DECARBONISATION OPTIONS FOR THE DUTCH BIOFUELS INDUSTRY

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Decarbonisation options for the Dutch biofuels industry

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MIDDEN project coordination and responsibility
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TNO Energy Transition has a twofold mission: to accelerate the energy transition and to strengthen the competitive position of the Netherlands. TNO conducts independent and internationally leading research and we stand for an agenda-setting, initiating and supporting role for government, industry and NGOs.

This report has been reviewed by Alco Energy Rotterdam B.V., BioPetrol Rotterdam B.V., BioMethanol Chemie Nederland B.V. and Neste Netherlands B.V. PBL and TNO Energy Transition remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Abbreviations

ALK	Alkaline Electrolysis
ATR	Autothermal reforming
BECCS	Bio-Energy with Carbon Capture and Storage
CAPEX	Capital Expenditure
CBS	Centraal Bureau voor de Statistiek
CCUS	Carbon capture utilization and storage
CHP	Combined Heat and Power generation
CMS	Cryogenic Membrane Separation
DDGS	Dried Distillers' Grain with Solubles
ETBE	Ethyl tert butyl ether
FAME	Fatty acid methyl esters
HVO	Hydrogen treated vegetable oil
OPEX	Operational Expenditure
ILUC	Indirect land use change
MDEA	Methyldiethanolamine
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
MJ	Megajoule
Mtoe	Million tonnes of oil equivalent
MVR	Mechanical vapor compression
OEM	Original equipment manufacturer
PEM	Proton Exchange Membrane
PJ	Petajoule
PORTHOS	Port of Rotterdam CO_2 Transport Hub and Offshore Storage
POX	Partial oxidation
RED	Renewable Energy Directive
SMR	Steam methane reforming
UCO	Used cooking oil

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Summary

The biofuel production in the Netherlands amounted to 69 PJ in 2018. This report investigates four major Dutch biofuel industries in Delfzijl and Rotterdam, which each have a production capacity of more than 350 kton. The industries which are included in the scope are:

- Alco Energy Rotterdam B.V.;
- BioPetrol Rotterdam B.V.;
- BioMethanol Chemie Nederland B.V., and
- Neste Netherlands B.V.

These industries produce various types of biofuels such as ethanol, biodiesel and biomethanol, to be blended with fossil fuels for use in engines as promoted by the European policies. The current yearly greenhouse gas emissions of these industries vary from 36 kton to 353 kton CO_2-eq. Most of the CO_2 emissions are energy related, natural gas is used for heat and electricity produced with either boiler or CHP.

The main opportunities for decarbonising the biofuel industries' heat supply include electrification (heat pumps, electric boilers) and substitution of natural gas with hydrogen or biogas. CCUS (Carbon Capture, Utilisation and Storage), mainly for concentrated biogenic CO_2 is another important option. A full supply chain analysis of emissions and decarbonisation options for biobased fuels is beyond the scope of this report.

Table 1. Overview of the main biofuel industries in the Netherlands

Characteristics	Alco Energy	BioPetrol	BioMCN	Neste Oil
Name	Alco Energy Rotterdam B.V.	BioPetrol Rotterdam B.V.	BioMethanol Chemie Nederland B.V.	Neste Netherlands B.V.
Fossil CO_2 Emissions [kton CO_2-eq] (2018)	340	36	217	8
Feedstock	Maize	Rapeseed oil and sunflower oil	Natural gas and biogas	Animal fats and UCO
Product	Bioethanol	Biodiesel	Biomethanol and methanol	Biodiesel
Technology	Dry milling and fermentation	Transesterification	Steam Methane Reforming	NExBTL
Production capacity (2017)	379 kton	400 kton	450[1] kton	1 Mton

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[1] The production capacity of BioMCN has increased in 2019 with the starting of 2nd production line to 900 kton.

FULL RESULTS

Introduction

This report describes the current status of the Dutch biofuel production industry and assesses the possible options to decarbonise them. This study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). MIDDEN aims to support industry, policy makers, analysts and the energy sector in their common efforts to achieve deep decarbonisation. The MIDDEN project will update and elaborate further on options in the future, in close connection with the industry.

Scope

Production locations include:
- Alco Energy Rotterdam B.V.;
- Biopetrol Rotterdam B.V.;
- BioMethanol Chemie Nederland B.V. (BioMCN);
- Neste Netherlands B.V.

Processes include:
- Dry milling and fermentation;
- Transesterification;
- The NExBTL process;
- Steam Methane Reforming.

Products include:
- Biomethanol;
- Fossil based methanol;
- Bioethanol;
- Biodiesel.

The main decarbonisation options are:
- Hydrogen;
- Biogas;
- Electric boilers;
- Heat pumps;
- Ultra-deep geothermal energy, and
- Carbon Capture Utilisation and Storage (CCUS).

Reading guide

Chapter 1 gives a general introduction to the biofuel industry in the Netherlands. In Chapter 2 we describe the current status of biofuel production processes and in Chapter 3 we discuss the relevant products and applications. Options for decarbonisation are systematically quantified and evaluated in Chapter 4. The feasibility and requirements of those decarbonisation options are discussed in Chapter 5.

1 Biofuel production in the Netherlands

This report discusses the production of liquid biofuels derived from biomass, which are used as an alternative to fossil fuels such as gasoline, diesel and aviation fuels (IEA, 2008). Biofuels are used for passenger cars, aviation, shipping, heavy vehicles and trains. The heavy-duty vehicles can use blends of biodiesel or ethanol (eg. B7, E10). Flex fuel car engines can use 100% blend of ethanol or biodiesel, or sometimes biogas or biomethane depending on the engine (Faaij et al., 2017). Biofuels vary in their potential to reduce greenhouse gas emissions when replacing fossil fuels. The greenhouse gas emission reductions depend on the feedstock (crop) used, and the effect of expanding cultivation of the crops on land use (Kazamia & Smith, 2014).

This chapter provides information on the consumption and production of biofuels in the Netherlands and the main biofuels production sites.

1.1 Consumption and production of biofuels in the Netherlands

In Europe, the production of biofuels has significantly increased from 2 Mtoe (84 PJ) in 2005 to 14 Mtoe (586 PJ) in 2016 (ETIP, 2018). In 2017, The Netherlands was the third largest producer of biofuels in Europe after Germany and France (see Figure 1) with a production of 1.65 Mtoe (69 PJ) (F.O. LICHTS, 2018).
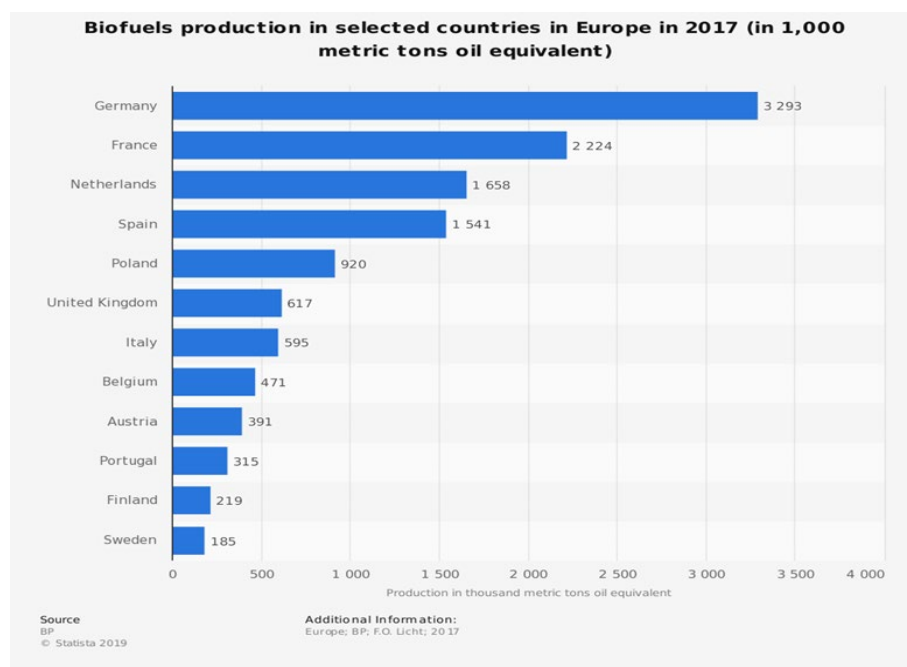

Figure 1. Biofuel production in selected countries in Europe in 2017 (in 1,000 metric tons oil equivalent) (F.O. LICHTS, 2018)

The large-scale production of biofuels in the Netherlands took off in 2009 (as seen in Table 2). Bioethanol is mainly produced from starch (wheat, tapioca) and biodiesel is mainly produced from used cooking oil (NEa 2016). The NEa provides details on the biofuels that are blended with fossil fuels. The main sources are animal fat, maize, sugar beet, sugar cane, wheat, wheat straw and used cooking oil (Nederlandse Emissieautoriteit, 2016). The largest share of the biofuels for the transport sector in 2016 came from biodiesel based on used cooking oil (61%) and animal fats (7%). The rest mainly came from ethanol produced from wheat, maize, sugarcane and sugar beets (Kwant et al., 2018).

Table 2. Production of biofuels in the Netherlands from 2006-2018 *(CBS, 2019)*

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Production (kton)	81	200	531	1,323	1,306	2,247	2,406	2,517	2,605	2,620	2,179	2,476	2,524

The total renewable energy consumption in the Netherlands amounted to 158 PJ in 2018 (Centraal Bureau voor de Statistiek, 2019). The consumption of biofuels in the Netherlands was 23 PJ in 2018 as seen in Figure 2 (Centraal Bureau voor de Statistiek, 2019).

Figure 2. Energy consumption from biomass in the Netherlands (Centraal Bureau voor de Statistiek, 2019)

The use of biofuels for road transport in the Netherlands is expected to increase to more than 40 PJ in 2020 and to level off to 34 PJ in the long term, according to the National Energy Outlook 2017 (ECN at al., 2017). These projections exclude biofuels consumption in international aviation and marine transport, which is currently low, but may increase in future.

1.2 Production sites in the Netherlands

Figure 3 shows the locations of biorefineries in Europe in 2017 (Bio-based Industries Consortium, 2018). Out of the biorefineries within the Netherlands, the four which have a production capacity of more than 350 kton are discussed in this report. Annex A includes an overview list of biofuels production sites in the Netherlands.

