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BIOFIT Case Study Report

AustroCel Hallein
Austria

Nature, dissemination level	**Report, public**
Dedicated to	**AustroCel Hallein (Austria)**
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1 Introduction to the case study

BIOFIT Case Study: Fermentation of liquor at the AustroCel Hallein pulp mill in Austria for the production of advanced bioethanol

Under the lead of project partner BEST, the fermentation of sulphite spent liquor (SSL) from the pulp production at AustroCel Hallein in Austria will be investigated. Retrofitting could lead to the production of 30 million litres of advanced bioethanol per year.

AustroCel processes spruce wood to dissolving pulp for cellulose applications, with a capacity of 160,000 t/a. The retrofit will add a fermentation step for the spent sulphite liquor. During the pulping process, sugars are formed, which will be fermented to advanced bioethanol. The planned capacity is 30 million litres per year, and an off-take agreement has been arranged with the Austrian mineral oil company OMV.

The Kick-off meeting took place in Hallein, in mid-2019. Main focus of the case study is the evaluation of a viable and sustainable advanced bioethanol production and its market. AustroCel already started to build the advanced bioethanol production plant. The plant has an investment volume of about 42 million euros and is scheduled to go into operation at the end of 2020.

2 Case study description

The first case study chapter is a description of three items: the current situation, the suggested retrofit, and what the alternative would be when no retrofit takes place.

2.1 The current situation

AustroCel Hallein[1] is located in Hallein, Austria, which belongs to Salzburg and is close to the German border. Figure 1 shows the plant and the factory area, which has about 34 hectares. The plant is close to the river Salzach and railroad tracks.

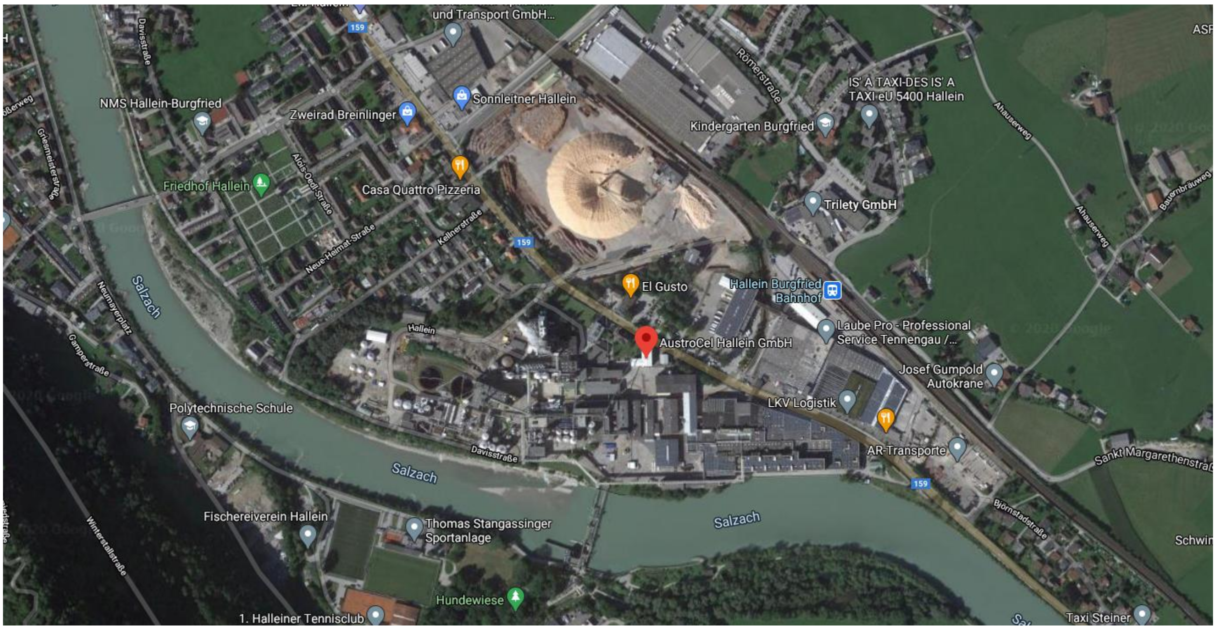


Figure 1: Location of the AustroCel Hallein plant

AustroCel Hallein has about 275 employees and an annual revenue of about 124 million €. 99.6 % of all fuels in the process are biofuels, the remaining 0.4 % are natural gas.

AustroCel Hallein is processing regional wood chips (spruce) into pulp. For the pulping process, only trunk wood (mainly sawmill residues), no branches, tops or bark, can be used. This pulp is nearly 100 % transported by train to Slovenia. It is intermediately stored in containers until further transport to Asia. There, the pulp is processed for viscose production. Global viscose market is growing, viscose consumption reached 6.5 million tonnes in 2017. There is also viscose pulp production in Finland, Czech Republic and Sweden. However, about two thirds of

[1] https://austrocel.com/en/

global viscose were produced in China, and further growth of 8.6 % annually from 2017 to 2022 is predicted. China is lacking wood, therefore about 62 % of their required viscose pulp had to be imported in 2017. Viscose is playing an important role for the textile fibre market, since cotton production is limited and consumption stayed stable since several years.

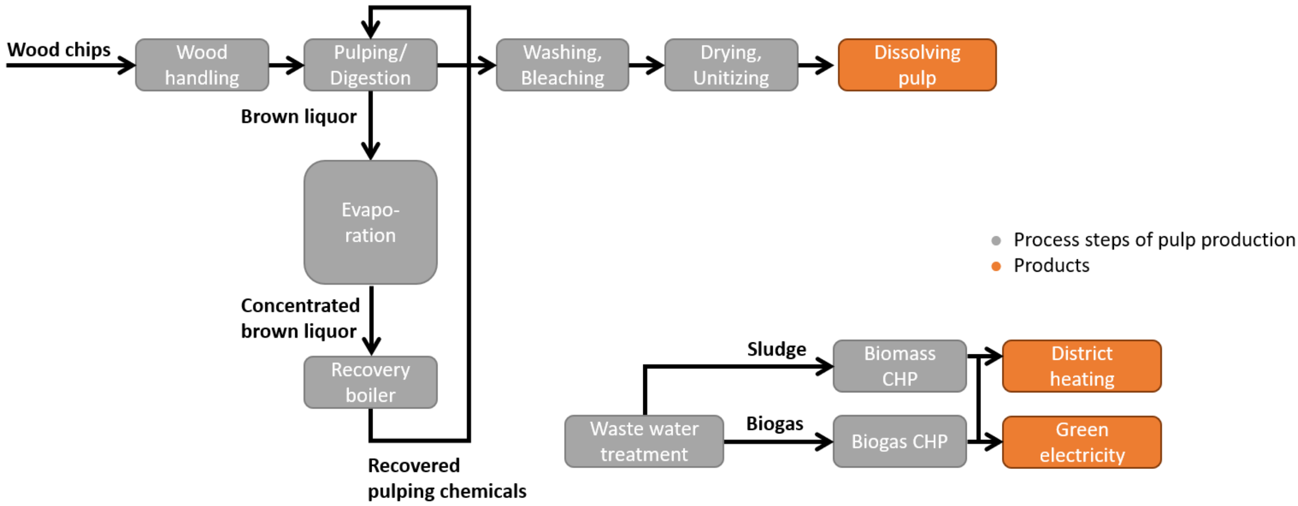


Figure 2: Flow sheet - Current situation

Figure 2 shows the simplified process of AustroCel Hallein. The spruce wood originates 56% from Austria, 39 % from Germany and 5 % from other EU countries and is certified with PEFC. The annual requirement of spruce is almost 900,000 m³. Around 95 % of the quantity are sawmill residues (wood chips) and the other 5 % are wood logs. De-barking and chopping of the logs (diameter 8-48 cm) are done at the company's wood yard. The wood chips are stored between three and six weeks on a doughnut-shaped pile, which contains about 110,000 m³.

The wood yard additionally processes 100,000 m³/a of biomass, which is combusted in a biomass CHP plant, together with bark, fine materials, rejects from digestion and sludge from the waste water treatment plant. Overall fuel requirement is 15 t/h. The biomass CHP plant has a capacity of 33 MW_{th} and an output of 100 GWh/y district heating, 45 GWh/y green electricity DT5 and 6 GWh/y green electricity DT7.

Spruce wood chips contain 44 % cellulose, 28 % lignin and 28 % hemicellulose. During the pulping or digestion process, lignin, sugars from hemicellulose and minerals are extracted. In a sulphite process, the resulting extraction liquid is called brown liquor or spent sulphite liquor (SSL). After digestion, nearly 40 % of the volume are fibres, that remain in the pulping process and are subsequently washed and bleached. After drying and utilizing, pulp is ready for transport. The other 60 % are brown liquor.

AustroCel Hallein also has four biogas reactors, which anaerobically digest condensate from evaporation and bleaching filtrates. 1,600 m³ biogas are produced per hour. This biogas is combusted in the own biogas CHP plant in order to generate 76 GWh district heating and green electricity.

Additionally, 5,932 photovoltaic modules, with a surface of nearly 10,000 m² and a peak performance of 1,483 kWh are installed on the roof. The generated green electricity is fed into the public power grid and provides energy for about 400 households since 2014.

The plant of AustroCel Hallein is a biorefinery. In 2018, about 160,000 t of pulp, nearly 100 GWh green electricity and more than 100 GWh district heating were provided. The planned retrofit in order to produce second generation bioethanol is widening the product portfolio.

High purity of fibres results in an increased amount of brown liquor occurring during the pulping process, as well as an increased sugar content within the brown liquor. The capacity of the recovery boiler of AustroCel Hallein constitutes a bottleneck to capacity increases. AustroCel Hallein is selling part of its brown liquor, for use as a binding agent for the production of pellets, concrete etc. Since the price for brown liquor is not attractive, an in-house use is preferred. By fermenting the sugars within the brown liquor to ethanol and removing the ethanol from the slop which is returned to the recovery boiler, the volume of brown liquor in the recovery boiler is reduced while the concentration of recoverable chemicals is increased.

2.2 Suggested retrofit

This in-house use suggests further processing of pulping process by-product SSL to second generation or advanced bioethanol. Dry SSL contains 45-55 % lignosulfonate, 20-25 % sugars, 10-20 % salts and minerals and 10-15 % organic acids (approximate values).
Figure 3 shows the integration of bioethanol production in the existing pulp production process. During evaporation, SSL is branched off and subsequently fermented and distilled to separate the bioethanol.

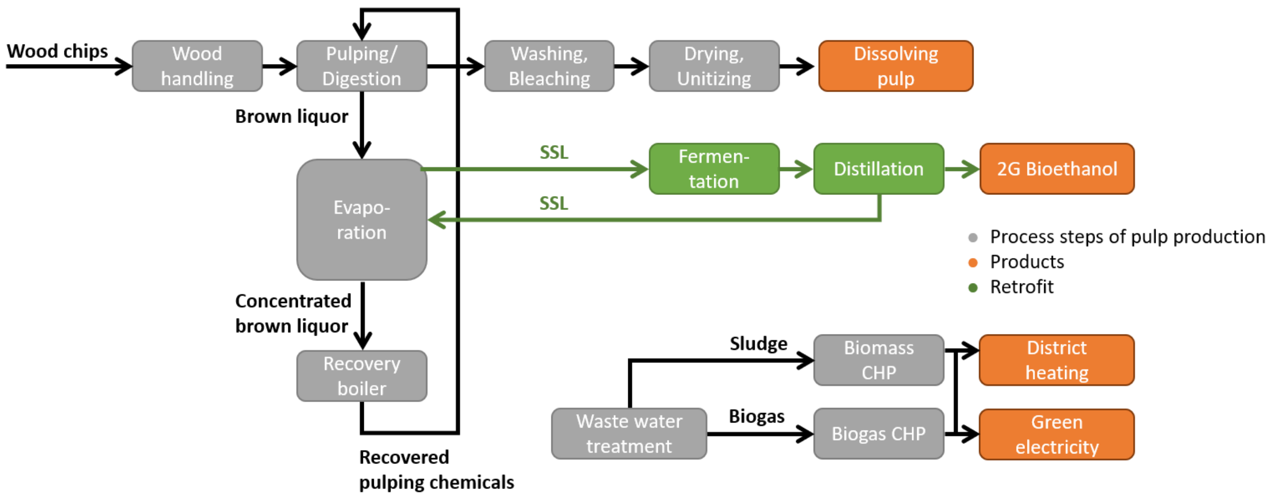


Figure 3: Flow sheet – Suggested retrofit

The pulping process runs constantly on 358 days per year, which secures resource availability. The use of yeast strains that are capable to convert C5 sugars can increase bioethanol yield. In addition, the bioethanol yield will increase proportionally to pulp production. Per 1 t of pulp, 2.52 t of brown liquor are produced, this represents 170.000 t pulp and 430.000 t concentrated brown liquor per year.

