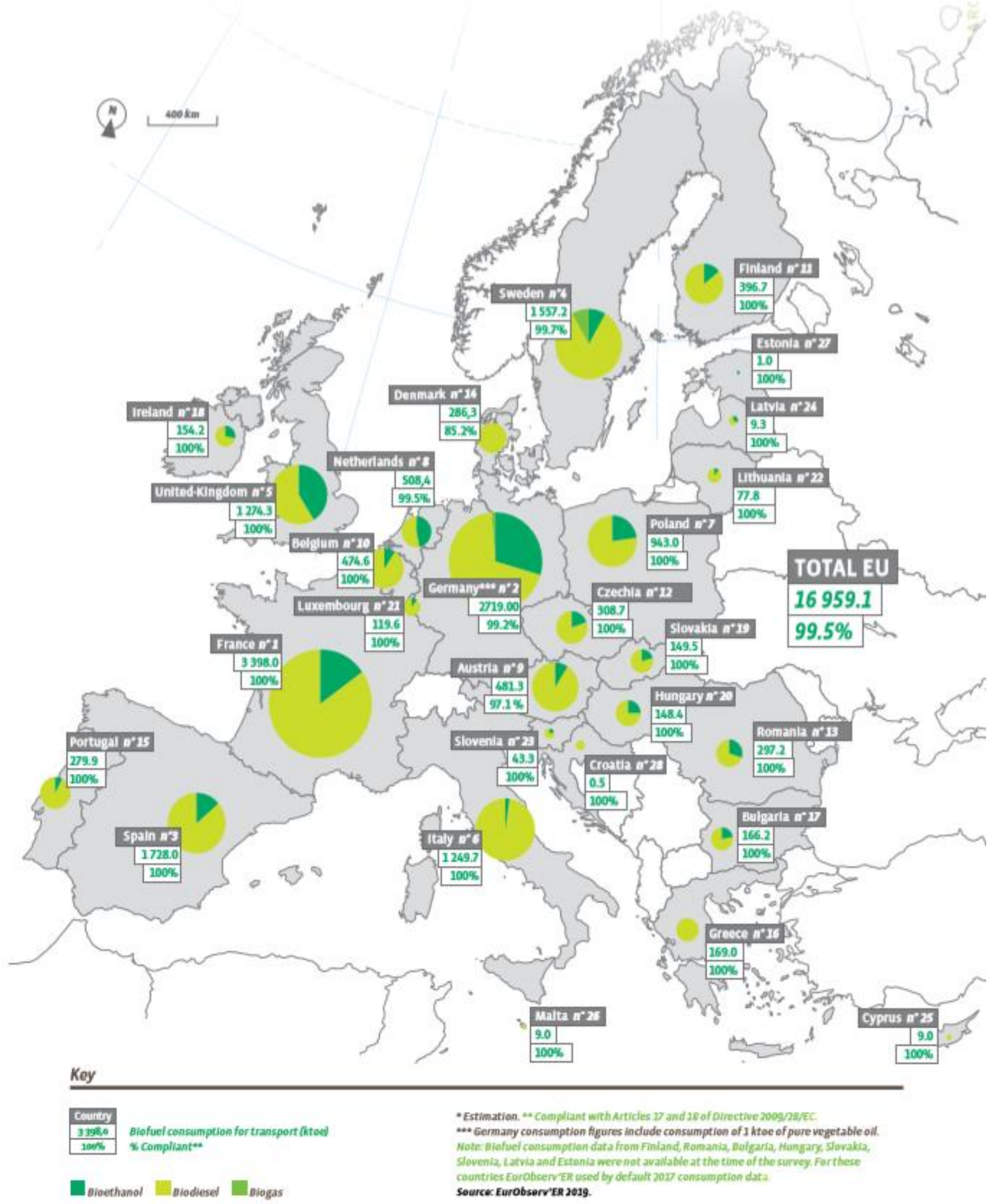


Figure 8: Biofuels consumption for transport in the EU in 2018 in ktoe (EurObserv'ER, 2019)

Bioethanol for the transport sector is either directly blended with fossil fuels or converted to ETBE (Ethyl-tert-butylether) before blending. Consumption of bioethanol is increasing in Spain, UK, Poland, Italy and the Netherlands. Reasons were changes in legislation, e.g. in Spain and the Netherlands the common incorporation quotas are increased gradually. France additionally invested in infrastructure of E10 and E85 pumps. Germany decreased ETBE, which favoured E5 consumption. Consumption is decreasing in UK, contrary to the increasing biodiesel consumption. (EurObserv'ER, 2019)

France was the main consumer of biofuels in 2018. Growth in biofuels consumption was mainly driven by increased bioethanol consumption. Investment in infrastructure for E10 and E85 (895 stations), the support of E85 fuel conversion kits for gasoline vehicles and the attractive price for E85 (0.7€/l) were main drivers, which leaded to an increase in flex-fuel vehicles too. (EurObserv'ER, 2019)

The consumption of E10 blend is increasing in France, where already 32% of petrol sales were E10 in 2016. Only Finland had a higher share of E10, namely 63%. The share of E10 in Germany was 12.6%. (IRENA, 2019) In the Netherlands fuel distributors must offer E10 since 2019. (Flach, Lieberz, & Bolla, 2019) The majority of Belgian gasoline became E10, due to an increase of bioethanol mandate in 2017. However, gasoline without any bioethanol is available for use in older cars and small engines. (Lieberz, 2019) Outside of Europe, E10 is available in the USA, Australia, New Zealand and Brazil. (IRENA, 2019)

Main markets for E85 are in Sweden and France. E10 and E85 are increasing in France due to investments in infrastructure and competitive prices. Also, in Sweden E85 demand is increasing, but due to increasing gasoline prices and tax exemptions. However, tax exemption ended in 2016, which is in favour of gasoline over E85. (Flach, Lieberz, & Bolla, 2019)

Another bioethanol-containing fuel quality is ED95. This fuel consists of 95% bioethanol and 5% additives, and it is suitable for use in diesel engines. ED95 is currently marketed in France, Sweden, Norway and Finland. (E4tech, 2019)

<u>Trade</u>

About 618 million litres of first-generation bioethanol was imported to the EU in 2018. Main origins of bioethanol imports to the EU in 2018 were: Pakistan (127 million litres), USA (101 million litres), Guatemala (85 million litres), Brazil (73 million litres), Russia (61 million litres), Paraguay (56 million litres), South Africa (18 million litres), Moldova (14 million litres), Ukraine (7 million litres) and Bolivia (7 million litres). (ePURE, 2018) Main global bioethanol producers are USA, Brazil and EU. Main bioethanol consumer is the USA, with a high domestic production and import mainly from Brazil. (Maluf de Lima & Rumenos Piedade Bacchi, 2018)

In 2018, Spain imported 12 ktoe (equal 24 million litres) bioethanol and exported 174 ktoe (equal 344 million litres). France imported 133 ktoe (equal 263 million litres) bioethanol and exported 260 ktoe (equal 514 million litres). This indicates a low import dependency for bioethanol. Since Portugal is not producing bioethanol itself, it is dependent on imports. In 2018, Portugal imported 7 ktoe (equal 14 million litres) bioethanol. (EUROSTAT, 2020)

6.1.3 EU advanced bioethanol market

Production

The current production of advanced bioethanol in the EU is estimated at around 50 million litres. (Flach, Lieberz, & Bolla, 2019)

Most advanced bioethanol producers utilize agricultural residues, such as wheat straw or corn stover. Borregaard, Domsjö Fabriker and AustroCel Hallein are utilizing brown liquor from wood pulping for their production. St1 is fermenting organic wastes to bioethanol. (ETIP Bioenergy, 2020)

Table 9 lists operational advanced bioethanol production facilities in Europe. The joint capacity amount to 63,420 t/y (equal 79.9 million litres). This indicates a current capacity utilization of about 60%.

Table 9: Operational advanced bioethanol production facilities5

Company	Country	City	TRL[6]	Start-up year	Capacity t/y (million litres)
Borregaard Industries ChemCell Ethanol	Norway	Sarpsborg	9	1938	15,800 (19.9)
Domsjö Fabriker	Sweden	Ornskoldsvik	8	1940	19,000 (23.9)
St1 Cellulonix Kajaani	Finland	Kajaani	6-7	2017	8,000 (10.1)
St1 Etanolix Jokioinen	Finland	Jokioinen	9	2011	7,000 (8.8)
Chempolis Ltd. Biorefining Plant	Finland	Oulu	6-7	2008	5,000 (6.3)
St1 Etanolix Gothenburg	Sweden	Gothenburg	9	2015	4,000 (5.0)
Clariant Sunliquid	Germany	Straubing	6-7	2012	1,000 (1.3)
St1 Etanolix Hamina	Finland	Hamina	9	2008	1,000 (1.3)
St1 Etanolix Vantaa	Finland	Vantaa	9	2009	1,000 (1.3)
St1 Etanolix Lahti	Finland	Lahti	9	2009	1,000 (1.3)

[5] http://www.etipbioenergy.eu/images/ETIP-B-SABS2_WG2_Current_Status_of_Adv_Biofuels_Demonstrations_in_Europe_Mar2020_final.pdf

[6] Technology readiness level

IFP Futurol	France	Bucy-Le-Long	6-7	2016	350 (0.4)
SEKAB Biorefinery Demo Plant	Sweden	Ornskoldsvik	8	2004	160 (0.2)
Borregaard BALI Biorefinery Demo	Norway	Sarpsborg	6-7	2012	110 (0.1)

Table 10 lists advanced bioethanol production facilities, which are currently under construction. The joint capacity amounts to 96,000 t/y (equal 120.9 million litres). (ETIP Bioenergy, 2020)

Table 10: Advanced bioethanol production facilities under construction

Company	Country	City	TRL	Start-up year	Capacity (t/y)
Clariant Romania	Romania	Podari	8	2021	50,000 (63.0)
AustroCel Hallein	Austria	Hallein	8	2020	30,000 (37.8)
ArcelorMittal Ghent Steelanol	Belgium	Ghent	9	2020	16,000 (20.2)

Following advanced bioethanol production facilities, with a joint capacity of 380,000 t/y (equal 478.6 million litres), are planned for the next years (see Table 11).

Table 11: Planned advanced bioethanol production facilities

Company	Country	City	TRL	Start-up year	Capacity (t/y)
Kanteleen Voima Nordfuel biorefinery	Finland	Haapavesi	6-7	2021	65,000 (81.9)
INA	Croatia	Sisak	8	-	55,000 (69.3)
Enviral Leopoldov Site	Slovakia	Leopoldov	9	-	50,000 (63.0)
St1 Cellulonix Kajaani 2	Finland	Kajaani	8	2024	40,000 (50.4)
St1 Cellulonix Pietarsaari	Norway	Pietarsaari	8	2024	40,000 (50.4)
St1 Cellulonix Follum	Norway	Ringerike	8	2024	40,000 (50.4)
Versalis Crescentino restart	Italy	Crescentino	8	2020	40,000 (50.4)
ORLEN Poludnie	Poland	Jedlicze	9	-	25,000

Jedlicze Site					(31.5)
Sainc Energy Limited Cordoba	Spain	Villaralto	8	2020	25,000 (31.5)

The current production capacity of advanced bioethanol in Europe amounts to 63,420 t/y (equal 79.9 million litres). Further 96,000 t/y (equal 120.9 million litres) of capacity are currently under construction. Additionally, a capacity of 380,000 t/y (equal 478.6 million litres) is planned, most of it until 2024. If all of the planned plants will be constructed, the total advanced bioethanol production capacity of Europe will be 539,420 t/y (equal 679.4 million litres).

In Spain one advanced bioethanol plant, with a capacity of 25,000 t/y (equal 31.5 million litres) is planned for 2020. France already has an operational plant, with a capacity of 350 t/y (equal 0.4 million litres). However, advanced biofuel consumption rises slowly in France. (EurObserv'ER, 2019) Portugal is not producing advanced bioethanol and there are no construction plans known.

6.2 Policy framework and blending mandates

Current EU policy for renewable energy is set in the EU Energy and Climate Change Package (CCP) and the Fuel Quality Directive (FQD). The Renewable Energy Directive is part of the CCP and specifies requirements for liquid biofuels. Sustainability requirements are set in the Indirect Land Use Change (ILUC) Directive. (Flach, Lieberz, & Bolla, 2019)

The RED II, published in 2018, is the amendment of the original Renewable Energy Directive. It defines sustainability and GHG emission criteria. GHG emission values and calculation rules for liquid biofuels are provided in Annex V. GHG savings thresholds for biofuels in transport are 65%, when the plant goes into operation from January 2021. In order to avoid ILUC, the RED II set limits for ILUC-risk biofuels. The limit affects counting towards national targets, but not production and trade itself. The limit will decrease over the years and reach zero in 2030. There are exemptions and certifications for low ILUC-risk biofuels. (EurObserv'ER, 2019)

The share of renewable energy in final energy consumption has to be at least 14% by 2030. RED-II additionally sets targets for advanced biofuels of 0.2 % advanced biofuels by 2022, 1 % by 2025, and 3.5 % by 2030. Advanced biofuels are defined as biofuels produced of feedstocks, listed in Annex IX Part A. In order to reach the 14% target the share of advanced biofuels can be double counted in the national energy balance (considering the energy content twice). The RED II caps first generation biofuels with 7%. Additionally, there is a 1.7% cap for biofuels produced from feedstocks from Annex IX, Part B by 2030.

In line with the earlier Renewable Energy Directive and the ILUC directive, Member States have set various national blending mandates and double counting rules, which are listed in Table 12. The transposition of RED II into national legislation has yet to be done.

Table 12: Mandates by Member States for 2020 (Lieberz, 2019)

Country	% Overall	% Biodiesel	% Bioethanol	Double counting
Austria	8.75			Yes, waste and residues including lignocellulosic materials
Belgium		8.5	8.5	Possible upon approval
Bulgaria		5.0 conv. 1.0 adv.	10.0	No
Croatia	8.81	7.49	1.0	Yes, advanced and waste-based biofuels
Czech Republic	10.0	6.0	4.1	Yes, advanced biofuels
Denmark	5.75			
Finland	20.0			
France		7.7	7.5	Lignocellulosic and waste-based biofuels, max. 0.35% biodiesel, 0.3% bioethanol
Germany				No
Greece		7.0	3.3	No
Hungary		6.4	6.4	No
Ireland	10.0			Yes, UCO and animal fat
Italy	9.0			Advanced biofuels (max. 1%)
The Netherlands	16.4			Yes, waste-based biofuels, excluding UCO and animal fat
Poland	8.5			Yes
Portugal	10.0			Yes, among others lignocellulosic material
Romania	10.0	6.5	8.0	Yes
Slovakia	7.6			Yes
Slovenia	7.5			Yes
Spain	8.5			Yes, among others lignocellulosic material, corn cobs, wine lees[7]
Sweden				
UK	10.6			Yes, waste and residues, energy crops, development fuels

Additionally, some member states (Bulgaria, Denmark, France, Germany, Italy, Slovakia and UK) have set specific national targets for the share of advanced biofuels. These targets vary between 0.05% in e.g. Bulgaria and 1% in e.g. Italy by 2020. Some member states also set caps

[7] Details in Spanish language only: https://www.boe.es/diario_boe/txt.php?id=BOE-A-2018-5890

for crop-based biofuels and GHG emission reduction. Germany and Sweden did not set blending mandates, but GHG emission reduction targets. (Lieberz, 2019)

Spain

The blending mandates in Spain were raised from 4.1% in 2013, 4.3% in 2016, 5% in 2017, 6% in 2018, 7% in 2019 to 8.5% in 2020. These increasing blending mandates result in a growing bioethanol market in Spain, with increasing consumption and export volume. Lignocellulosic material, corn cobs and wine lees are qualified as feedstock for advanced biofuels, and bioethanol made from these feedstocks is therefore double counted in Spain. (Lieberz, 2019)

France

France increased blending mandates from 7% in 2012 to currently 7.5%. Advanced biofuels are double counted in France since 2014. However, the quantity of advanced biofuels that can be double counted is limited (Table 12). This should hinder an increase of advanced bioethanol import by supporting domestic first-generation biofuels production. (Lieberz, 2019) Additionally, France sets following advanced biofuels targets, 1.8% in 2023 and 3.8% in 2028 for the petrol sector, and 0.85% in 2023 and 2.2% in 2028 for the diesel sector. (EurObserv'ER, 2019)

Portugal

Portugal increased blending mandates from 5.5% in 2014, 7.5% in 2015 to 10% in 2020. In 2019 blending mandates were decreased to 7% for one year. (Lieberz, 2019) Double counting is, among others, valid for lignocellulosic raw materials. However, bioethanol is expected to have minor contribution for reaching the blending mandate, since the gasoline market is small and further decreasing in Portugal. Additionally, Portugal does not produce bioethanol. (Guerrero, 2017)

6.3 EU bioethanol market development

According to the EU Reference Scenario from 2016, gasoline consumption is expected to decrease continuously until 2030 and stabilize afterwards, which can be seen in Figure 9. Reasons for that development are more stringent emission requirement for emission standards after 2020 (Capros, 2016) Due to blending mandates and incentives, demand for bioethanol will rise, even when demand for gasoline decreases. (E4tech, 2019)

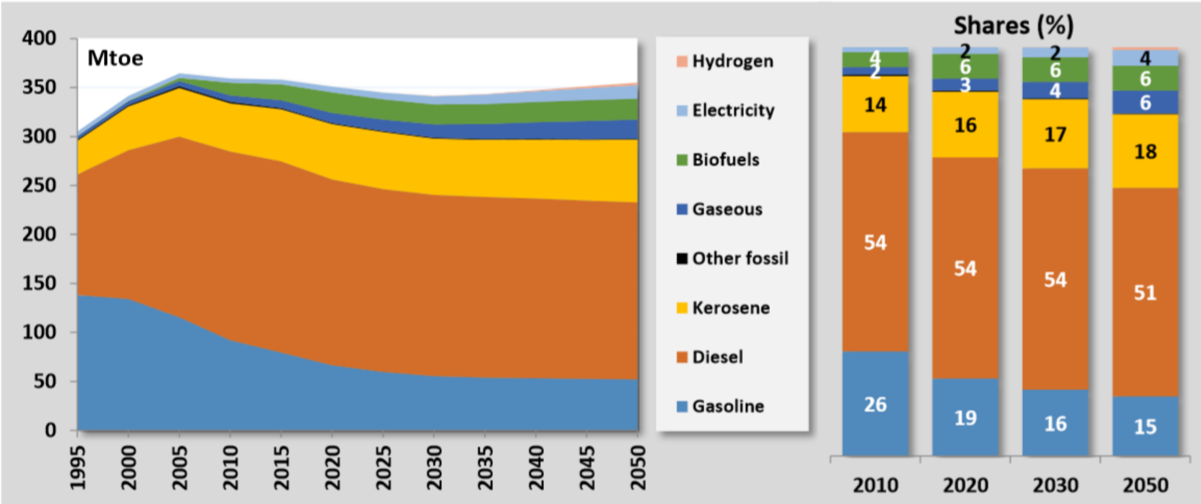


Figure 9: Scenario - Final energy demand in EU transport by fuel type

Current policy scenarios, such as the EU Reference Scenario, are not suitable for reaching Paris Climate Targets. These scenarios show the path that is possible with the current political framework. In order to achieve climate targets, further political measures are necessary. Scenarios, aiming for significant reduction of GHG emissions, show a much higher contribution of biofuels, and also electricity. One example is the 2DS (2°C Scenario) of IEA, published in the report "Energy Technology Perspectives 2017". Figure 10 shows the final energy demand of the global transport sector in the 2DS. Total global transport energy demand will amount to about 110 EJ in 2030 and will decrease to 100 EJ in 2060. Biofuels are expected to contribute more than a quarter to the energy demand of the transport sector in 2060.

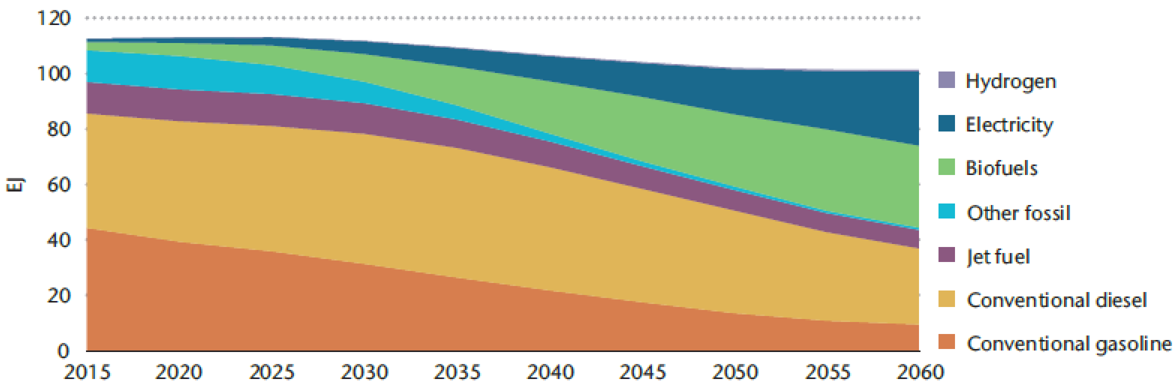
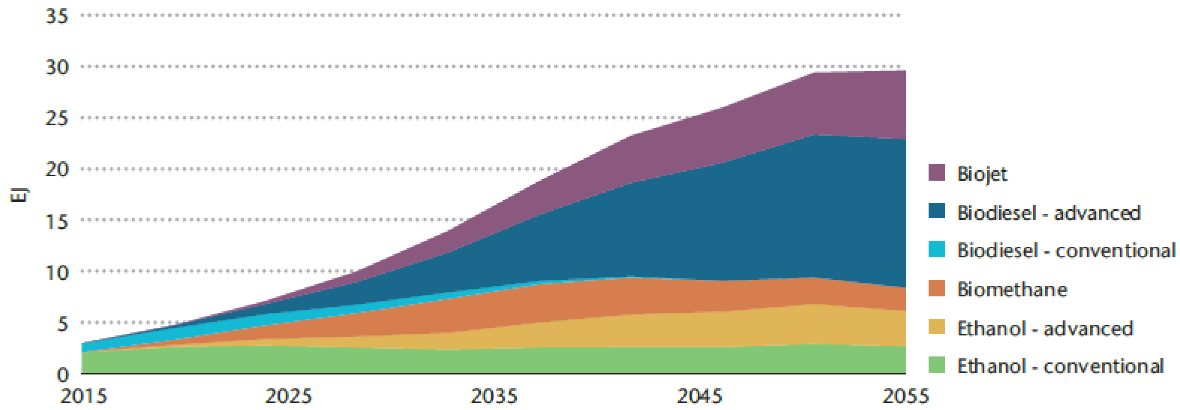


Figure 10: Final global transport energy demand in the 2DS by IEA

IEA additionally provides final global energy demand of the transport sector by fuel type. Figure 11 shows a high contribution of biodiesel, followed by biojet, bioethanol and biomethane. Total amount of energy, provided by biofuels is expected to be about 12 EJ in 2030 and nearly 30 EJ in 2060. About 2.5 - 5 EJ (equal to 118- 235,9 million l) are expected to be provided by bioethanol, conventional and advanced. (IEA , 2017)



Notes: Conventional biodiesel refers to crop-based FAME biodiesel; advanced biodiesel refers to a range of advanced biofuels suitable for use in the diesel pool.