Figure 4 gives an overview of the biofuel industries in the Netherlands within the scope of this project. These biorefineries are:
- Alco Energy Rotterdam B.V. located in Europoort;
- BioPetrol Rotterdam B.V. located in the Botlek;
- BioMethanol Chemie Nederland B.V. (BioMCN) located in Delfzijl.
- Neste Netherlands B.V. located in the Maasvlakte.
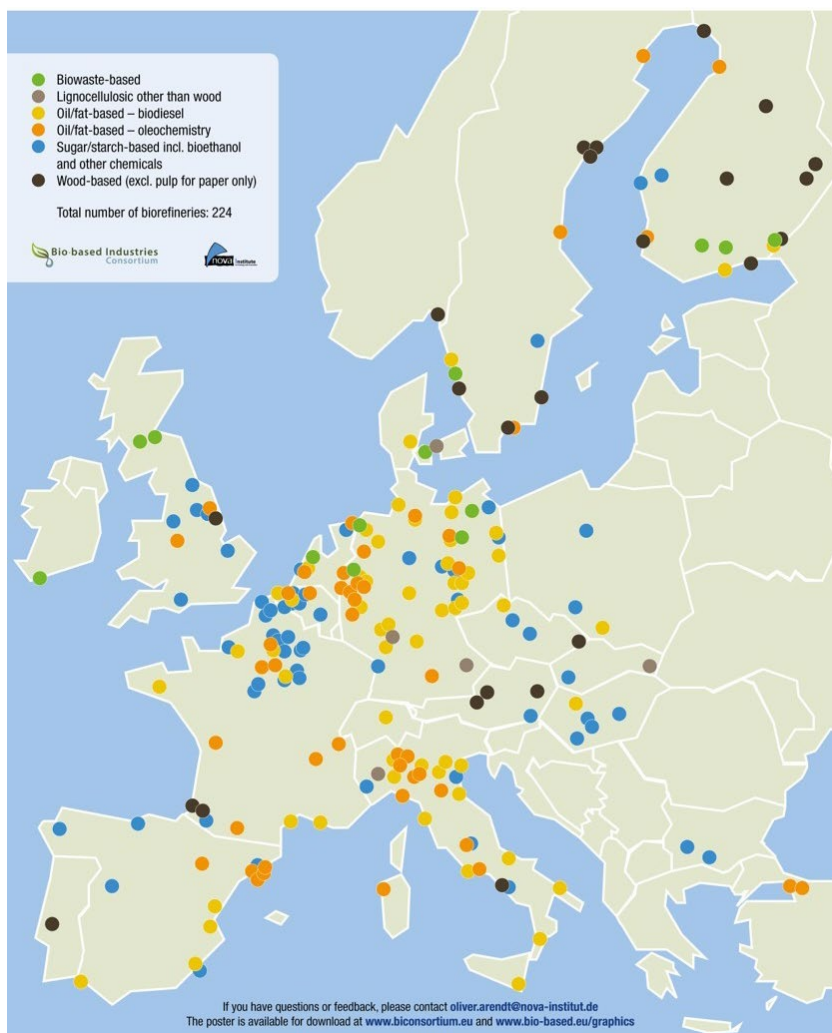
Figure 3. Biorefineries in Europe in 2017 *(Bio-based Industries Consortium, 2018)*

Figure 4. Overview of the biofuel companies in the scope of the project

1.2.1 Alco Energy Rotterdam

The bioethanol production facility of Alco Energy Rotterdam B.V. is located in Europoort in Rotterdam (see Figure 5) and was founded in 2010. Previously, the production site was owned by Abengoa Bioenergy Netherlands B.V. However, due to bankruptcy the production was shut down and then the facility was purchased by Alco group (GAVE, 2015).

The installation of Alco Energy can produce 480 million litres of bioethanol per year using the dry milling and fermentation process. The production facility uses maize as feedstock. There is also a CHP plant on-site. This production facility can produce 360 kton of DDGS (Dried Distilled Grain with Soluble) and 300 kton of biobased CO_2 which can be distributed to nearby greenhouses in the Westland (ALCO Group, 2019). According to the Dutch Emissions Authority (NEa), Alco Energy in Rotterdam emitted 340 kton CO_2-eq in 2018 (NEa, 2019).

Figure 5. Alco Energy Rotterdam B.V. (Water talent, 2017)

1.2.2 Biopetrol Rotterdam

The biodiesel production facility of Biopetrol Rotterdam B.V. is located in the Botlek (see Figure 6) and was founded in 2006. It is owned by Glencore Agriculture, a trading company. The installation produces around 400 kton of biodiesel per year (GAVE, 2015). The production facility uses mainly rapeseed and sunflower oil as feedstock. Biopetrol Rotterdam B.V. also produces 60 kton of glycerol which is used for pharmaceutical grade purposes (Biopetrol, Personal communication, 26 June 2019). A total of 69 employees worked at Biopetrol in 2016 (Port of Rotterdam, 2016). The total investment made at the plant is around 100 million euros (GAVE, 2015). According to the Dutch Emissions Authority (NEa), the site emitted 36 kton CO_2-eq in 2018 (NEa, 2019).
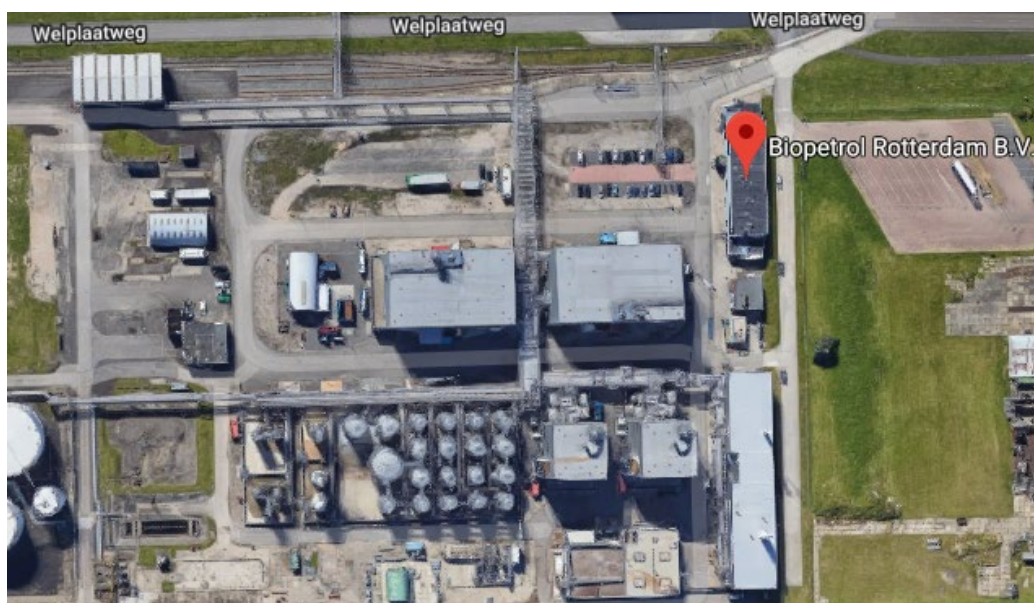

Figure 6. Biopetrol Rotterdam B.V.

1.2.3 BioMethanol Chemie Nederland

BioMCN B.V. is located in Delfzijl (see Figure 7). Formerly the site was known as Methanor, a joint venture founded in 1976 by Akzo and DSM to produce methanol from natural gas from the Groningen gas field (Mulder, 2017). Methanor had two production lines with a total nameplate capacity of almost 800 kton (Mulder, 2017). Due to increasing gas prices and international competition, the fossil-based production was closed down in 2006 (Mulder, 2017; Reinshagen, 2011).

Shortly after 2006, BioMCN started production in one production line based on residual glycerol flows from biodiesel production in 2006. Its ambition was to become the largest site in the world to process various biobased flows via synthesis gas to biomethanol. A plan from 2010 to build a EUR 500 mln plant for converting residual wood into methanol did not materialise and was finally cancelled in 2017 (Mulder, 2017). OCI took over the plant in 2016 (Mulder, 2017; RTV Noord, 2015), and plans to restart methanol production in 2019 to the full capacity of almost 1 Mton even if it is fossil-based methanol (Bilfinger, 2018). Several plans for biobased production are developed.

According to the Dutch Emissions authority (NEa), the methanol factory of BioMCN emitted 217 kton of CO_2-eq. in 2018 (NEa, 2019). Figure 8 gives an overview of the history of emissions of BioMCN B.V.
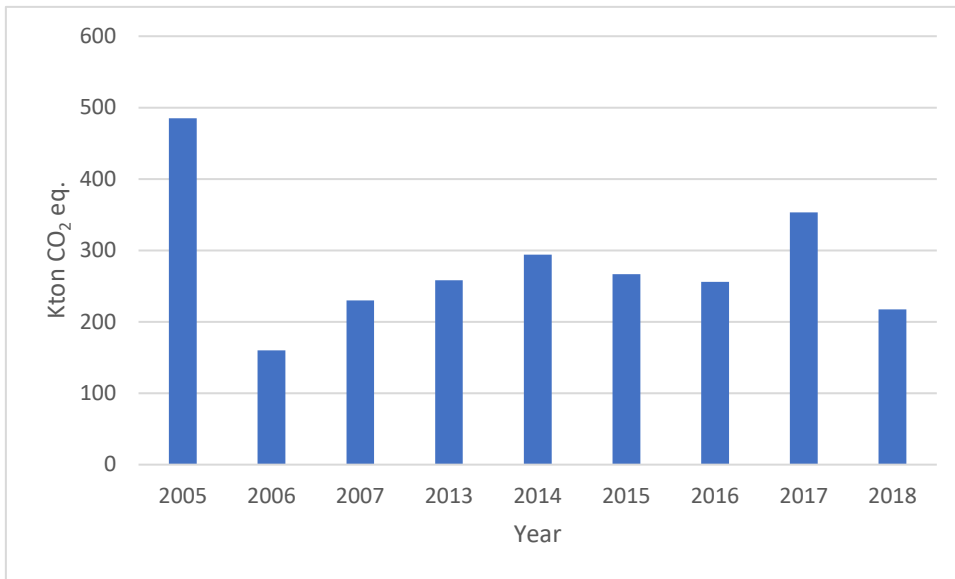

Figure 7. BioMCN B.V. (Groningen Seaports, 2017)

Figure 8 History of emissions of BioMCN B.V. *(NEa, 2019)*

1.2.4 Neste Netherlands

Neste Netherlands B.V. is located on the Maasvlakte (see Figure 9) and was founded in 2011 with an initial investment of EUR 670 mln (Neste, 2012). Neste produces diesel using the NExBTL hydrotreated vegetable oil (HVO) production process. In addition to diesel, smaller amounts of renewable gasoline, propane and isoalkane are produced (Neste, 2016). The production capacity of the plant in the Port of Rotterdam is 1 million[2] tons per year (Neste, 2012). Feedstock used for the production of the diesel includes waste fats, residues, and vegetable oils (Neste, 2016). The site is not participating in the European Union Emissions Trading Scheme (ETS).

Neste invested EUR 60 mln in 2015 to build a plant to produce and store bio-LPG (bio propane) in Rotterdam. The initial capacity of the biopropane plant is 30-40 kton per year (Hydrocarbons Technology, 2015). Neste and Ikea has partnered up to produce renewable biobased polypropylene plastic with 20% renewable content in a pilot at commercial scale in 2018 (NESTE, 2018). Neste is also looking to construct a kerosene plant for the aviation sector with an investment of EUR 100 million (WFM editor, 2019).

Figure 9. Neste Netherlands B.V. *(Neste, 2012)*

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[2]   The maximum production value of Neste NExBTL process is 1.2 Mton/yr biodiesel (van Staalduinen, 2007). In this report, figures are based on the intended production of 1 Mton biodiesel per year.

1.3   Overview of the main biofuel industries

Table 3 provides an overview of the biofuel industries in the scope of this study in the Netherlands. An overview of other industries can be found in Appendix A.