The bioethanol will be transported 100 % by train, every few weeks. The railway tracks are directly connected with the plant. Per year, about 20 full block trains are planned.

Timeline of the retrofit

History

- 1941 – 1988 Bioethanol production at the pulp mill in Hallein (6,000l/d), experiences with spent liquor as substrate and conventional yeast.
- 2007 – 2009 Technical pre-project and conceptual engineering
- 2011 Product changed from paper to dissolving pulp, increasing SSL and sugar content and therefore increasing bioethanol yield possible

Project schedule

- July 2017: Concept and basic engineering in cooperation with suppliers for fermentation and distillation plants, planning of tank farm and filling station
- October 2017: First information and consultation with authorities and county government
- 2018: Finalizing of basic engineering (layout, site integration, production plant components), tender phase and project economics presentation to investors, start of pilot-scale fermentation for validation of yield and optimization of process parameters

- 2019: Contract signature of main equipment suppliers, filing for building and operational permit, detail engineering, start of civil construction, signing of supply agreement with OMV
- Q4 2020: Commissioning phase after 18 months project realization
- 2021: Full-scale production

AustroCel Hallein already conducted 60 fermentation and distillation trial runs in lab scale. Substrate and by-products were comprehensively analysed. Different yeast strains and their properties were cultivated and evaluated in a microbiology lab. Process parameters and their effects on sugar conversion rate and yeast viability were tested. A pilot fermentation plant is operating since more than 2 years.

Secured offtake was important for AustroCel Hallein, therefore they already signed a supply agreement with OMV, the Austrian mineral oil company. 30 million litres bioethanol per year could substitute about 1 % of gasoline demand by 2025.[2]

The retrofit is expected to have operational and investment advantages compared to the greenfield scenario. Feedstock and energy supply of the pulp production process provide ideal boundary conditions for retrofitting. 30 million litres of bioethanol produced in Austria will decrease fuel imports (1% of gasoline demand in Austria) and contribute to the EU SET-plan and the Paris Climate Agreement (50,000 t CO_2 savings). Additionally, it is an investment for a sustainable bioeconomy and a step forward to fulfilment of blending mandates for advanced biofuels according to RED-II.

2.3 Alternative to the retrofit

The alternative scenario foresees the production of second-generation or advanced bioethanol in a greenfield facility from cellulosic waste. The bioethanol production capacity is estimated at 30 million litres per year. For producing this amount, about 430,000 t/a SSL would be needed, when C5 and C6 sugars are utilized. Figure 4 shows the simplified process of cellulosic bioethanol production. Cellulosic waste is milled, cleaned and further pre-treated. After an enzymatic hydrolysis, cellulosic feedstock is filtrated and lignin is branched off. Subsequently, the cellulosic feedstock is fermented and finally distilled.

[2] https://www.omv.com/en/news/191003-omv-and-austrocel-hallein-sign-bioethanol-supply-agreement

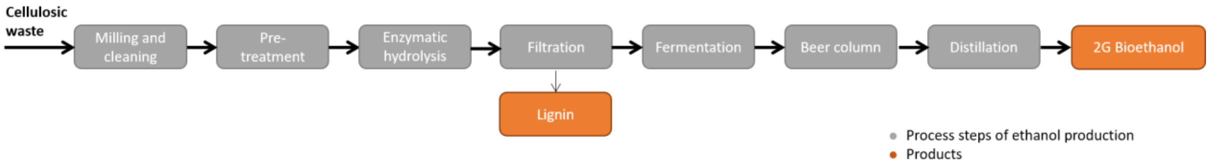


Figure 4: Flow sheet - Alternative scenario

3 Supply chain assessment

Since the suggested retrofit is not influencing the supply chain, this assessment is only a short description.

AustroCel Hallein is planning to further process a pulping process by-product. This by-product is called brown liquor, or spent sulphite liquor (SSL). This feedstock is fermented in order to produce bioethanol. Since brown liquor is listed in RED-II, Annex IX, Part A, feedstock and the resulting product are considered as advanced.

Currently AustroCel Hallein is selling parts of their SSL, since the capacity of the recovery boiler is not sufficient to cope with the huge amounts. Per year, about 430.000 t of SSL are produced, from which up to 30 million litres (25,000 t) of bioethanol can be produced. The market for SSL consists of quite small niches in relation to the total amount that is normally used in the pulp mills themselves for chemical recovery and energy supply. Concentrated SSL achieves different prices on the market depending on application and quality.

Planned production capacity of advanced bioethanol is 30 million litres per year. This amount would substitute about 0.2 % of transport fuels consumed in Austria, or about 1 % of gasoline. Since the feedstock is a by-product, there are no availability issues. However, production capacity of bioethanol is limited by the production capacity of dissolving pulp, the main product of AustroCel Hallein. A simplified supply chain is illustrated by Figure 5.

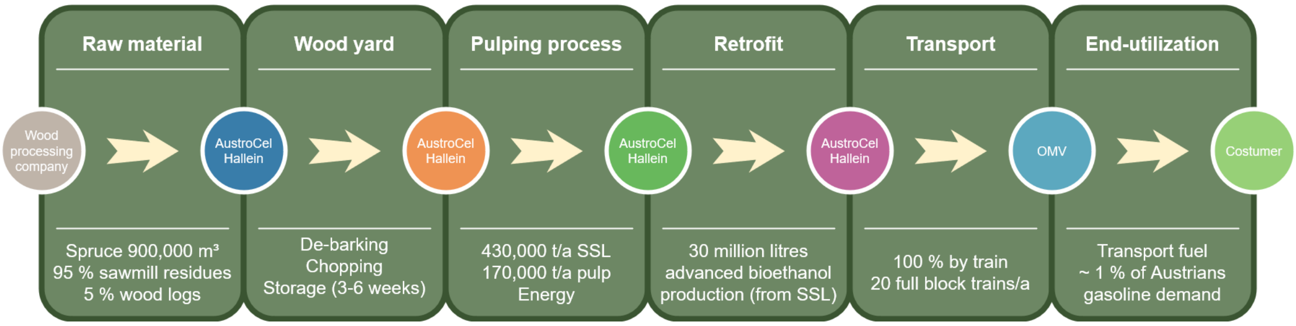


Figure 5: Simplified supply chain

4 Market assessment

This chapter is providing an overview on European and Austrian political framework and an overview on European bioethanol production, consumption and trade. Additionally, other European advanced cellulosic bioethanol plants, which are already constructed or planned, are listed. Further, market prices and bioethanol market developments are addressed.

4.1 Political framework

EU

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 high 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, the transposition of RED-II into national legislation has yet to be done.

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

Austria

In Austria, the RED and FQD sustainability criteria have been implemented by two separated ordinances, the Ordinance on Agricultural Feedstocks for Biofuels and Bioliquids and the certification of commercialized biofuels. The Austrian Decree on Transportation Fuels provides that up to a certain limit no tax is levied on bioethanol or biodiesel. Tax concessions are granted for sulphur-free fuels with a biofuel share of 4.4% minimum. And since 2000, pure biofuels have been exempted from mineral oil tax. In 2007, the Bioethanol Blending Order entered into force, which allows refunding of mineral oil duty for E75 blends. (Bacovsky, 2018)

Austrian blending mandates between 2012 and 2020 were 5.75% overall, divided in 6.3% biodiesel and 3.4% bioethanol. Since 2020, the overall percentage is 8.75% without division between fuels. The introduction of E10 was already discussed, but never enforced. Double counting is valid for waste materials and residual products from agricultural and forestry production including fisheries and aquaculture, residues from processing, cellulosic non-food materials or lignocellulosic materials. (Lieberz, 2019)

Further legislation, transposing RED-II into national law has yet to be created and will consitute the framework for targets beyond 2020. Setting specific targets for the use of advanced biofuels, according to RED-II, will increase market demand for advanced biofuels. RED-II foresees following targets for advanced biofuels: 0.2% by 2022, 1% by 2025 and 3.5% by 2030 of final consumption of energy in the transport sector.

4.2 Bioethanol market overview

4.2.1 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 EU bioethanol production increased by 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 gasoline-type fuels, compared to diesel. (EurObserv'ER, 2019)

Figure 6 shows the development of first-generation bioethanol production and consumption in the EU from 2007 to 2018. As can be seen, the formation of a market equilibrium, through an alignment of supply and demand. The share of bioethanol in gasoline consumption is about 5% and remained unchanged over the last years. (Neumann, et al., 2019)

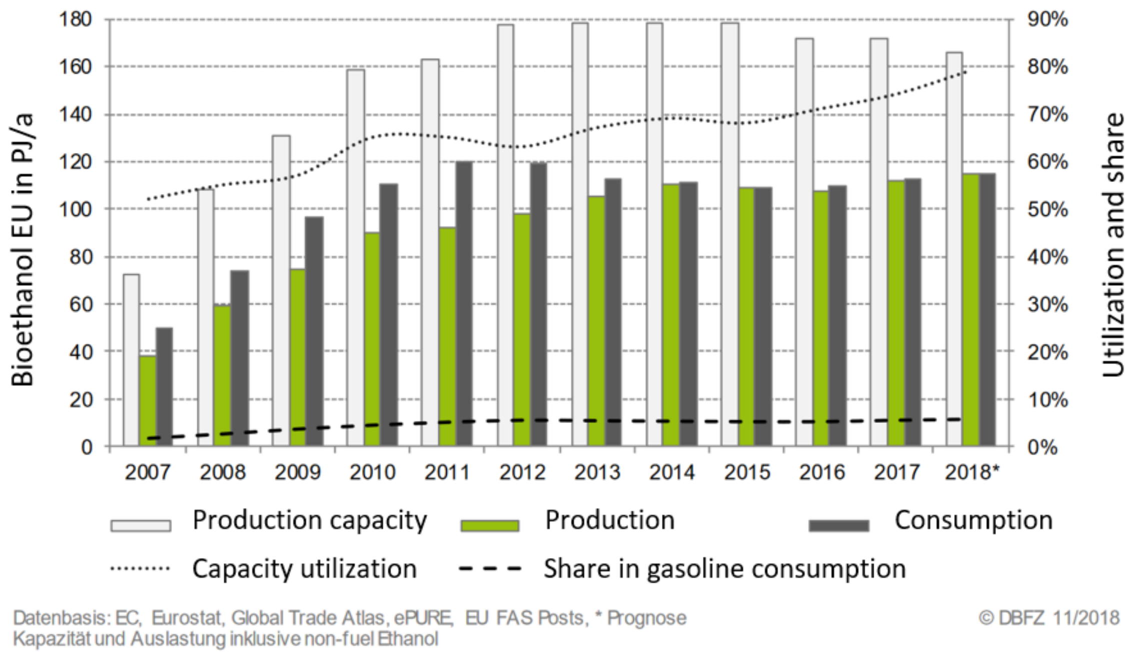


Figure 6: Development of bioethanol market (Neumann, et al., 2019)

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 1.