Figure 11: Biofuels final global transport energy demand by fuel type in the 2DS by IEA

There are already initial signals from the oil industry, which see low-carbon liquid fuels as an important measure for achieving climate targets. Fuels Europe published their Vision 2050 and a press release, with the core statement that in 2050, low-carbon liquid fuels could reduce net GHG emissions from passenger cars and vans by 87% compared to 2015.[8]

Consumption of biofuels is expected to increase significantly, mainly due to legal obligations. However, double counting and caps for first-generation biofuels will minder that effect. The theoretically maximum consumption of first-generation biofuels in the EU (including UK) will be 23 Mtoe (equal 45.5 billion litres) until 2022 and 21 Mtoe (equal 41.5 billion litres) until 2030. The decrease is explained by legal framework, such as caps. The theoretical maximum production of biofuels (first-generation and advanced biofuels) in the EU (including UK) is estimated to be 36 Mtoe (equal 71.2 billion litres), which is more than twice the volume of 2018. Overall biofuels consumption in the transport sector could further increase theoretically up to 30 Mtoe (equal 59.3 billion litres) until 2030. (EurObserv'ER, 2019)

The IEA estimates that global bioethanol production will reach 121 billion litres by 2030, which would be an increase of 23% compared to 98 billion litres in 2015. (E4tech, 2019) Main bioethanol markets are in Brazil and the USA. These two markets are independent in the short term, but will influence each other in the long term. (Dutta, 2020)

A decline in average production costs, due to innovative technologies and resulting gain of productivity is increasing the competitiveness of bioethanol and will further lead to market growth. Additionally, awareness has to be risen, for example promoting flex fuel vehicles. (Maluf de Lima & Rumenos Piedade Bacchi, 2018)

In 2017, about 4% of first-generation bioethanol consumed in the EU were imported. Imports were decreasing from about 20% in 2012, due to anti-dumping measures. A repeal of anti-dumping duties on US imports and a change to the Mercosur tariff quota would facility trade

[8] https://www.fuelseurope.eu/clean-fuels-for-all/vision-2050/

between EU, USA and Mercosur countries. (E4tech, 2019) If these measures are implemented, imports could increase again in the future.

Main barriers for the USA for exporting bioethanol to the EU are high import duties and sustainability criteria (50% GHG reduction compared to fossil fuels). (Flach, Lieberz, & Bolla, 2019)

Advanced biofuels

According to the Sub Group of Advanced Biofuels (SGAB), HVO and lignocellulosic bioethanol are the only advanced biofuels technologies which are ready for the market. In order to reach European transport decarbonisation targets, lignocellulosic bioethanol needs to be supported. For example, by higher blends, such as E20 and E85 or by entering the diesel sector with ED95. (Maniatis, Landälv, Waldheim, van der Heuvel, & Kalligeros, 2017)

Based on the data of the EU Reference Scenario and considering the 7% cap and the ILUC Directive, 10-15 Mtoe (equal 19.8-30.0 billion litres) of advanced bioethanol production is feasible by 2030. About the same amount of advanced renewable diesel (HVO) is feasible by 2030. These amounts of advanced biofuels would represent 6% to 9% of the total energy use in the European transport sector, without double counting. In order to realize this scenario for advanced bioethanol, each year 5-10 plants would need to be installed. According to SGAB, there would be enough biomass, waste streams and residues available to reach this scenario. (Maniatis, Landälv, Waldheim, van der Heuvel, & Kalligeros, 2017)

Main barriers for cellulosic bioethanol are high research and production costs and regulatory uncertainties. (Flach, Lieberz, & Bolla, 2019) Feedstock availability, quality and price variations are not seen as a burden for an increase of advanced bioethanol production. (IRENA, 2019)

Currently, there is no global trade with advanced bioethanol. A scenario of a study conducted by E4tech estimates a supply of advanced bioethanol outside of the EU of about 3.6 billion litres by 2030. Half of it is expected to be produced in the USA. It is further estimated that only about 0.9 billion litres would be available for import to the EU. This is due to incentives for advanced bioethanol within the USA. It is estimated that there would be enough lignocellulosic waste and residues to produce up to 718 billion litres advanced bioethanol worldwide by 2030. This indicates that feedstock availability is not limiting future EU imports. (E4tech, 2019)

6.3.1 Bioethanol blends

In the EU about 90% of petrol cars are compatible with E10. Especially cars produced after 2010 are likely to be compatible.

From a supply perspective, higher blends, such as E15, E20 or even E85 would not be a challenge, however huge investments in infrastructure would be needed. Governmental promotion for e.g. E85 and flex-fuel vehicles would be needed to generate a market pull for lignocellulosic bioethanol. (IRENA, 2019)

E4tech conducted a study in order to calculate bioethanol demand in two scenarios. In scenario 1, 20% E20 and 80% E10 are assumed. In scenario 2 it is assumed that 100% of petrol sales in the EU are E20 blends. (E4tech, 2019)

- For scenario 1 there would be a need for bioethanol of 8.8 billion litres (additional 3.5 billion litres above 2017) by 2030. The additional amount can be reached by using underutilized capacities (2.9 billion litres) and cellulosic bioethanol (2.8 billion litres). Without double counting a share of 0.5% advanced biofuels could be reached. In comparison, the target of RED II is 1.75% (considering double counting). (E4tech, 2019)
- Scenario 2 requires 17.1 billion litres (additional 9.9 billion litres above 2017) bioethanol. For reaching this amount, an increase of first-generation bioethanol production (2.9 billion litres) and capacities (4.1 billion litres) and therefore additional land for crops would be needed. Additionally, lignocellulosic bioethanol production (2.8 billion litres) and first-generation bioethanol imports (0.9 billion litres) would need to be increased. (E4tech, 2019)

The results show that bioethanol demand will increase, even though gasoline demand is decreasing until 2030. And it shows that biomass availability and the 7% cap on crop-based biofuels would not be a burden to achieve these scenarios. However, if 100% E20 would be introduced, the bioethanol market would need to grow strongly. (E4tech, 2019)

6.3.2 Costs for advanced bioethanol production

In general, biofuels are more expensive than fossil fuels. A main part of biofuel production costs are the costs for feedstock. Therefore, biofuels based on waste-streams seems to be the most competitive, except if there is an intensive pre-treatment of the waste stream necessary. It is expected that mid- to long-term, competitiveness of advanced bioethanol will increase, due to economies of scale and learning curve effects. (Festel, Würmseher, Rammer, & Boles Eckhard, 2014) However, production costs of advanced biofuels have not decreased in recent years. On average, feedstock costs represent 33-39% of total costs and operation costs represent 33-42%. (Witcover & B. Williams, 2020)

Table 13 shows total lignocellulosic bioethanol production costs in a low, medium and high scenario. According to that, production costs vary between 85 and 158 €/MWh. Considered are: capital costs, costs for feedstock, enzymes and operation and maintenance. The energy conversion efficiency is estimated to be 40%. (Landälv, Waldheim, Maniatis, van den Heuvel, & Kalligeros, 2017) The report “Advanced Biofuels – Potential for Cost Reduction”[9], published by IEA Bioenergy Task 39 in 2020, confirmed that these cost estimations are still reasonable.

[9] http://task39.sites.olt.ubc.ca/files/2020/02/Advanced-Biofuels-Potential-for-Cost-Reduction-Final-Draft.pdf

Table 13: Production costs of lignocellulosic bioethanol (Landälv, Waldheim, Maniatis, van den Heuvel, & Kalligeros, 2017)

	LOW	MEDIUM	HIGH
	Low (2570 EUR/kW) Capital 20y/8% Feed at 10 EUR/MWh EUR/MWh	Low (2570 EUR/kW) Capital 15y/10% Feed at 13 EUR/MWh EUR/MWh	High (3650 EUR/kW) Capital 15y/10% Feed at 20 EUR/MWh EUR/MWh
Capital	32	42	60
Feedstock	25	33	50
Enzymes	15	15	30
Other O&M	13	13	18
Total	85	103	158

Figure 12 shows the minimum selling price for cellulosic bioethanol. For the calculation, an investment of 270 million USD for a plant producing 90,000m³ (66MW, 8,000h) bioethanol was assumed for 2008. It is further assumed that this investment fall to 190 million USD in 2016. This is equal to an investment of 3.65 €/kWh in 2008, falling to 2.57 €/kWh in 2016. 2.57 €/kWh and a capital corresponding to 15 years and 10% weighted average cost of capital (WACC) results in a cost of capital for lignocellulosic bioethanol production of 42 €/MWh. The minimum selling price of lignocellulosic bioethanol, according to this calculation, is between 75 €/MWh and 150 €/MWh. (Landälv, Waldheim, Maniatis, van den Heuvel, & Kalligeros, 2017)

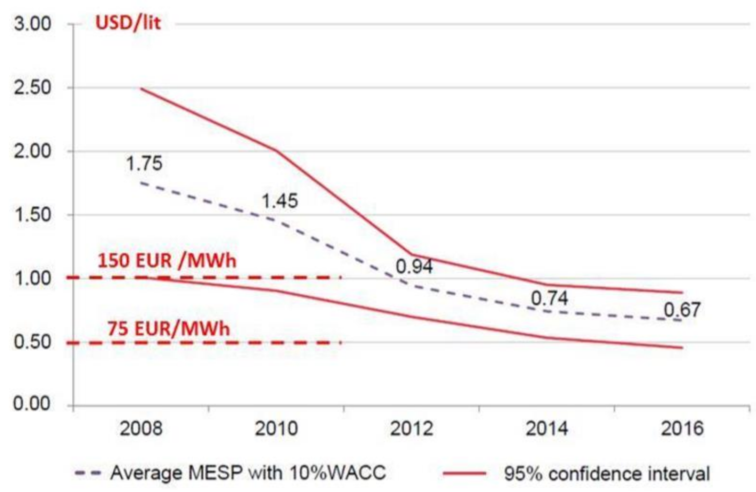
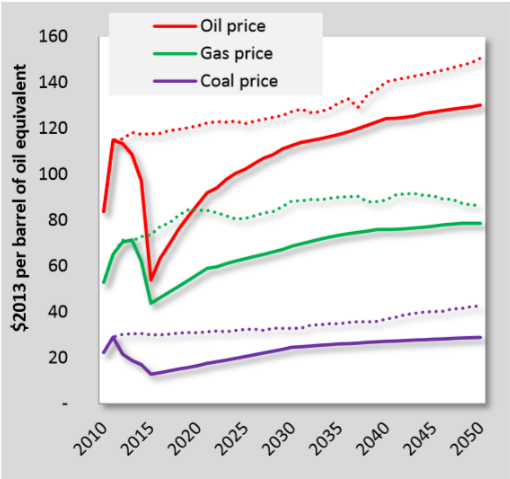


Figure 12: Minimum (cellulosic) ethanol selling price (MESP)

The value of bioethanol provided by BCyL amount to 500€/m³, which is equal to 87,72€/MWh and fully in line with the minimum bioethanol selling price.

Following, the value of bioethanol is compared with the crude oil price in order to show competitiveness. The current crude oil price is about 40 USD/barrel, which is equal to about 21 €/MWh (1 USD = 0,89€). However, due to the Covid-19 pandemic, crude oil price dropped and is currently rising again. Because of this fluctuation this value is not expressive. At mid-2019, beginning of 2020, crude oil price varied around 60 USD/barrel, which is equal to 32 €/MWh. The value of 87,72€/MWh is still significantly higher than the current crude oil price.

According to the EU Reference Scenario, published in 2016, the future cost of crude oil is expected to steadily increase until 2050, which can be seen in Figure 13. (Capros, 2016)



Note: Dotted lines represent the previous Reference Scenario

Figure 13: Price fossil fuel import (Capros, 2016)

The crude oil price for 2020 of 90 USD/barrel (equal to about 40€/MWh, calculated with the exchange rate of 1 USD = 0,7255 € from 2013) is highly overestimated in this scenario, due to the prior mentioned fluctuations. For 2030 the scenario projects a crude oil price of 110 USD/barrel, which is equal to about 48 €/MWh. This value is still much lower than the bioethanol value of 87,72€/MWh. This indicates that lignocellulosic bioethanol is not economically competitive to crude oil without further incentives and policy support.

6.4 Summary

Even though petrol sales are decreasing in the EU, bioethanol production and consumption is expected to steadily increase. Spain and France have large petrol markets, whereas the petrol market of Portugal is small, due to its smaller population. Nearly 90% of total EU petrol sales contain bioethanol, mostly in small shares, such as E5 and E10. High blends are rare, but e.g. France and Sweden developed national markets.

Bioethanol production capacities in Spain and France are unchanged for several years and not fully utilized, which indicates growing consumption possibilities. There is no bioethanol production in Portugal. France is one of the biggest producers of first-generation bioethanol with a high domestic consumption. Reasons for that are high investments in E85 infrastructure and support of flex-fuel vehicles. Spain has a high bioethanol consumption as well, which is due to gradually increasing blending mandates. Bioethanol import dependency is small in Spain and France. Whereas, due to a lack of domestic production, it is high in Portugal.

Advanced bioethanol production capacity is growing in Europe, since there is planned capacity, which is more than 8 times compared to the current capacity level. France is already producing small amounts of advanced bioethanol, but market grows slowly. In Spain a production plant is planned. Portugal is not producing first-generation or advanced bioethanol and there are no respective plans known.

Spain increased blending mandates gradually, which results in increasing bioethanol consumption and bioethanol exports. Bioethanol produced from lignocellulosic materials, wine lees and corn stover is double counted.

France is not gradually increasing blending mandates, but has set specific targets for advanced biofuels. Double counting of lignocellulosic bioethanol is limited, in order to avoid increasing import in favour of domestic production.

Portugal has high blending mandates and lignocellulosic bioethanol is double counted. But due to the small petrol market, bioethanol is not expected to have a high contribution in meeting national targets.

Biomass availability and the 7% cap on crop-based biofuels would not be a burden to foster bioethanol market. Main barriers for cellulosic bioethanol are high research and production costs and regulatory uncertainties. Currently and in near future, bioethanol is not competitive to crude oil prices and therefore production is not economic. However, in order to reach the 14% target and the national specific advanced bioethanol targets, lignocellulosic bioethanol is needed, since it is the only advanced biofuel for petrol cars which is ready for the market. This indicates a necessity of policy support and incentives, e.g. an increase in bioethanol blends, such as E10, E20 or E85.

7 Techno-economic assessment

7.1 Technical description

In this technical description, we first discuss the process characteristics of the current situation and thereafter the two retrofit options. In general, Biocarburantes de Castillas y Leon (BCyL) produces first-generation bioethanol from corn. The BCyL plant has a capacity of 562,8 kton of corn which is converted to 241.670 m^3 of bioethanol year-round. The starch is hydrolysed into simple sugars using amylases which are subsequently fermented by yeast. Part of the CO_2 that is released from the fermentation process is recovered and purified. A maximum of 40.000 tonnes CO_2 can be sold to third parties. During ethanol recovery, the water becomes separated from the ethanol fraction which contains the remaining grain, called spent grain. The spent grain can be recovered from the water fraction to produce the side product distillers dried grains (DDGS). Approximately 142.8 kton of DDGS can be produced as side product per year. The process requires 55,7 GWh of electricity and a total of 1 TWh of natural gas.

The first retrofitting option replaces a small part of the feedstock with industrial waste from a yeast production industry and wine alcohol. Both sustainable feedstocks are supplemented within the ethanol recovery process. The process takes in 537 kton of corn and is replete with 20.000 m^3 of industrial waste and 9.680 m^3 of wine alcohol. When the ethanol output remains constant, less input material is required. Specifically, the amount of enzyme and yeast decreases proportional to the amount of feedstock that is replaced. This also means that there is less spent grain to recover for the production of DDGS. In fact, 136 kton of DDGS can be produced from the input material which is almost 7 kton less compared to the current situation. The complete overview of this retrofit including its mass balance is provided in Figure 14.

The second retrofitting option integrates a second-generation facility with the current operating first-generation plant. The main advantage of such integration is the possibility to share units between facilities, such as ethanol recovery, DDGS production, and the utilities. Figure 14 instantly reveals the level of integration as the ethanol recovery operates as central hub within the entire process. Both fermented streams from the first- and second-generation facilities are transferred to the ethanol recovery unit. Furthermore, the stillage from both facilities can be processed within the same DDGS production facility. It must be noted that the DDGS production facility requires an additional dryer in order to process the stillage properly. As a consequence, extra natural gas must be supplemented. The process takes in 493 kton of corn and is replete with 128,5 kton of corn stover, 20.000 m^3 of industrial waste and 9.680 m^3 of wine alcohol. The amount of ethanol produced is identical in all options, however, part of the output in this process consists of bioethanol produced from corn stover (19.000 m^3). Also, an additional facility directly affects the utility requirements. For instance, extra natural gas needs to be supplied to the steam boiler to produce the steam required for the pre-treatment (steam explosion) of corn stover. The complete overview of this retrofit including its mass balance is provided in Figure 14.

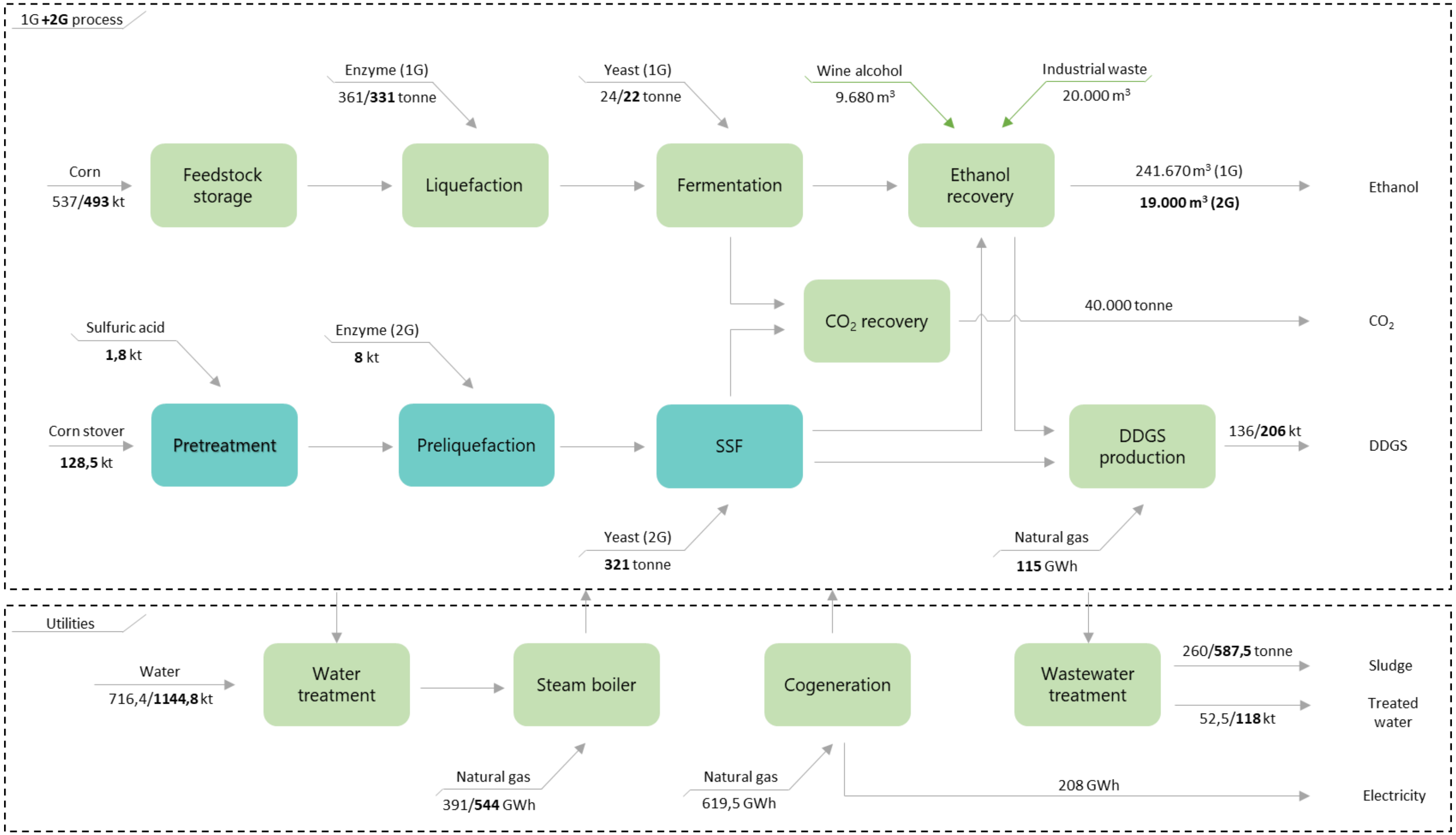


Figure 14: Overview of both retrofit options with corresponding mass balance. The green rectangles depict the first-generation process and the blue rectangles depict the integrated second-generation process. The mass balances of both retrofits are shown underneath the arrows. The numbers corresponding to the second-generation process are shown in bold. The arrows representing wine alcohol and industrial waste are shown in green to clearly indicate that these inputs are associated with the first-generation process. Please note that the ethanol-rich stream from SSF is first introduced into a beer column before the CO_2 recovery stage, however, is not included in the overview.

Logo partners that contributed addresses partners that contributed

7.2 Economic description

Bioenergy is one of the pillars of the EU renewable energy transition towards a low carbon economy. One way in which bioenergy production can be increased is through retrofitting. In this specific case, the production of advanced bioethanol from corn stover in the existing first-generation ethanol plant of Biocarburantes de Castilla y Leon will be investigated. In addition, the possibility to add sustainable feedstock to the existing first-generation facility will be investigated. The sustainable feedstock includes industrial wastes and wine alcohol. This assessment addresses the economic feasibility of co-producing advanced bioethanol and, to a lesser extent, the addition of sustainable feedstock to the existing facility. The costs of both the integrated plant and the addition of sustainable feedstock will be compared to the costs of the currently operating first-generation facility.
The total capital costs (CAPEX) and operating costs (OPEX) are required as input for the economical comparison between each retrofitting option. The input data for the economic assessment are described in Table 14.

Table 14: Input data of advanced ethanol production and the addition of sustainable feedstock in the existing first-generation ethanol plant, used for the economic assessment.

	1G	sustainable feedstock	2G + additional feedstock
Financing (CAPEX)			
Conveyer	€0	€0	€97.689
Steam explosion unit	€0	€0	€5.430.100
Filter	€0	€0	€783.300
Heat exchangers	€0	€0	€562.500
Preliquefactor	€0	€0	€5.437.300
SSF Unit	€0	€0	€14.419.600
Beer well	€0	€0	€563.900
Beer column	€0	€0	€725.900
Evaporator	€0	€0	€412.600
Pumps	€0	€0	€196.858
Industrial waste equipment	€0	€100.000	€100.000
Additional boiler	€0	€0	€1.231.631
Additional dryer	€0	€0	€485.700
Financing (OPEX)[a]			
Cost of corn	€112.560.000	€107.436.720	€98.587.400
Cost of enzyme (1G)	€1.787.940	€1.706.584	€1.463.935
Cost of yeast (1G)	€144.900	€138.575	€118.450
Cost of grid electricity	€4.459.392	€4.321.688	€4.880.048
Cost of natural gas	€25.331.250	€25.272.365	€31.958.750
Cost of water	€929.627	€909.835	€1.453.888
Cost of industrial waste	€0	€340.000	€340.000
Cost of wine alcohol	€0	€6.485.600	€6.485.600
Cost of corn stover	€0	€0	€6.035.092
Cost of sulfuric acid	€0	€0	€141.808
Cost of enzyme (2G)	€0	€0	€2.243.612
Cost of yeast (2G)	€0	€0	€1.846.325
Cost of additional staff	€0	€0	€425.301
Cost of sludge management	€5.590	€5.590	€12.631
Cost of wastewater treatment	€70.875	€70.875	€159.360
Loans (€/year)			
Loans total	€0	€6690	€1.922.174
Earnings (€/year)			
Earnings CO_2	€240.000	€240.000	€240.000
Earnings electricity	€19.750.500	€19.750.500	€19.750.500

Earnings DDGS	€29.988.000	€28.550.508	€43.303.869
Earnings ethanol (1G)	€120.835.000	€115.335.000	€105.835.000
Earnings ethanol (2G)	€0	€8.250.000	€22.500.000

[a] On a yearly basis

CAPEX

By producing advanced bioethanol from corn stover, new equipment needs to be installed. The main advantage of integrated production is that it enables to share units between separate facilities. Still, due to the lignocellulosic nature of corn stover, units such as steam explosion, preliquefaction and SSF are required to hydrolyse the lignocellulosic content of corn stover into its polymeric constituents. Furthermore, conditions such as the temperature do vary significantly between units, and thus multiple heat exchangers are required to control the temperature. The costs of these heat exchangers are combined into a single cost by adding the costs of all single heat exchangers into one overall price. In the case of retrofitting the facility to produce advanced bioethanol, sustainable feedstock is being added to the rectifier unit. Therefore, a storage unit for the sustainable feedstock is required. All individual units with their corresponding costs are listed in Table 14. These costs are the actual installed costs which include the equipment, piping, civil, instrumentation, electrical, insulation and paint costs. To be able to co-produce advanced bioethanol from corn stover, a total investment of € 30.450.000, -is required. When only sustainable feedstock is added as additional ethanol source, only the instalment of industrial waste equipment is necessary, which will require a total investment of € 100.000, -.