Table 3. General characteristics of the biofuel industries

Characteristics	Alco Energy	BioPetrol	BioMCN	Neste oil
Name	Alco Energy Rotterdam B.V.	BioPetrol Rotterdam B.V.	Biomethanol Chemie Nederland B.V.	Neste Netherlands B.V.
Corporate group	ALCO	GLENCORE	OCI	NESTE
Address	Merwedeweg 10	Welplaatweg 108	Oosterhorn 10	Antarctica-weg 185
Postal code	3198 LH	3197 KS	9936 HD	3199 KA
Locality	Europoort, Rotterdam	Botlek, Rotterdam	Delfzijl	Maasvlakte, Rotterdam
Employees (Port of Rotterdam, 2016)	80 (currently 110)	69	70	110
Fossil CO_2 emissions [kton CO_2-eq] (2018) (NEa, 2019)	340	36	217	8
Biobased CO_2 emissions [kton CO_2 eq.] (2017)	300			42
Feedstock	Maize	Rapeseed oil and sunflower oil	Natural gas and biogas	Animal fats and UCO
Product	Bioethanol	Biodiesel	Biomethanol and methanol	Biodiesel
Technology	Dry milling and fermentation	Transesterification	Steam methane reforming	NExBTL
Production capacity	379 kton (2016)	380 kton	450 kton[3]	1 Mton

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[3]   The current production capacity of BioMCN has increased to 900 kton with the start of 2nd production line in August, 2019

2 Biofuels and methanol production processes

This chapter describes and quantifies existing biofuels production processes. An overview of energy and materials flows per process is given in separate sections on the four companies.

2.1 Dry milling and fermentation process (Alco Energy Rotterdam B.V.)

In this section the bioethanol production process based on dry milling and fermentation will be discussed which is currently used by Alco Rotterdam B.V. Figure 10 provides a schematic overview of the production process. The Alco Energy Rotterdam production process uses maize as raw material. The starch in the grains is used to produce ethanol. The protein rich parts of the grain are used as a nutritious component for animal feed (dried distillers' grains with solubles (DDGS)) (Alco Energy 2019). The biogenic CO_2 produced in this process is used for greenhouses in the Westland area. The CO_2 is transferred by Linde/OCAP with a capacity of 42 ton/hr. The plant has a permitted capacity to produce 480 million litres (379 kton; 10 PJ) of bioethanol, 360 kton of DDGS and 300 kton of biogenic CO_2. The estimated maize input to produce these quantities amount to 1137 kton. The plant has a CHP with a capacity of 48 MW for the supply of heat and electricity (ALCO Group, 2019). With efficiency measures, Alco can still increase the material throughput capacity with more than 25% in the current configuration.

The process can be divided into six steps:
- Cleaning and milling;
- Cooking and liquefaction;
- Saccharification and fermentation;
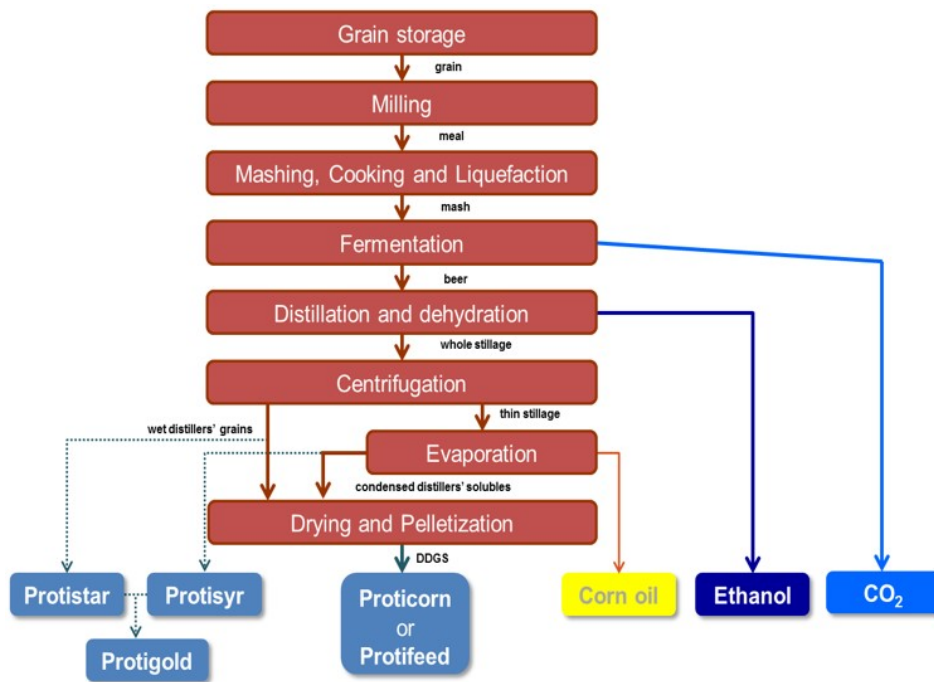- Distillation;
- Evaporation;
- Drying.

Figure 10. Schematic presentation of the production process of Alco Energy Rotterdam B.V. *(ALCO ENERGY, 2019)*
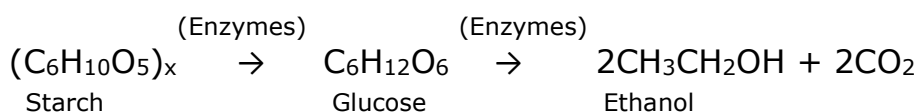
Cleaning and milling

The first step for the bioethanol production is feedstock preparation. The maize needs to be cleaned and ground into a coarse powder in a hammer mill or roller mill and then it is fed into a mashing system to be mixed with water (Schwietzke et al., 2009). There are six hammer mills in parallel, with destoner and magnetic separator incorporated in mill (ALCO ENERGY, 2019).

Cooking and liquefaction

In the next process step, the mash (mixture of meal and recuperated water at 55-60 °C) goes through a cooker where steam (>120 °C) breaks the starch granules and sterilizes the mash (ALCO ENERGY, 2019). Subsequently, an alpha amylase enzyme is added to the liquified mash further breaking down the starch into dextrin. Then the mix is cooled down from 85 °C to 35 °C (Schwietzke et al., 2009).

Saccharification and fermentation

In this process step, the cooled mash is pumped into a fermenter where simultaneous saccharification and fermentation is taking place. In addition to this, a second enzyme, gluco-amylase, and yeast is added to the mash (Schwietzke et al., 2009). The fermentation process is a sensitive batch process, which lasts around 50-60 hours at a temperature of 30 to 32 °C to produce 'beer' (16-18% alcohol by volume) (ALCO ENERGY, 2019). The chemical reaction involved in the process is described below (Clifford, 2018).

$$\underset{\text{Starch}}{(C_6H_{10}O_5)_x} \xrightarrow{\text{(Enzymes)}} \underset{\text{Glucose}}{C_6H_{12}O_6} \xrightarrow{\text{(Enzymes)}} \underset{\text{Ethanol}}{2CH_3CH_2OH + 2CO_2}$$

Distillation

The subsequent ethanol separation process occurs in a distillation column to purify the alcohol stream. The ascending vapour and descending beer liquid are in contact using disks and donuts in the distillation column (ALCO ENERGY, 2019). The alcohol vapour remains in the top of the column, while the liquid stripped of alcohol is removed at the bottom of the column. During distillation, impurities such as esters, aldehydes, higher alcohols or fusel oils are removed to produce a raw alcohol of 95 or 96% strength by volume (Clifford, 2018; Schwietzke et al., 2009).

The top flow is further dehydrated through molecular sieves, where the remaining water is removed to produce ethanol containing less than 0.3% water (95% v/v ethanol →99.8% v/v ethanol) (ALCO ENERGY, 2019).

Centrifugation and evaporation

The bottom flow (beer stripped of alcohol) is further processed involving a centrifugation step, separating the fibre fraction (wet distillers' grains) from the clarified liquid (thin stillage) which evaporates the thin stillage to a syrup (condensed distillers solubles).

Drying

The wet distillers' grains and condensed distillers solubles are then mixed and dried to form Dried distillers' grains with solubles (DDGS) (ALCO ENERGY, 2019; Clifford, 2018). The process includes decanting, evaporation and drying as seen in Figure 11. Decanting is done by using eight Alfa-Laval SG2 decanters which separate 12% (solid) whole stillage into thin stillage (8% suspended solids) as well as wet cake (35% solids) (ALCO Group, 2019). A HPD (Veolia) 4 effect evaporator is used to concentrate the thin stillage (8% dm) into syrup (45% dm) using waste energy (ALCO Group, 2019). Drying is done through three swiss combi dryers with a capacity for evaporating 35 ton/hr and drying is done in absence of oxygen using an integrated thermal oxidizer (ALCO Group, 2019). Furthermore, the dried mixture is pelletized by four Stolz pellet processes (ALCO Group, 2019).

Figure 11. Process of Dry distillers grain with soluble (ALCO ENERGY, 2019)

CHP plant

Alco operates a CHP plant with a capacity of 48 MW which uses natural gas to produce electricity and steam (110 ton/hr) for the above processes. The CHP plant uses a Siemens SGT-800 turbine (ALCO Group, 2019). Annually, approximately 225 GWh of electricity is sold to the grid and around 160 GWh is used for the production process. Table 4 gives an estimated overview of the energy input and output of Alco Energy.

Table 4. Energy input and output of the process at Alco Energy Rotterdam *(ALCO ENERGY, 2019)*

Energy	Value	Unit	Pj	Source
CO_2 Emissions (Fossil)	340	kton		NEA
Natural Gas	190	MNm^3	6.0	calculated, based on NEA
Input CHP	*142*	*MNm^3*	*4.5*	*estimated*
Input boiler, drying, etc.	*47*	*MNm^3*	*1.5*	*estimated 25%*
Generated process steam CHP	110	ton/hr	2.5	reported output Alco
Generated electricity	392	GWh	1.5	assuming 93% load
Used electricity	*166*	*GWh*	*0.6*	*assuming 93% load*
Exported electricity	*225*	*GWh*	*0.9*	*reported output Alco*

2.2 Transesterification process (Biopetrol Rotterdam B.V.)

This section explains the transesterification process which is used by Biopetrol Rotterdam B.V. for the production of biodiesel.

Figure 13 provides an overview of the production process of Biopetrol Rotterdam B.V. Currently, mostly rapeseed and sunflower oil, and minor shares of soybean oil are used as a feedstock for the production process. The production process uses sodium methylate as a catalyst. The methanol and water is used for the production of glycerol. The plant has a permitted capacity to produce approx. 380 kton (14.4 PJ) of biodiesel, 9500 kton of waste water and methanol mixture, and 36 kton of fossil CO_2 emissions (Luna et al., 2013; NEa, 2019). The estimated oil input as feedstock for producing these quantities amount to 380 kton. The production process needs 6 kton of catalyst (Sodium methylate), 34 kton of Methanol and 9500 kton of water (Luna et al., 2013). The oil types are interchangeable and their use depends on supply and customer preferences. The outputs of this process are biodiesel and glycerol. The glycerol produced is used for pharmaceutical purposes (Georgogianni et al., 2009).