Table 1: 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

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

Currently, there is only one bioethanol production facility in Austria, producing 250 million litres first-generation bioethanol per year. It is operated by Agrana and located in Pischelsdorf, which is about 300km from Hallein. The bioethanol production facility in Pischelsdorf has sufficient production capacity and feedstock availability in order to cover the whole first-generation bioethanol demand of Austria, even if E10 would be introduced. Currently, about half of the produced bioethanol is exported.[4]

Consumption

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.

Figure 7 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) and the Netherlands with 169.7 ktoe (equal 335 million litres). The bioethanol consumption of Austria in 2018 amounted to 57.6 ktoe (equal 113.8 million litres). (EurObserv'ER, 2019) This is about half of the amount of bioethanol produced.

[4] https://www.agrana.com/en/products/bioethanol#!bioethanol-produktion

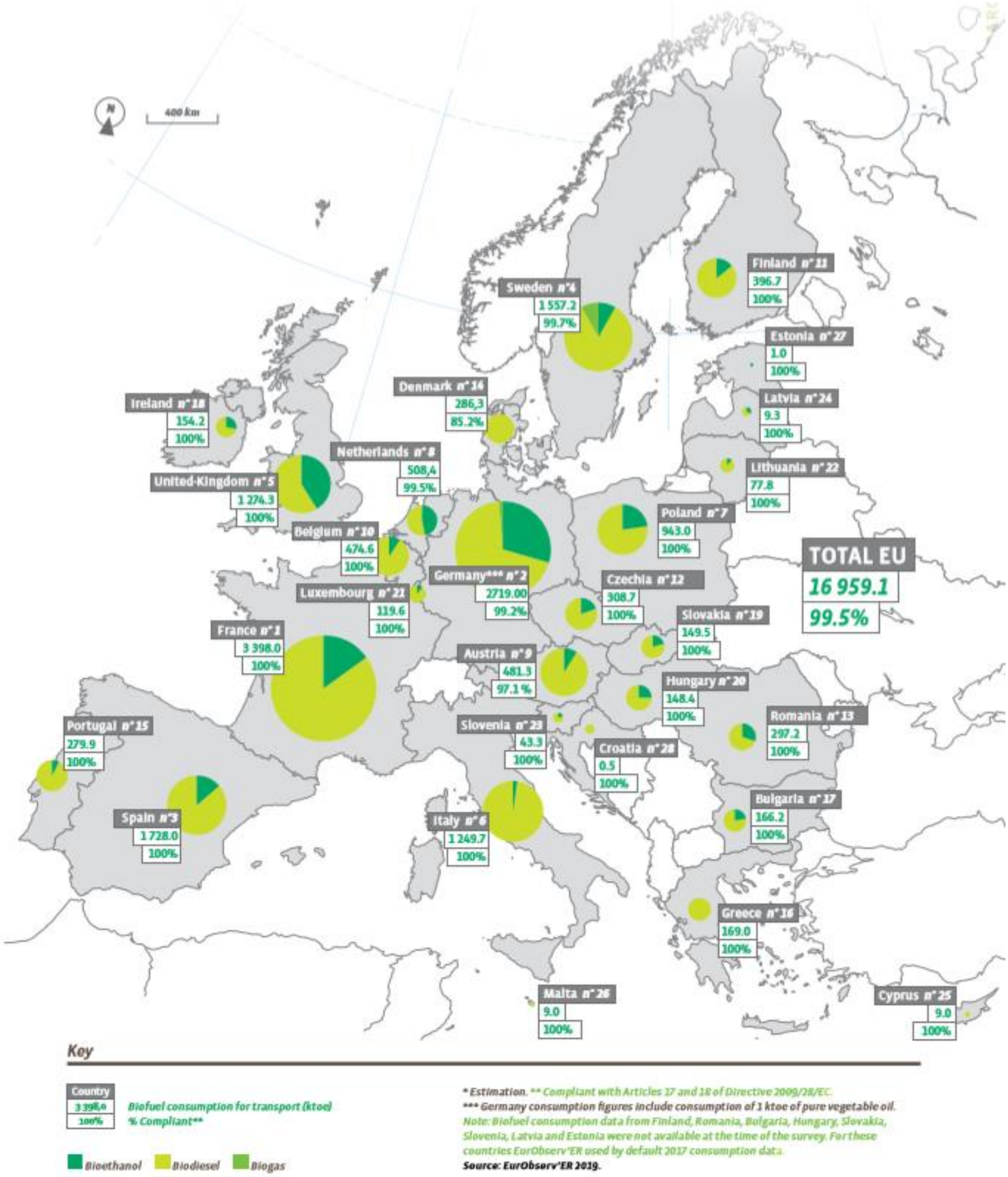


Figure 7: Biofuels consumption for transport in the EU in 2018 in ktoe (EurObserv'ER, 2019)

Bioethanol for the transport sector is either directly blended with fossil fuels (E5 and E10 in gasoline-type engines, E85 in flex fuel vehicles) 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) 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)

Trade

About 618 million litres of first-generation bioethanol were 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) Since Austria is producing about double the amount of bioethanol needed (250 million liters), at least half of it is exported.

4.2.2 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 and Domsjö Fabriker are utilizing brown liquor from wood pulping for their production, such as AustroCel Hallein. St1 is fermenting organic wastes to bioethanol. (ETIP Bioenergy, 2020)

Table 2 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 2: Operational advanced bioethanol production facilities[5]

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)

[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

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)
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 3 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 3: Advanced bioethanol production facilities under construction

Company	Country	City	TRL	Start-up year	Capacity t/y (million litres)
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 4).

Table 4: Planned advanced bioethanol production facilities

Company	Country	City	TRL	Start-up year	Capacity t/y (million litres)
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	Norway	Ringerike	8	2024	40,000

Cellulonix Follum					(50.4)
Versalis Crescentino restart	Italy	Crescentino	8	2020	40,000 (50.4)
ORLEN Poludnie Jedlicze Site	Poland	Jedlicze	9	-	25,000 (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, equal 343,735 toe). In Austria, AustroCel Hallein is the only advanced bioethanol production facility known. Compared to the targets for advanced biofuels by the RED-II (0.2 % by 2022, 1 % by 2025 and 3.5 % by 2030), planned production capacity would reach about 0.12 %, assuming a final energy consumption for transport of 286,777,587 toe in 2018 (without UK).[7]

4.3 Market price of advanced bioethanol

In general, biofuels are more expensive than fossil fuels. A main part of biofuel production costs are feedstock costs. Therefore, biofuels based on waste-streams or by-products seem to be more 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 5 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

[7] https://ec.europa.eu/eurostat/databrowser/view/ten00124/default/table?lang=en

Biofuels – Potential for Cost Reduction”[8], published by IEA Bioenergy Task 39 in 2020, confirmed that these cost estimations are still reasonable.

Table 5: 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

Since AustroCel will use a by-product as feedstock and therefore have low feedstock costs, the low scenario should fit. Also, CAPEX and OPEX of cellulosic bioethanol production is expected to be lower for AustroCel, compared to a greenfield scenario, since the planned production is integrated into the pulp mill.

4.3.1 Minimum selling price for cellulosic ethanol

Figure 8 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)

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

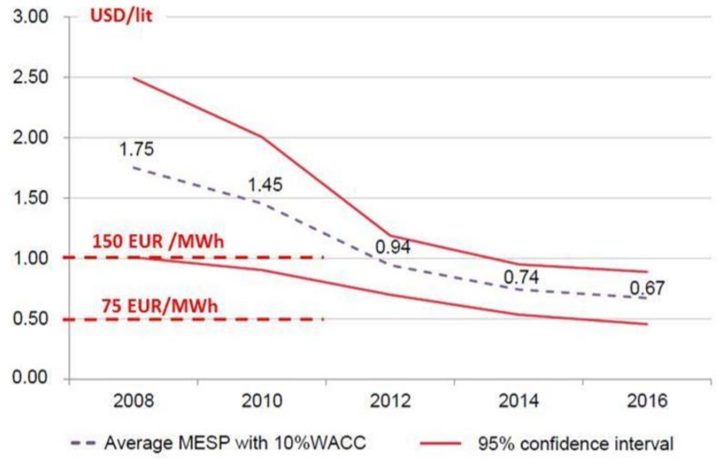


Figure 8: Minimum (cellulosic) ethanol selling price (MESP)

The projected fossil fuel price in the EU Reference Scenario from 2016 is 48€/MWh in 2030. (Capros, 2016) Currently and without further incentives, advanced biofuels will not be competitive with fossil fuels. However, if there is an extensive increase in the production capacity of advanced biofuels and if there are incentives, such as carbon pricing, advanced biofuels can be competitive in the long term.

4.3.2 Comparison of production costs of advanced biofuels

Figure 9 compares the production costs of cellulosic ethanol with the production costs of other advanced biofuels. It can be seen that cellulosic ethanol is, with production costs between 29 €/GJ and 44 €/GJ (103 – 158 €/MWh), comparably more expensive than the other advanced biofuels. This is mainly due to high capital and feedstock costs. The other advanced biofuels include methane produced by anaerobic digestion (AD), production of hydrotreated vegetable oil (HVO), bio-oils, Fischer-Tropsch (FT) liquids, methane and methanol produced by thermal gasification or synthesis and production of 1 ½ generation bioethanol from corn fiber integrated into a conventional corn bioethanol plant. (Waldheim, et al., 2020)

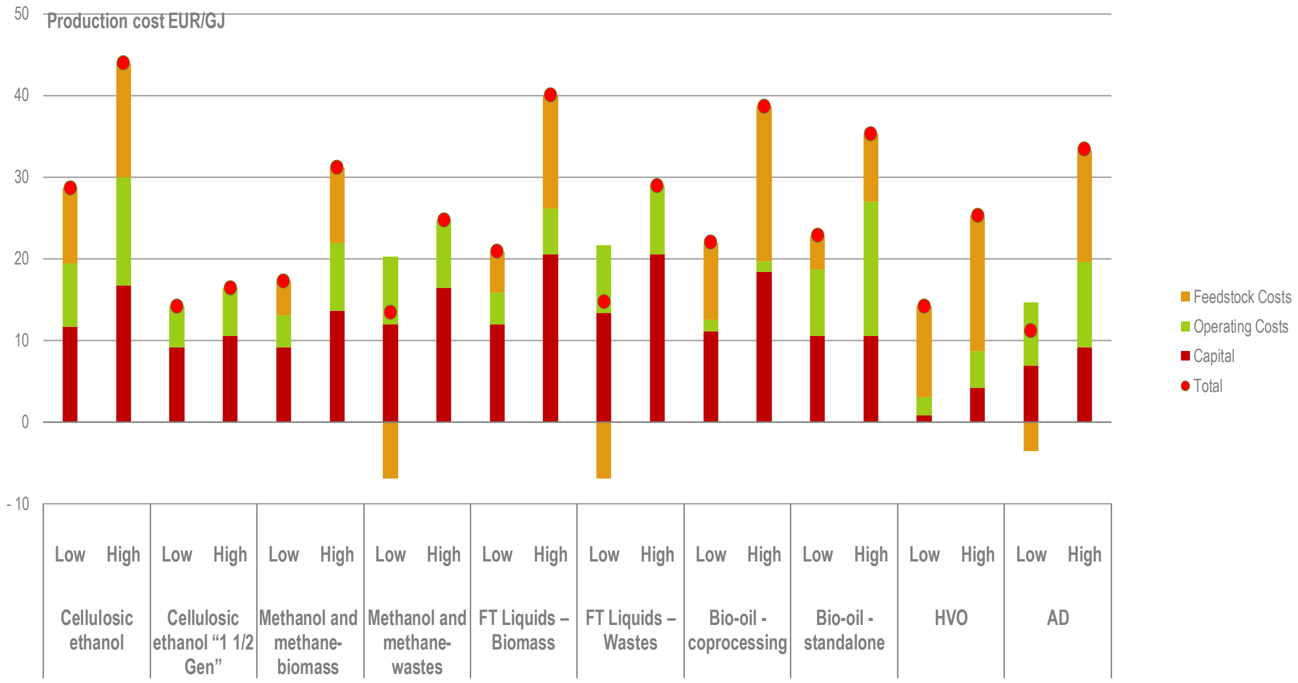


Figure 9: Comparison of current production cost ranges of advanced biofuels

Process improvements and lower cost of capital will decrease the production costs of advanced biofuels in the medium term. Table 6 lists this price range development. The production costs of cellulosic bioethanol will decrease from 29 – 44 €/GJ (103 – 158 €/MWh) to 20 – 31 €/GJ (72 – 112 €/MWh). This represent a reduction of capital costs by 25 – 50% and a reduction of operating costs by 10 – 20%. Feedstock costs reduction is limited. (Waldheim, et al., 2020) However, since AustroCel Hallein is using a by-product, feedstock costs will remain stable.