OPEX

Due to the partially reallocation of ethanol production from corn to corn stover, less input materials have to be utilised in the existing first-generation facility. Evidently, this affects the overall costs for these input materials. For instance, feedstock allocation is accountable for most of the operational costs. When either simply sustainable feedstock is added or in combination with corn stover, less corn input is required when the ethanol output remains constant. As the price of corn stover is significantly lower compared to corn, the overall cost for feedstock allocation decreases significantly. Still, in the case of producing advanced bioethanol, other input materials need to be added to properly hydrolyse corn stover. These input materials include sulfuric acid, cellulases (referred as “enzyme (2G)”), and additional yeast culture. Cellulases are distinct in function compared to the amylases that are required to hydrolyse corn. The price of cellulases is remarkably lower than amylases on a per kg basis, however, the opposite is true when the overall price is weighed against the ethanol production. While the costs for amylases are determined at €6,5 per m^3 of ethanol, while the costs of cellulases are determined at €118 per m^3 of ethanol. This reflects the higher expenditures for the cellulases compared to the amylases. Furthermore, since the production of advanced ethanol from corn stover requires additional units, the consumption of utilities such as electricity, natural gas and process water increases accordingly. At last, due to the expansion of the existing facility to enable the production of advanced bioethanol, additional staff is required. At least 15 operators and 3 supervisors are required to facilitate the production. The associated costs have been calculated by using average wages of plant operators and plant supervisors in Spain (Table 15).

Earnings

In all cases, a certain amount of CO_2 can be sold to third parties. The maximum amount that can be sold is 40.000 tons per year. In the current situation as well as in the proposed retrofits, the CO_2 production exceeds the maximum amount. Consequently, the rest of the produced CO_2 is emitted. Hence, the earnings from CO_2 are identical for each situation. The main difference in the overall earnings between all cases is caused by a variation in DDGS and ethanol output. Corn stover is an additional source for DDGS production, and therefore, the overall output of DDGS is substantially higher in case of retrofitting a second-generation facility. Also, the ethanol produced from corn stover and additional feedstocks are more valuable to blenders due to the double counting legislation imposed by the REDII for advanced biofuels. Blenders only have to mix half of the mandatory volume with advanced bioethanol in order to comply with blending obligations. As a result, the market price of advanced bioethanol from corn stover is significantly higher compared to first-generation bioethanol. The market price of advanced bioethanol from corn stover is 750 €/m^3, while the price of first-generation bioethanol has been established at 500 €/m^3.

Table 15 shows the various assumptions that were considered for the techno-economic evaluation. The average wage of Plant Operators and Plant Supervisors are extracted from various sources to calculate the extra expenses when implementing the additional 2G unit. Furthermore, the discount rate was selected appropriately to the project risks and the average inflation rate in Spain over the last 10 years. A discount rate of 11% is commonly used for projects concerning the integration of a 2G unit at an existing 1G plant. In addition, it has been established that the average inflation rate in Spain is 1,1% over the last 10 years. Taking into account both factors, the overall discount rate is set to 12%.

Table 15: Assumptions used for the economic assessment.

Item	Value	Source
Average wage Plant Operator	€ 20.500, -/year	https://www.linkedin.com/salary/plant-operator-salaries-in-spain
Average wage Plant Supervisor	€ 39.267, -/year	https://www.salaryexpert.com/salary/job/plant-supervisor/spain
Discount rate	12%	Techno-economic evaluation of integrated first- and second-generation ethanol production form grain and straw; Elisabeth Joelsson et al. 2016
Project lifetime	20 years	Based on depreciation period
Loan payback time	20 years	Based on depreciation period

7.3 Economic assessment

For each of the retrofitting options, a cash flow analysis was carried out. The metrics considered in this assessment are net present value (NPV), internal rate of return (IRR), and the payback period of the retrofit investment. The simple payback period (t_P), i.e. the amount of time required to regain the value of the original investment, is calculated from the capital investment (C_0) and the annual cash flow (R_C):

$$t_p = \frac{C_0}{R_C}$$

NPV is an indicator of how much value an investment or project adds to the business. When the NPV is positive, the retrofit is feasible because value is added to the business. The NPV is determined by the sum of the future cash flows (C_t) generated by the investment over a series of time periods (t). The NPV is a function of the discount rate (i) and utilisation period (n) of the investment:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+i)^t}$$

Finally, the IRR is the average interest rate paid per year. The IRR of an investment is the discount rate at which the net present value of costs of the investment equals the net present value of the benefits of the investment. In other words, IRR can be found when NPV equals zero. More profitable investments will have a higher IRR than investments of low profitability.

The results from the cash flow analysis are shown in Figure 15. The orange bars represent the cumulative cashflow, determined by adding the annual net cashflow to the overall project investment. The blue bars represent the net cashflow, which is a result of the annual losses or profits gained due to a higher OPEX or through OPEX saving respectively when compared to the current situation.

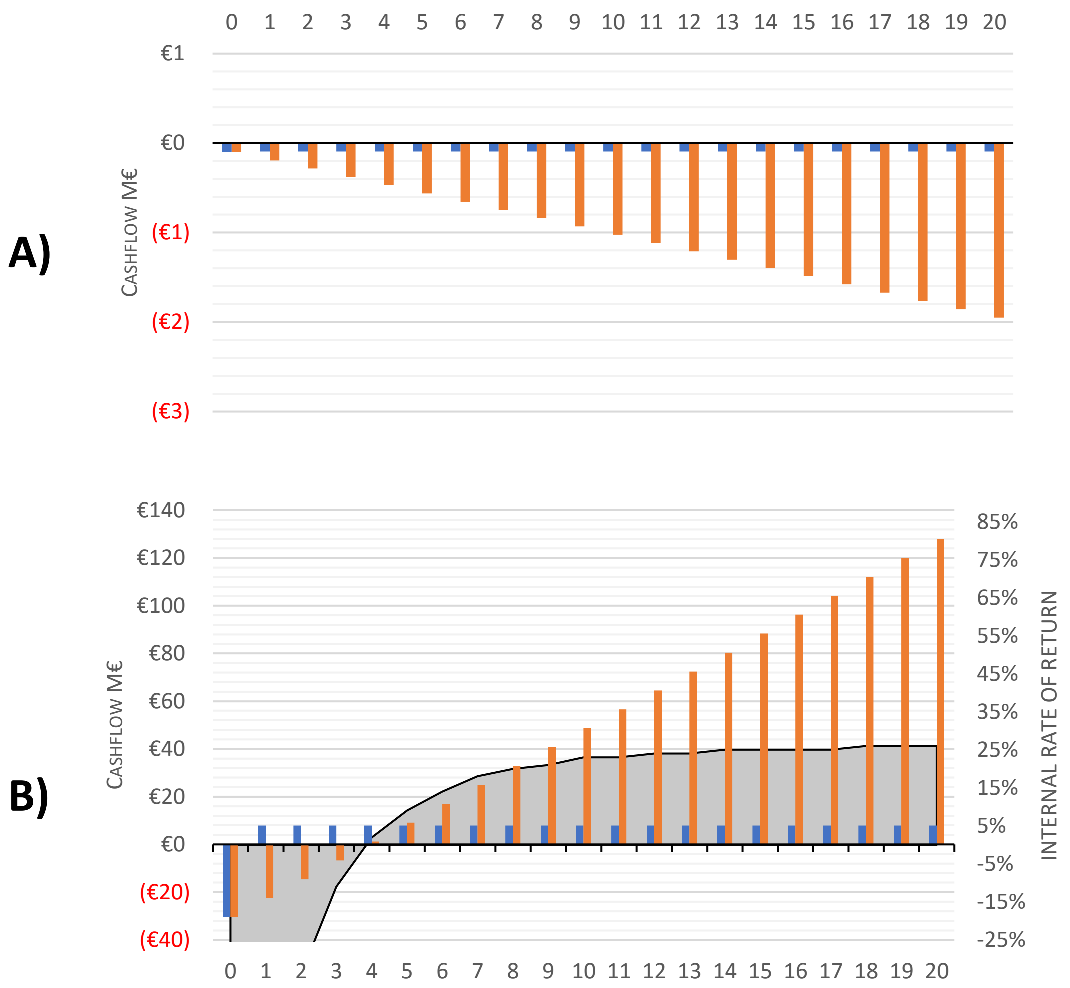


Figure 15: Cashflow charts the two retrofits over a period of 20 years. A) retrofitting additional sustainable feedstocks. B) retrofitting both sustainable feedstocks and an extra facility to produce advanced bioethanol from corn stover. Metrics of retrofit A): Net Cashflow; €-92.440, Cumulative Cashflow; €-1.948.812. Metrics of retrofit B): Net Cashflow; €7.916.169, Cumulative Cashflow; €127.876.318, IRR; 26%.

The grey area represents the yearly internal rate of return, calculated for the project lifetime of 20 years. Here, the net cashflow is determined by the difference in OPEX between the specific retrofit and the current situation. A positive net cashflow means lower OPEX requirements as opposed to first-generation ethanol production. The yearly OPEX savings remain constant and thus identical cashflows are obtained each year. The increase in cumulative cashflow is the result of a constant positive net cashflow. Inversely, a decrease in cumulative cashflow is caused by a constant negative cashflow. The higher the cumulative cashflow, the more profit is earned over the project lifetime. For the IRR, a larger surface above the x-axis signifies a superior net return. Furthermore, the position where the line crosses the x-axis denotes the year where the total investment is regained. Year 0 denotes the time of investment and thus a negative cashflow is observed. Dependent on the OPEX difference between the specific retrofit and the current situation, the net cashflow shows either a yearly profit or a yearly loss. The yearly profits or losses remains the same over the entire project lifetime, reflecting the constant net cashflow in Figure 15. The accumulation of the yearly losses or profits, beginning from the initial investment, is the actual cumulative cashflow of the project. Both graphs in Figure 15 are very different from each other due to the fact that the addition of sustainable feedstock is running at a loss, while the production of advanced bioethanol from corn stover is profitable when compared to the current situation. Because the addition of sustainable feedstock is running at a loss, caused by higher OPEX requirements as opposed to the current situation, an IRR value of this retrofit does not exist. The IRR is an important metric to determine the economic feasibility and will be further discussed in section 'Determining economic feasibility by means of IRR'.

Determining economic feasibility by means of NPV

A positive NPV indicates that the projected earnings generated through retrofitting, exceeds the anticipated investment. Only investments with positive NPV values should be considered. Figure 16 depicts the NPVs of the two retrofit options. For retrofitting solely sustainable feedstock, a negative NPV is observed of €710.000. This indicates that this specific retrofit option holds higher OPEX requirements compared to the current situation and is running at a loss.

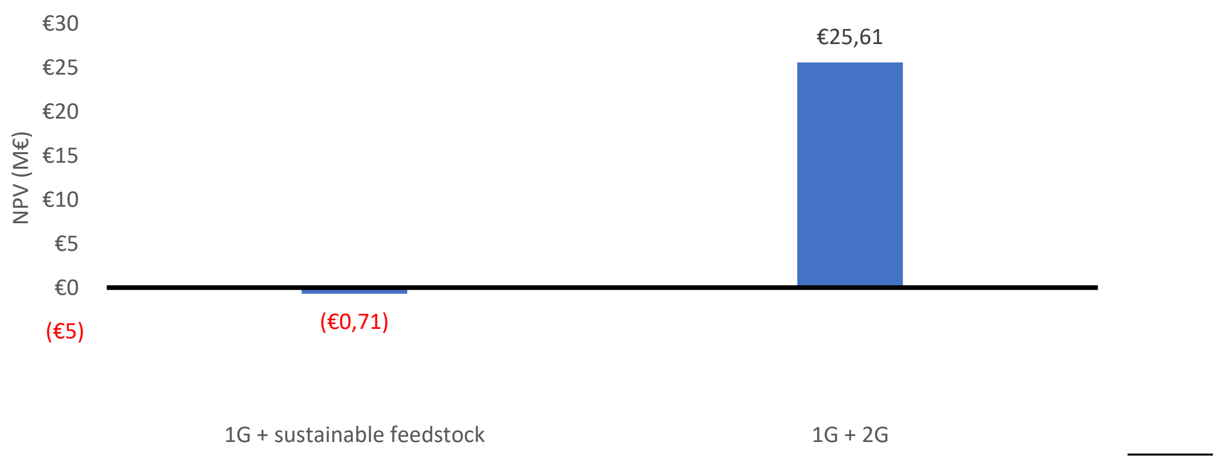


Figure 16: Net Present Value of eacht retrofit option. The determination of the NPV is the sum of the future cash flows (Ct) generated by the investment over a series of time periods (t). The NPV is a function of the discount rate (i) and utilisation period (n) of the investment. The NPV is calculated over a time period of 20 years, with a discount rate of 12%.

The negative NPV is a reflection of the results presented in Figure 15 (graph A), which can mainly be attributed to the decrease in revenues from DDGS production. For retrofitting both the sustainable feedstock and the integrated production of advanced bioethanol from corn stover, a positive NPV is observed of € 25.610.000, -. The reason why such a great difference in NPV is observed between the retrofit options, is that the revenues from DDGS and ethanol production are substantially higher in case of integrated second-generation ethanol production. Case in point, an additional 19.000 m^3 of advanced ethanol will be produced which has a significantly higher market value than first-generation ethanol. For illustrating purposes, the total revenues from integrated second-generation ethanol production is € 191.630.000, - per year, while the revenues from solely adding sustainable feedstock is € 172.126.000, - per year.

Determining economic feasibility by means of IRR

The economic feasibility is not only determined by using the NPV, but often collectively with the IRR of the project. As mentioned before, an IRR value of retrofitting solely sustainable feedstock does not exist, simply because this retrofit is running at a loss compared to the current situation. Hence, there is no return of the initial investment. The integration of second-generation ethanol production shows an IRR value higher than the discount rate, which is 26% versus a discount rate of 12% per year. This indicates the economic viability of this retrofit. Furthermore, as the IRR area in graph B already reveals, the payback period of the initial investment is approximately 3,8 years.

IRR sensitivity analysis

A sensitivity analysis was performed to test the robustness of the economic assessment. To understand the impact of fluctuations in the input values upon the conclusions of the economic assessment, five main variables were considered: Corn price, corn stover price, DDGS earnings, output of advanced bioethanol and CAPEX. A 10% variation was applied on the four variables.

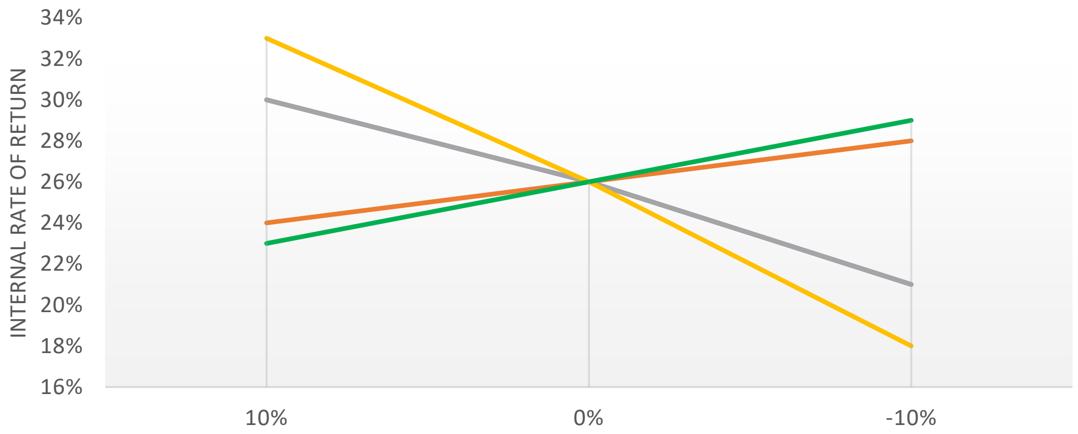


Figure 17: Sensitivity analysis for the impact of corn price, corn stover price, DDGS earnings, output of advanced bioethanol and CAPEX. The blue line represents the impact on fluctuations in corn price, the orange line represents the impact on fluctuations in corn stover price, the grey line represents the impact on changes in DDGS earnings, the yellow line represents the impact on changes in advanced bioethanol output, and the green line represents the impact on changes in CAPEX. The blue line is not visible as it is covered by the yellow line which shows an identical sensitivity.

Figure 17 contains a spider chart showing the impact of the five variables on the IRR of retrofitting the integrated production of advanced bioethanol. The blue line represents the impact on fluctuations in corn price, the orange line represents the impact on fluctuations in corn stover price, the grey line represents the impact on changes in DDGS earnings, the yellow line represents the impact on changes in advanced bioethanol output, and the green line represents the impact on changes in CAPEX. By looking at the spider chart, the nature of the relationship is readily observed. Figure 17 shows that all relationships are linear. In this way, the sensitivity towards a variable can be determined by the slope of the line (i.e. a steeper line implies greater sensitivity). As expected, there is a positive correlation between the IRR and the fluctuations in corn stover price and CAPEX. Furthermore, there is a negative correlation between the IRR and the fluctuations in corn price, DDGS earnings and ethanol output. The reason why fluctuations in corn stover price shows a positive correlation while fluctuations in corn price show a negative correlation, is because of the feedstock reallocation. For instance, when the price of corn increases with 10%, the IRR of the retrofit situation will be positively affected as more corn is being utilised in the current operating process. As such, the higher the fluctuations in corn price the more the IRR of the retrofit will improve. On the contrary, when the price of corn stover increases with 10%, the IRR of the retrofit situation will be negatively affected as corn stover is currently not being used as feedstock. As such, the more the price of corn stover increases, the more attractive the current process will be. The most sensitive variable that influences the economic viability quite significantly is the advanced ethanol output. A 10% decrease in advanced ethanol output results in an IRR of 18%, slightly higher than the discount rate of 12%. Only a very large decline in ethanol output (~17%) would result in an IRR below the threshold of 12%, thereby suffering a negative NPV.

The 2nd generation ethanol price of 750 €/m^3 is the minimum selling price. Therefore, an additional sensitivity analysis on the 2nd generation ethanol price has been considered, which extrapolates the IRR and NPV of both retrofit cases up to a selling price of 1000 €/m^3.

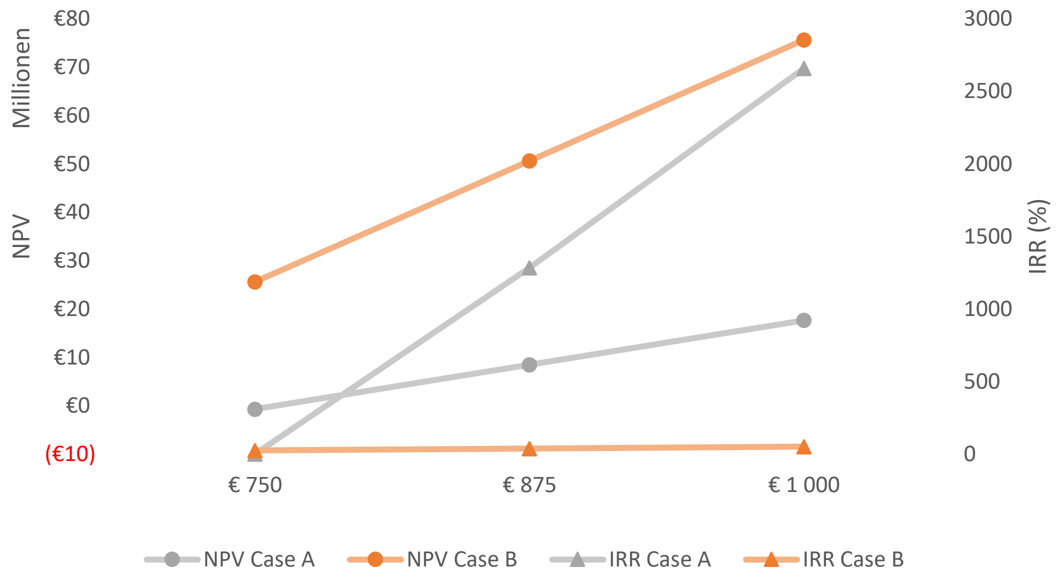


Figure 18: Extrapolation of the 2nd generation ethanol price.

Considering a price of a 1000 €/m^3, the IRR of Case A substantially increases up to 2658%, while the IRR of Case B slightly increases to 51%. This enormous difference in sensitivity and especially the outcome between the IRR of both cases is due to the specific investment required per case. Conversely, it is observed that the NPV of Case B is more sensitive than Case A. Obviously, the difference in ethanol output between the cases is the major contributor to this observation.

General discussion

The economic feasibility of the two retrofits was determined by using economic metrics, such as IRR and NPV. In addition, a sensitivity analysis was performed to understand the impact of variation in five variables on the economic feasibility. According to both the cashflow and the metric values, retrofitting solely additional feedstock is economically infeasible as it shows a negative cashflow and consequently a negative NPV of €710.000. The foremost reason of it being economically infeasible is that such a retrofit produce far less DDGS which is the second most important source of revenue. Integrating 2G with the current 1G facility shows a positive NPV of €25.610.000 and an IRR of 26%, which is significantly higher than the discount rate of 12%. This indicates the economic viability of this retrofit. The sensitivity analysis reveals that the yield of advanced ethanol has a great impact on the economic viability. Product loss beyond 17% would result in a negative NPV and would consequently be considered economically infeasible.

In addition, an analysis on the extrapolation of the 2nd generation bioethanol price have been included. The analysis discloses the complete effects of the price elevation. Obviously, increasing the selling price has a positive effect on the NPV and IRR of both cases. However, these metric values are impacted differently between cases. On the one hand, the IRR of Case A is superior to that of Case B, while the NPV of Case B is superior to that of Case A. An exceptional IRR like that of Case A is desirable for project exposed to high risks. Alternatively, Case B is more profitable compared to Case A and should only be considered when no risks are encountered.

Ultimately, integrating 2G with the current 1G is economically feasible, however, is exposed to a certain risk. Moreover, due to the poor economic performance of the small retrofit where only additional feedstock is used, it should be reconsidered whether this should be implemented in the large retrofit. The decrease in revenues from DDGS is considerable and should be taken into account when a final decision is made on the extend of the retrofit.

Conclusion economic assessment

From the economic assessment it can be concluded that solely adding additional feedstock such as industrial waste and wine alcohol results in a negative cashflow and consequently a negative NPV when an advanced ethanol (double counting) selling price of 750 €/m^3 has been considered. Therefore, this option is regarded as economically infeasible. Noteworthy, the metric values are considerably improved in case the minimal ethanol selling price is increased up above that minimum of 750 €/m^3. Currently, Advanced Ethanol (Double Counting) selling price is continuously increasing and has even reached 1200 euros/m^3, which makes it a very economically profitable case. In addition, it is important to highlight that it is a proven process on an industrial scale, with an important market, a very low CAPEX and that it can be implemented in the short term. Industrial waste rich in ethanol and wine alcohol are both included in the EU directive (REDII Annex IX) to encourage their processing at an industrial level. The low capex needed and the use of proven technology in order to process these streams, guide us to consider it as a profitable retrofit option for the bioethanol facilities as long as the premium obtained is adequate to cover the transportation and processing of those ethanol sources.

In some cases, as in the case of the wine or sugar industry, the use of their secondary or residual streams creates a synergy between different productive sectors that benefits them all as well as it helps avoiding depopulation of rural areas being mostly all this mentioned sectors located on them.

Retrofitting the 2G facility to the existing operation is economically feasible within its current boundaries. It must be noted that a reduction of 17% in advanced ethanol yield renders this option economically unattractive. Although this case study presents better economic profitability that solely adding additional feedstock such as industrial waste and wine alcohol, it is important to take into account that the uncertainty in the efficiency of the process is higher, which creates a greater risk for the plant operator. Therefore, it is important to continue promoting R&D&I activities in this field.