The Lurgi transesterification process is used for the production of biodiesel from vegetable oils. The transesterification process is used with a closed loop water wash to minimize the production of waste water (Air Liquide, 2017). The process also involves a gas boiler using natural gas producing 13 bar steam with 94% efficiency (Pim Bakker, personal communication, 26th June, 2019). The estimated natural gas use is 20 mln NM_3 for the steam and drying purposes. More than half of the natural gas is used for generating steam and the rest is mainly used for drying purposes. The steam of 195 °C is mainly applied for separation of water from the product flow. The chemical reaction involved in the transesterification process used in at Biopetrol Rotterdam B.V. is shown in Figure 12 (Van Gerpen et al., 2004).
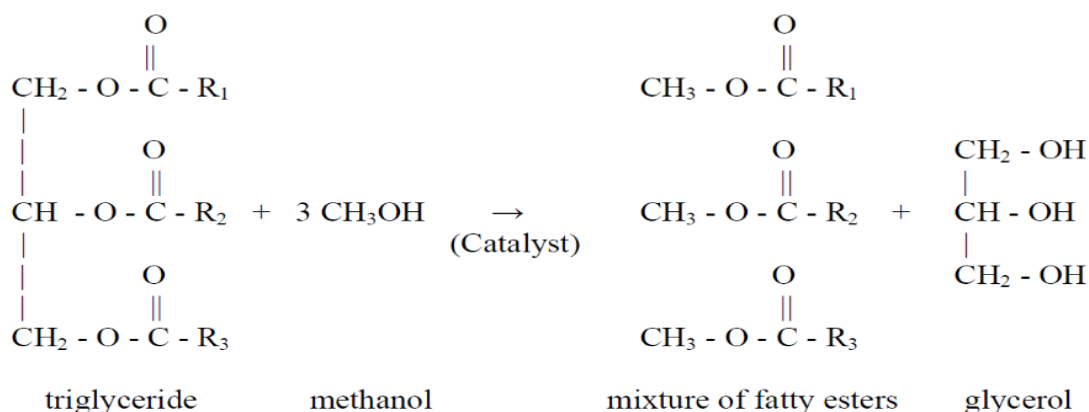
$$\begin{array}{cccccc}
& \text{O} & & & \text{O} & \\
& \| & & & \| & \\
\text{CH}_2\text{-O-C-R}_1 & & & \text{CH}_3\text{-O-C-R}_1 & & \\
| & & & & & \\
| & \text{O} & & & \text{O} & \text{CH}_2\text{-OH} \\
| & \| & & & \| & | \\
\text{CH-O-C-R}_2 & + \ 3\ \text{CH}_3\text{OH} & \xrightarrow[\text{(Catalyst)}]{} & \text{CH}_3\text{-O-C-R}_2 & + & \text{CH-OH} \\
| & & & & & | \\
| & \text{O} & & & \text{O} & \text{CH}_2\text{-OH} \\
| & \| & & & \| & \\
\text{CH}_2\text{-O-C-R}_3 & & & \text{CH}_3\text{-O-C-R}_3 & & \\
\text{triglyceride} & \text{methanol} & & \text{mixture of fatty esters} & & \text{glycerol}
\end{array}$$

Figure 12. Chemical reaction of the transesterification process *(Van Gerpen et al., 2004)*

The Lurgi transesterification process involves thorough mixing of methanol with oil in the presence of sodium methylate (alkali catalyst), separating lighter methyl ester from heavier glycerol due to gravity (Air Liquide, 2017; Luna et al., 2013). This is a continuous process that requires a temperature of around 60 °C and atmospheric pressure (Air Liquide, 2017). Crude glycerine of more than 80% purity is produced as co-product. The process only uses sodium hydroxide or hydrogen chloride that is in the glycerine, which can be removed easily through distillation (Air Liquide, 2017).

The production process is explained in following steps:
- Reactor 1
- Reactor 2
- Water wash and transesterification.

The production process involves mixing of oil, methanol and sodium methylate catalyst in Reactor 1**.** There it is separated into two phases: a lighter methyl ester/oil phase and a heavier phase consisting mainly of glycerine and water.

The lighter methyl ester/oil is blended with additional methanol and catalyst in Reactor 2**.** There, gravity separation is used to maximize the biodiesel quality and yield (Luna et al., 2013). This mixture is further washed with water to remove glycerol, impurities or methanol dissolved in the ester phase.

The heavier phase consists mainly of glycerine and water (Air Liquide, 2017; Luna et al., 2013). The Lurgi process recycles the glycerol phase from Reactor 2 with an excess of methanol and catalyst to Reactor 1. The glycerol phase containing excess methanol is distilled in the methanol recovery column which uses water from the wash water column after leaving Reactor 1 to recover the methanol. The methanol is sent back to Reactor 1, thus all of the methanol is consumed in the production of methyl ester (Luna et al., 2013). In addition to this, the heavier fraction of the methanol recovery column is processed in the glycerine water evaporation column to retrieve the crude glycerine (60-65%) as a by-product that can be further upgraded to pharmaceutical glycerine (99.8%) by distillation, bleaching and vacuum drying (Air Liquide, 2017).
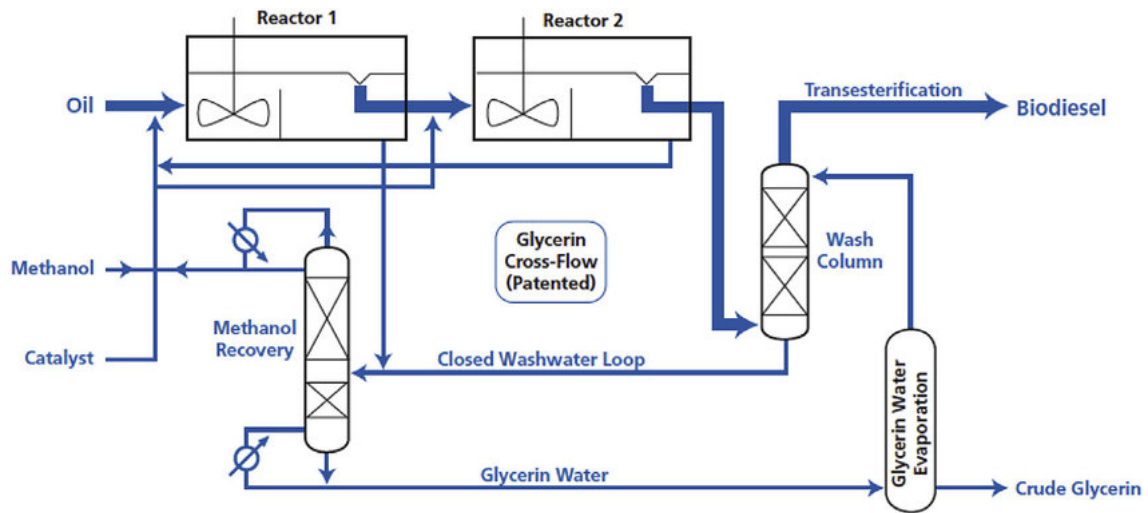
Figure 13. Schematic presentation of the transesterification process of Biopetrol Rotterdam B.V. (Luna et al., 2013)

Table 5 gives an overview of the input and output of Biopetrol Rotterdam B.V., which produces 385 kton/yr biodiesel from rapeseed oil and sunflower oil.

Table 5. Input and output for the transesterification process

		Value	Unit	Energy [PJ]	Sources
Input	Raw material (rapeseed oil)	385	kton		Calculated based on Luna et al., 2013
	Electricity	12	GWh	0.04	Personal communication
	Natural gas (total)	20	mln Nm^3	0.65	Calculated, based on NEa
Output	Biodiesel	380	kton	14.1	Calculated based on Luna et al., 2013
	Crude glycerol	36	kton		Calculated based on Luna et al., 2013
	CO_2 emissions (fossil)	36	kton		NEa, 2019

2.3   Steam Reforming (BioMCN B.V.)

This section provides an overview of the steam methane reforming process for the production of methanol currently used by BioMCN. BioMCN has two lines of production which have a capacity of 450 kton/year per line. The lines have emission factors of 0.77 ton of CO_2/ton of methanol (line 1) and 0.73 ton of CO_2/ton of methanol (line 2), respectively. On-site there is also an expander turbine which can use grey hydrogen from both lines to produce electricity. Both lines can use liquified CO_2.

The chemical reaction involved in the steam reforming process is shown below (Arthur, 2010). The first two reaction refer to syngas production, the last two reactions refer to methanol synthesis.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$CO + H_2O \rightarrow CO_2 + H_2$$

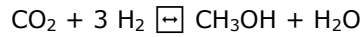$$CO + 2H_2 \leftrightarrow CH_3OH$$

$$CO_2 + 3 H_2 \leftrightarrow CH_3OH + H_2O$$
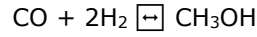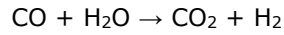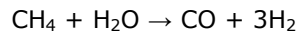
Figure 14 provides a schematic overview of the process of methanol production using steam reforming where natural gas is the feedstock (Aasberg-Petersen et al., 2008; Compagne, 2017; Haverford et al., 2010).

The production process can be sub-divided into three parts:
- Steam Reforming
- Conversion to methanol
- Distillation.
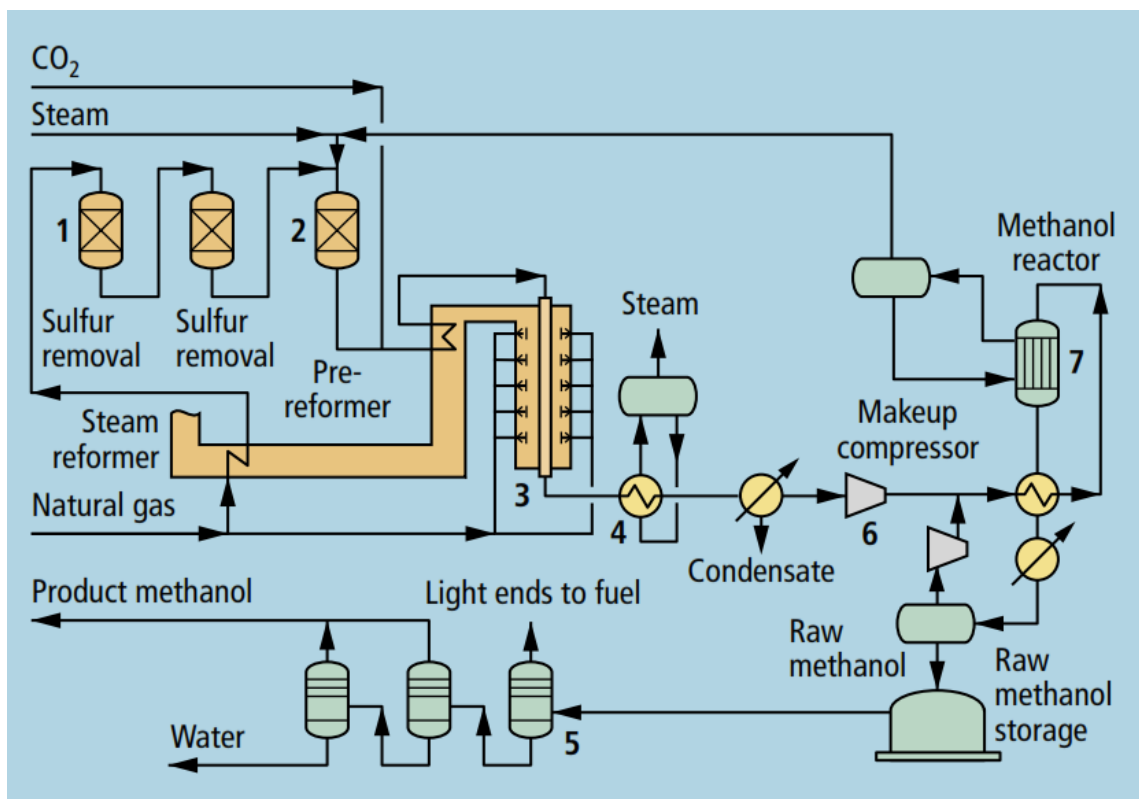
Figure 14. Schematic overview of the steam reforming process (Aasberg-Petersen et al., 2008)

Steam reforming

The steam reforming takes place at 850-860 °C. In this process, steam and methane are converted catalytically and endothermically to hydrogen and carbon dioxide (Arthur, 2010).