Table 6: Comparison of production costs development of advanced biofuels

		Cellulosic ethanol	Methanol/ Methane Biomass	Methanol/ Methane Waste	FT Liquids - Biomass	FT Liquids Waste	Bio-oil	HVO	AD Methane
Current costs	Lo	28.6	17.2	13.3	20.8	14.7	21.9	14.2	11.1
	Hi	43.9	31.1	24.7	40.0	28.9	38.6	25.3	33.3
With process improvements	Lo	21.1	12.8	10.0	17.8	11.1	20.8	14.2	11.1
	Hi	33.9	28.3	22.2	34.7	26.1	36.7	25.3	33.3
Lower cost of capital	Lo	19.7	11.7	8.1	15.6	8.9	18.3	13.9	9.4
	Hi	31.1	26.1	18.9	31.1	21.9	33.1	24.4	31.4

In a long term, experience will lead to a further reduction of capital and operating costs, in line with the learning curve. The production costs of conventional bioethanol have fallen by 20% for each doubling of cumulative capacity. It is likely that this effect can also be seen for advanced bioethanol production costs. However, the scope for such reduction is hard to estimate.

4.4 EU transport 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 10. Reasons for that development are more stringent emission requirements for emission standards after 2020. (Capros, 2016) Due to blending mandates and incentives, demand for bioethanol are expected to rise, even when demand for gasoline decreases. (E4tech, 2019)

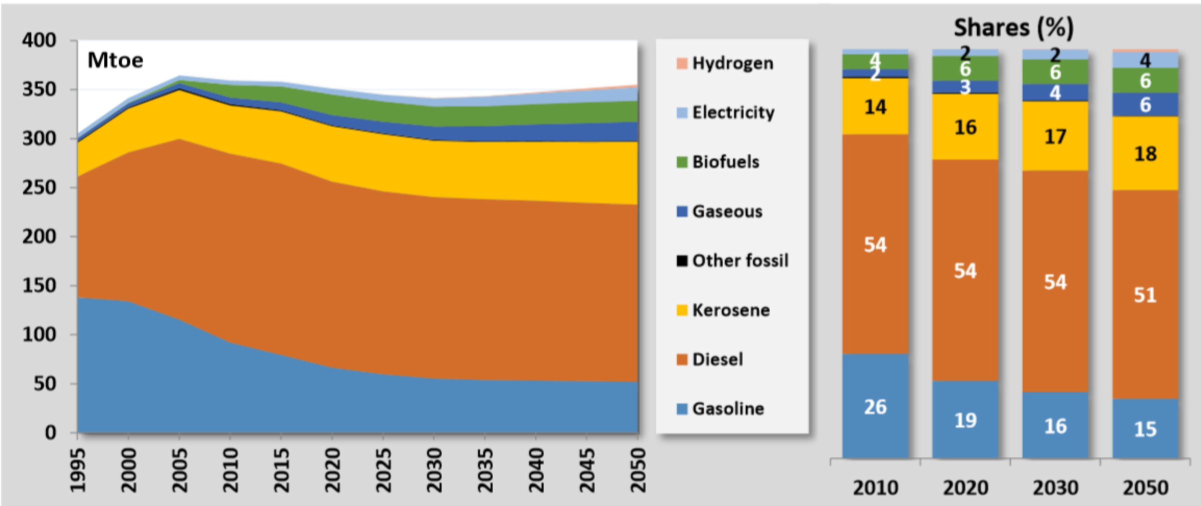


Figure 10: Scenario - Final energy demand in EU transport by fuel type

Current policy scenarios, such as the EU Reference Scenario, are not suitable for reaching Paris Climate Targets. These scenarios show the expected path according to 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 11 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 foreseen to contribute more than a quarter to the energy demand of the transport sector in 2060.

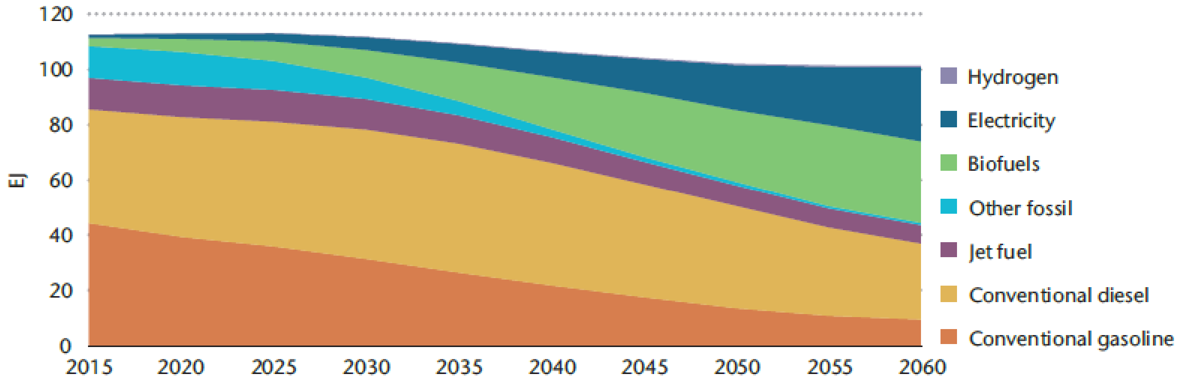
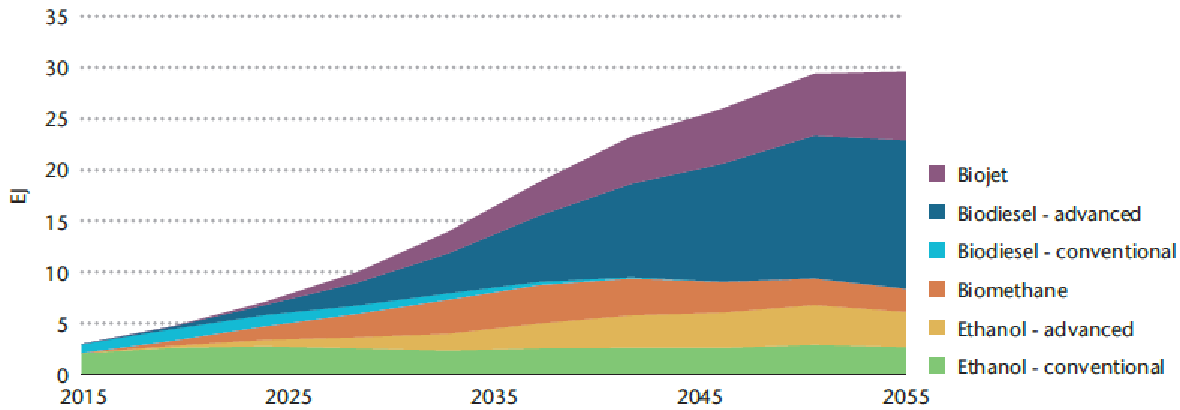


Figure 11: Final global transport energy demand in the 2DS by IEA

IEA additionally provides final global energy demand of the transport sector by fuel type. Figure 12 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 12: 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.[9] Additionally, a website was implemented by Fuels Europe, presenting an ambitious pathway for reaching

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

climate neutrality until 2050, based on the plans of the European Commission.[10] This pathway foresees a major role for biofuels from lignocellulosic residues and wastes until 2050, reaching a production of up to 4 Mtoe (equal 8 billion litres) until 2030.

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 theoretical 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 lower interest in biofuels with a high ILUC effect and increasing importance of electric vehicles. 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) According to this assumption, production capacities would be higher than demand in 2030.

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, public awareness of the multiple benefits of using biofuels has to be risen, for example promoting flex fuel vehicles that allow using high-level blends of biofuels. (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 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)

[10] https://www.cleanfuelsforall.eu/the-pathway/

Advanced biofuels

According to the Sub Group of Advanced Biofuels (SGAB), HVO from waste and lignocellulosic bioethanol are the only advanced biofuels technologies which are ready for the market. However, these advanced biofuels are very different from a market perspective. HVO, which is mainly produced from used cooking oil (UCO), listed in RED-II, Annex IX, Part B, is limited by the 1.7 % cap. Whereas lignocellulosic bioethanol, using feedstocks from RED-II, Annex IX, Part A, has a minimum requirement.

In order to reach European transport decarbonisation targets, for example the 14 % renewable energy target until 2030, higher blends of biofuels, such as E20, E85 or ED95 (by entering the diesel sector) are needed. (Maniatis, Landälv, Waldheim, van der Heuvel, & Kalligeros, 2017) Otherwise the required quantities of biofuel cannot be utilized in the existing vehicles. Since conventional ethanol is limited, it also needs lignocellulosic ethanol to meet the requirement. Therefore, lignocellulosic ethanol should be supported, starting with investment support for demonstration facilities.

SGAB proposed biofuel targets until 2030 for two scenarios. 13.2 % (base scenario) or 16.7 % (progressive scenario) of the total energy demand of the transport sector should be provided by advanced biofuels, low carbon fossil fuels, e-fuels or conventional biofuels. Based on the data of the EU Reference Scenario and considering the 7 % cap and the ILUC Directive, these targets could be achieved, with a production of 10-15 Mtoe (equal 19.8-30.0 billion litres) of advanced bioethanol by 2030. About the same amount of advanced renewable diesel (HVO) would be produced by 2030, according to these scenarios. 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 these scenarios 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 these scenarios. (Maniatis, Landälv, Waldheim, van der Heuvel, & Kalligeros, 2017)

Main barriers for cellulosic bioethanol are high investment 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 in 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)

4.5 Summary market assessment

Even though gasoline sales are decreasing in the EU, bioethanol production and consumption is expected to increase due to EU climate goals. First-generation bioethanol capacities in Austria are unchanged for several years and provided by only one plant. Austria is exporting about half of the produced bioethanol, since this plant was designed for an introduction of E10, which was not enforced yet.

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. So far, Austria is not producing advanced bioethanol. However, the amount of advanced bioethanol produced by AustroCel Hallein (30 million liters) would substitute about 0.2% of transport fuels consumed in Austria or about 1% of gasoline. Biofuel produced from brown liquor is eligible for double counting in Austria.

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 investment and production costs and regulatory uncertainties. Since AustroCel Hallein is using a by-product as feedstock and is integrating the process, feedstock costs, as well as, CAPEX and OPEX should be lower compared to greenfield plants. However, lignocellulosic bioethanol production costs are higher than the price for fossil gasoline. A supportive political framework and substitution obligations lead to lignocellulosic bioethanol production. 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 gasoline 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.