8 Sustainability (CERTH and CST Leaders)

8.1 Social aspects

In addition to the economic and environmental sustainability associated with the production of advanced bioethanol, it is important to identify its social effects for the development of any policy that can promote such biofuel. In this project, the main social effects related to the retrofit of the first-generation bioethanol industry have been identified. Employment throughout the value chain is the main social aspect influenced by this retrofit and new job opportunities will appear in the following sectors:

- Engineering companies: engineers and construction workers will be needed to carry out the retrofit of the plant.
- Bioethanol facility: new staff will be required to operate the retrofitted facility.
- Agricultural sector: farmers will be able to make a profit from agricultural waste.
- Logistics company: new transportation contracts will be required due to the high consumption of lignocellulosic biomass required in this type of process.

The use of lignocellulosic residues, such as the agricultural residues considered in this study, as raw material to produce biofuels is another important social and economic effect in rural areas as it contributes to the management of those residues within circular economy framework.

Finally, the retrofitting replaces part of the current food-related feedstock by lignocellulosic biomass, which is not linked to the food market. This represents an important social benefit and helps to achieve European regulation in this commitment.

8.2 Policy issues: RED

As part of the EU2020 climate and energy package, the European Union passed a major directive on bioenergy and biofuels in 2009 "The Renewable Energy Directive (RED) (2009/28/EC)"[10]. The RED set targets for renewable energy consumption, including a sub-target mandating 10% of energy used in transport to be produced with renewable sources. This directive also introduced a set of sustainability criteria excluding biofuels produced on land with high biodiversity value or carbon stocks and fuels made from feedstocks originating from recently deforested land or drained peatland. Furthermore, biofuels were required to provide at least a 35% GHG reduction compared to fossil fuels in order to be accounted in the renewable energy target and to be eligible for public financial support.

In November 2016, the European Commission published a large package of measures in its "Clean Energy for all Europeans"[11] initiative. As part of this package, the Commission adopted a legislative proposal for a recast of the Renewable Energy Directive (RED II[12]). The European Parliament and the EU Council proposed amendments and a final compromise deal among the EU institutions was agreed on 14 June 2018[13]. This policy update provides an overview of the provisions relating to transport fuels in the final compromise document.

In RED II, the overall EU target for Renewable Energy Sources (RES) consumption by 2030 has been raised from the originally proposed 27% to 32%. The Commission's original proposal has been reintroduced in the final agreement for RES in the transport sector: Member states must require fuel suppliers to supply a minimum of 14% of the energy consumed in road and rail transport by 2030 as renewable energy. The exact trajectory to achieve these targets will be defined for each member states in the Integrated National Energy and Climate Plans. These

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[10] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, Official Journal of the European Union, L 140/16, April 23, 2009. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A32009L0028

[11] "Clean Energy for All Europeans" DG Energy, European Commission, accessed March 7, 2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans

[12] Kristine Bitnere, The European Commission's renewable energy proposal for 2030, (ICCT: Washington, DC 2017). https://theicct.org/sites/default/files/publications/RED%20II_ICCT_Policy-Update_vF_jan2017.pdf

[13] General Secretariat of the Council of the European Union, Interinstitutional file, Proposal for a Directive of the European Parliament and of the Council on the promotion of the use of energy from renewable sources - Analysis of the final compromise text with a view to agreement, 21 June 2018. https://www.consilium.europa.eu/register/en/content/out?&typ=ENTRY&i=LD&DOC_ID=ST-10308-2018-INIT

plans will be designed by each member state following the guidelines set out in the Energy Union Governance Regulation[14].

Within the 14% transport target, there is a sub-target for advanced biofuels produced from feedstocks in Part A of Annex IX, including rape seed. These fuels must be supplied at a minimum of 0.2%[15] of transport energy in 2022, 1% in 2025 and increasing to at least 3.5% by 2030. Advanced biofuels will be double counted towards both the 3.5% target and towards the 14% target.

The maximum contribution of biofuels produced from food and feed crops will be frozen at 2020 consumption levels plus an additional 1% with a maximum cap of 7% of road and rail transport fuel in each member state. If the total share of conventional biofuels is less than 1% by 2020 in any member state, the cap for those countries will still be 2% in 2030. Further, if the cap on food and feed crops in a member state is less than 7%, the country may reduce the transport target by the same amount. Fuels produced from feedstocks with “high indirect land-use change-risk” will be subjected to a more restrictive cap at the 2019 consumption level, and will then be phased out to 0% by 2030 unless they are re-evaluated and certified as “low indirect land-use change-risk.” “Low indirect land-use change-risk” feedstocks include those that are produced on land that was not previously cultivated.

8.3 Methodology: Environmental assessment

In line with the RED II, the following process steps should be considered in the life cycle analysis of bioethanol:

- ✓ cultivation/extraction of feedstocks;
- ✓ carbon stock changes caused by land use change;
- ✓ emissions from processing;
- ✓ emissions from transport and distribution;
- ✓ emissions from the fuel in use;
- ✓ emission savings from carbon capture and geological storage;
- ✓ emission savings from carbon capture and replacement; and

[14] European Commission, DG Energy, ‘Governance of the Energy Union’. Accessed on 07/03/2018. https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/governance-energy-union

[15] All percentages in this list refer to the total final energy consumed in the road and rail transport sector.

- ✓ use of the co-products.

It should be noted that all the aforementioned processes are directly linked to bioethanol production.

According to RED II, co-products[16] from the production and use of biofuels should be taken into account in the calculation of GHG emissions. It is mentioned that the substitution method is appropriate for the purposes of policy analysis, but not for the regulation of individual economic operators and individual consignments of transport fuels. In those cases, the energy allocation method is the most appropriate method, as it is easy to apply, is predictable over time, minimises counter-productive incentives and produces results that are generally comparable with those produced by the substitution method. In the present analysis, the energy allocation method is used.

Moreover, as stated in RED II, no emissions shall be allocated to wastes and residues. Assuming that DDGS product is not the primary aim of the production process of the BCyL plant, DDGS production is not taken into account in the calculation of GHG emissions.

A simplified approach for the LCA conducted in this work[17] is described in the RED II. According to the Directive, it is imperative to carry out the GHG emission analysis and quantify the GHG savings of biofuels brought in the EU market. The GHG emissions from both the production and utilization of biofuels are calculated as (EU 2018):

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \text{ [g } CO_{2eq}/MJ_{bioethanol}]$$ [18]

where:

E = Total emissions from the use of the bioethanol;

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualized emissions from carbon stock changes caused by land-use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

[16] Co-products are the primary aim of the production process.

[17] A "full LCA approach" according to ISO 14 040 of transportation biofuels might result in most cases in a higher GHG emission and thus lower GHG saving compared to the simplified approach of RED II.

[18] The emission (E) can be negative if the emission savings (e.g. e_{ccr}) are higher than the emissions (e.g. e_p, e_{td}).

e_u = emissions from the liquid in use;

e_{sca} = emission savings from soil carbon accumulation via improved agriculture management;

e_{ccs} = emission savings from carbon capture and geological storage; and

e_{ccr} = emission savings from carbon capture and replacement.

As stated in the Directive, the effect of machinery and equipment manufacturing is not investigated.

According to RED II, the default percentage of GHG emission savings from the production of ethanol from corn lies between 40 to 48%. Regarding the production of bioliquid, the default value for cultivation 'e_{ec}' is 25.5 gCO_{2eq}/MJ and the relevant value for processing 'e_p' is estimated to be 29.1 gCO_{2eq}/MJ. The corresponding value for transport and distribution 'e_{td}' is 2.2 gCO_{2eq}/MJ. The total emissions for all the aforementioned processes, i.e. cultivation, processing, transport and distribution, amount to 56.8 gCO_{2eq}/MJ.

8.3.1 Boundaries of system

The system's boundaries of the process chains are shown diagrammatically in simplified FiguresFigure 19Figure 22 for the current, retrofit (Cases 1 and 2) and alternative scenarios. Regarding the current scenario, the system's boundaries involve: (i) the cultivation of corn grain, (ii) its transport over a total distance of 5 km by truck, (iii) the pre-treatment process of corn grain before its processing, (iv) the operation of boilers to produce the heat required for the process, and the grid electricity consumption also required for the process,[19] (v) the electricity production from the gas turbine, and (vi) the production process of both ethanol and DDGS.

[19] For the relevant calculations, electricity mix of Spain was employed.

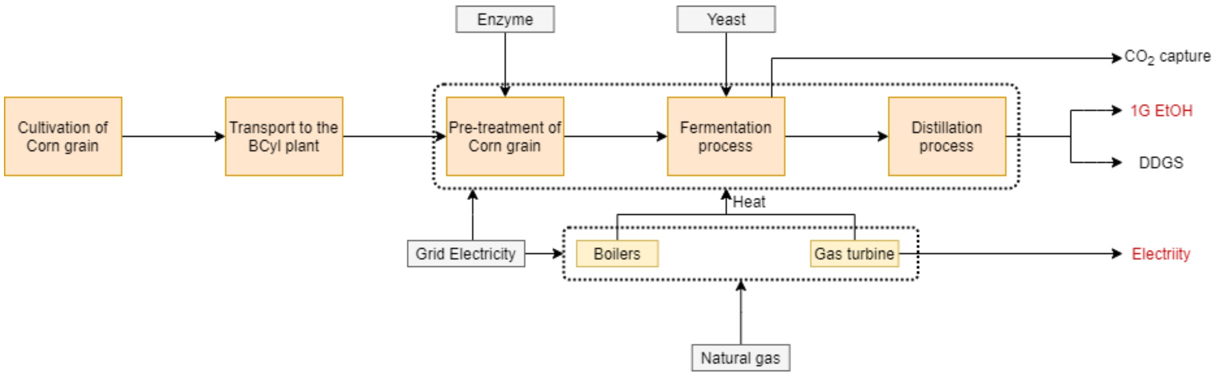

Figure 19. System boundaries for GHG calculation for the current scenario.

Regarding the Case 1 of retrofit scenario, the relevant system's boundaries are shown in Figure 20. In particular, they involve: (i) the cultivation of corn grain, (ii) its transport over a total distance of 5 km by truck, (iii) the pre-treatment process of corn grain before its processing, (iv) the implementation of industrial rich-ethanol waste and wine alcohol into the distillation area, (v) their transport over a total distance of 200 km by truck, (vi) the operation of boilers to produce the heat required for the process, and the grid electricity consumption also required for the process, (vii) the electricity production from the gas turbine, and (viii) the production process of both 1G & 2G ethanol and DDGS.

In this point, it is significant to mention that in the RED II (ANNEX V, article 18) it is reported that no life-cycle GHG emissions are associated with waste and residues (including agricultural residues directly from the field), as well as, residues from processing, up to the process of their collection, irrespectively of whether they are processed to interim products before being transformed into the final product. Thus, no life-cycle GHG emissions are associated with the corn stover, industrial waste and wine alcohol up to the process of collection. This is the reason why the emissions derived from the extraction/ cultivation of these raw materials are not taken into account in the bioethanol production process (i.e. e_{ec} = 0 in the equation of total GHG emissions of bioliquids).

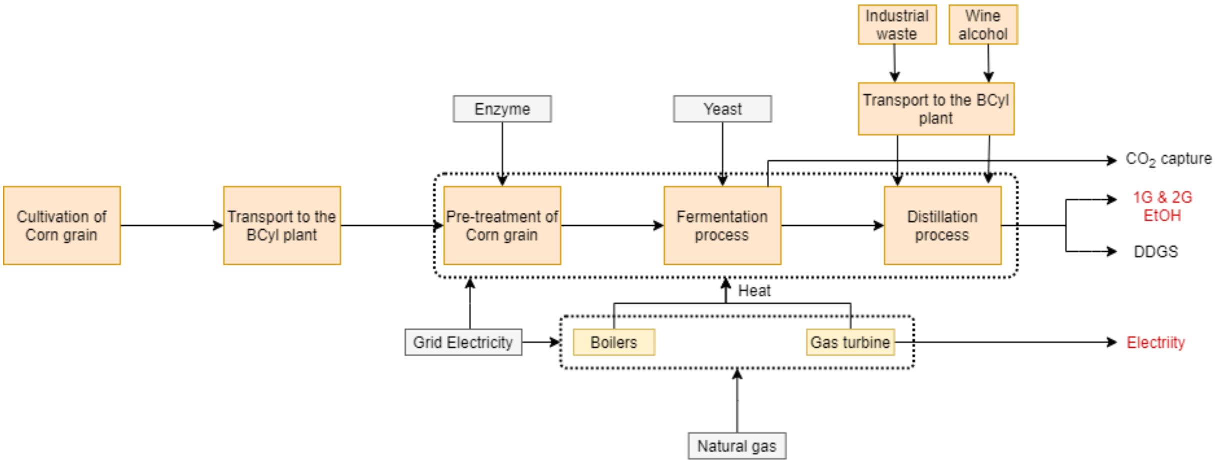

Figure 20. System boundaries for GHG calculation for the retrofit scenario (Case 1).

Correspondingly, the system's boundaries of Case 2 are shown in Figure 21; they involve: (i) the cultivation of corn grain, (ii) its transport over a total distance of 5 km by truck, (iii) the corn stover transport over a total distance of 5 km by truck from its collection location (iv) their pre-treatment process before their processing, (v) the implementation of industrial rich-ethanol waste and wine alcohol into the distillation area, (vi) their transport over a total distance of 200 km by truck, (vii) the operation of boilers to produce the heat required for the process, and the grid electricity consumption also required for the process, (viii) the operation of gas turbine to produce the required electricity for the dryers, as well as, the operation of dryers to meet the heat requirements of the DDGs production process, (ix) the electricity production from the gas turbine, and (x) the production process of both 1G & 2G ethanol and DDGS.

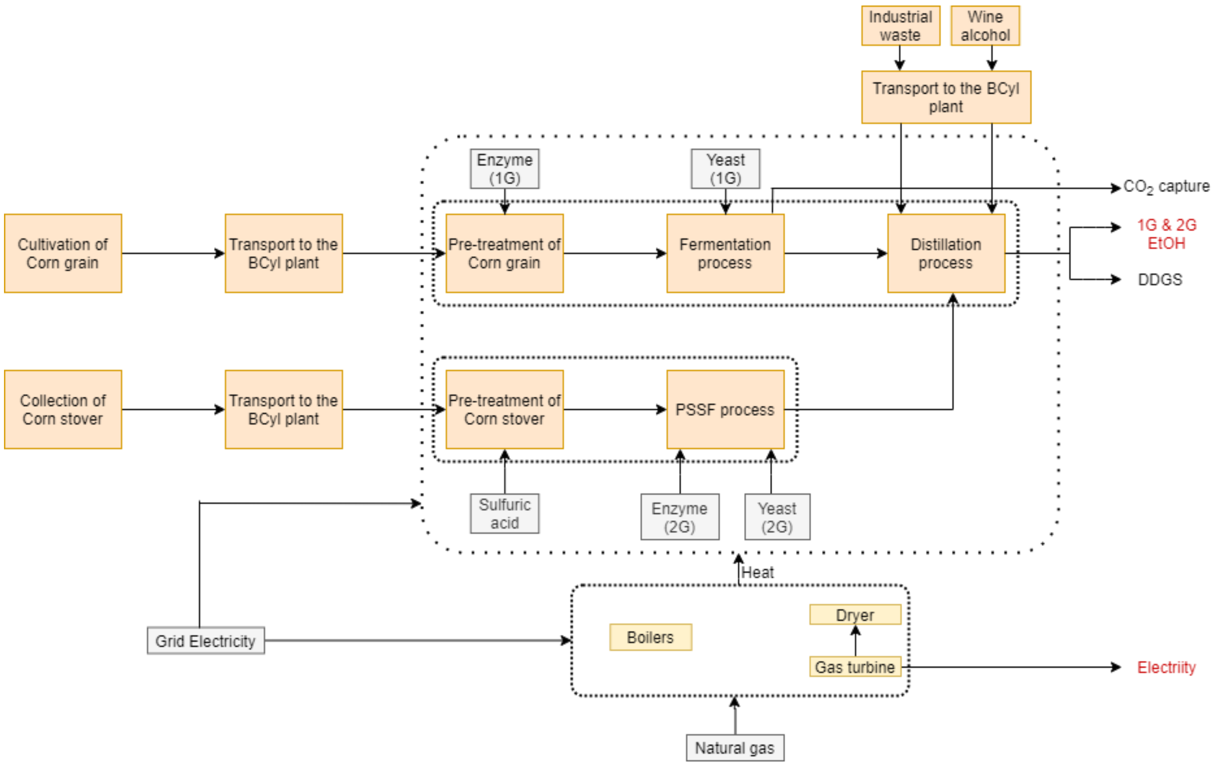

Figure 21. System boundaries for GHG calculation for the retrofit scenario (Case 2)[20].

The relevant system's boundaries of the alternative scenario are shown in Figure 22. They involve: (i) corn stover transport over a total distance of 5 km by truck from its collection location, (ii) its pre-treatment process in which corn stover is split into a WIS and a prehydrolysate fraction, (iii) the operation of boilers to produce the heatrequired for the process, using lignin (produced from the ethanol recovery process), biogas and sludge

[20] The indication of 1G and 2G in enzyme and yeast is used for the categorization of the different production processes of 1G and 2G ethanol, respectively.

(produced from the anaerobic digestion) as fuels, (iv) the electricity production from the steam turbine, and (v) the WIS and prehydrolysate fraction processing to produce 2G ethanol.

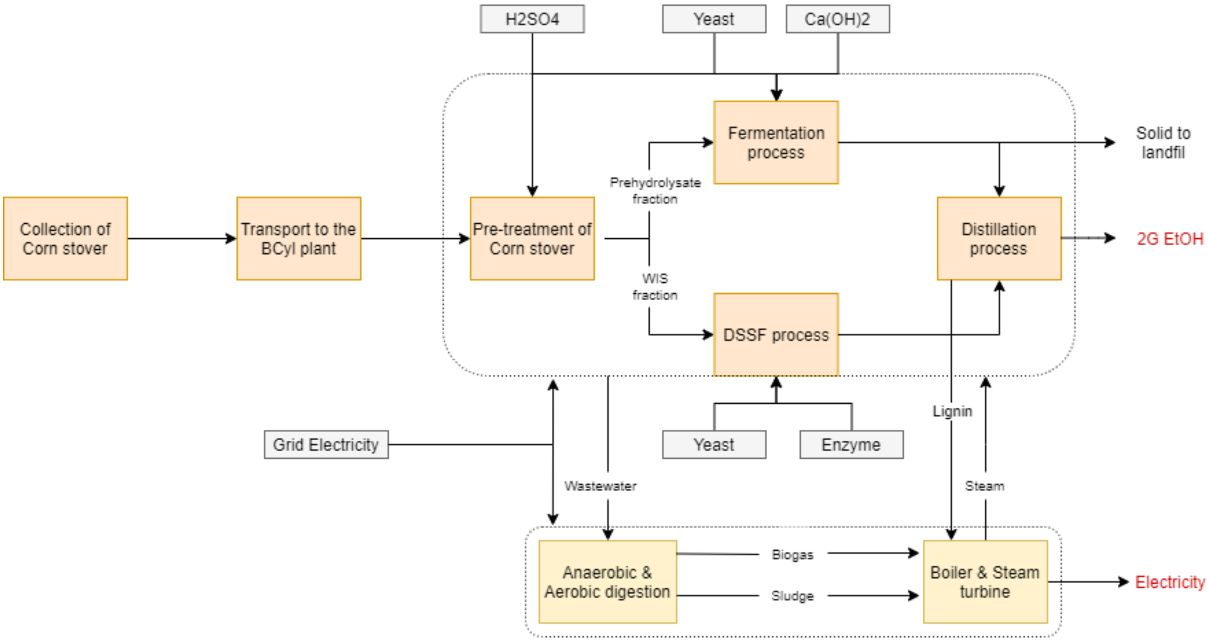

Figure 22. System boundaries for GHG calculation for the alternative scenario.

8.3.2 Functional Unit

The functional unit provides the reference to which the inputs and outputs of the systems are normalised. Based on the RED II, the functional unit can be defined and quantified as follows (EU 2018): "*Greenhouse gas emissions from biofuels, E, in terms of grams of CO_2-equivalent per MJ of fuel, gCO_{2eq} /MJ*".

The GHG emission savings from bioethanol are calculated as (EU 2018):

$$SAVING = (E_{F(t)} - E_{B(t)}) / E_{F(t)}$$

where:

E_B = total emissions from the bioethanol in [g CO_{2eq}/MJ];

E_F = total emissions from the fossil fuel comparator in [g CO_{2eq}/MJ].

In RED II (Annex V, part B in paragraph 19) referred that:

"*For biofuels used as transport fuels, the fossil fuel comparator $E_{F(t)}$ shall be 94 gCO_{2eq}/MJ.*"

8.4 Results

The environmental performance of current, retrofit and alternative scenario is carried out employing the SimaPro 8.2 software, which is a Life Cycle Assessment tool. According to ISO 14044, a LCA study includes four interrelated phases: (i) scope and definition of system's boundaries, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation of results, which are addressed in the following chapters. For the life-cycle environmental analysis, the IMPACT 2002+ methodology was implemented. Note that all processes assumed are in accordance with the database Ecoinvent v3 of SimaPro software. The Life Cycle Impact Assessment methodology IMPACT 2002+ represents a combined mid-point/ damage-oriented approach; it links all types of life cycle inventory results throughout 14 mid-point categories to four damage categories, i.e., (i) human health, (ii) ecosystem quality, (iii) climate change, and (iv) resources. In accordance with other environmental assessment methods (i.e. Ecoindicator 99, ReCiPe, CML-2001, etc.), IMPACT 2002+ evaluates only GHG emissions from fossil fuels (i.e. it does not consider biogenic emissions).

8.4.1 The current situation

Regarding the current scenario, all input data related to energy flows, consumption of raw materials and environmental releases of the analyzed process (see

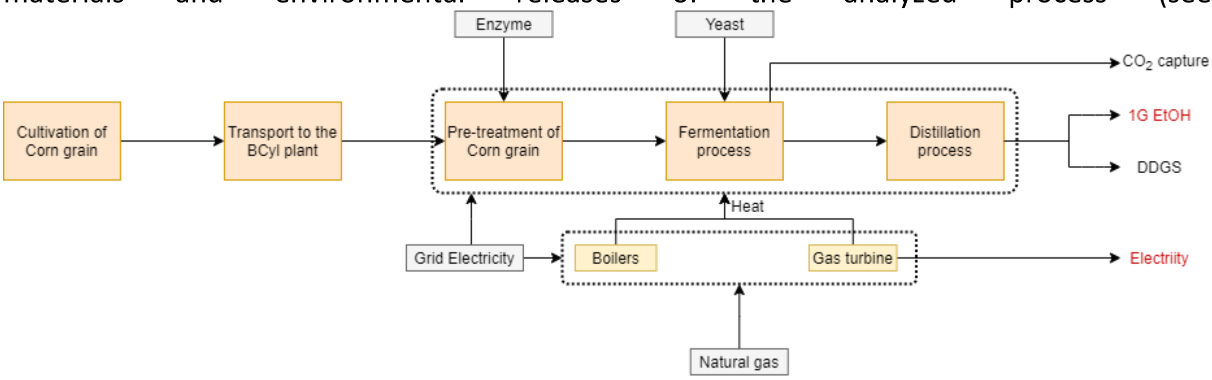

Figure 19) are included in the environmental analysis. More specifically, the system boundaries include:

- The cultivation process of corn grain, including the use of fertilizers;
- The transportation of corn grain from the cultivation location to the processing plant, including the fuel used in the truck;
- The electricity from Spanish electricity grid required for the operation of the plant;

- The enzyme[21] and yeast used as processing aids in the pre-treatment and fermentation processes, respectively;
- The heat and electricity produced from the boilers and the gas turbine, respectively, including the consumption of natural gas required for their operation.