First, desulphurization of the natural gas occurs if necessary. The desulphurized natural gas is mixed with steam (optionally CO_2) and preheated to about 500 °C prior to entering the reformer tubes (Arthur, 2010). For the endothermic reforming reaction, heat is supplied by the combustion of fuel in the reformer furnace and hot effluent gas exiting the reformer is used for the production of steam (Arthur, 2010). The synthesis gas is produced by tubular steam reforming. After that, the syngas is used in the conversion process to produce methanol and surplus hydrogen (Haverford et al., 2010). This hydrogen can be purged and used as reformer fuel. With adding liquid CO_2, this hydrogen can also be used for additional methanol production. Furthermore, the addition of liquid CO_2 optimises the synthesis gas composition for methanol production (Aasberg-Petersen et al., 2008; Haverford et al., 2010; Lücking, 2017). The addition of liquid CO_2 in reforming results in a reduction in the energy consumption of 5–10% compared to a conventional plant (Aasberg-Petersen et al., 2008; Haverford et al., 2010). The energy use for the process per metric ton of methanol is 32 GJ without CO_2 addition and 29.5 GJ with CO_2 addition (Haverford et al., 2010). Table 6 gives an overview of the input and output flows of the production process of BioMCN. This reflects the situation with one production line, operating two lines would approximately double the quantities. The share of biomethanol in total methanol production is currently said to be around 15 percent (Bilfinger, 2018).

Conversion to methanol
In this process, methanol is produced using a low-pressure catalytic reaction of syngas. The low pressure (50-60 bar) and temperature range of 250-260°C provide favourable conditions for the synthesis of methanol and completely inhibit the production of by-products (Arthur, 2010). The most common catalyst used in low-pressure methanol production is a copper-zinc oxide catalyst with aluminium oxide or chromium(III) oxide (Cu – ZnO – Al_2O_3 /Cu – ZnO – Cr_2O_3) (Lücking, 2017). The syngas produced afterwards in reaction is compressed to 80-100 bar before it is fed into the methanol reactor (Arthur, 2010).

Distillation
In this process, the water-methanol mixture is distilled to stabilize methanol, either by distillation or by deep flashing, to expunge the volatile components such as CO_2. There are three important grades[4] of methanol (Arthur, 2010).

Biomethanol
According to BioMCN, the production of biomethanol is carried out in two ways. The first method is to use biogas from bio-fermentation plants. The biogas is made from, for example, cow manure and upgraded to natural gas network quality (Bilfinger, 2018). The second method is based on additional liquid CO_2 injection as there is a surplus of hydrogen in the production process. The biogenic CO_2 (produced from biogas production) is purchased and mixed with hydrogen to produce biomethanol using methanol synthesis (Vaartjes 2017). For flexibility reasons, green gas certificates are used to compensate the use of natural gas, which allows methanol to be sold as green methanol or biomethanol. A further step for more sustainable methanol would be to produce hydrogen with electrolysis using renewable electricity, combined with biogenic CO_2 (Bilfinger, 2018).

Table 6 gives an overview of inputs and outputs for BioMCN. It reflects the situation before the restart of the second production line.

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[4] Chemical grade AAA (99.85 wt% MeOH, 0.1 wt% water, and concentrations of higher alcohols at parts-per-million levels); fuel grade (97wt% MeOH, 1 wt% water, 1.5wt% alcohols and 0.5wt% of process oil) and, MTBE grade (97wt% MeOH, 1wt% water, 2wt% alcohols, 150ppm methyl acetate, 0.3wt% inert liquid medium).

Table 6. Input and output (mass and energy) of BioMCN production, one line in operation *(Elektronisch Milieujaarverslag, 2019)*

Input	Quantity	Unit	(MNm³)	Energy (PJ)
Natural gas and biogas feedstock	370	kton	445	14.1
Liquified CO_2	pm			
Input (Energy Flows)	**Quantity**	**Unit**	**(MNm³)**	**Energy (PJ)**
Natural gas	64.4	kton	77.3	2.4
hydrogen from separation	16.1	kton	194.3	2.1
methane from separation	12.0	kton	21.6	0.8
Electricity	16.6	GWh		0.06
Output	**Quantity**	**Unit**		**Energy (PJ)**
Methanol and bio-methanol	450	kton		9.0
Fossil based CO_2 emissions	217.5	kton		

2.4 NExBTL process (Neste Netherlands B.V.)

This section explains about the technology used by Neste Oil for the production of biodiesel. Neste Oil uses the NExBTL HVO (Hydrotreated Vegetable Oil) process, which uses the waste and residue fat fractions coming from food, fish and slaughterhouse industries, as well as from non-food grade vegetable oil fractions as feedstock (Neste, 2016). The NExBTL process can be subdivided into pre-treatment, hydro treatment, stripping, isomerization and stabilization. The hydrogen used for the NExBTL process is acquired from third parties or produced on-site using membrane separation and stripping and isomerization (van Staalduinen, 2007). The chemical reaction involved in the Neste NExBTL process is shown in Figure 15 (Neste, 2016).
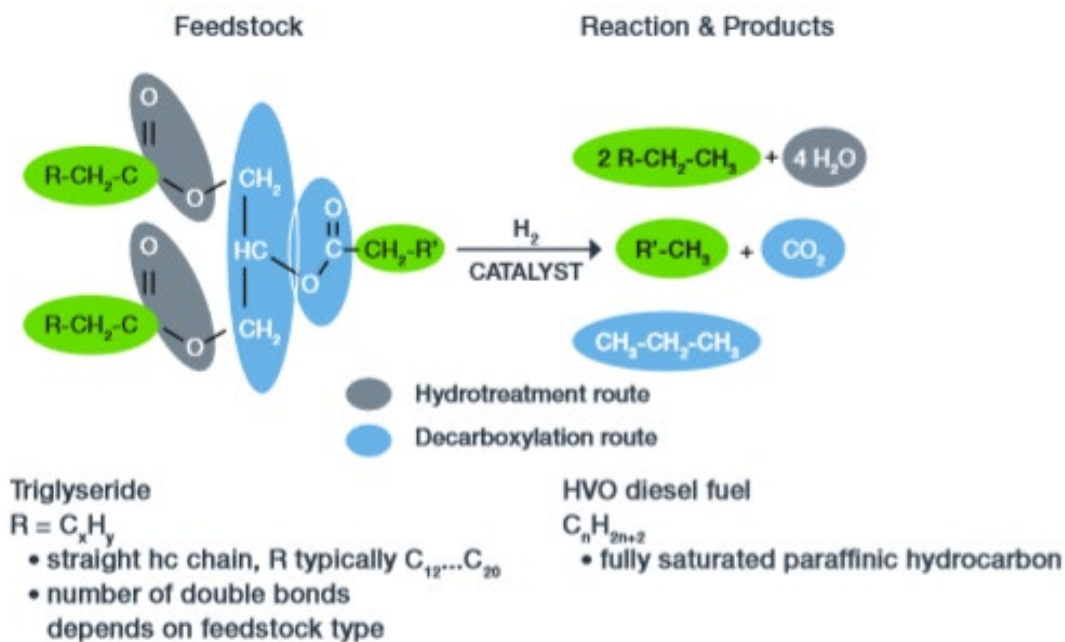

Figure 15. Chemical reaction involved in Neste NExBTL (Neste, 2016)

Figure 16 shows an overview of the Neste NExBTL technology. In this process, the hydrogen which is used to remove oxygen from the triglyceride vegetable oil molecules thus, splitting the triglyceride into three separate chains creating hydrocarbons similar to diesel fuel components (Neste, 2016). The production process can be sub-divided into six process steps:

- Pre-treatment (impurities removal)
- Hydro treatment: Hydrodeoxygenation (HDO) (oxygen removal, paraffins production, propane production)
- Stripping
- Isomerization
- Stabilization (removal of residual light gases)
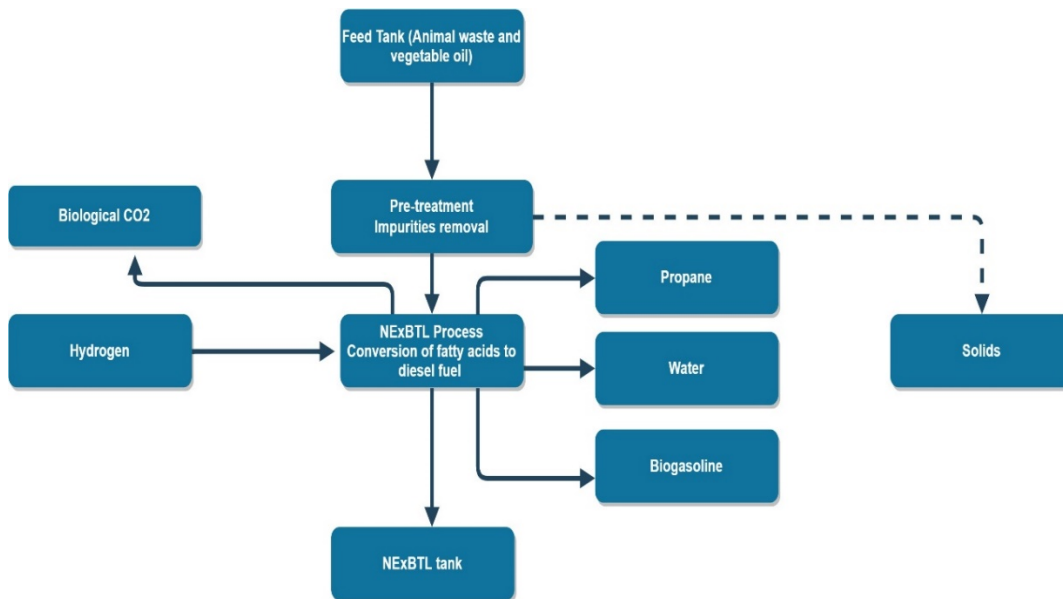- Recycle (hydrogen recovered & recycled; water, carbon dioxide removal, light gases recovered).

Figure 16. Schematics presentation of Neste NExBTL process, adapted from: (Nikander, 2008; van Staalduinen, 2007)

Pre-treatment Process
In this process, the feedstock is waste and animal fats and vegetable oils which passes through the pre-treatment Unit (PTU) to reduce the impurities by filtration, citric acid, phosphoric acid (50-75%), bleaching earth and silica, thus to enhance long catalyst lifetime. The feedstock is heated through outgoing stream of pre-treated oil and steam, steam is purchased from Uniper. The PTU is designed for continuous processing of vegetable oils and fats which is based on a bleaching unit with temperature up to 100°C. The bleaching unit operational configuration depends on type and quality of feedstock and it can be operated independently from the rest of plants. The process involves wet bleaching and dry bleaching to pass it through a filtration process to produce pre-treated oil. This pre-treated oil is fed through heat exchangers to heat up the feedstock in the storage tank. The process generally involves addition of acid to form a salt and removing it by precipitation. The result of this process is further fed through silica and/or bleaching earth which act as an adsorbent to further reduce impurities and the levels of avid or bleaching earth used are in range of 0.003 to 0.0003 kg/kg of NExBTL renewable diesel (NESTE OIL, 2013). Approximately 1 mln tonnes of pre-treated oil is processed per year (van Staalduinen, 2007). Table 7 and Figure 17 gives an overview of the input and output of the pre-treatment process per ton of diesel.