4.6 SWOT-analysis

Strengths and weaknesses of lignocellulosic ethanol and the supply chain and opportunities and threats of the lignocellulosic ethanol market and political framework are summarized in Table 7.

Table 7: SWOT-analysis lignocellulosic bioethanol

STRENGTHS	WEAKNESSES
Utilization of an on site by-product - secured feedstock availability Railway connection and short transport distances Successfull trial runs Integrated production process Offtake agreement	Production capacity of lignocellulosic ethanol is limited by the production capacity of dissolving pulp (main product of AustroCel Hallein)
OPPORTUNITIES	**THREATS**
In line with European Climate Goals Only advanced bioethanol producer in Austria Feedstock eligible for double counting Miminum requirements due to advanced biofuels targets (RED-II) Ready for the market	High investment and production costs Regulatory uncertainties Higher price compared to fossil gasoline Necessity of political support and incentives

5 Sustainability assessment

5.1 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)". 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 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

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[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

[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.

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.

5.2 Methodology: Environmental Assessment

In line with the RED II Directive, in the environmental analysis for the bioethanol production the following process steps should be considered:

- ✓ cultivation/extraction of feedstocks;
- ✓ carbon stock changes caused by land use change;
- ✓ emissions from processing;
- ✓ emissions from transport and distribution;
- ✓ emissions from the fuel use;
- ✓ emission saving from carbon capture and geological storage;
- ✓ emission saving from carbon capture and replacement;
- ✓ emission saving from excess electricity from cogeneration and
- ✓ use of the co-products.

It should be noted that all the aforementioned processes are directly linked to the production of bioethanol, while other products, such as pulp, electricity and heat, are not taken into account.

A simplified approach for the LCA conducted in the present work[16], is described in the RED II. According to the Directive, it is imperative to carry out the GHG emission analysis and quantify the GHG emission savings of biofuels brought in the EU market. The GHG emissions from both the production and utilization of biofuels are calculated as (EU 2018):

[16] 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.

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \text{ [g } CO_{2eq}/MJ_{bioethanol}]$$ [17]

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;

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 Directory, the effect of the machinery and equipment manufacturing is not investigated.

5.2.1 Boundaries of system

Baseline Scenario:

The system's boundaries of the baseline scenario (existing AustroCel biorefinery) are illustrated in Figure 13. They involve: (1) the production of brown liquor after the pulping process, (2) the evaporation process of brown liquor so as to be concentrated before its burning, (3) the combustion of the concentrated brown liquor in the recovery boiler CHP to coproduce heat and electricity and recover the chemicals to be reused in the pulp mill, (4) the production of lignosulfonate in the evaporation plant to be sold as a concrete additive, and (5) the operation of condensing steam turbine to convert the surplus heat energy to electrical energy. It is worth mentioning that, in the process chain, the effect of processing wood chips (spruce) into dissolving pulp is not investigated in this research work.

[17] 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}).

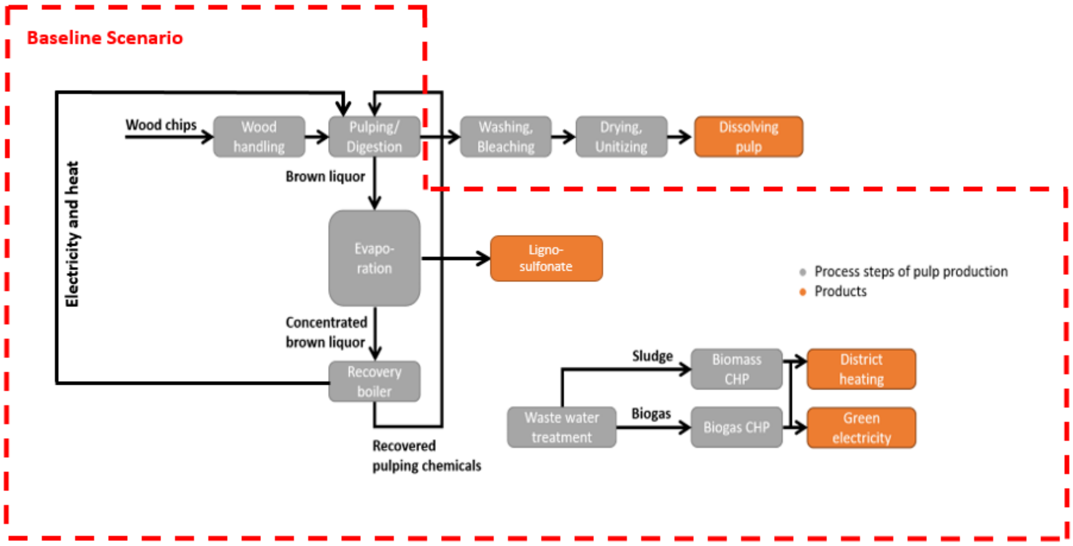

Figure 13: System boundaries of the baseline scenario

5.2.2 Functional Unit

The functional unit provides the reference to which the inputs and outputs of the systems are normalized. Based on the RED II, the functional unit is defined and quantified as follows (EU 2018): "*Greenhouse gas emissions from biofuels, E, expressed 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):

$$Savings = \left(E_{F(t)} - E_{B(t)}\right)/E_{F(t)}$$

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

5.3 Results

The environmental performance of each one of the scenarios considered in the present work, i.e. baseline, retrofit (cases 1-3) scenarios, 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) system's boundaries definition, (ii) inventory analysis, (iii) impact assessment, and (iv) interpretation of results; these phases are addressed in the following sections. In order to assess the potential life-cycle environmental impacts (in terms of GHG emissions), the IMPACT 2002+ methodology was implemented. It should be noted that all the processes included in the systems' boundaries investigated, are in accordance with the database Ecoinvent v3. Briefly, 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. Eco indicator 99, ReCiPe, CML-2001, etc.), IMPACT 2002+ evaluates only GHG emissions from fossil fuels (i.e. it does not consider biogenic emissions).

5.3.1 The current situation

Regarding the operation of the AustroCel biorefinery without bioethanol production (baseline scenario), all input data related to energy flows, consumption of raw materials and environmental releases of the analyzed process (see Figure 13) are included in the environmental analysis. More specifically, the system's boundaries include:

- The production of brown liquor after the pulping process; As it has already been mentioned, brown liquor is a rigid residue from pulp processing; thus, the GHG emissions from the extraction/ cultivation and transport of raw material resources are considered to be zero, up to the process of their collection in the evaporation plant of pulp mill;
- The combustion of brown liquor in the recovery boiler CHP so as to (i) produce sufficient heat for on-site consumption, and (ii) recover the chemicals to be reused in the pulp mill;
- The consumption of a constant proportion of natural gas – below 0.5% of the fuel mix - for boiler start-up after outages, as well as, for emergency supply during transient operating conditions;
- The operation of a condensing steam turbine to convert the surplus heat energy to electrical energy. It is worth mentioning that the condensing (steam) turbine does not consume any fuel, but converts surplus heat to electricity, which is not consumed at the plant. Therefore, electricity production comes only from renewable-based CHP power plants, i.e. brown liquor CHP, biomass CHP and biogas CHP plant. According to AustroCel, the electricity generated from the condensing steam turbine amounts to 19.7 GWh/a.

The GHG emissions of the baseline scenario are summarized in Table 8. The annual total GHG emissions are estimated to be 547 tn CO_{2eq}. The operation of the brown liquor CHP exhibits the highest GHG emissions, estimated at 320 tn $CO_{2eq.}$/a. On the other hand, the boiler start-up process clearly performs better, with a GHG emissions figure evaluated at 227 tn $CO_{2eq.}$/a. It is interesting to note that, although fossil natural gas is consumed to make-up for starting-up the boiler, the better performance of the boiler is directly related to the very small contribution of natural gas (<0.5%) to the fuel mix. The relative contribution of each one of the two aforementioned processes to the global warming category, is illustrated in Figure 15.

It is evident that the operation of the brown liquor CHP accounts for 58.50% of the total GHG emissions, whilst the rest 41.50% comes from the boiler start-up process.

Table 8 GHG emissions related to each process of the baseline scenario

Process	CO_2 emissions (tn CO_2/a)
Operation of brown liquor CHP	320
Start-up boiler (NG)	227
Total	**547**

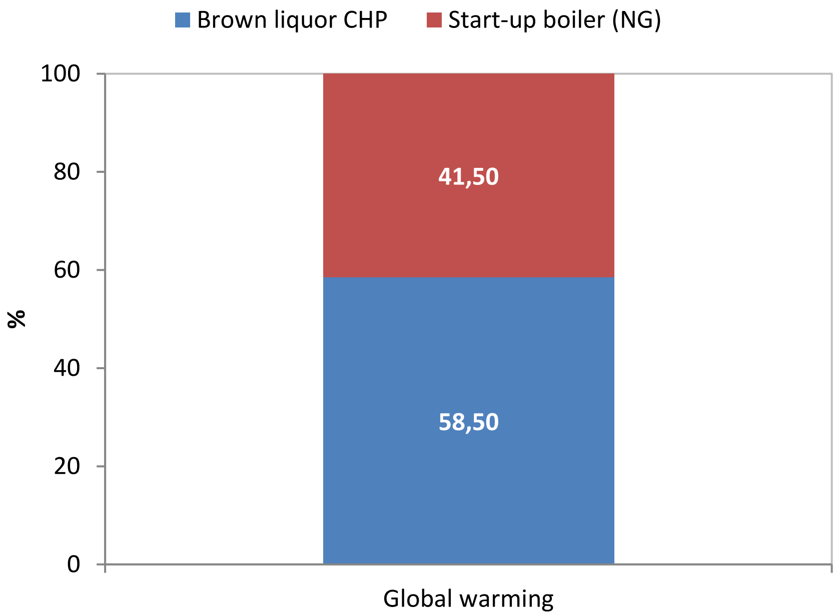

Figure 14 Characterization results related to GHG emissions from the operation of the AustroCel biorefinery without bioethanol production (baseline scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

The life cycle contribution of the baseline scenario in four damage-oriented impact categories, is presented in Figure 16. It is evident that the adverse, environmental-wise impact in the categories of human health, ecosystem quality and resources is associated with the start-up boiler process. This could be attributed to the fact that conventional natural gas is utilized for starting up the boiler. Specifically, in the category or resources, the poor performance of the boiler is due to the extraction process of the natural gas fuel; this process is associated with the energy surplus required for further mining of the fuel in the future. Furthermore, in the first two categories, i.e. human health and ecosystem quality, its adverse impact is directly connected to the high releases of toxic substances into the environment during the extraction and combustion processes of the natural gas fuel. On the other hand, the operation of the brown liquor CHP dominates the total scores (58.50%) in the climate change impact category.

The high impact of the (liquor) CHP plant in this category could be attributed to its significant shares in the energy production in the current situation.