The GHG emissions of the current scenario are summarized in Table 16. The estimated total GHG emissions are approximately 339,132 $tnCO_{2eq}$/a in case of CO_2 capture is not taken place and 299,132 $tnCO_{2eq}$/a in case of CO_2 capture is taken place. The contribution of the emissions of each stage of the process to the Global Warming impact category, is illustrated in

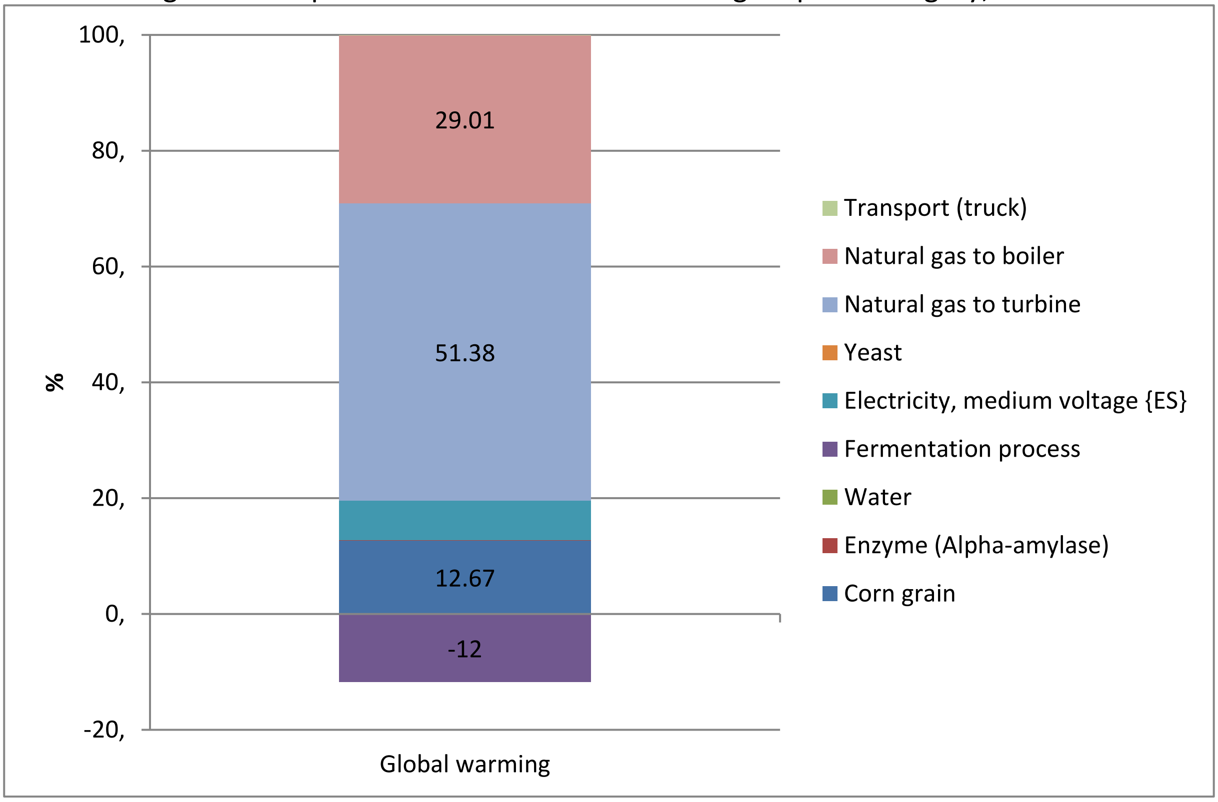

Figure 23. It is evident that the operation of the gas turbine for electricity generation contributes the most to the total Global Warming Impact, accounting for up to 51.38%. The emissions derived from the heat production of boilers are also significant (29%); they could be attributed to the natural gas consumption in the boilers. In addition, GHG emissions associated with the corn grain account for 12.67%, due to the utilization of fertilizers in the cultivation process (in the field). The contribution of transport, as well as, of yeast, enzyme, and water consumption is almost negligible (<0.20%). GHG emissions associated with the fermentation process have biogenic origin due to the utilization of corn and account for 12% of the total emissions. These emissions are captured and sold to a soft drink company. Towards this direction fossil CO_2 emissions, used during the carbonation stage of beverage production, are avoided indirectly as they are replaced by the biogenic emissions from the

[21] The enzyme used in all the scenarios is alpha-amylase based on bibliographic references.

fermentation process. The negative value on figure is due to the emission saving from carbon capture and replacement during the fermentation process. Last, but not least, the emissions derived from the grid electricity consumption are minor (6.73%). It is worthnoting that the Spanish electricity mix is is not free of environmental burdens from a life cycle perspective, as it is mainly based on fossil fuels (petroleum, natural gas and coal consumption). However, in the case study investigated, the electricity from grid has small effects on GHG emissions, as compared to the adverse impacts of the operation of boiler and natural gas.

Table 16. GHG emissions related to each process of current scenario.

Processes	**Emissions ($tnCO_{2eq}/a$)**
Corn cultivation	43,000
Transport of corn from the cultivation location to plant	231
Electricity consumption	22,900
Yeast consumption	46.40
Enzyme consumption	454
Water consumption	0.72
Heat production from boilers	98,500
Gas turbine cogeneration system	174,000
Total emissions without CO_2 use	339,132.12
CO_2 savings from the fermentation process	- 40,000
Total emissions with CO_2 use	299,132.12

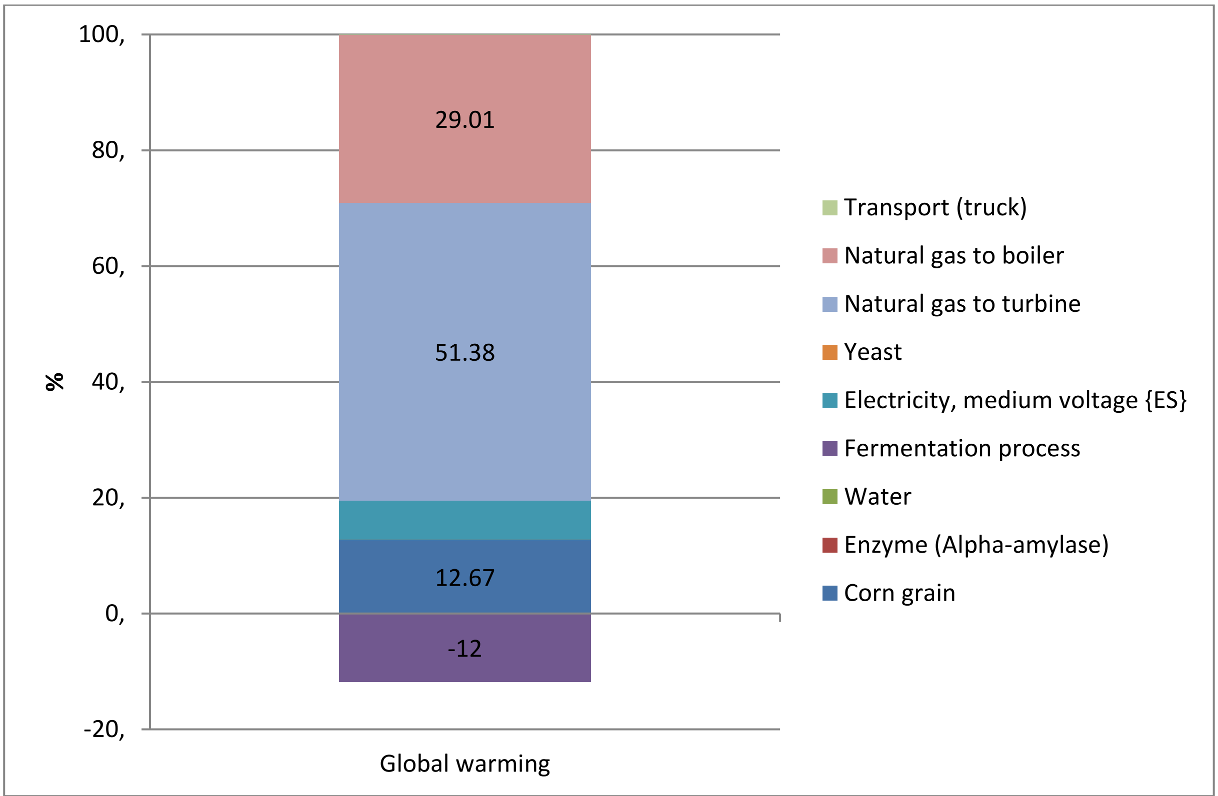

Figure 23. Characterization results related to GHG emissions from the operation of BCyL plant using corn as feedstock (current scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

Figure 24 illustrates the environmental impact of the process steps in four damage-oriented impact categories, namely, (i) human health, (ii) ecosystem quality, (iii) climate change and (iv) resources. It is evident that the gas turbine operation dominates the total scores (>51%) in the categories of human health, climate change and resources. Significant impact on the same categories has also the operation of boilers (ranging from 14-29%). This is due to the fossil fuel formation of natural gas and the harmful components (e.g. chemicals and metals) released from its combustion and excavation processes. These components are significant contributors to human toxicity (carcinogenic effects), respiratory effects (inorganic and organic compounds), ecotoxicological emissions, etc. The impact category of ecosystem quality is an exception; in this category, the corn grain dominates the total scores (58.02%). This adverse impact is associated with the biodiversity loss and changes in soil quality, due to the cultivation process of corn. CO_2 emissions arised from the fermentation process have no influence on climate change, because corn is a biomass resource (biogenic emissions). Electricity consumption has a moderate effect on all impact categories, with the most significant impact in the ecosystem quality (15.44%). The moderate impact on this category is due to the Spanish electricity grid mix, which is mainly derived from fossil resources (i.e. petroleum, natural gas, and coal). It is worth mentioning that the negative value on climate change category is due to the emissions saving from carbon capture and replacement during the fermentation process.

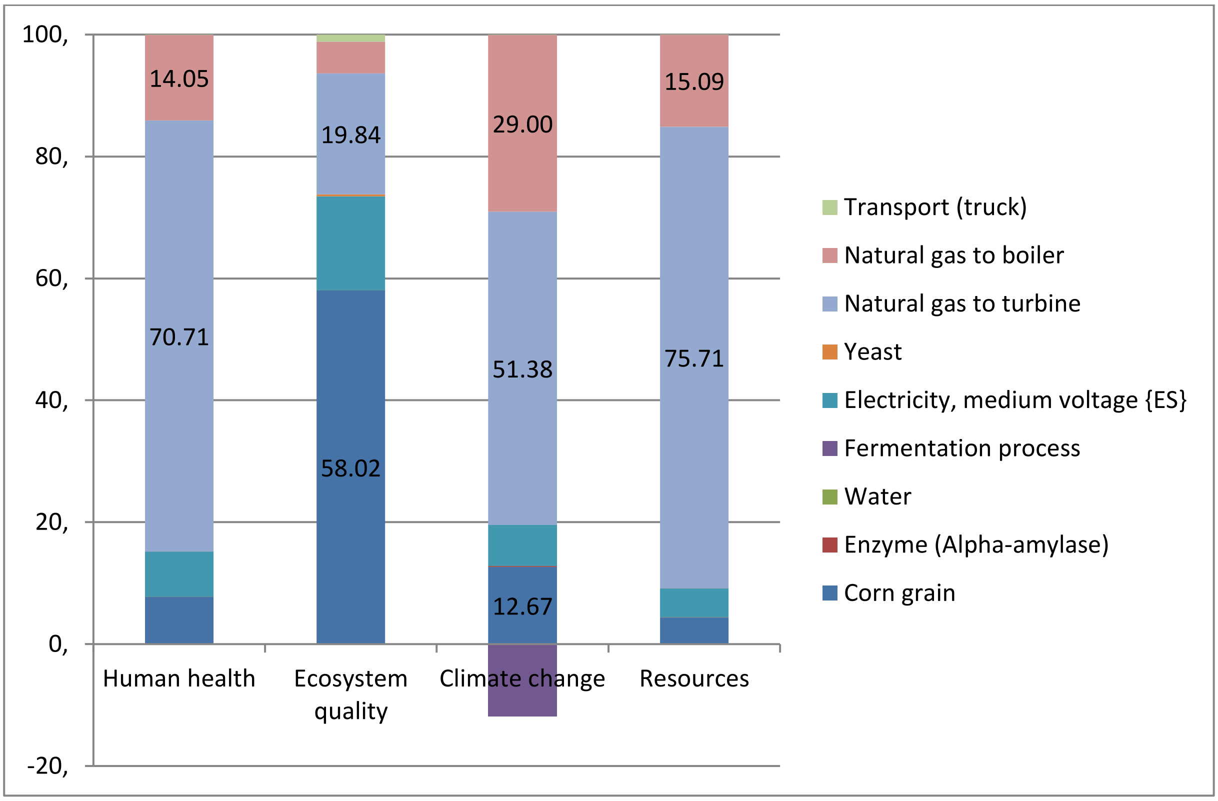

Figure 24. Damage assessment results related to the different impact categories for the BCyL plant using corn as feedstock (current scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

8.4.2 Suggested retrofit

<u>Case 1</u>

In retrofit scenario, all inputs and outputs of the system boundary presented in Figure 20, encompass:

- The cultivation process of corn grain, including the use of fertilizers;
- The transportation of corn grain from the cultivation location to the processing plant, including the fuel used in the truck;
- The implementation of industrial waste and wine alcohol in the process;
- The transportation of industrial waste and wine alcohol from the collection location to the processing plant, including the fuel used in the truck;

- The electricity from Spanish electricity grid required for the operation of the plant;
- The enzyme and yeast used as processing aids in the pre-treatment and fermentation processes, respectively;
- The heat and electricity produced from the boilers and gas turbine, respectively, including the consumption of natural gas required for their operation.

The GHG emissions related to each process of Case 1 of the retrofit scenario are summarized in Table 17. The estimated total GHG emissions are about 338,063 $tnCO_{2eq}$/a in case of CO_2 capture is not taken place and 298,063 $tnCO_{2eq}$/a in case of CO_2 capture is taken place. The relevant contribution from each process step of the BCyL plant to the Global Warming Category is shown in

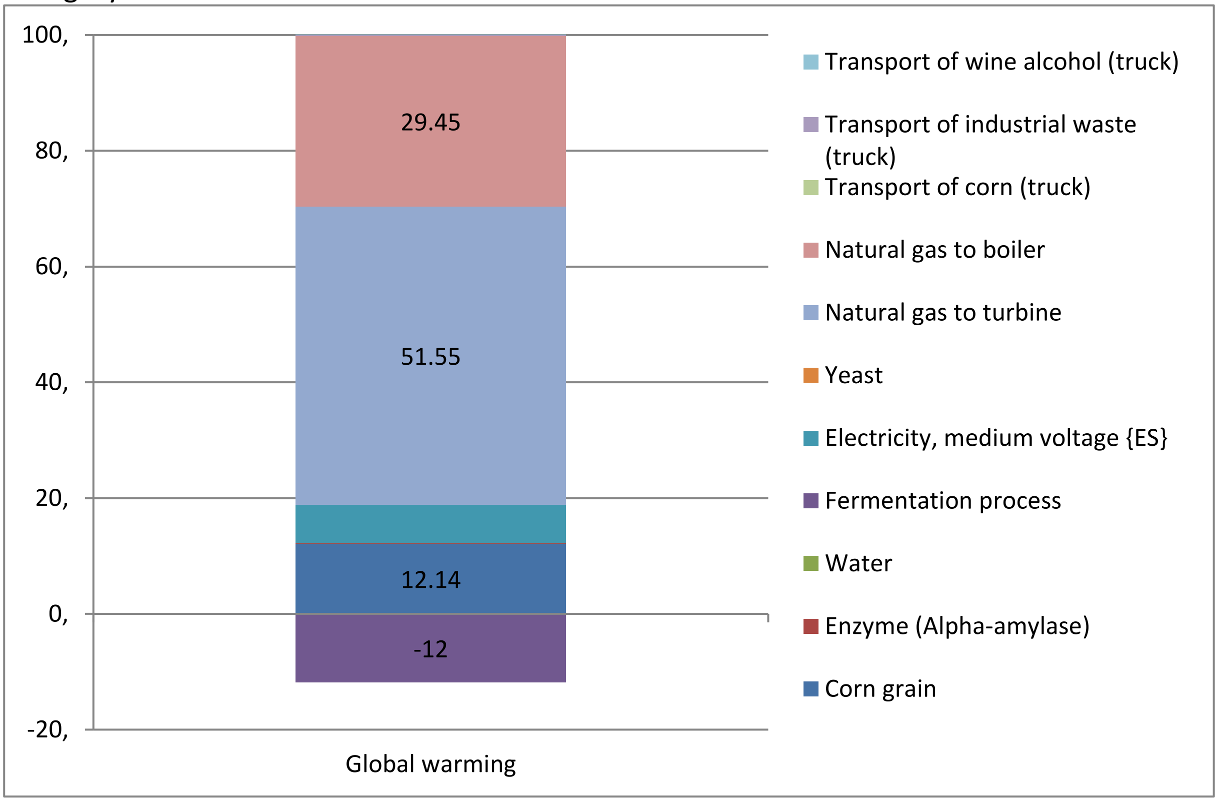

Figure 25. It is clearly seen that the gas turbine operation dominates the total scores (51.55%) in this impact category. In addition, the GHG emissions from the operation of boilers are significant (29.45%) as well. The GHG emissions associated with the corn cultivation process account for up to 12.14%, due to the utilization of fertilizers during this process. The effects of transport, as well as, of yeast, water and enzyme consumption on the Global Warming category are negligible (<0.1%), as compared to the relevant ones associated with the operation of gas turbine and boilers. GHG emissions associated with the fermentation process, which accounted for up to 12% of the total emissions, are captured and sold to a soft drink company, avoiding indirectly the utilization of fossil CO_2 emissions into the carbonation stage of beverage production. The negative value is due to the emission saving from carbon capture and replacement during the fermentation process. Last, but not least, no GHG emissions are

associated with wine alcohol and industrial waste up to the stage of collection, due to RED II sustainability rules.

Table 17. GHG emissions related to each process of retrofit scenario (Case 1).

Processes	Emissions (tnCO_{2eq}/a)
Corn cultivation	41,100
Industrial waste	-
Wine alcohol	-
Transport of corn from the cultivation location to plant	220
Transport of industrial waste from the collection location to plant	364
Transport of wine alcohol from the collection location to plant	0.43
Electricity consumption	22,200
Yeast consumption	44.40
Enzyme consumption	433
Water consumption	0.71
Heat production from boilers	99,700
Gas turbine cogeneration system	174,000
Total emissions without CO_2 use	**338,062.54**
CO_2 savings from the fermentation process	**- 40,000**
Total emissions with CO_2 use	**298,062.54**

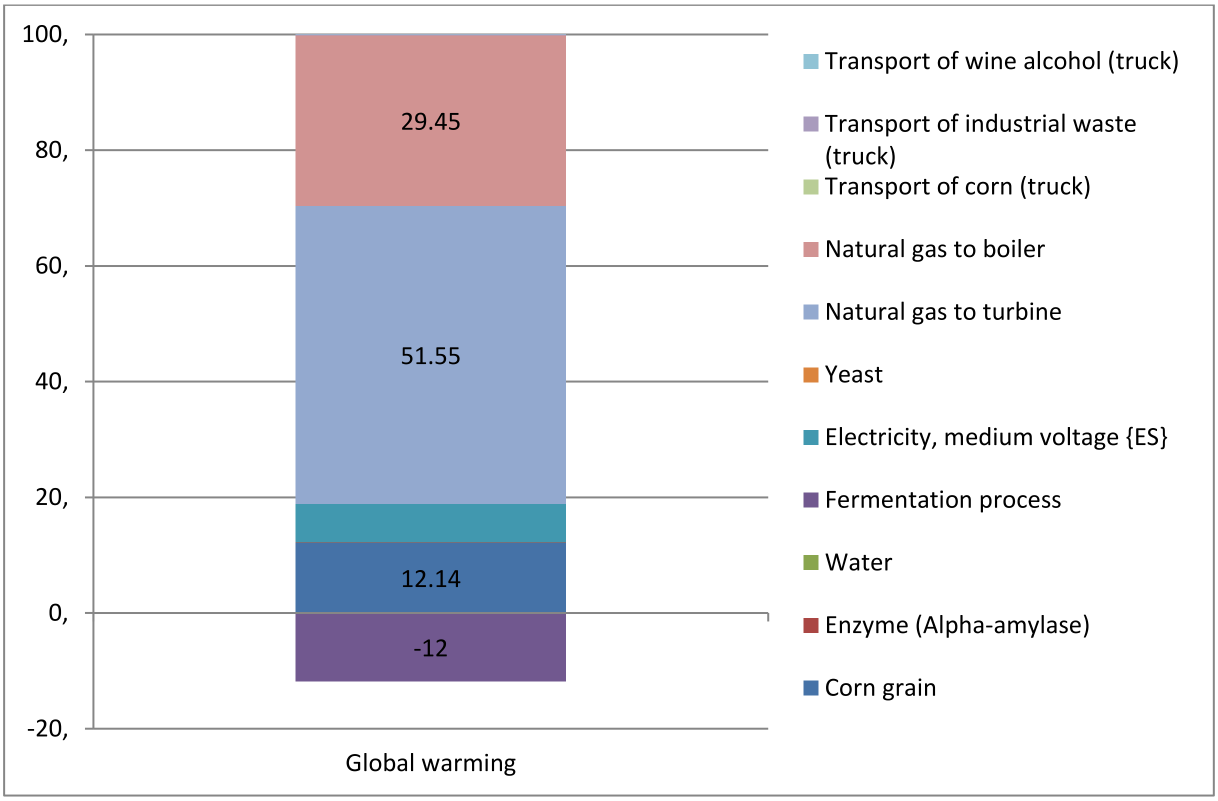

Figure 25. Characterization results related to GHG emissions from the operation of BCyL plant using corn, industrial waste and wine alcohol as feedstock (retrofit scenario – Case 1). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

The relative contribution of all processes related to the operation of the BCyL plant in the four damage-oriented impact categories is illustrated in

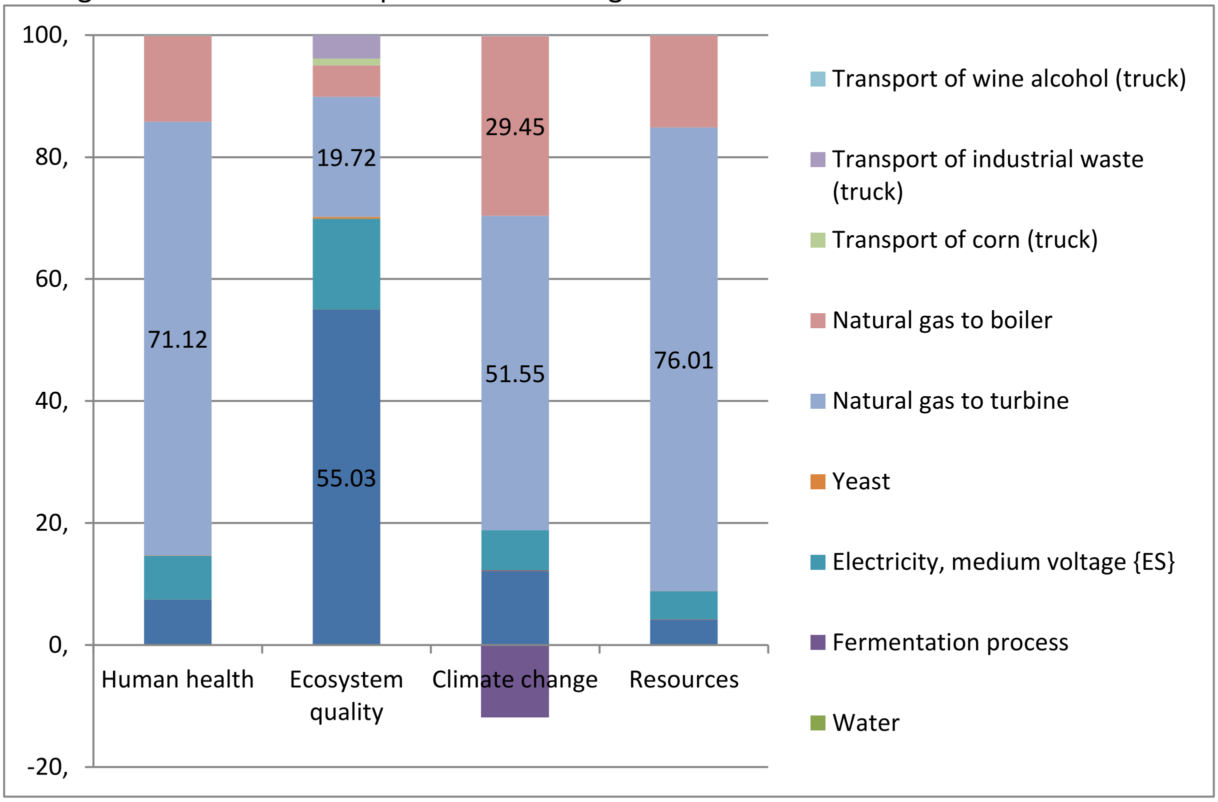

Figure 26. It is evident from this figure that the stage of gas turbine operation is the most impact intensive one in the categories of human health (71.12%), climate change (51.55%) and resources (76.01%). These adverse impacts are mainly attributed to the combustion of fossil natural gas. The category of ecosystem quality is the only exception. In this category, the corn grain dominates the total scores (55.03%), due to both biodiversity loss and changes in soil quality associated withcorn cultivation. On the other hand, electricity consumption has a moderate effect on ecosystem quality (14.87%), but minor effects on human health (7.19%), climate change (6.56%) and resources (4.63%), as compared to the relevant effects of boilers and gas turbine. The moderate impact of grid electricity to the ecosystem quality category can be attributed to the significant shares of fossil fuels in the energy mix. It is worth noting that the negative value on climate change category is due to the emissions saving from carbon capture and replacement during the fermentation process.