Table 7. The input and output of pre-treatment process of NExBTL per ton of diesel (Nikander, 2008)

Input	Quantity	Unit
Raw material	1,214	Kg
Cooling water	70	Kg
Process chemicals	3	Kg
Process water	28	Kg
Steam	657	MJ
Electricity	50	MJ
Output	**Quantity**	**Unit**
Pre-treated oil	1,191	Kg
Dried solid waste	13	Kg
Waste water	111	Kg
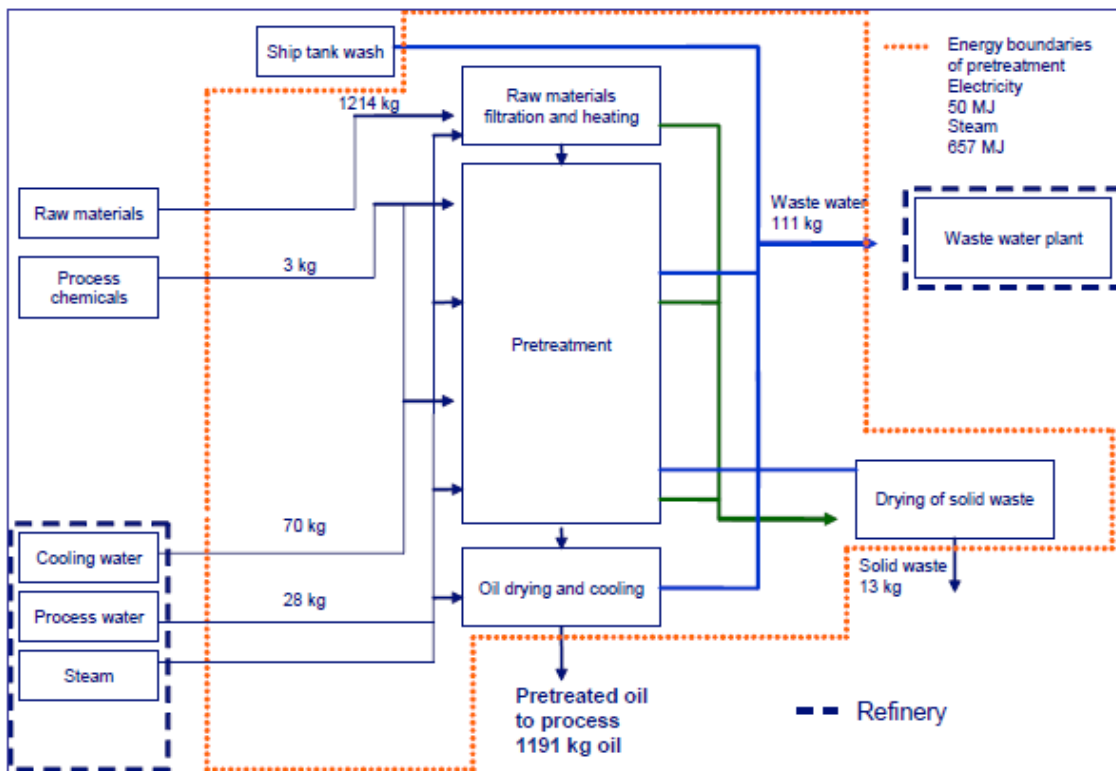
Figure 17. Schematics of pre-treatment process for NExBTL process *(Nikander, 2008)*

Hydro deoxygenation (HDO)

This process involves the catalytic hydro treatment of pre-treated oil in the reactor filled with catalyst bed. This is causing vegetable oils to react with hydrogen until branched and light hydrocarbons are formed in three straight chain paraffins. Also, propane, water and carbon dioxide are formed through consecutive reactions (NESTE OIL, 2013).

The triglycerides are converted 100% in the reactor and the reaction step is referred to as hydro deoxygenation (HDO). The reaction occurs at elevated temperature and pressure where triglycerides react with hydrogen with catalyst. The reactor is heated using thermal oil. This oil is heated with natural gas. The reaction is exothermic, thus the excess heat is

removed and used for heating up the incoming feed, reducing external energy requirement. The hydrogen comes from membrane separation and recycling flows from stripping and isomerization (van Staalduinen, 2007), and from third parties. In addition, the high pressure and low pressure propane rich off gas produced during the production is fed to the recycle section when water has been condensed out for recycle and reuse (NESTE OIL, 2013).

In addition to HDO, the paraffins are isomerized to improve the cold flow properties of the final product. The liquid hydrocarbons are fed to the diesel stabilization column (NESTE OIL, 2013). Table 8 and Figure 18 give an overview of the input and output of the NExBTL process per ton of diesel.

Table 8. The input and output of NExBTL process (excluding pre-treatment) per ton of diesel (Nikander, 2008)

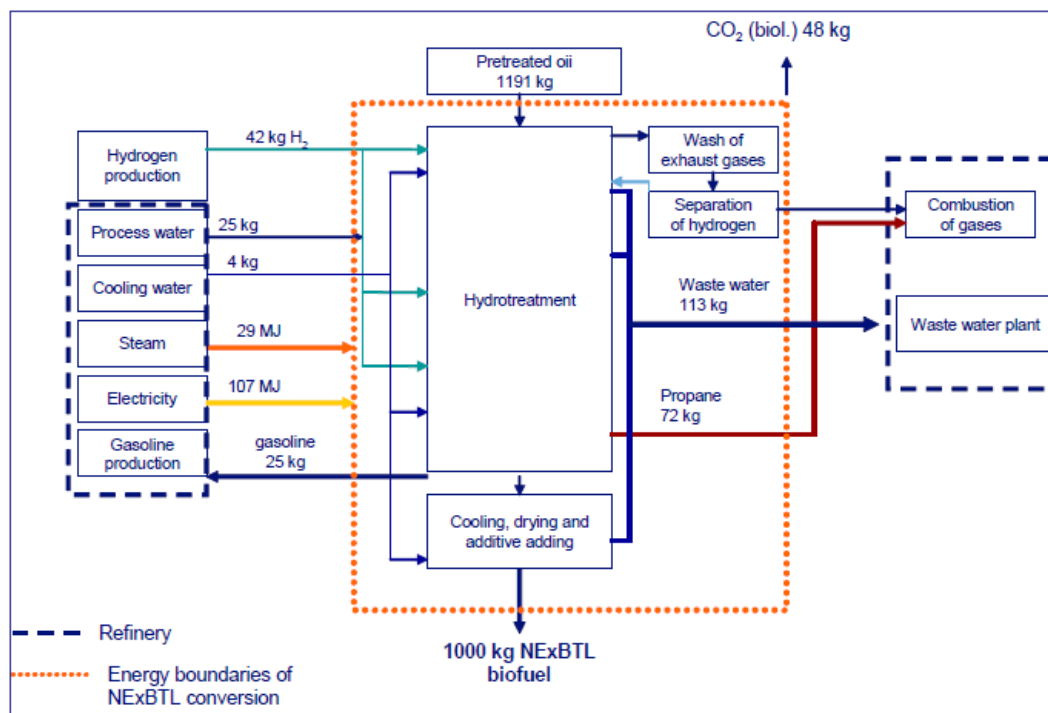| Input	Quantity	Unit
Pre-treated oil	1,191	kg
Hydrogen	42	kg
Cooling water	4	kg
Process water	25	kg
Steam	29	MJ
Natural gas for oil heating	8.6	MJ
Electricity	107	MJ
Output	**Quantity**	**Unit**
NExBTL	1,000	kg
Bio gasoline	25	kg
Propane	72	kg
Waste water	113	kg
Biological CO_2 from process	48	kg

Figure 18. Schematics of NExBTL process (Nikander, 2008)

Stripping

In this process, the bottom stream from hydrogen treatment in a stripped of water, hydrogen sulphide, carbon dioxide and carbon monoxide using warm hydrogen. These components are removed to deactivate the catalyst in isomerization. The hydrogen comes from recycle stream from isomerization, where the hydrogen is supplemented from third parties. Further, after stripping the remained branched hydrocarbons are further processed in isomerization. The warm hydrogen is cooled in a condenser after stripping process.

Isomerization

The branched hydrocarbons from the stripper are isomerized in a reactor using a catalyst, to produce diesel under a high pressure and high temperature. Hot oil is used to heat the process. This oil is heated with natural gas. The majority of the hydrogen flow, together with the recycled hydrogen flow from the stripper is compressed. Further, a small part of hydrogen stream is immediately recycled to isomerization reactor.

Stabilization

The products of the isomerization reactor are sent to the stabilization column to separate the light hydrocarbons by stripping low pressure steam. The low pressure steam is generated in the waste heat boiler by the condensate. Also, the hydrocarbons which are stripped are called light propane (NESTE OIL, 2013). The NExBTL formed contains water, which is removed by drying the NExBTL stream using drip catcher. The water released during this process is acidic and goes through acid gas removal and hydrogen treatment to be stripped of CO_2 and H_2S.

Recycle section (gas separation)

In this process, the gas mixtures from the stabilization are separated using absorber (amine unit) and methyl diethanolamine (MDEA) under high pressure into individual gas streams of hydrogen which goes to hydrodeoxygenation process for use and MDEA solution dissolved with carbon dioxide and hydrogen sulphide. The recycle section which contains wash columns and regeneration columns. The carbon dioxide and water streams are cleaned before its released to the atmosphere or waste water system.

3 Biofuel products and applications

In this section, the main drivers behind Dutch biofuel industry, products and applications are discussed. An overview of the relevant technical standards for biofuels in Europe is also provided.

3.1 Drivers for the Dutch biofuels industry

Biofuels consumption for transport in the Netherlands is mainly driven by the European policies and their implementation at the national level (Hamelinck et al., 2019). The biofuel directive of 2003 prescribed member states to set the share of biofuels to 2% by 2005 and to 5.75% by 2010 (Directive 2003/30/EC, 2003). However, there were some questions on the sustainability of the biofuels due to rising prices of food, negative impacts on the biodiversity and GHG emissions caused by crop cultivation and land use change (Grinsven & Kampman, 2013).

In 2009 the Renewable Energy Directive (2009/28/EC, RED) came into effect which included sustainability criteria for biofuels. The RED introduced a binding target of 10% of renewable energy in transport by 2020. Next to that, the Fuel Quality Directive (2015/652) obliged a reduction of average GHG intensity of the transport fuels sold on the market by 6% by 2020 compared with 2010 (DIRECTIVE 2009/28/EC, 2009; DIRECTIVE 2009/30/EC, 2009).

The RED was implemented by the Dutch government in 2011 and obliges Dutch fuel suppliers to sell a certain share of biofuels on the market (Grinsven & Kampman, 2013). Until 2014, there were separate sub-targets for biofuels shares in petrol and diesel, but were discontinued from 2015 onwards (MINISTERIE VAN INFRASTRUCTUUR EN MILIEU, 2016; NEa, 2016). Table 9 provides the biofuel obligations until 2020 (van Grinsven & van Essen, 2015); (NEa, 2018).