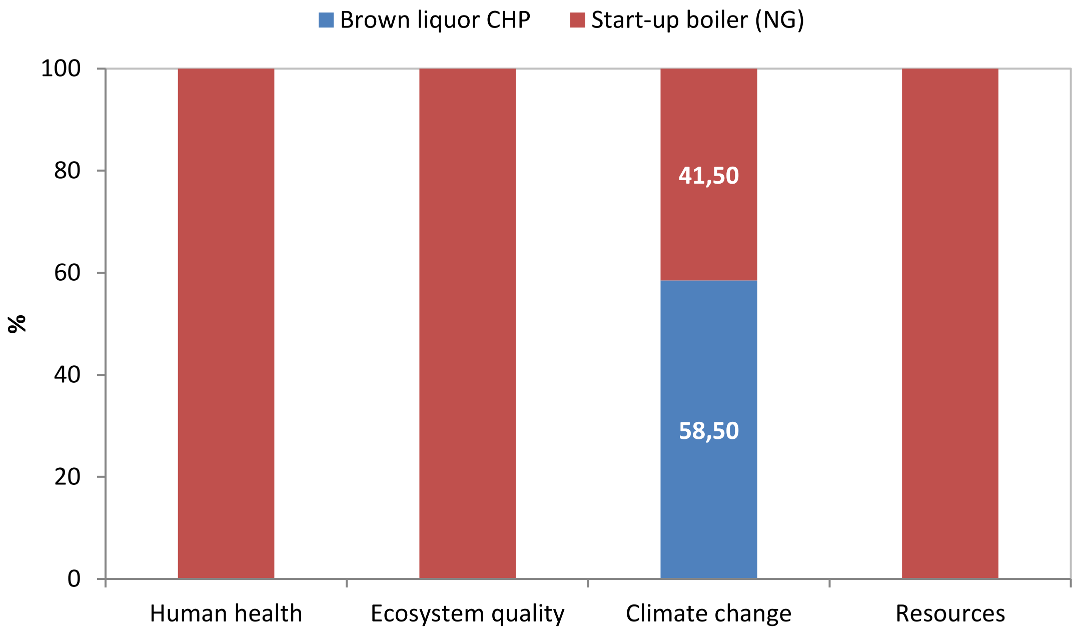

Figure 15 Damage assessment results related to the different impact categories for the operation of the AustroCel biorefinery without bioethanol production (baseline scenario). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

5.3.2 The retrofit scenario

The boundaries of the AustroCel biorefinery with bioethanol production (retrofit scenario), as it modelled in the present work, was shown in Figure 14. For the three cases investigated, our model involves:

- The production of brown liquor after the pulping process and its combustion to the brown liquor CHP, so as to produce the amount of sulphite spent liquor (SSL) required for the bioethanol production. The heat generated in the CHP plant is utilized for meeting the heat requirements for both on-site consumption and the operation of the bioethanol plant;
- The fermentation process - accomplished by yeast - to convert the sugars in the SSL into bioethanol;
- The utilization of chemicals, namely caustic soda solution, phosphoric acid, sulfuric acid and urea, as auxiliary materials for the bioethanol production.
- The operation of the recovery boiler (liquor) CHP to coproduce electricity and heat and to recover the chemicals to be reused in the pulp mill;

- The operation and generation stage (combustion process) of the biogas and the biomass CHP plants to compensate for the increase in heat demand due to the bioethanol plant operation.
- Regarding the Case 1, the operation of the condensing steam turbine to convert the surplus heat into electrical energy, and;
- The transportation of the produced bioethanol by electrified train to different mineral oil providers across Europe.

At this point, it should be noted that, in the three cases investigated, a constant proportion of natural gas – below 0.5% of the fuel mix – is consumed for boiler start-up after outages, as well as, for emergency supply during transient operating conditions.

Primary (foreground) data related to energy flows and consumption of raw materials for the three different cases of the retrofit scenario considered in this research work, are summarized in Table 9. The effect of the operation stage of the CHP plants on GHG emissions is addressed by adopting their relative contribution in the energy production in the AustroCel biorefinery with bioethanol production (see Table 10). It should be noted that all input data given in Tables 9 and 10, were obtained from the AustroCel company; 2018 was chosen as the reference year.

Table 9 Key parameters of the life cycle inventory for the operation of the AustroCel biorefinery with bioethanol production

Input	Unit	Case 1 "18 kt EtOH & 160 pulp"	Case 2 "22 kt EtOH & 160 pulp"	Case 3 "24 kt EtOH & 170 pulp"
Liquor	tn/a	806,400	806,400	858,800
Heating value of liquor	GJ/tn	3.41	3.41	3.41
Sugar content of liquor	tn/a	57,262	57,262	57,262
Yeast	tn/a	1.0	1.0	1.0
Caustic soda solution	tn/a	210	210	223
Phosphoric acid	tn/a	148	148	157
Sulfuric acid	tn/a	185	185	197
Urea	tn/a	905	905	962
Start-up boiler (NG)	MWh/a	2000	2000	2000
Wood biomass (fuel)	MWh/a	10,952	29,542	32,092
Electricity demand	MWh/a	9450	9450	9450
Heat demand	MWh/a	66,308	66,308	70,452
Transportation distance	km	350	1000	350

Table 10 Contribution (%) of the CHP plants in the energy production in the AustroCel biorefinery with bioethanol production

Energy production mix	Case 1 "18 kt EtOH & 160 pulp	Case 2 "22 kt EtOH & 160 pulp"	Case 3 "24 kt EtOH & 170 pulp"
Electricity			
Brown liquor CHP	72.6%	71.4%	72.5%
Biomass CHP	16.2%	17.7%	17.1%
Biogas CHP	10.7%	10.9%	10.3%

Condensation turbine	0.5%	-	-
Heat			
Brown liquor CHP	71.7%	69.9%	70.8%
Biomass CHP	24.3%	26.3%	25.4%
Biogas CHP	4.0%	4.1%	3.9%
Condensation turbine	-	-	-

Table 11 summarizes the results obtained, in terms of annual GHG emissions, for the three operation options analyzed in the present research work. It is evident that, regarding bioethanol production without utilizing CO_2 from the fermentation process, case 1 exhibits the less GHG emissions, evaluated at 1360 tn$CO_{2eq.}$/a, followed by case 3 with 1522 tn$CO_{2eq.}$/a. The GHG emissions figure for case 2 is estimated at 1683 tn$CO_{2eq.}$/a, which ranks it as the worst option between the retrofit cases investigated. This is directly connected to the highest transport distance (in a 1000 km radius, compared to a 350 km radius in cases 1 and 3) for the bioethanol distribution to the Austrian mineral oil provider. Calculated results considering the CO_2 use in bioethanol production present an opposite behaviour; case 3 performs better, with a GHG emissions figure of -21,979 tn$CO_{2eq.}$/a, followed by case 2 with 20,436 tn$CO_{2eq.}$/a, and case 1 with -17,005 tn$CO_{2eq.}$/a.

Table 11 GHG emissions related to each process of the retrofit scenario for the three cases

Process	**CO_2 emissions (tn $CO_{2eq.}$/a)**		
	Case 1	***Case 2***	***Case 3***
Yeast	2	2	2
Chemicals	637	637	677
Biogas CHP	7	8	7
Biomass CHP	69	134	141
Brown liquor CHP	320	320	340
Transportation	106	362	135
Start-boiler (NG)	220	220	220
Total without CO_2 use	**1360**	**1683**	**1522**
CO_2 use from fermentation*	-18,365	-22,119	-23,501
Total with CO_2 use	**-17,005**	**-20,436**	**-21,979**

* The negative values are due to the emissions saving from carbon capture and replacement during the production process of bioethanol.

The relative contributions of the different bioethanol production stages to the Global Warming Category, without considering the utilization of the CO_2 emissions from the fermentation process, are demonstrated in Figure 17. It is evident that the utilization of chemicals, required in the production process of bioethanol, is a significant contributor to GHG emissions, accounting for 46.82%, 37.8643.54% and 44.49% of the total global warming potential, in cases 1, 2 and 3, respectively. The major source of emissions from chemicals is the production of urea (about 72% in all cases), as illustrated in Figure 18. This is directly connected to the consumption of resources for the production of chemicals. The next significant contributor to the total GHG emissions is the operation and generation stage (combustion process) of the brown liquor CHP plant (23.53%, 19.02% and 22.35% in cases 1, 2 and 3, respectively). Conversely, both the biomass (wood) CHP and the biogas CHP plant perform better, as compared to the brown liquor CHP. In general, the combustion process in either biomass or biogas CHP plants is more impact intensive one (in terms of methane (CH_4)), than the relevant one in brown liquor CHP. For instance, based on the relative literature, the (fossil) CH_4 emissions from combustion in biomass CHP plants amount to 0.005 g/MJ fuel, whilst the corresponding ones from the combustion in brown liquor CHP plants reach 0.003 g/MJ fuel[18,19]. However, the poor performance of the recovery boiler (liquor) CHP plant could be attributed to its significant shares (>68%) in the energy production in all cases of the retrofit situation. Furthermore, the boiler start-up procedure accounts for about 13-16% of the total GHG emissions. This is mainly due to the consumption of fossil natural gas for starting up the boiler. Transportation of the produced bioethanol by electrified train to the mineral oil providers across Europe has relatively small environmental impact in cases 1 and 3, as compared to the utilization of chemicals and the operation of the brown liquor CHP plant. Case 2 is an exception. In this case, the transportation's impact accounts for 21.54% and it is associated with high transportation distance (1000 km). Last, but not least, the contribution of the production of yeast, required for the fermentation process, was found to be negligible in all cases analyzed. This is mainly due to the fact that the yeast accounts for a very small part, less than 1%, in the production of bioethanol.

[18] Biograce 4d, 2018: The BioGrace GHG calculation tool: a recognized voluntary scheme, http://www.biograce.net/content/ghgcalculationtools/recognisedtool/

[19] GEMIS 4.95: GEMIS - Globales Emissions-Modell integrierter Systeme, http://iinas.org/gemis-de.html

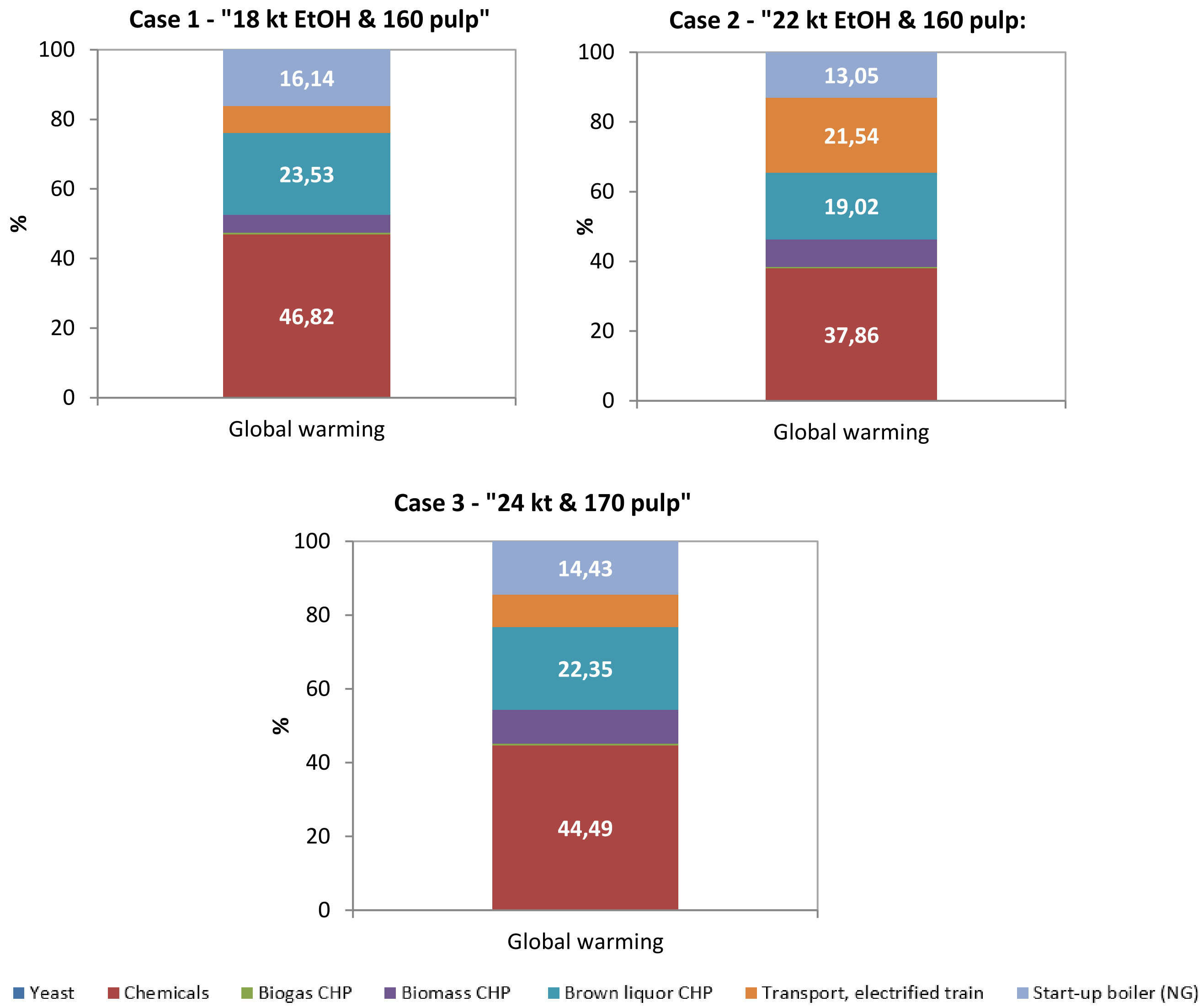

Figure 16 Characterization results related to GHG emissions from the operation of the AustroCel biorefinery with bioethanol production, without CO_2 use. The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