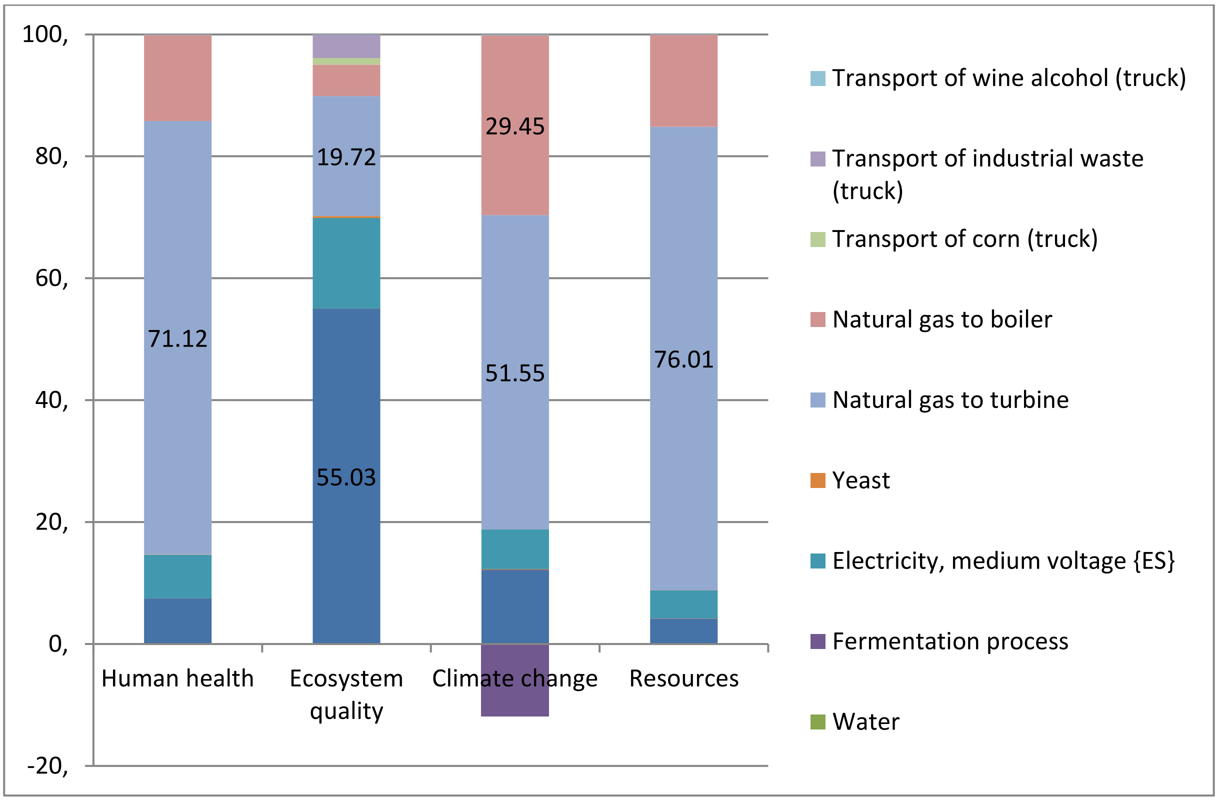

Figure 26. Damage assessment results related to the different impact categories for the BCyL plant using corn, industrial waste and wine alcohol as feedstock (retrofit scenario – Case 1). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

Case 2

Regarding Case 2 of the retrofit scenario, the system boundaries presented in Figure 21, encompass:

- The cultivation process of corn grain, including the use of fertilizers;
- The transportation of corn from the cultivation location and corn stover from the collection location to the processing plant, including the fuel used in the truck;
- The implementation of industrial waste and wine alcohol in the process;
- The transportation of industrial waste and wine alcohol from the collection location to the processing plant, including the fuel used in the truck;
- The electricity from Spanish electricity grid required for the operation of plant;
- The yeast and enzyme used as processing aids in the process, as well the sulfuric acid additive;

- The heat produced from the boilers and burners, and electricity produced from gas turbine, including the consumption of natural gas required for their operation.

The total annual emissions of Case 2 amount to 382,044 $tnCO_{2eq}$ in case of CO_2 capture is not taken place and 342,044 $tnCO_{2eq}$/a in case of CO_2 capture is taken place (Table 18). It is evident from

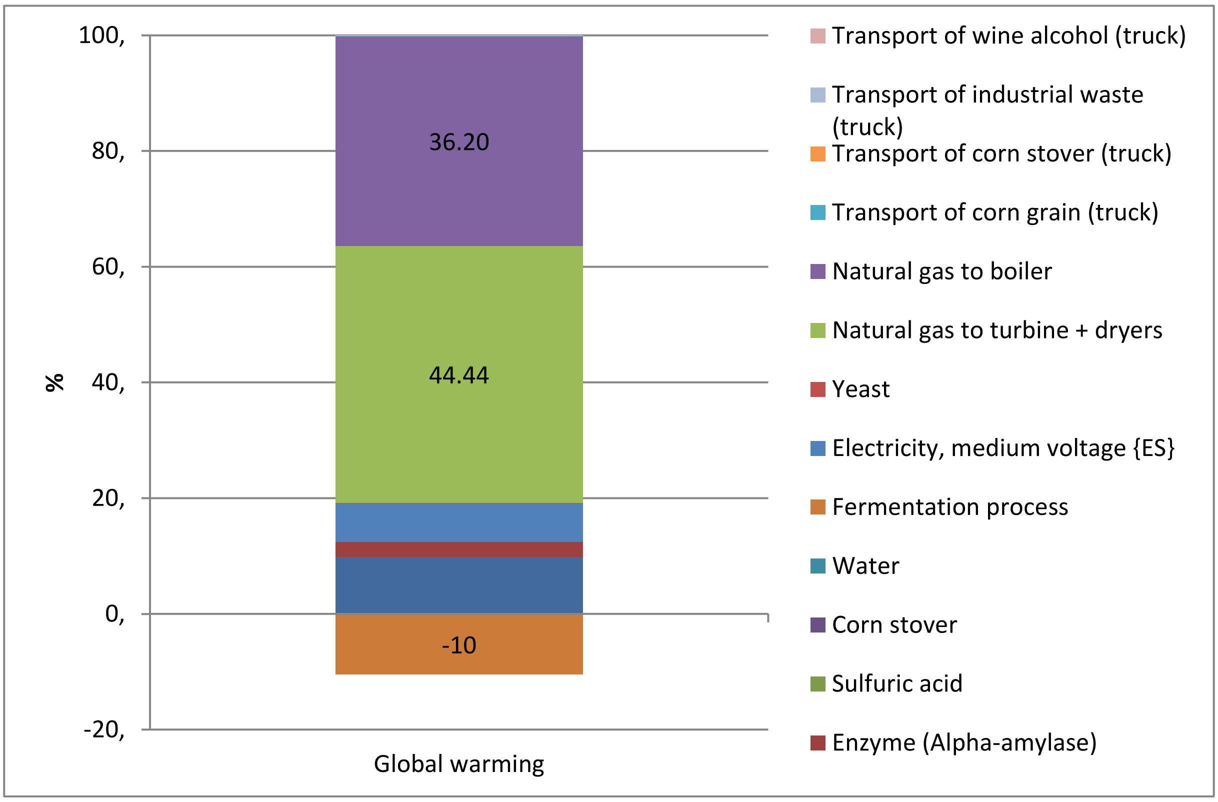

Figure 27 that the combustion of natural gas in the combustion chamber of gas turbine and boilers of the BCyL plant is the most significant contributor to GHG emissions, accounting for 44.44% and 36.20% of the Global Warming, respectively. This is attributed to the formation process of natural gas. The impact of electricity consumption and corn grain consumption amounts to 6.54% and 9.85%, respectively. These adverse impacts are due to the Spanish electricity mix, which is mainly based on fossil fuels consumption, and the fertilizer utilization during the cultivation process of corn, respectively. The relevant impact of transport, yeast, water and sulfuric acid consumption in the Global Warming category is negligible (<0.17%), while the impact of enzyme consumption amounts to 2.62%. No GHG emissions are related to the corn stover, wine alcohol and industrial waste, due to the RED II rules. On the other hand, GHG emissions on the fermentation process, which accounted for up to 10% of the total emissions, are no emitted to the atmosphere but are captured and sold to a soft drink company, avoiding indirectly the utilization of fossil CO_2 emissions into the carbonation stage of beverage production. The negative value is due to the emission saving from carbon capture and replacement during the fermentation process.

Table 18. GHG emissions related to each process of retrofit scenario (Case 2).

Processes	**Emissions ($tnCO_{2eq}/a$)**
Corn cultivation	37,700
Corn stover collection	-
Industrial waste	-
Wine alcohol	-
Transport of corn from the cultivation location to plant	202
Transport of corn stover from the collection location to plant	52.80
Transport of industrial waste from the collection location to plant	364
Transport of wine alcohol from the collection location to plant	0.43
Electricity consumption	25,000
Yeast consumption	632
Enzyme consumption	10,000
Sulfuric acid consumption	91.40
Water consumption	1.13
Heat production from boilers	138,000
Gas turbine cogeneration system	170,000
Total emissions without CO_2 use	**382,043.76**
CO_2 savings from the fermentation process	**- 40,000**
Total emissions with CO_2 use	342,043.76

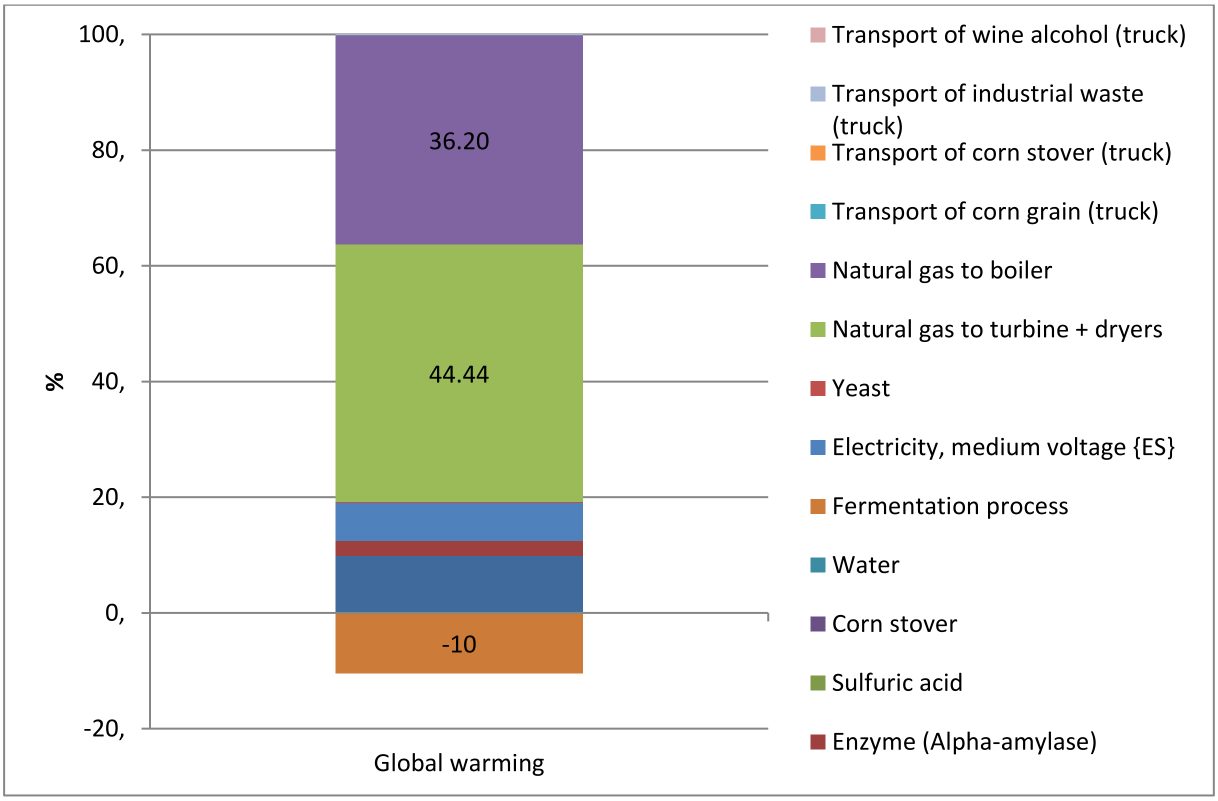

Figure 27. Characterization results related to GHG emissions from the operation of BCyL plant using corn, corn stover, industrial waste and wine alcohol as feedstock (retrofit scenario – Case 2). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

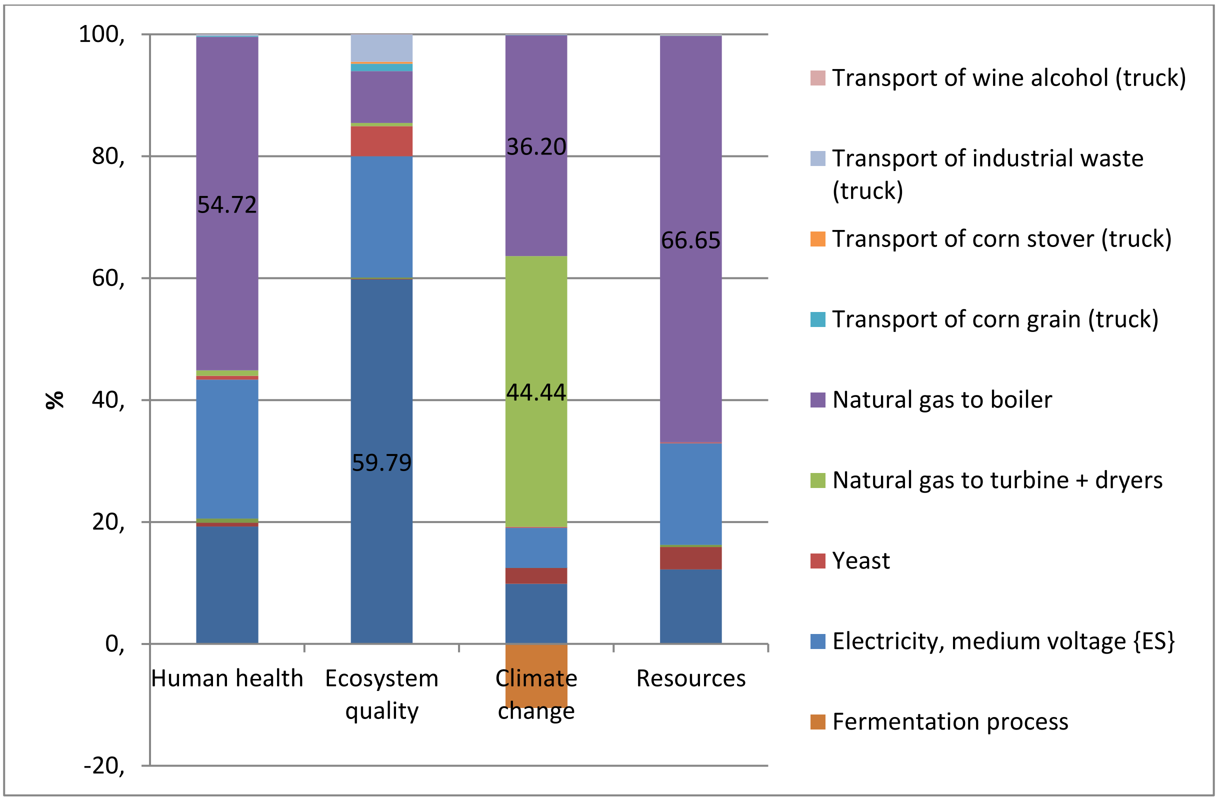

Figure 28 shows that the stage of boiler operation is the most impact intensive one in the categories of human health (54.72%) and resources (66.65%). On the other hand, the corn grain cultivation dominates the total scores on the ecosystem quality (59.79%), while the operation of gas turbine and dryers has major effect on climate change (44.44%). Electricity consumption has a moderate effect on human health (22.78%), ecosystem quality (19.88%) and resources (16.64%), as compared to the corresponding effects of boilers and corn grain cultivation. Last but not least, it should be noted that the negative value on climate change category is due to the emissions saving from carbon capture and replacement during the fermentation process.

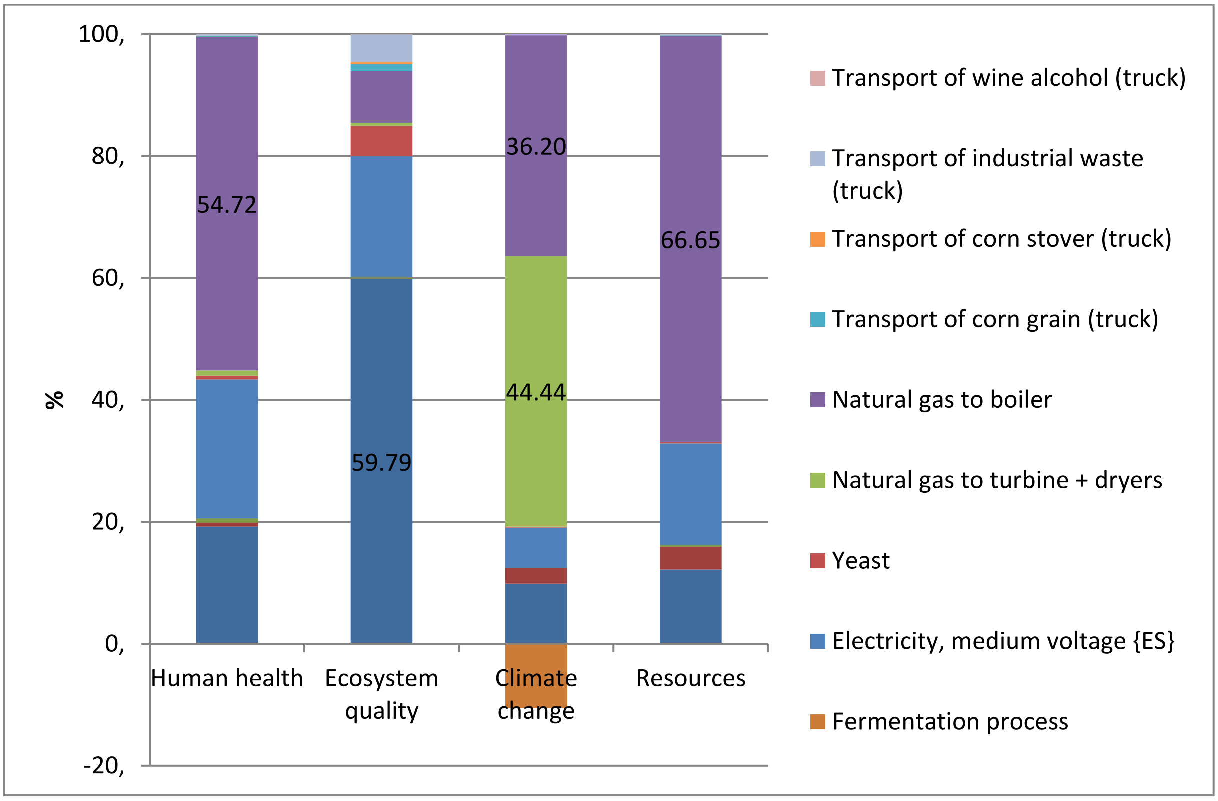

Figure 28. Damage assessment results related to the different impact categories for the BCyL plant using corn, corn stover, industrial waste and wine alcohol as feedstock (retrofit scenario – Case 2). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

8.4.3 Alternative scenario

In the alternative scenario (see Figure 22), the system boundaries include:

- The transportation of corn stover from the collection location to the processing plant, including thetransportation fuel;
- The electricity consumption from the Spanish electricity grid required for the operation of plant;
- The consumption of yeast, enzyme, sulfuric acid and calcium hydroxide as processing aids in the process;
- The heat and electricity produced from the boiler and steam turbine, respectively, from the combustion of biogas, sludge and lignin;
- The ethanol and solid waste production as outputs of the fermentation process; solid waste is disposed to landfill.

Regarding the alternative scenario, the total amount of GHG emissions is calculated to 31,024 $tnCO_{2eq}$ annually. The contribution of the emissions of each stage of the process to the Global Warming impact category is illustrated in

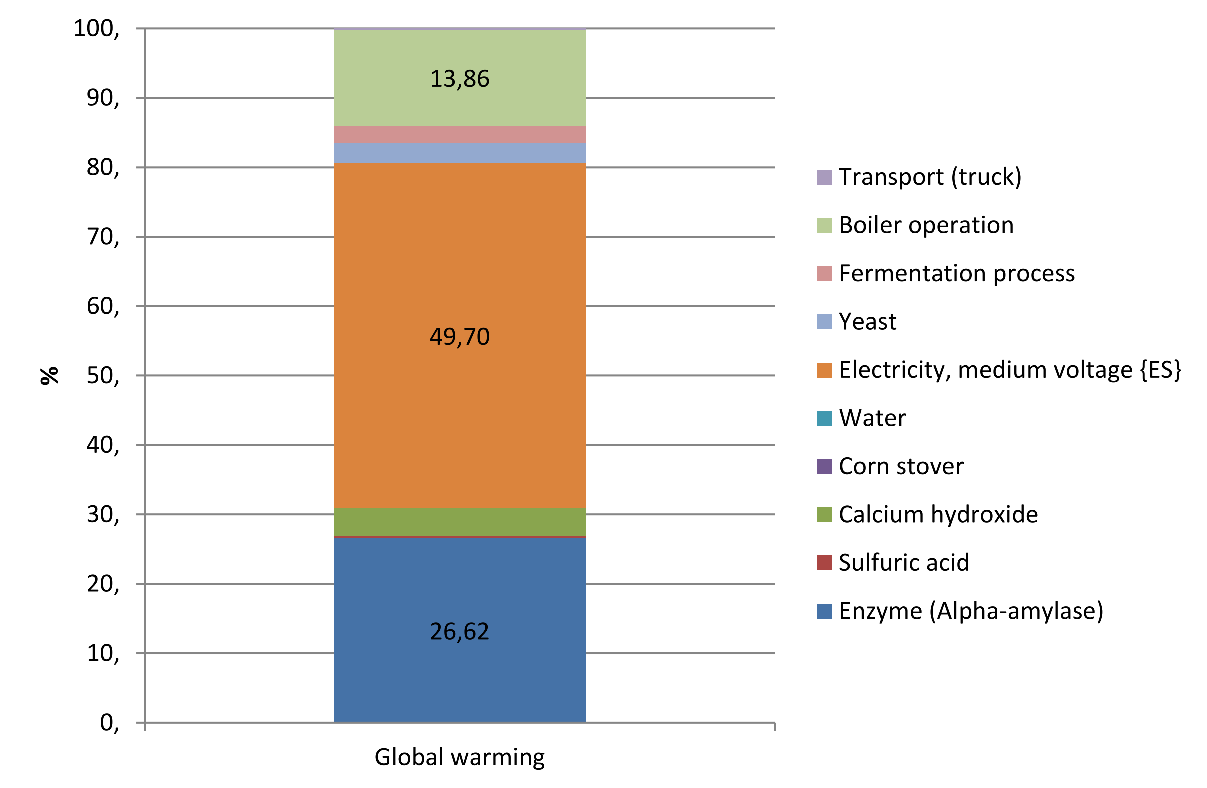

Figure 29. Electricity consumption is the most significant contributor to GHG emissions, accounting for 49.70% of the Global Warming category. The impact of enzyme consumption is also significant, accounting for 26.62%. The utilization of coal for the production process of enzyme is responsible for this adverse impact. The relevant impact of calcium hydroxide and yeast consumption amounts to 4.04% and 2.98%, respectively. The impact of transport, sulfuric acid and water consumption are negligible (<0.26%), as compared to the relevant one of the aforementioned process steps. Compare to the previous cases investigated, the fermentation process has a minor impact (2.40%) on the Global warming category. This impact is attributed to to the fact that the remaing solid on the filters of the fermentation process is disposed into landfill. Last but not least, the combustion of biogas and lignin is free of environmental burdens from a life cycle perspective, due to their biogenic origin. Nevertheless, the sludge is not considered biogenic, as it is produced from the wastewater treatment process of the industrial waste. Thus, the impact of the boiler operation (13.86%) is derived only from the sludge combustion.