Table 9. Renewable energy obligations in transport sector in 2015-2020, minimum percentage of renewables in energy for transport *(NEa, 2018)*

	2015	2016	2017	2018	2019	2020
Total obligation	6.25%	7%	7.75%	8.5%	12.5%	16.4%

Due to Indirect Land Use Change (ILUC) caused by food-based biofuel production, the EU approved the ILUC Directive in 2015 which amended the RED and the Fuel Quality Directive to address ILUC. The directive (2015/1513) limited the maximum contribution of food based biofuels to 7% in 2020 and also introduced a voluntary target of 0.5% advanced biofuels in road transport by 2020 (Bitnere, 2017). Furthermore, the directive introduced the double-counting mechanism, which means advanced biofuels can be counted double (on energy basis)towards the renewable energy target of 10% (ETIP Bioenergy, 2017; Hamelinck et al., 2019). Figure 19 gives an overview of the relation between different types of biofuels for realising the 10% target (van Grinsven & van Essen, 2015).
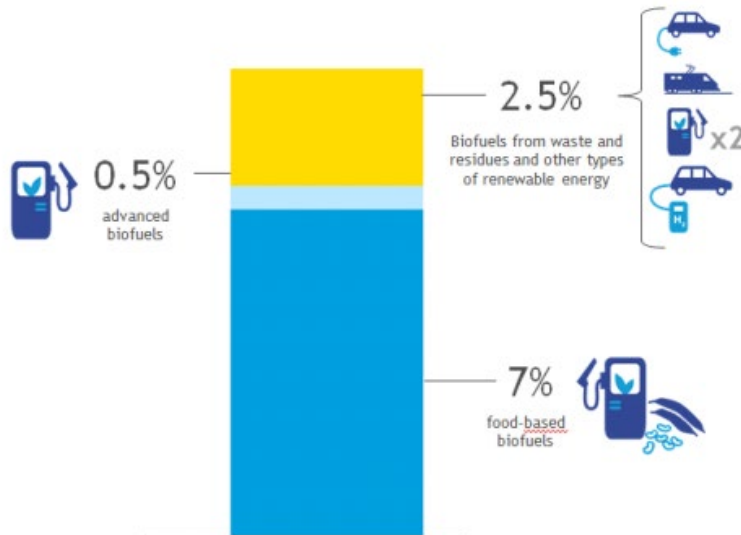
Figure 19. The target for 10% biofuel target for transport (van Grinsven & van Essen, 2015)

The revised RED II (2018/2001/EU) specifies a 14% target for renewable energy in road and railway transport by 2030. In this directive first generation biofuels are capped at max. 7% in 2030 (Bitnere, 2017; European Commission, 2018).

Figure 20 reflects RED II proposal for fuel suppliers (Bitnere, 2017; European Commission, 2019). The share of advanced biofuels has to be at least 1% in 2025 and at least 3.5% in 2030 (European Commission, 2019). Furthermore, palm oil, which results in high-ILUC has to be phased out by 2030 (Bitnere, 2017).

Figure 20. Renewable energy in transport post 2020 in Europe *(European Commission, 2018)*

Hence the future expansion of biofuels markets in Europe depends on the commercial deployment of advanced biofuels which utilizes waste, residues and energy crops (grown on marginal land) as feedstocks (ETIP Bioenergy, 2017).

3.2   Types of biofuels

In the EU, liquid biofuels are defined as transport fuels such as biodiesel, bioethanol, biogas/biomethane which are made from biomass. Biofuels are generally categorised as conventional/first-generation or advanced/second-generation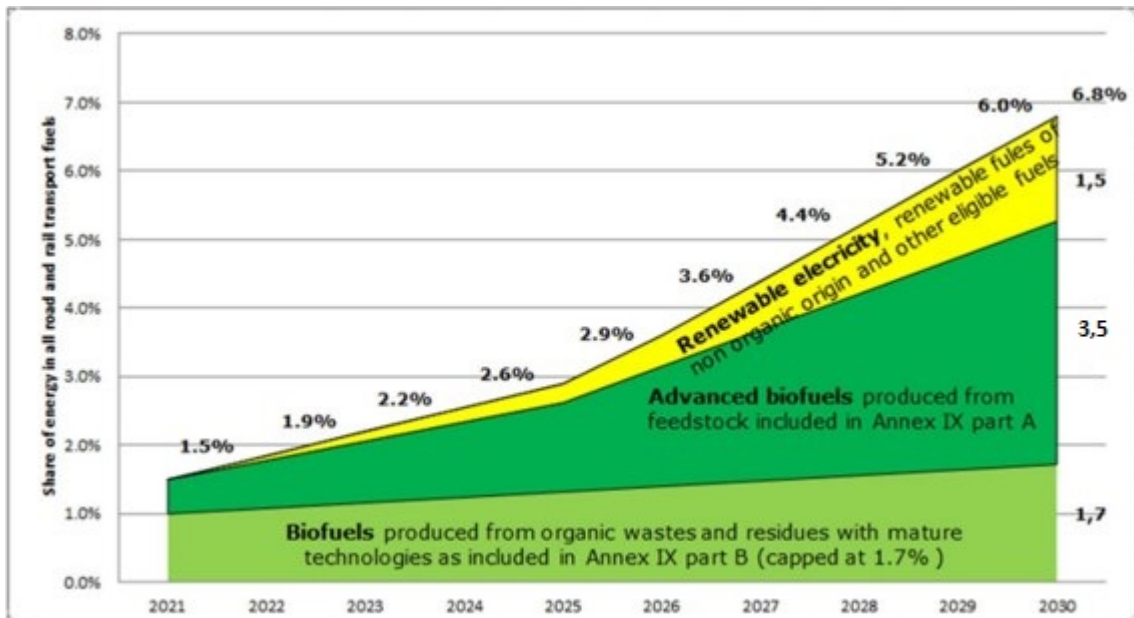 biofuels. Conventional biofuels refer to biofuels produced from food and feed based crops. Advanced biofuels refer to biofuels and biogas produced from wastes and residues (i.e. manure, straw, forestry residues).

First-generation biofuels
First-generation biofuels include ethanol and biodiesel generated from food and feed crop based feedstocks. Ethanol is mostly produced from the fermentation of C6 sugars (mostly glucose) in sugarcane and maize. Other feedstocks to produce first-generation bioethanol include whey, barley, potato wastes, and sugar beets (Lee & Lavoie, 2013). Biodiesel is produced through a chemical process (transesterification), where the feedstocks are oily plants and seeds. The process involves extraction of oil and breaking the long chain fatty acids to glycerol, and replacing it with methanol to produce biodiesel (Lee & Lavoie, 2013).

Second-generation biofuels
Second-generation biofuels are defined as fuels produced from different non-food feedstocks, especially but not limited to lignocellulosic biomass. Feedstock used for second-generation biofuels is usually separated into three main categories: homogeneous (white wood chips), quasi-homogeneous (agricultural and forest residues) and non-homogeneous (municipal solid waste) (Lee & Lavoie, 2013). The conversion process for the production of second generation biofuels is depicted in Figure 21.
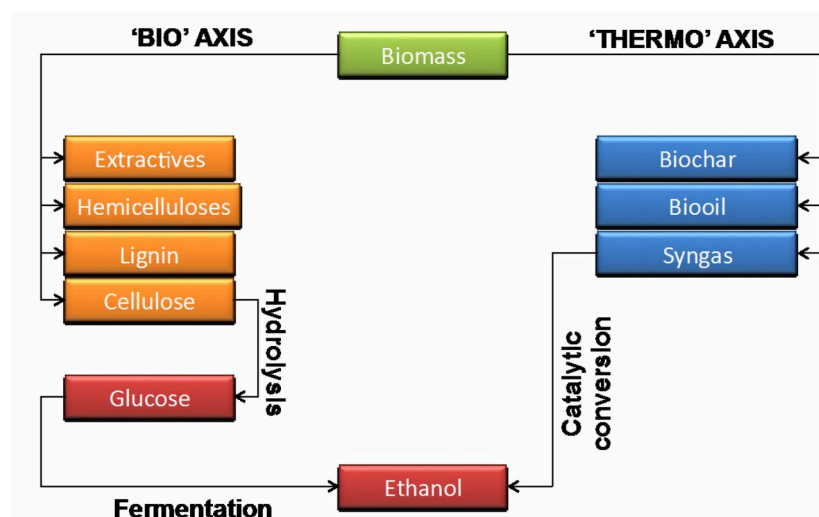

Figure 21. Schematics of the pathways for conversion of lignocellulosic biomass into biofuels (Lee & Lavoie, 2013)

Third-generation biofuels

Third generation biofuels are produced from algal biomass, which has a rapid growth yield compared to lignocellulosic biomass (Brennan & Owende, 2010). The production of biofuels from algae is dependent on the lipid content of microorganisms. The algae mainly used is chlorella due to its high lipid content (60-70%) (Liang et al., 2009) and high productivity (Chen et al., 2011). There are various technical and geographical challenges associated with algal biomass (Lee & Lavoie, 2013). Lipids from algae can be processed via transesterification to produce biodiesel or through hydrogenolysis to produce kerosene grade alkane suitable for use as drop-in aviation fuels (Tran et al., 2010).

Feedstock for biofuels

In the EU, bioethanol is mainly produced from grains and sugar beet derivatives which include cereals (74%), sugars (15%) and ligno-cellulosic (11%) (ePURE, 2017; European Bioenergy Day, 2017). As for feedstock, wheat is mainly used in North-western Europe, whereas maize is predominantly used in Central Europe and Spain for bio-ethanol. Sugar beets are used in France, Germany and Belgium for production of bio-ethanol. Hence, the required feedstock for the 2016 production (4 million litres of bioethanol) was estimated at 8.9 million metric tons of cereals and 8.8 million metric tons of sugar beets. Thus, about 2.9% of total EU cereal production and about 7.0% of total sugar beet goes to biofuels production (European Bioenergy Day, 2017). According to European renewable ethanol association (ePURE), 5.5 million tonnes of co-products including 4 million tonnes of animal feed were produced in 2016.

The food versus fuel debate is about the potential impact of the first generation biofuels on global food supply (Tomei & Helliwell, 2016). The food versus fuel argument questions the ethics of diverting land from food to energy production, and consist of two key parts: first, the demand for biofuels has an impact on food prices, which disproportionately affects poor people in the global South (Monbiot, 2004, 2007, 2012); and second, it leads to competition with existing food production in established agricultural areas or requires expansion into new environments (Tomei & Helliwell, 2016). The UN Food and Agriculture Organisation[5] and the International Food Policy Research Institute state that biofuels and food production can also be mutually supportive. A recent analysis finds there is no evidence of biofuels impacting the local food security and there is a small impact on global prices (Faaij et al., 2017).

Technical Standards for biofuels in Europe

The EU regulations described below outline the fuel content standards for biodiesel, ethanol and methanol (TransportPolicy, 2018). Standardization helps in diminishing trade barriers, promotes safety, increases compatibility of products, systems and services, and promotes common technical understanding. These standards are developed by the European Committee for Standardization (CEN) (Rutz & Janssen, 2006).

Biodiesel
- **EN 14214** which includes the basic specification for FAME (fatty acid methyl ester) fuel for diesel engines. B100 fuel which meets the standard can be used unblended in diesel engine (if engine is adapted to operate on B100) or blended with petroleum diesel fuel (Moser, 2009; Rutz & Janssen, 2006).
- **EN 590** which is European diesel fuel specification applicable to biodiesel blends up to 7% of FAME (Moser, 2009; Rutz & Janssen, 2006).

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[5]   UN Food and Agriculture Organisation Director General José Graziano da Silva speaking at the Global Forum for Food and Agriculture (2015)

Ethanol
- **EN 15376** provides the specification of blending of ethanol in gasoline in the EU (Rutz & Janssen, 2006).
- **EN 228** is specification for European gasoline fuel applicable to ethanol blends up to 10% (Rutz & Janssen, 2006).

Methanol
- **EN 228** provides the specification for low percentage methanol-gasoline blends up to 3% (ETIP Bioenergy, 2016).

HVO (Biodiesel)
- **EN 15940:2016** provides the specification for paraffinic diesel fuels and also covers synthetic Fischer-Tropsch products GTL, BTL and CTL. HVO can be blended without any limit or in addition to max 7% vol FAME (Neste, 2016).