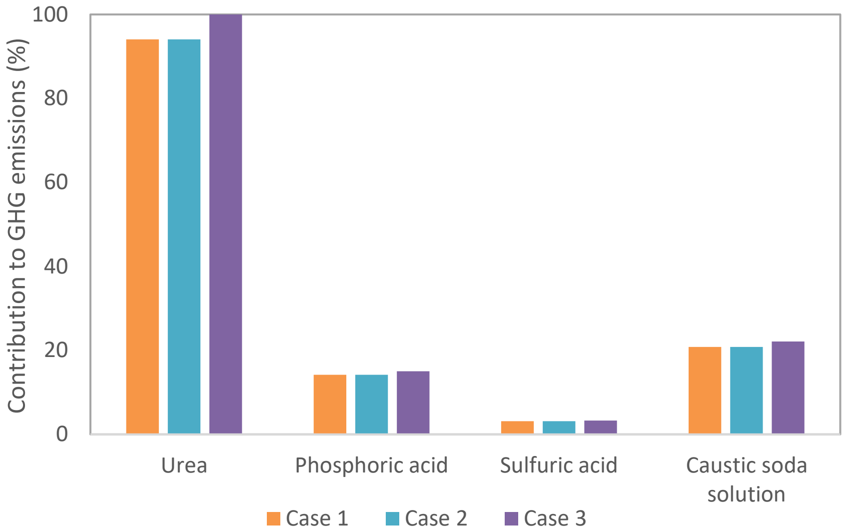

Figure 17 Contribution of the production process of chemicals to the GWP category

The life cycle contribution of the operation of the AustroCel biorefinery with bioethanol production (for the three cases) in four damage-oriented impact categories, is illustrated in Figure 19. It is evident from this figure that, in all cases investigated, the operation and generation stage (combustion process) of the biomass CHP power plant has the highest adverse impacts (>41%) in two out of the four categories, namely human health and ecosystem quality. The poor performance in these impact categories could be probably attributed to the main pollutants of the wood biomass combustion process, i.e., nitrogen dioxide (NO_2), particulates (PM_{10}) and sulfur dioxide (SO_2). These toxic substances may attribute to human toxicity (e.g., carcinogenic and non-carcinogenic effects), respiratory effect (inorganic, organic compounds), as well as, to ecosystem effects. Conversely, the small impact (<10%) of the combustion of the wood biomass in the category of climate change is mainly associated with the renewable characteristics of the wood resources (biogenic emissions from the combustion process). Regarding the use of chemicals (i.e., caustic soda solution, phosphoric acid, sulfuric acid and urea), which are required for the production of bioethanol, their production process dominates the total scores (>61%) in the category of resources, for all the three cases analyzed. The major source of emissions from chemicals was the conventional production process of urea. Transportation of the produced bioethanol by electrified train to the mineral oil providers across Europe has considerable life cycle impacts in the categories of ecosystem quality and climate change; it accounts for up to 51.52%% and 29.25%%, respectively, in case 2, which is associated with the highest transportation distance. The high CO_2, SO_2 and NO_x emissions from the electrified train, are responsible for the moderate contribution in these categories. On the other hand, the boiler start-up procedure accounts only for about 13-16% of the total GHG emissions in the impact categories of climate change and resources. This is mainly due to the consumption of fossil natural gas for starting-up the boiler. The operation and generation stage (combustion process) of the brown liquor CHP plant has relatively small impacts in all categories, except for the climate change (23.53%, 19.02% and 22.35%, in cases 1, 2 and 3, respectively). Last, but not least, the production process of yeast required for the bioethanol production, as well as, the combustion process in the biogas CHP power, are almost free of environmental burden. This is, perhaps, associated with their very small contribution in the production process of bioethanol.

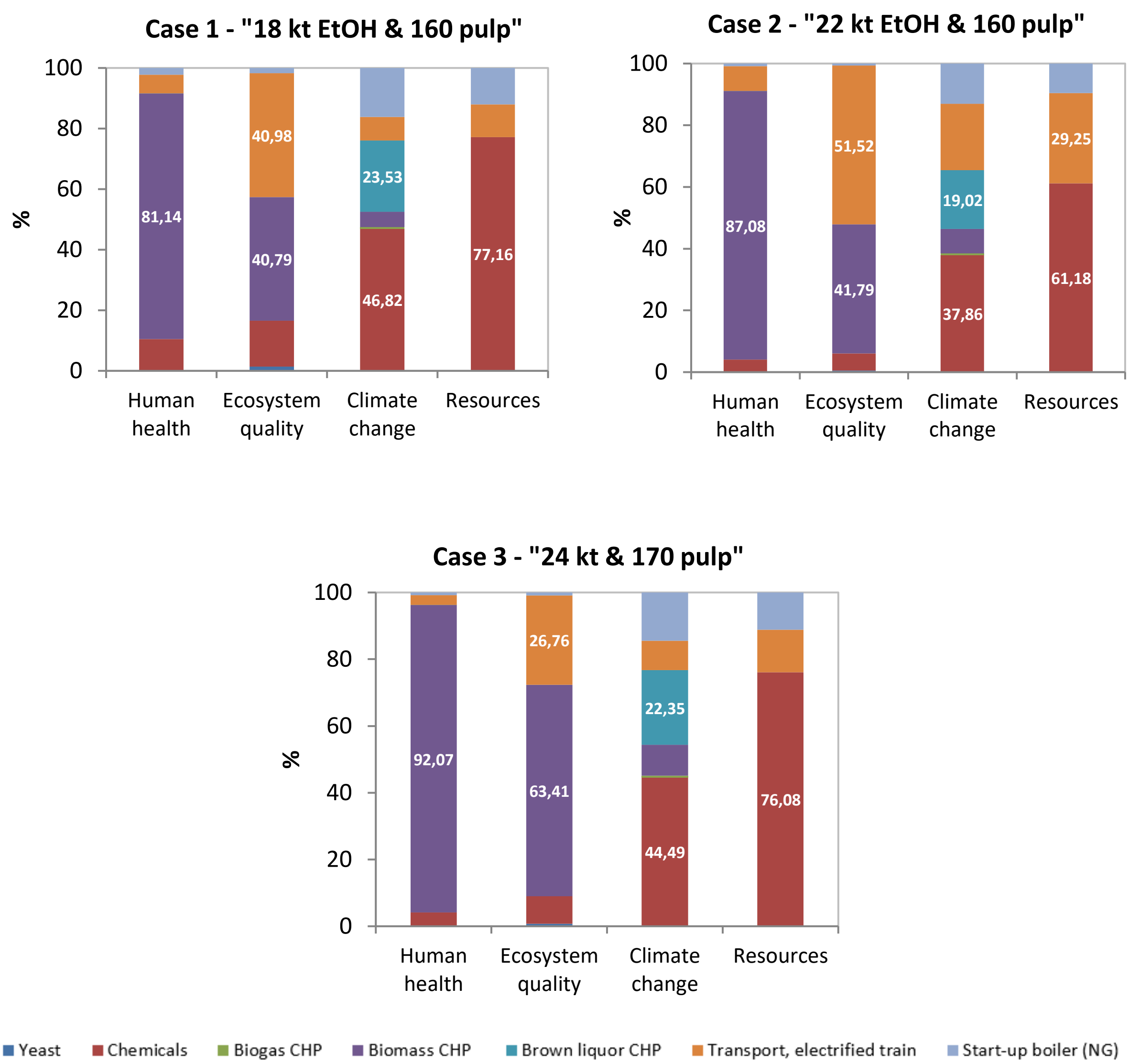

Figure 18 Damage assessment results related to the different impact categories for the operation of the AustroCel biorefinery with bioethanol production, without CO_2 use). The IMPACT 2002+ Method is used (All impact scores are displayed on a 100% scale)

Estimated GHG emissions (in tn $CO_{2eq.}$/a) related to each process of the retrofit scenario for the three cases investigated, have been already presented in Table 11. In addition to this table, Figure 20 illustrates the relevant comparative results, in terms to contribution (%) to the global warming impact category. It is shown that, without CO_2 use, case 2 performs worse than any other case. The poor performance of this operation option is directly related not only to the higher utilization of chemicals required for the production of bioethanol, but also to the highest transportation distance of the produced bioethanol and the highest contribution of both biomass CHP and recovery boiler CHP plant to the energy production in the biorefinery situation. It can be concluded that the global warming impact depend, to a part, on the bioethanol yields (ton bioethanol ton liquor) from each case. Regarding the utilization of CO_2 in the bioethanol production, results exhibit an opposite behaviour; case 1 is the most impact intensive one, followed by cases 2 and 3.

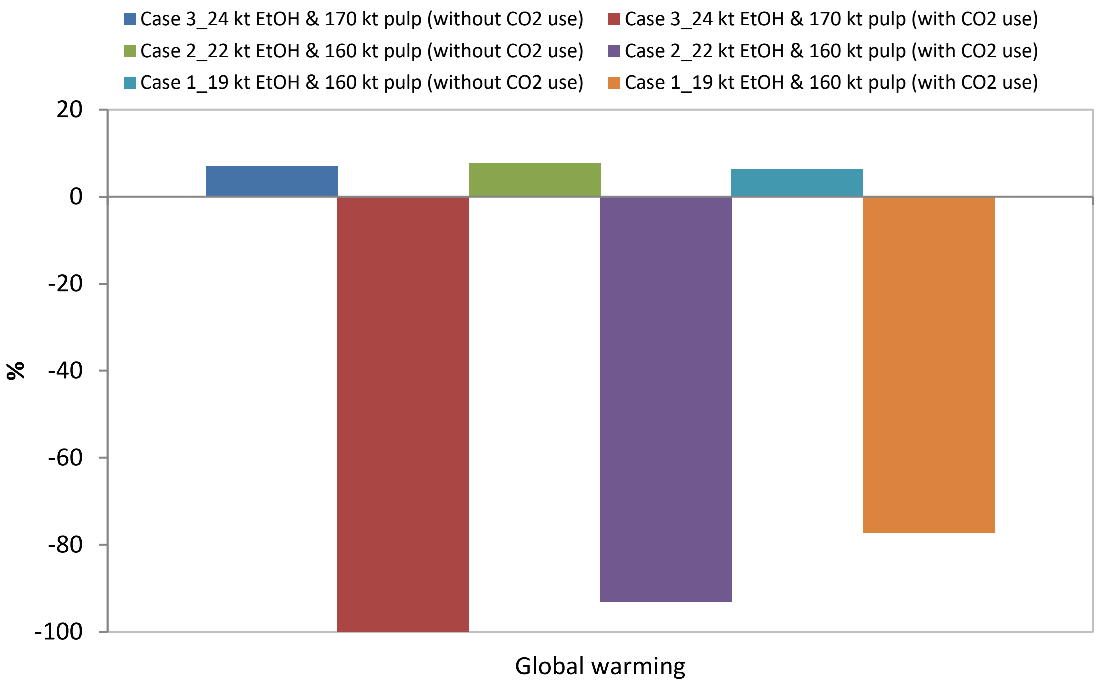

Figure 19 Comparative characterization results related to total GHG emissions of the three cases, using the IMPACT 2002+ Method (All impact scores are displayed on a 100% scale)

5.4 Summing-up

The comparative results presented in this work for the baseline and retrofit (cases 1-3) scenarios, are illustrated in Figures 21.