Table 19. Emissions in each stage of the alternative process.

Processes	Emissions ($tnCO_{2eq}/a$)
Corn stover collection	-
Transport of corn stover from the collection location to plant	46.90

Electricity consumption	15,800
Yeast consumption (total)	946
Enzyme consumption	8,460
Sulfuric acid consumption (total)	80.80
Calcium hydroxide consumption	1,280
Water consumption	0.29
Heat and Electricity production from boilers and steam turbine	4,410
Ethanol production from fermenters	763
Total	**31,023.99**

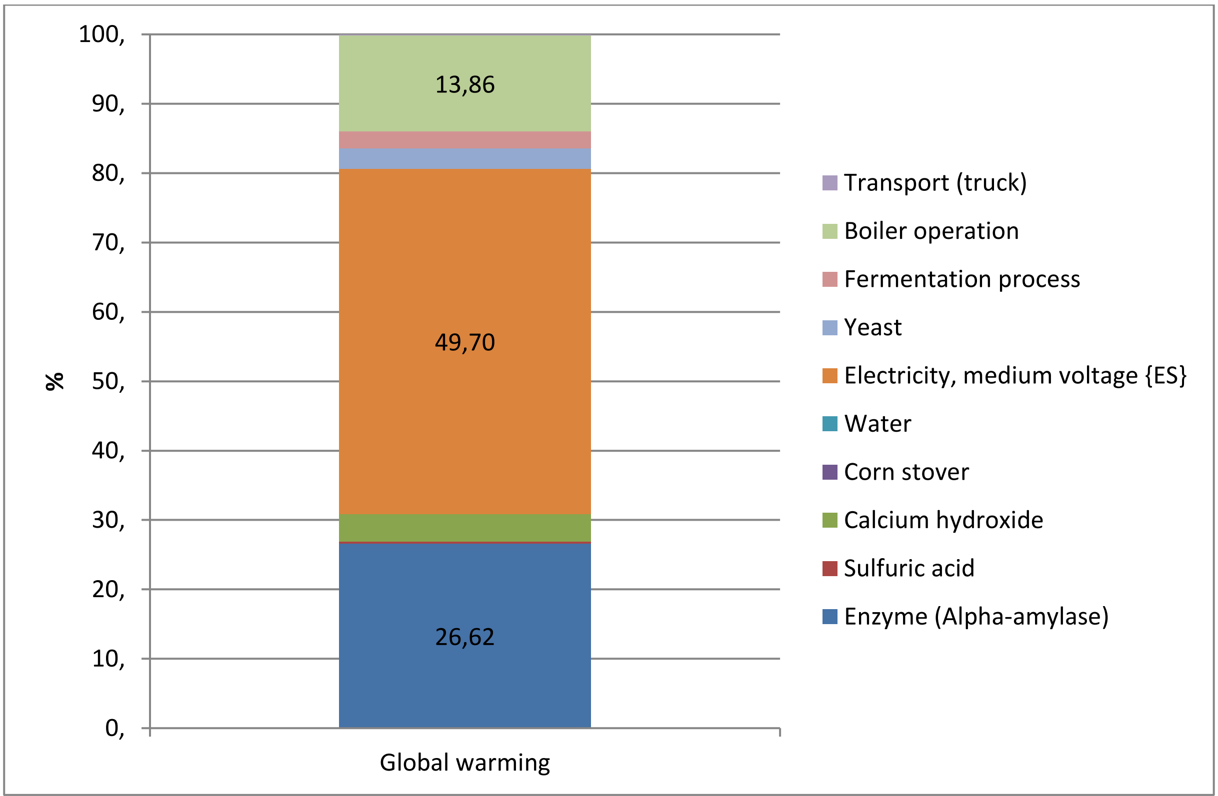

Figure 29. Characterization results related to GHG emissions from the operation of BCyL plant using only corn stover as feedstock (alternative scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

The relative contribution of all processes related to the operation of the BCyL plant in four damage-oriented impact categories is illustrated in Figure 30. Electricity consumption is the most impact intensive one in the categories of climate change (49.70%) and resources (72.24%). The electricity mix of Spain, which is fossil fuels-based (i.e. petroleum, natural gas and coal), is responsible for these adverse impacts. In addition, in the categories of climate change and resources, the impact of enzyme consumption amounts to 26.62% and 21.47%, respectively. This impact is mainly attributed to the energy (from coal) consumed for its production process. On the other hand, in the categories of human health and resources, the boiler operation dominates the total scores, accounting for 95.33% and 90.45%, respectively. These adverse impacts are due to the produced dust from burning slugde in the boiler. Dust is a mix of many chemicals that are responsible for human health damages; these toxic substances may contribute to human toxicity (carcinogenic and non-carcinogenic effects), respiratory effects (inorganics and organics compounds), ionizing radiation, and ozone layer depletion.

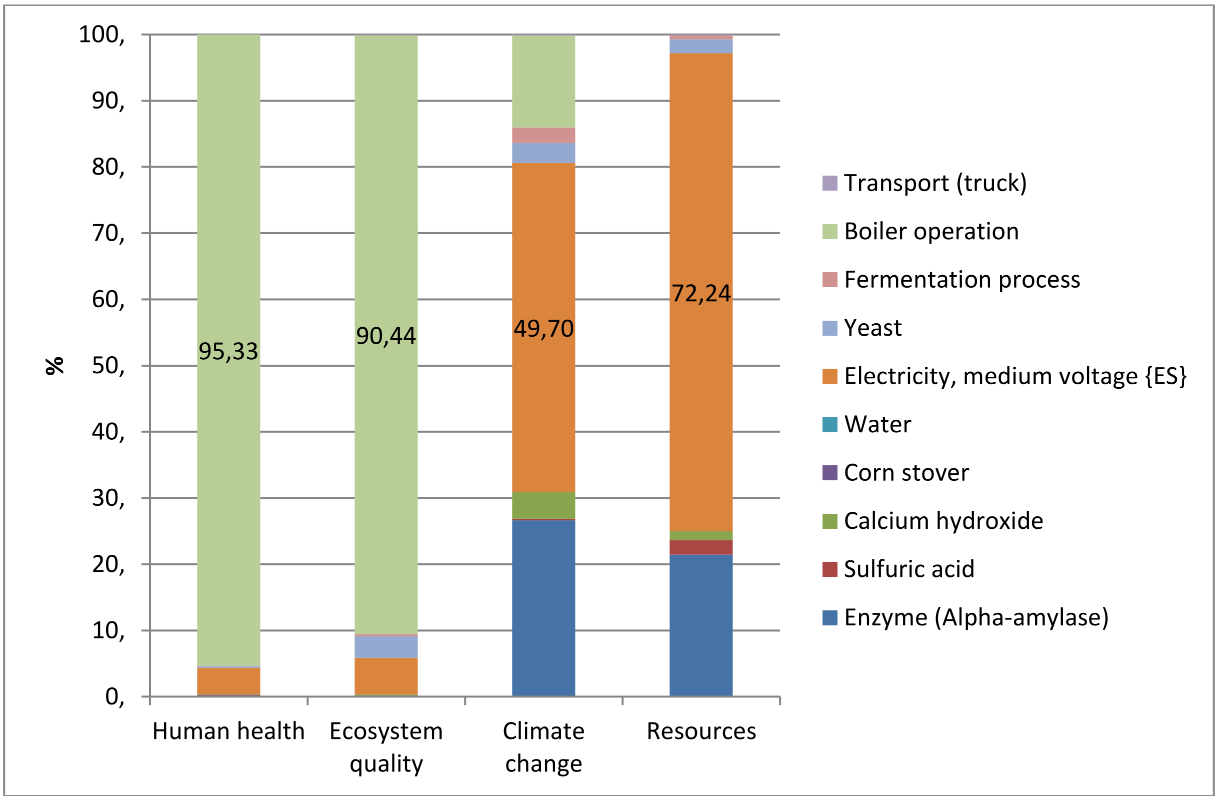

Figure 30. Damage assessment results related to the different impact categories for the BCyL plant using exlusively corn stover as feedstock (alternative scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale).

8.5 Summing-up

The comparative results presented in this work, are illustrated in

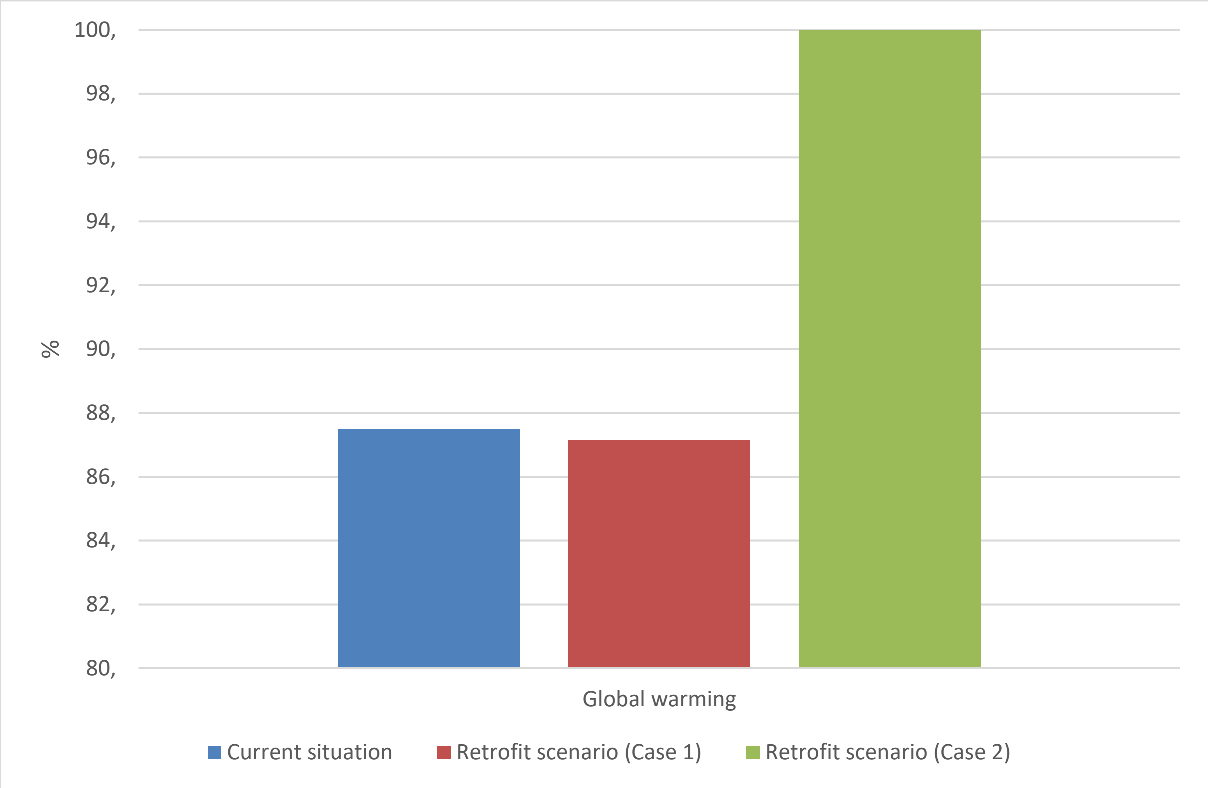

Figure 31 and Figure 32 in the case of the current situation and both cases of retrofit scenario.

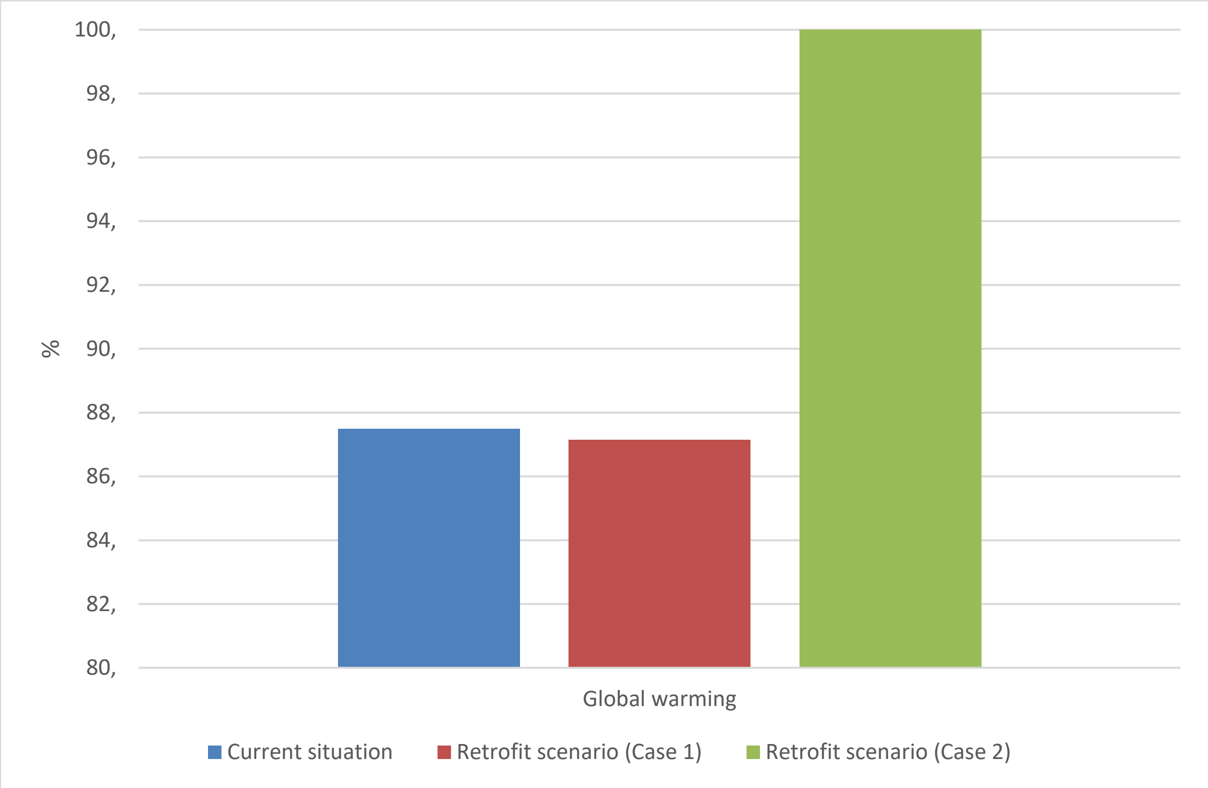

Figure 31 indicates that the current situation and Case 1 of the retrofit scenario exhibit similar environmental behavior with respect to the Global warming impact category. This is largely attributed to the fact that the main, environmentally adverse, impact is associated with the operation of boilers. Although the utilization of industrial waste and wine alcohol are included in the system's boundaries of Case 1 (retrofit scenario,) the consumption of natural gas dominates the total scores in the global warming category. Regarding Case 2 of the retrofit scenario, the environmental benefits from the utilization of waste as feedstock (i.e. industrial waste, wine alcohol and corn stover), reversed from the increased demand for energy consumption in the process. Thus, increasing the amount of natural gas combusted in the boiler results in more GHG emissions emitted to the atmosphere.

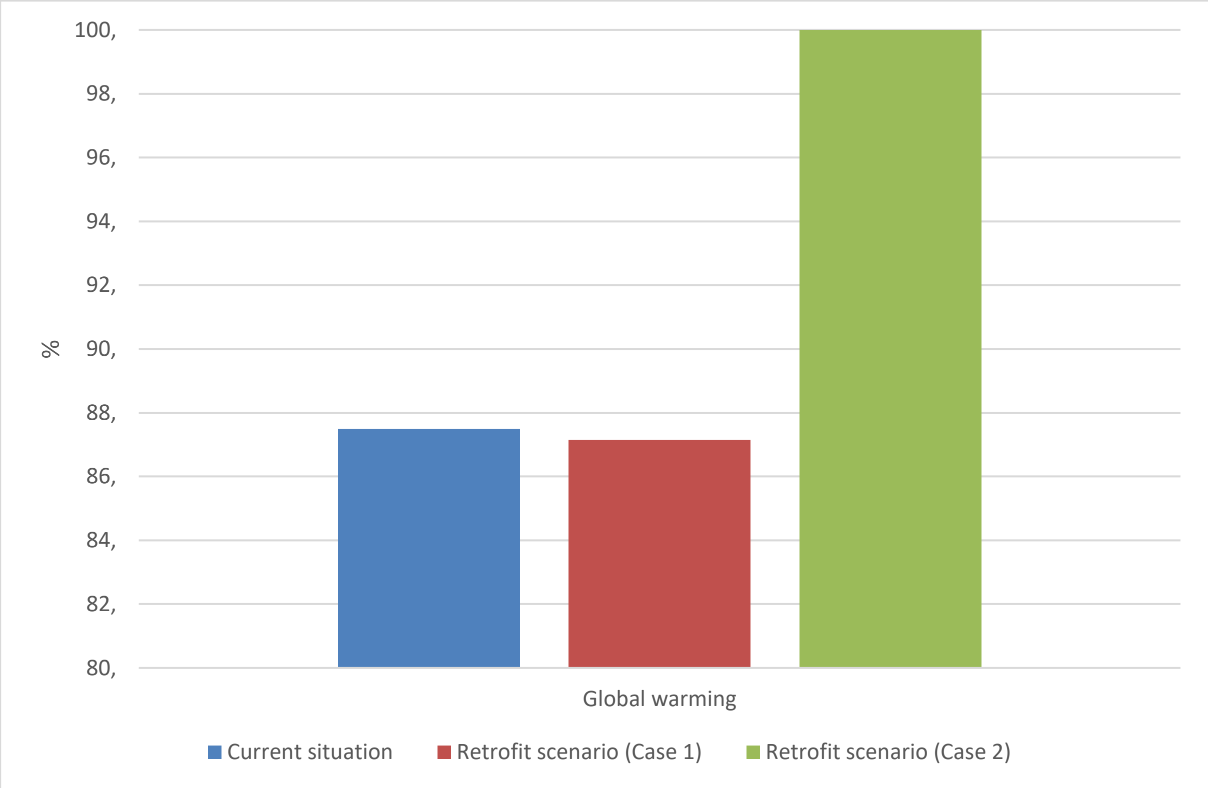

Figure 31. Comparative characterization results related to total GHG emissions of current situation and retrofit scenario (Cases 1 and 2) using the IMPACT 2002+ Method (All impact scores are displayed on a 100% scale).

The impacts of the current and retrofit scenario (Case 1 & 2) in the four damage-oriented environmental categories are illustrated in Figure 32. Although Case 2 of the retrofit scenario contributes the most to the climate change impact category (100%), it has the lowest impact in the categories of human health (35.44%), ecosystem quality (84.45%) and resources (31.27%). These results indicate the environmental benefits of using waste as feedstock in an industrial process. These benefites can be attributed to the fact that the collection of waste is free of environmental burdens, according to RED II rules. Regarding the current situation and Case 1 of the retrofit scenario, it seems to have similar effects in all damage-oriented impacts.

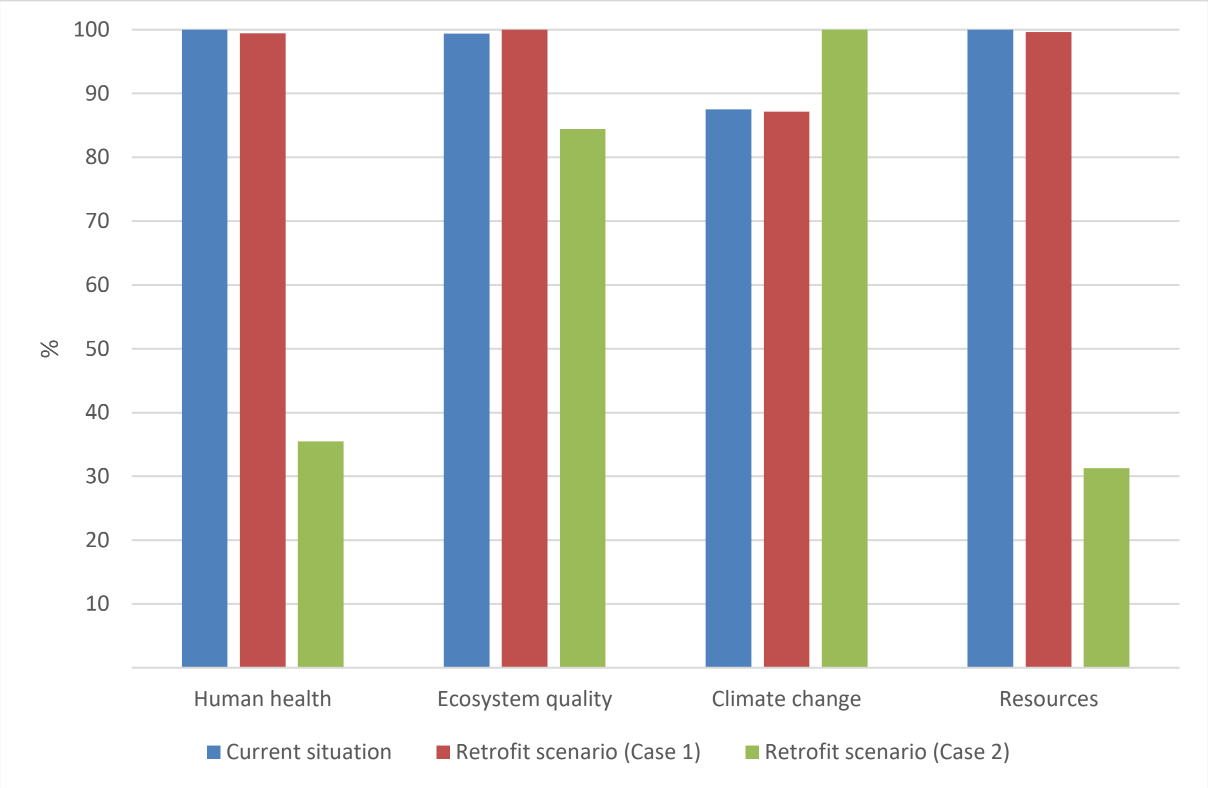

Figure 32. Comparative damage assessment results related to total GHG emissions of current situation and retrofit scenario (Case 1 and 2) using the IMPACT 2002+ Method (All impact scores are displayed on a 100% scale).

In order to provide comparable results among all the scenarios investigated in this work, the total GHG emissions are allocated to the final products (i.e. ethanol and electricity) using the energy allocation method as it set to the RED II. Regarding the emissions to ethanol product, the exclusive use of corn stover as feedstock seems to be the most appropriate, environmental-wise way (Figure 33). This is due to the emissions released from the cultivation and collection process of corn grain, in contrast to the zero emissions during the collection of corn stover according to RED II. Additionally, the utilization of biogas and lignin as fuels for the operation of boiler in the alternative scenario presents the best environmental performance. On the other hand, the natural gas consumption in the current and retrofit scenarios has a highly adverse effect on Global warming category, due to its fossil origin.

A summary of the comparative results of the environmental analysis is collectively presented in Table 20.

Table 20. Comparative results of all scenarios.

	Emissions to ethanol				Emissions to electricity			
	CO_{2eq}/year		CO_{2eq}/m^3/year		CO_{2eq}/year		CO_{2eq}/MWh/year	
Scenario	*Without CO_2 capture*	*With CO_2 capture*	*Without CO_2 capture*	*With CO_2 capture*	*Without CO_2 capture*	*With CO_2 capture*	*Without CO2 capture*	*With CO_2 capture*
Current	286,321	252,550	1.18	1.05	52,811	46,582	0.25	0.22
Retr. 1	285,418	251,647	1.18	1.04	52,645	46,416	0.25	0.22
Retr. 2	322,550	288,779	1.33	1.19	59,494	53,265	0.29	0.26
Alter/ve	21,986		0.73		9,038		0.16	

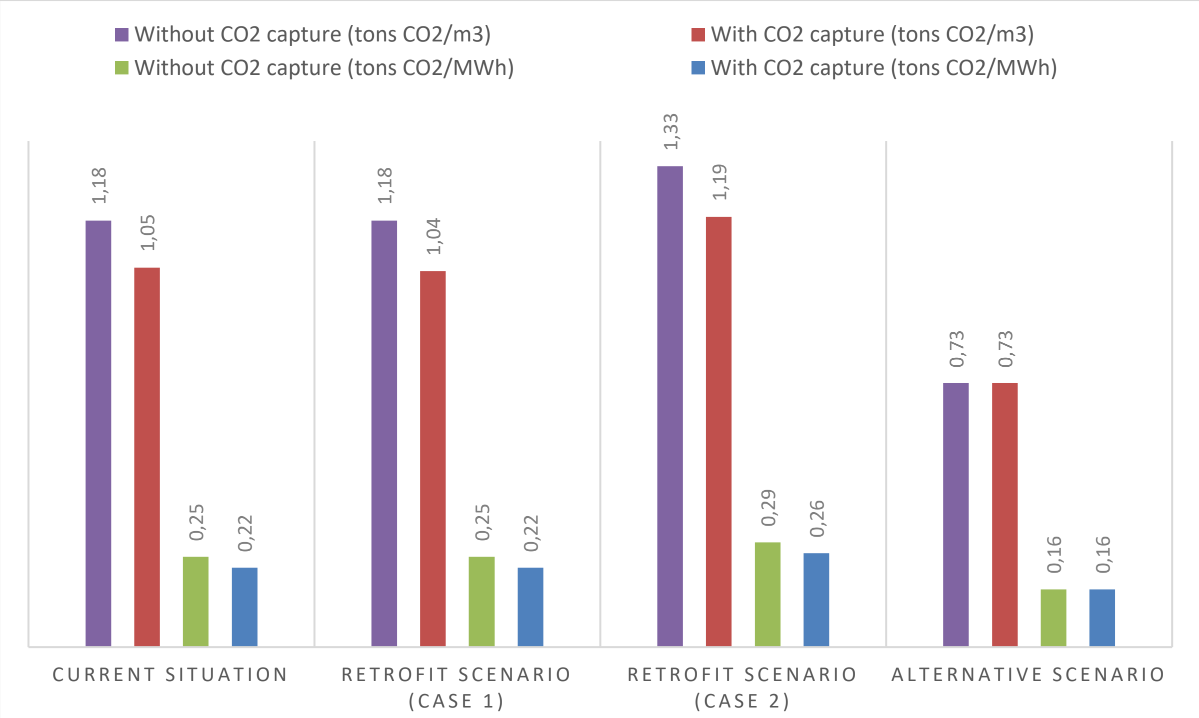

Figure 33. Comparative results of all scenarios using the energy allocation method to the final products.

8.6 Conclusions

A rigorous life-cycle analysis was carried out in order to assess the environmental impact associated with the production and utilization of fuels derived from food biomass, non-food biomass and industrial-derived wastes, in the transport sector. Particular emphasis was given to the evaluation of the GHG emissions that arise from the production and utilization of (i) corn grain ('current scenario'), (ii) corn grain and stover, industrial waste and wine alcohol ('retrofit scenario'), and (iii) corn stover ('alternative scenario'). The environmental benefits of using the aforementioned food and non-food biomass fuels were also examined by calculating the GHG emission savings to be incurred by the replacement of conventional crude oil.

The total emissions for the production of 241,670 m^3/year ethanol and 207,900 MWh/year electricity from corn grain amount to 339,132 $tnCO_{2eq}$/a without CO_2 capture and 299,132 $tnCO_{2eq}$/a with CO_2 capture. These values is higher than the corresponding of Case 1 which emitted 338,063 $tnCO_{2eq}$/a without CO_2 capture and 298,063 $tnCO_{2eq}$/a with CO_2 capture, and utilizing in addition to corn grain, wine alcohol and industrial waste as feedstock. In Case 2 in which corn grain, corn stover, wine alcohol and industrial waste are used, the total emissions are the highest and amount to 382,044 $tnCO_{2eq}$/a without CO_2 capture and 342,044 $tnCO_{2eq}$/a with CO_2 capture. In the alternative scenario, the total emissions for the production of 30,000 m^3/year ethanol and 57,520 MWh/year electricity from corn stover amount to 31,024 $tnCO_{2eq}$/a. CO_2 capture is not taken place in the alternative scenario.

In order to provide comparable results with the fuel comparator determined by RED II (amounted to 94 gCO_{2eq}/MJ), the GHG emissions savings, defined as the emissions avoided from the production of bioliquids, have been calculated per MJ of produced energy from ethanol. It was found that 39.98% GHG emissions savings are associated with the current scenario (food biomass utilization) in case of CO_2 capture is not taken place. In case of CO_2 capture is taken place, the relevant saving is 47.06%. On the contrary, the GHG emissions savings associated with the production of 1G and 2G ethanol, in case of no CO_2 capture, amount to (i) 40.17% in case of using corn grain, wine alcohol and industrial waste (56.24 gCO_{2eq}/MJ), (ii) 32.39% in case of using corn grain, corn stover, wine alcohol and industrial waste (63.56 gCO_{2eq}/MJ), and (iii) 62.87% (34.90 gCO_2eq/MJ) in case of using corn stover only. The relevant values in case of CO_2 capture are (i) 47.25% GHG emissions savings in case of using corn grain, wine alcohol and industrial waste (49.58 gCO_{2eq}/MJ) and (ii) 39.47% GHG emissions savings in case of using corn grain, corn stover, wine alcohol and industrial waste (49.58 gCO_{2eq}/MJ). These values are comparable with the ones reported in the relevant literature, estimating GHG emissions in the range of (a) 52 - 75 gCO_{2eq}/MJ[22] in case of corn grain ethanol, and (b) 40 – 47.80 gCO_{2eq}/MJ[23] in case of corn stover ethanol.

Although the utilization of biomass fuels seems to be the most appropriate, environmental-wise way of producing transport fuel, the increased energy demand of the process has negative effect of the results in terms of GHG emissions. However, it is worthmentioning that

[22] https://www.tandfonline.com/doi/full/10.1080/17597269.2018.1546488
[23] https://doi.org/10.1016/j.apenergy.2018.10.091

the exclusive production of 2G ethanol from corn stover is a more promising, environmental-friendly, alternative to the production of 1G ethanol from corn grain. This is due to the fact that the production of 1G ethanol from corn grain is associated with the emissions arised from its cultivation and collection stage, as well as, with the increased demand for natural gas and electricity. In contrast, no GHG emissions are attributed to the collection of corn stover and the utilization of biogenic sources for heat production in the case of exclusive production of 2G ethanol. At this point, it should be interesting to note that one important challenge in the BCyL plant process is to substitute natural gas with a more environmentally friendly fuel from biogenic source.

A summary of the results of the environmental analysis are collectively presented in Table 21.

Table 21. Overview results of environmental assessment

Inputs (in SimaPro software)	**Outputs (from SimaPro and RED II)**	
Current scenario		
- 562,800 tons corn grain input - 378 tons enzyme input - 25.20 tons yeast input - 731,900 tons water input - 5 km transport distance of corn grain - 55,742.40 MWh of electricity consumption - 619,500 MWh of natural gas consumption to turbine - 393,750 MWh of of natural gas consumption to boiler - 40,000 tons CO_2 capture from fermenter	**Without CO_2 capture**	**With CO_2 capture**
	339,132 $tnCO_{2eq/a}$	**299,132 $tnCO_{2eq/a}$**
	56.42 gCO_{2eq}/MJ	**49.76 gCO_{2eq}/MJ**
	39.98% saving according to REDII	**47.06% saving** according to REDII
Retrofit scenario		
- 537,183.60 tons corn grain input - 9,680 m^3 wine alcohol input - 20,000 m^3 industrial waste input - 360.80 tons enzyme input - 24.10 tons yeast input - 716,405.80 tons water input - 5 km transport distance of corn	**Without CO_2 capture**	**With CO_2 capture**
	Case 1	
	338,063 $tnCO_{2eq/a}$	**298,063 $tnCO_{2eq/a}$**

- 200 km transport distance of wine alcohol - 200 km transport distance of industrial waste - 54,021.10 MWh of electricity consumption - 619,500 MWh of natural gas consumption to turbine - 391,394.60 MWh of of natural gas consumption to boiler - 40,000 tons CO_2 capture from fermenter	**56.24 gCO_{2eq}/MJ**	**49.58 gCO_{2eq}/MJ**
	40.17% saving according to REDII	**47.25% saving** according to REDII
- 492,937 tons corn grain input - 128,680 tons corn stover input - 9,680 m^3 wine alcohol input - 20,000 m^3 industrial waste input - 8,344.20 tons enzyme input - 343.20 tons yeast input - 1,772.60 tons sulfuric acid input - 1,144,794.10 tons water input - 5 km transport distance of corn grain - 5 km transport distance of corn stover - 200 km transport distance of wine alcohol - 200 km transport distance of industrial waste - 61,000.61 MWh of electricity consumption - 619,500 MWh of natural gas consumption to turbine - 543,623.25MWh of of natural gas consumption to boiler - 115,226.65 MWh of of natural gas consumption to dryer burners - 40,000 tons CO_2 capture from fermenter	***Case 2***	
	382,044 $tnCO_{2eq/a}$	**342,044 $tnCO_{2eq/a}$**
	63.56 gCO_{2eq}/MJ	**56.90 gCO_{2eq}/MJ**
	32.39% saving according to REDII	**39.47% saving** according to REDII
Alternative scenario		

- **114,351 tons corn stover input** - **7,051 tons enzyme input** - **514 tons yeast input** - **1,559 tons sulfuric acid input** - **1,426 tons calcium hydroxide input** - **288,638 tons water input** - **5 km transport distance of corn stover** - **38,515 MWh of electricity consumption** - **Outputs from fermenters:** ➢ **22,713 tons CO_2**	31,024 $tnCO_{2eq/a}$
	34.90 gCO_2eq/MJ
	62.87% saving according to REDII

➢ **399 tons water** ➢ **2,461 tons solid to landfil** - **Emission gases from boiler:** ➢ **114,260 tons CO_2** ➢ **3,998 tons NO_2** ➢ **22,686 tons O_2** ➢ **373,561 tons N_2** ➢ **72,198 tons water**	

* The savings are calculated according to the equation in page 30.

9 Risks (CST leaders)

In order to make a decision on investments, the risks need to be assessed and ranked on importance

9.1 Risk assessment for the retrofit

Through this project, the main risks related to the retrofit of the first-generation bioethanol industry have been determined. In this study, in order to assess the importance of the risks, the probability and the consequence of each of them have been determined. For this purpose, a probability scale from 1 to 4 has been established, being 1 almost impossible, 2 improbable, 3 common, and 4 very common. Similarly, a scale from 1 to 4 has been established for the consequence, being 1 plant in operation, 2 slight reduction in plant operation, significant reduction in plant operation, and 4 plant shutdowns. Total risk is calculated with the following equation:

$$\text{Total risk} = \text{Probability X Consequence}$$

Table 22 shows a comprehensive list of the risks identified, the probability and the consequence of each risk and the possible mitigation action.

Table 22. List of the risks identified, the probability and the consequence and the mitigation action

Risk	Probability (1 – 4)	Consequence (1 – 4)	Total risk (1 – 16)	Risk mitigation action
Change in regulations concerning the use of biofuels	3	3	9	Diversification in products: bioethanol 1G, bioethanol 2G, industrial alcohol, etc..
Decrease in support for biofuels compared to other renewable resources in the transport sector such as renewable electricity (electric car) or hydrogen	3	2	6	Diversification in other technologies such as hydrogen, jet fuel, bioplastics, etc
Raw material supply	3	2	6	Diversification of raw materials
Variability in the price of raw materials	3	2	6	Diversification of raw materials
Raw material storage / Safety stock to maintain production	2	2	4	Investment in storage
Safety in raw material storage	2	1	2	Investment in storage
Decrease in fuel use caused by a decrease in mobility due to the pandemic.	1	2	2	Diversification in products
8.- Risk in the process. Efficiency issues	1	1	1	Investment in R&D&I

The main risk identified by this assessment is the **change in regulations concerning the use of biofuels** which presents a **total risk score of 9**. Currently, in Spain the Royal Decree that includes the objectives of biofuels established in the RED II directive for the years 2021-2025 to update the RD 1085/2015 is still under review. This directive could confirm the obligation to meet the target of 1% of consumption of advanced biofuels by 2030. This regulation is under permanent review, which generates great uncertainty to decide the possible future investments by the biofuel industry. Other European countries have transposed the European directive RED II more quickly and clearly, helping to promote the biofuels market. Specifically, in the case of advanced fuels, there are countries in which the use of these biofuels is promoted through the double counting mechanism established in the REDII directive. However, in the case of Spain, although double counting mechanism is approved, there is still no improved price to use these advanced biofuels. Without this financial support, there would not make sense to invest in retrofitting to obtain advanced biofuels that have much higher specific costs than first-generation biofuels.

Other important risks determined with a **total risk score of 6** are the following:

- **Decrease in the support for biofuels compared to other renewable resources in the transport sector such as renewable electricity (electric car) or hydrogen.** In recent years in Spain and other European countries there is greater support for other renewable energies and alternative technologies such as hydrogen and the electric car, than for biofuels, which would have a rapid and direct application in the current fuel market and which could reduce CO_2 emissions significantly.
- **Raw material supply.** One of the risks of second-generation ethanol production plants is the raw material supply. Specifically, in the case study of Biocarburantes de Castilla y Leon plant, around 130,000 tonnes per year of corn stover would be needed for the production of about 19,000 m^3 of advanced ethanol. This agricultural residue is not currently harvested in the Castilla y León area, so it would be necessary to adapt the current production of the corn crop and farmers would need to acquire the necessary machinery for its collection. In addition, due to the high consumption of this lignocellulosic raw material, the logistical resources for this type of plant crop are very important in relation to transport, storage and process feeding.

- **Variability in the price of raw materials.** The possible variation in the price of the raw material is an important risk for the profitability of the process. At present, corn stover is considered a residue and has a relatively low price, but if its consumption as a raw material starts growing, the price could also increase. One of the possibilities to mitigate this risk is the diversification into different raw materials. In this case study, wheat straw could also be used, much more common in the area where the Biocaraburante de Castilla y Leon plant is located. The main problem for the use of wheat straw is its use for livestock. This raw material already has its own market and this new use could cause a price increase since it is not considered as a waste itself.

The next risk in order of importance is the **raw material storage (total risk score of 4)**. It is essential to maintain a safety stock to guarantee the production. To ensure a safety stock with a minimum of 6 - 8 days of raw material and close to the plant, it would be necessary to have a relatively large storage. In this case study, to produce 19,000 m^3 per year of advanced bioethanol, approximately 130,000 tonnes of corn stover would be needed (about 370 tonnes per day). To ensure the production, 3,000 t of safety stock would be needed, plus the capacity to continue supplying continuously. To mitigate this risk, it would be important to invest in storage.

Finally, the following risks have been identified with a slight importance:

- **Safety in raw material storage (total risk score of 2).** There is a significant risk of fire and self-ignition in large cereal straw stores. On the one hand, it could be stored outside to ensure adequate aeration conditions, but if the raw material has excessive moisture, it could lead to self-combustion. In this case it would be necessary for the storage to have a roof with its own firefighting measures. This could significantly increase the storage cost in order to ensure adequate conditions to avoid a possible plant shutdown.
- **Decrease in fuel use caused by a decrease in mobility due to the pandemic (total risk score of 2).** In the last year, a reduction in mobility caused by an event such as a pandemic can significantly reduce the fuel consumption, up to 90%. At present, with partial confinements there is a reduction in mobility of around 40%, so it is necessary that bioethanol be used for other applications. From now on, there is the possibility that companies remain part of their staff teleworking, so fuel consumption will not to recover the consumption data prior to the pandemic. Therefore, it will be necessary to adapt the needs of the market and to diversify into different products and applications.
- **Risk in the process. Efficiency issues (total risk score of 1).** In contrast to 1G bioethanol production processes, advanced bioethanol production processes usually show less conversion efficiencies and higher operational costs. In this sense, potential changes in process efficiencies, market trends and final prices may have an important impact in the viability of the process. Therefore, it is important to continue promoting R&D&I activities in this field.

10 Key Performance Indicators (KPI)

The following items are defined as the KPIs for the business cases in order to evaluate the different cases. The KPIs can also be aggregated to obtain overall numbers for the BIOFIT project. The KPIs should not be used as a comparison between the case studies or as a ranking tool, since the KPIs will quickly result in unfair comparisons between the different scenarios.

Each KPI will be calculated separately and even though some KPIs may be interconnected (such as biomass use and bioenergy production), they will all be independently evaluated and discussed.

Technical KPIs

The following technical KPIs are defined:

- **Increase in biomass converted per year**

The increase in biomass conversion for the retrofit compared to the current situation should be determined.
In Retrofit Case 1, a reduction of 22,030 tonnes of biomass converted per year is obtained, since part of corn grain is replaced with an industrial rich-etanol waste to produce 2G ethanol. In Retrofit Case 2, part of the grain is replaced by lignocellulosic biomass (corn stover), obtaining an increase in converted biomass per year of 60,877 tonnes.

- **Increase in bioenergy or biofuel generated per year**

In this case study, it is assumed that part of the 1G ethanol production is replaced by 2G ethanol, therefore there is no increase in bioenergy or biofuel generated per year production.

Economic KPIs

The following economic KPIs are defined:

- **Internal rate of return; IRR**

Based on the data provided by the economic assessment, the internal rate of return will be determined. The IRR value of the retrofit Case 2 is 26%.

- **CAPEX reduction compared to alternative**

The CAPEX reduction is calculated by subtracting the CAPEX required for the retrofit from the CAPEX required for the alternative scenario. In this case study, the CAPEX reduction obtained is 99,9 % and 57% for retrofit Case 1 and Case 2, respectively.

Environmental KPIs

- **Carbon dioxide Equivalent Emission Reduction of supply chain and operation**

Greenhouse Gases (GHGs) are gases in the atmosphere that absorb infrared radiation that would otherwise escape to space; thereby contributing to rising surface temperatures. There are six major GHGs: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulphur hexafluoride (SF6). Emissions of other gases can be converted to CO_2 equivalents through specific methodologies. Since the main sources for CO_2 emissions are combustion processes related to energy generation and transport, CO_2 emissions can therefore be considered a useful indicator to assess the contribution of retrofitting on climate change.
In Retrofit Case 1 the Carbon dioxide Equivalent Emission Reduction obtained is 0.32% without CO_2 capture and 0.35% with CO_2 capture. In Retrofit Case 2, the results obtained are -12.65% without CO_2 capture and -14.35% with CO2 capture

- **Increased efficiency of resources consumption**

Percentage and mass reduction in non-renewable material consumption of the project. As proposed in the "Clean Energy for All Europeans", the target for renewable energy consumed should reach 32%. Through assessing the specific KPI, the renewable share of energy will be monitored and thus the expectation will be met. ["Clean energy for all Europeans | Energy." [Online]. Available: https://ec.europa.eu/energy/en/topics/energy-strategy-and-energy-union/clean-energy-all-europeans. [Accessed: 22-Jan-2019].]

Table 23 shows the results of the different KPIs obtained in this study.

Table 23. Key Performance Indicators (KPI).

KPI	value
Increase in biomass converted per year (comparing retrofit scenario with current scenario)	Retrofit case 1: -22030 tonne/year Retrofit case 2: 60877.02 tonne/year
Increase in biomass converted per year (comparing retrofit scenario with alternative scenario)	Retrofit case 2: 13469.3 tonne/year
Increase in bioenergy or biofuel generated per year	0
Internal rate of return; IRR	Retrofit case 2: 26%

CAPEX reduction compared to alternative	Retrofit case 1: 99,9% Retrofit case 2: 57%
Carbon dioxide Equivalent Emission Reduction of supply chain and operation	Retrofit case 1: 0.32% without CO2 capture / 0.35% with CO2 capture Retrofit case 2: -12.65% without CO2 capture / -14.35% with CO2 capture
Increased efficiency of resources consumption	-

Calderón, C., Gauthier, G., & Jossart, J.-M. (2018). *Statistical Report 2018.* Bioenergy Europe.

Capros, P. (2016). *EU Reference Scenario 2016 - Energy, transport and GHG emissions - Trends to 2050.* European Commission .

Dutta, A. (2020). *Are global ethanol markets a "one great pool"?* Biomass and Bioenergy.

E4tech. (2019). *E20 Supply and Demand Study.*

EEA. (2018). *Quality and greenhouse gas intensities of transport fuels in the EU in 2017.* EEA.

ePURE. (2018). *European renewable ethanol - key figures 2018.*

ePURE. (2019). *E20 Supply and Demand Study - Final Report.* E4tech.

ETIP Bioenergy. (2020). *Current status of advanced biofuels demonstration in Europe.* ETIP Bioenergy.

ETIP Bioenergy. (2020). *Current status of advanced biofuels demonstrations in Europe.* ETIP Bioenergy.

EurObserv'ER. (2019). *Biofuels Barometer.*

EurObserv'ER. (2019). *The state of renewable energies in Europe.*

EUROSTAT. (2020). Database.

Festel, G., Würmseher, M., Rammer, C., & Boles Eckhard. (2014). *Modelling production cost scenarios for biofuels and fossil fuels in Europe.* Journal of Cleaner Production.

Flach, B., Lieberz, S., & Bolla, S. (2019). *EU Biofuels Annual 2019.* Global Agricultural Information Network.

Guerrero, M. (2017). *Portugal Biofuel Market Outlook 2017.* Global Agricultural Information Network.

IEA . (2017). *Technology Roadmap - Delivering Sustainable Bioenergy.*

IRENA. (2019). *Advanced Biofuels. What holds them back?* International Renewable Energy Agency.

Landälv, I., Waldheim, L., Maniatis, K., van den Heuvel, E., & Kalligeros, S. (2017). *Building up the future - Cost of Biofuel.*

Liebertz, S. (2018). *Biofuel Mandates in the EU by Member State in 2018.* USDA Foreign Agriculture Service.

Lieberz, S. (2019). *Biofuel Mandates in the EU by Member State in 2019.* Global Agricultural Information Network.

Maluf de Lima, L., & Rumenos Piedade Bacchi, M. (2018). *Global Ethanol Market: Commercialization Trends, Regulations, and Key Drivers.*

Maniatis, K., Landälv, I., Waldheim, L., van der Heuvel, E., & Kalligeros, S. (2017). *Building up the Future.* Sub Group on Advanced Biofuels.

Neumann, K., Schröder, J., Oehmichen, K., Etzold, H., Müller-Langer, F., Remmele, E., . . . Schmidt, P. (2019). *Monitoring Biokraftstoffsektor 4. Auflage.* DBFZ.

United Nations. (2016). *Second Generation Biofuel Markets: State of play, trade and developing country perspectives.*

Witcover, J., & B. Williams, R. (2020). *Comparison of "Advanced" biofuel cost estimates: Trends during rollout of low carbon fuel policies.* Transportation Research Part D.

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