The main differences of the three cases of the retrofit scenario compared to the baseline scenario were: (i) the amounts of brown liquor and energy wood, (iii) the transport distance, and (iii) the amounts of dissolving pulp, electricity, district heat and lignosulfonate.

It is shown that case 3 of the retrofit scenario with CO_2 utilization, presents the best operation option, due to significant emission savings from carbon capture and replacement in the bioethanol production process.

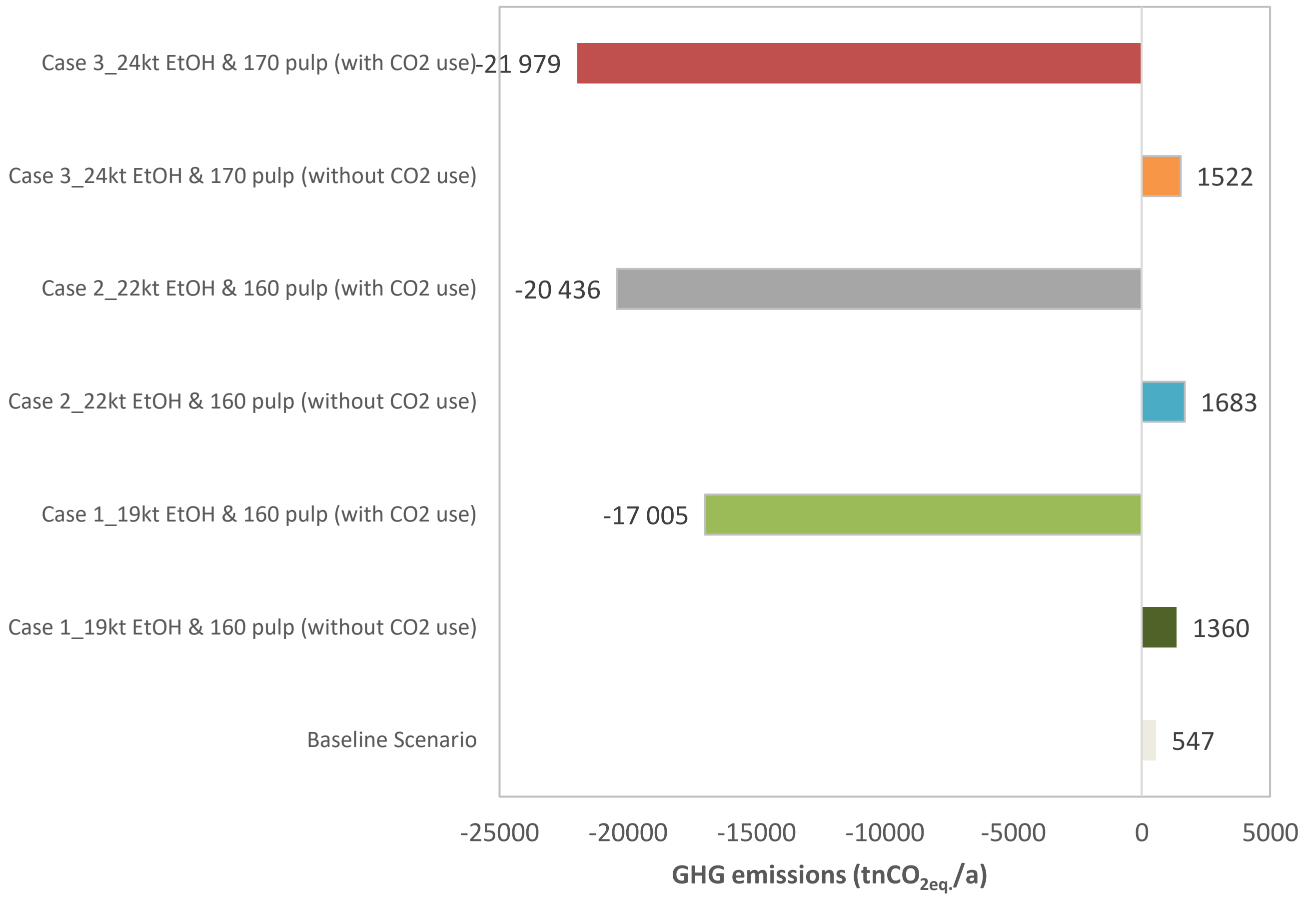

Figure 20 Comparative results related to total GHG emissions of baseline and retrofit (cases 1-3) scenario

5.5 Conclusions

The present work investigated the environmental performance of the existing AustroCel biorefinery, with bioethanol production. A thorough life cycle has been carried out for this purpose employing the Impact 2002+ methodology. The major findings of the present analysis are summarized in Table 21, and also in Figure 22.
The estimated GHG emissions of the retrofit scenario (with bioethanol production) are 1360, 1683 and 1522 tn $CO_{2eq.}$/a for cases 1, 2 and 3, respectively. The corresponding emissions figure per 1 MJ of bioethanol amount to 2.72, 2.81 and 2.39 $gCO_{2eq.}$/MJ, respectively. The highest GHG emissions of case 2 rank it as the worse option between the retrofit operation options. On the other hand, if the CO_2 utilization is taken into consideration, the total GHG emissions are evaluated at -17,005, -20,436 and -21,979 tn $CO_{2eq.}$/a, for cases 1, 2 and 3, respectively. The negative values are due to the emission savings from carbon capture and replacement during the fermentation process. It is found that case 3 - with CO_2 utilization - clearly performs better than all the retrofit cases investigated. It is worth mentioning that the aforementioned figures are consistent with the ones reported in a similar case study provided

by AustroCel, which estimated the GHG emissions for bioethanol from liquor in the range of -31.9 to 2.9 gCO_{2eq}/MJ.

The environmental benefits of the retrofit cases are demonstrated by comparing the GHG emissions of producing bioethanol from biogenic fuels (biomass, brown liquor and biogas), with the RED II fossil fuel comparator (94 $gCO_{2eq.}$/MJ). Calculated results show that, in case of no CO_2 utilization from the fermentation process, the emissions avoided (savings) from the use of bioethanol as a substitute of fossil fuel, reach about 97% for all the operation options analysed. In case of CO_2 utilization, the relevant emission savings increase significantly to about 136% for all the three cases, presenting a major improvement of the environmental footprint of the biorefinery.

It can be concluded that the integration of bioethanol production in the existing AustroCel biorefinery is a sustainable operation option, that minimizes the environmental impact of the existing biorefinery.

Table 12 Overview results of environmental assessment

Inputs	**Outputs**
Retrofit Scenario	
Case 1 - "18 kt EtOH & 160 pulp"	
	Without CO_2 use
	1360 tn $CO_{2eq.}$/a
	2.72 gCO_{2eq}/MJ
18,621 tn/a bioethanol	97.10 % greenhouse gas emissions savings compared to RED II
499,237,295 MJ bioethanol	**With CO_2 use**
	-17,005 tn $CO_{2eq.}$/a
	-34.06 gCO_{2eq}/MJ
	136.24 % greenhouse gas emissions savings compared to RED II
Case 2 - "22 kt EtOH & 160 pulp"	
	Without CO_2 use
	1683 tn $CO_{2eq.}$/a
	2.81 gCO_{2eq}/MJ
22,310 tn/a bioethanol	97.01 % greenhouse gas emissions savings compared to RED II
598,143,403 MJ bioethanol	**With CO_2 use**

	-20,436 tn $CO_{2eq.}$/a
	-34.50 gCO_{2eq}/MJ
	136.35 % greenhouse gas emissions savings compared to RED II
Case 3 - "24 kt EtOH & 170 pulp"	**<u>Without CO_2 use</u>**
23,705 tn/a bioethanol 635,527,366 MJ bioethanol	1522 tn $CO_{2eq.}$/a
	2.39 gCO_{2eq}/MJ
	97.45% greenhouse gas emissions savings compared to RED II
	<u>With CO_2 use</u>
	-21,979 tn $CO_{2eq.}$/a
	-34.58 gCO_{2eq}/MJ
	136.79 % greenhouse gas emissions savings compared to RED II

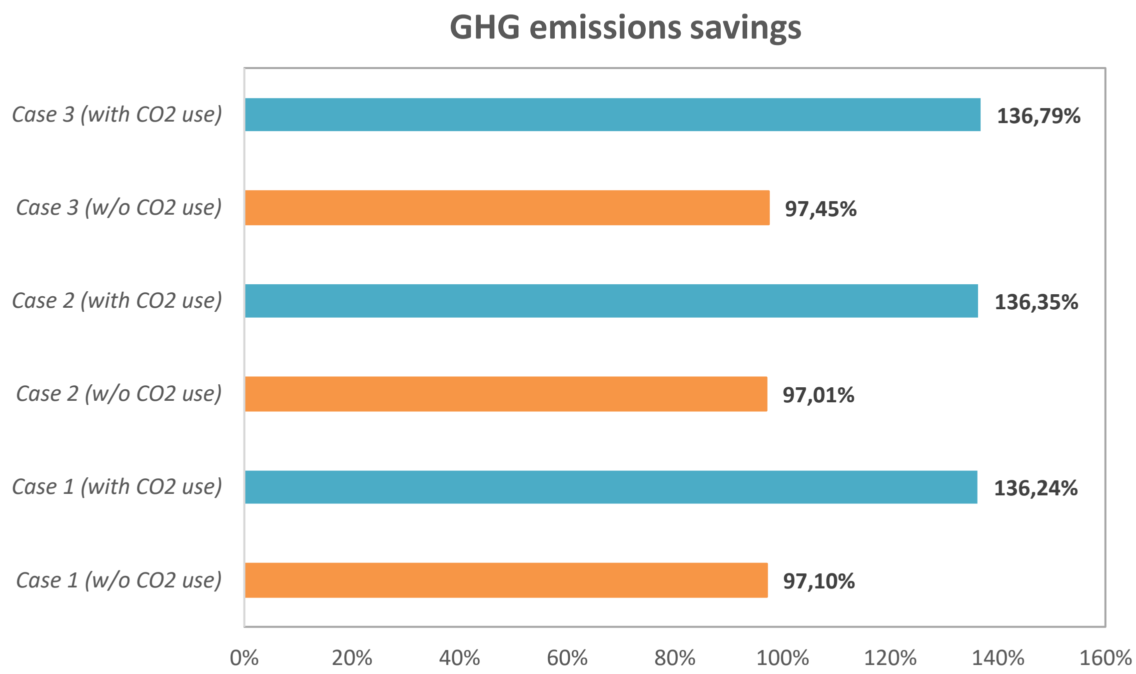

Figure 21 Comparative characterization results related to GHG emissions savings compared to RED II methodology (retrofit scenario)

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