Blending of biofuels

For the biofuels market, lacking compatibility with existing vehicle designs and current fuel distribution infrastructures is a big limiting factor. Generally called the "blend wall", considerable obstacles arise due to differences between the biofuel molecules and the petroleum-based fuels for which current infrastructure and vehicles are designed. In the EU, the restrictions are at the 10% (by volume) level for ethanol in gasoline, and 7% (by volume for Fatty Acid Methyl Ester biodiesel) in diesel in 2020. (FuelsEurope, 2018)

One of the possible solutions is the use of products with very high levels of biofuel, such as E85, B30, or B100[6]. However, these grades of fuel require specially adapted vehicles, dedicated infrastructure and large incentives for fuel providers and original equipment manufacturers (OEMs) to offer them at competitive prices (FuelsEurope, 2018).

The alternative could be to introduce higher standard grades like E20 and B10[7], but these might require additional pumps at the service station. Therefore, "drop in" fuels like Hydrogenated Vegetable Oil (HVO) and butanol can play a key role in bridging the gap between blend walls and biofuel targets (FuelsEurope, 2018).

3.3 Fuel properties

The difference between the thermo-chemical properties of biofuels and fossil-based fuels is described below along with the relevant application of the products in the European market.

Ethanol [C_2H_5OH]

Ethanol is utilized as substitute for gasoline or can be used as blend with gasoline. Also, ethanol is used for the petrol additive ETBE (Ethyl tert-butyl-ether) (ETIP Bioenergy, 2016). A comparison of the chemical properties of ethanol and petrol (gasoline) is seen in Table 10.

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[6]   B85: 85% Ethanol + 15% Gasoline. B30: 70% Biodiesel + 30% Diesel. B100: 100% Biodiesel
[7]   E15: 15% Ethanol + 85% Gasoline. B10: 10% Biodiesel + 90% Diesel.

Table 10. Comparison of Fuel properties ethanol *(ETIP Bioenergy, 2016)*

Property	Ethanol	Petrol
Density at 20°C [kg/l] (JRC, 2017)	0.79	0.74
Lower Heating Value [MJ/kg] (JRC, 2017)	26.8	43.2
Octane number*	>100	92
Fuel Equivalence[8]*	0.65	1
GHG [g/CO_2eq/MJ]**	Sugar beet ethanol: 33 Farmed wood ethanol: 20 Wheat straw ethanol: 11	93.3

Note: *Median values are used for ranges ** Total for cultivation, processing and transport

Application

Low percentage ethanol-gasoline blends (E5, E10) can be used in the conventional spark-ignition engines without any technical changes. For modern flexible fuel vehicles (FFV), the blend of EtOH-gasoline mixture up to 85% can be used. The ED95 (alcohol fuel) is used for heavy duty application on a limited scale (ETIP Bioenergy, 2016).

Fatty Acid Methyl Esters/Biodiesel (FAME) [$CH_3(CH_2)nCOOCH_3$]

FAME is used for substituting diesel, transportation fuel and power generation fuel (ETIP Bioenergy, 2016). Table 11 gives an overview of the difference between properties of FAME and diesel.

Table 11. Comparison of Fuel properties biodiesel *(ETIP Bioenergy, 2016)*

Property	FAME	Diesel
Density at 20°C [kg/l] (JRC, 2017)	0.89	0.83
Lower heating value [MJ/kg] (JRC, 2017)	37.2	43.1
Viscosity at 20°C [mm²/s]*	7.5	5
Cetane number*	56	50
Fuel Equivalence*	0.91	1
GHG [gCO_2eq/MJ]** (JRC, 2017)	Rapeseed biodiesel: 46 Waste vegetable or animal oil biodiesel: 10 Palm oil biodiesel: 54	95.1

Note:

*Median values are used for simplification

**Total for cultivation, processing and transport

Application

Blends with diesel up to 5-10% or 25-30% and 100% have been tested by the motor manufacturers. The seals and piping require modification to use 100% pure biodiesel. In EU, the use of biodiesel as a low-blend component in transport fuel is up to 7% according to EN 590 (ETIP Bioenergy, 2016).

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[8] Equivalence ratio can be defined as the stoichiometric mixture of air and fuel capable of burning all the fuel with no excess air (Brinkman, 1981).

Methanol (CH₄O)

Methanol is used as feedstock for the chemical processes as well as for blending with petrol (ETIP Bioenergy, 2016). Table 12 gives an overview of the difference of properties of methanol and petrol.

Table 12. Comparison of fuel properties methanol *(ETIP Bioenergy, 2016)*

Property	Methanol	Petrol
Density at 20°C [kg/l]	0.79	0.74
Lower heating value [MJ/kg] (JRC, 2017)	19.9	43.2
Octane number	>110	92
Fuel equivalence	0.48	1
GHG [gCO₂eq/MJ] (JRC, 2017)	Waste wood methanol:5 Farmed wood methanol:7	93.3

Application

The methanol blends with gasoline (up to 3%) as per EU standard EN 228 can be used in conventional spark engines without any technical changes. The use of alcohol fuels in heavy duty applications is still being investigated by motor manufactures (ETIP Bioenergy, 2016).

HVO/Neste Renewable diesel (hydrotreated vegetable oils and animal fats)[C₅₃H₉₄O₃]

Neste Renewable diesel is used for blending with diesel and these is no limit on blending. In addition to main product diesel, small amounts of renewable gasoline components, propane and isoalkane are also formed as side products (Neste, 2016). Table 13 gives an overview of the difference between properties of Neste diesel, diesel and FAME.

Table 13. Comparison of fuel properties HVO/Neste renewable diesel *(ETIP Bioenergy, 2016)*

Property	Neste Renewable Diesel	Diesel	FAME
Density [kg/m³] (JRC, 2017)	780	832	890 *(Neste, 2016)*
Lower Heating value [MJ/kg]	44.1	43.1	37.2 *(Neste, 2016)*
Cetane Number	>70	50	56 *(Neste, 2016)*
Viscosity at 20°C[mm²/s]	4.0	5	7.5 *(Neste, 2016)*
GHG [gCO₂eq/MJ] (JRC, 2017)	Palm Oil diesel: 57.2	95.1	Rapeseed biodiesel: 46 Waste vegetable or animal oil biodiesel: 10 Palm oil biodiesel: 54

Application

Renewable gasoline components can be blended with gasoline. This provides a high bioenergy value but has low octane numbers compared to ethanol. Biopropane can be used in cars and other applications which use LPG. It can also be used as renewable process energy at the production site to reduce the carbon footprint of products from NEXBTL process. Isoalkane can be used in a wide range of chemical applications such as paints and coatings. The NExBTL process can also be used for production of renewable jet fuel (Neste, 2016)**.**

3.4   Prices of biofuels

Prices of liquid fuels depend largely on feedstock prices. Wholesale prices of fossil-based fuels vary with the mineral oil[9] price, methanol prices vary with the natural gas price, but currently also depend on capacity shortages (Landälv, 2017). Based on the market information in this section, biofuel prices are still on a higher levels than fossil fuel prices, compared on energy content and also supportive policies to be introduced to facilitate the technology learning and production scale-up necessary to reduce costs of biofuels (IEA, 2019d). Figure 22 gives an overview of the global prices of oil since 2005.
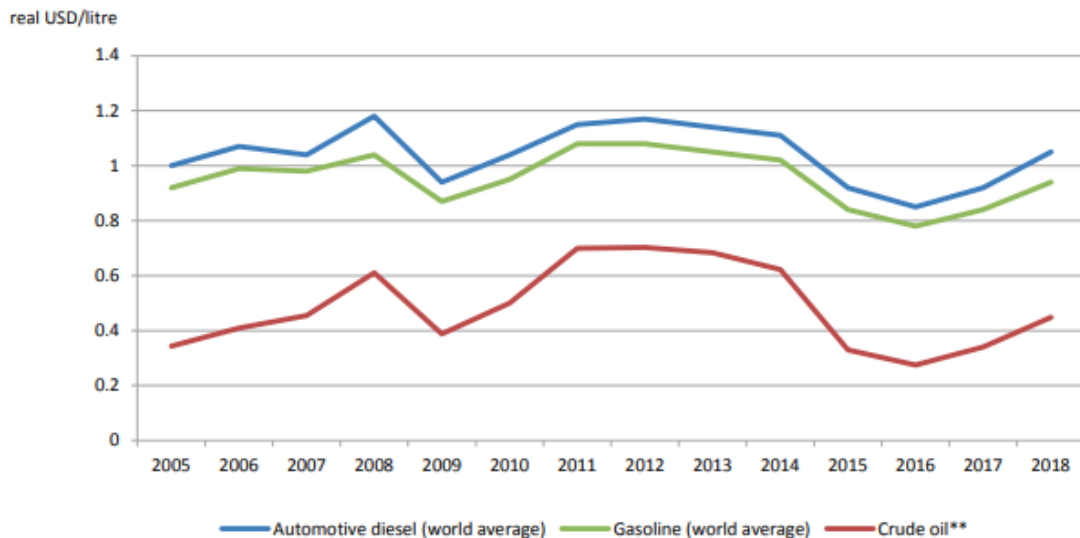
Note: *Prices of gasoline and automotive diesel are in 2015 US dollars. **Crude oil refers to nominal prices

Figure 22. Global fuel price changes *(IEA, 2019e)*

Biodiesel
Figure 23 give the price indication of the biodiesel available in market in terms of USD/ton from 2013-2019 (Neste, 2019) and compared to Figure 29 automotive diesel price, the prices of biodiesel are still high.

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9   Mineral oil is a colourless, odourless liquid present in various cosmetics and personal care products (U.S. National Library of Medicine, 2018).
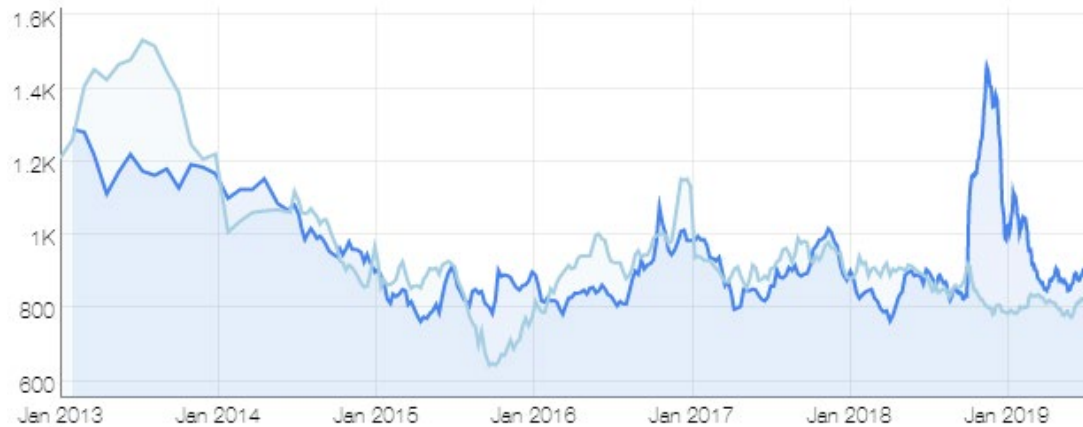
Figure 23. Biodiesel prices (SME & FAME) Source: Thomson Reuters, Starsupply, OPIS

Bioethanol

Figure 24 gives an overview of the price of bioethanol in the market with the price of the Netherlands and Brazil (Phillips et al., 2018).
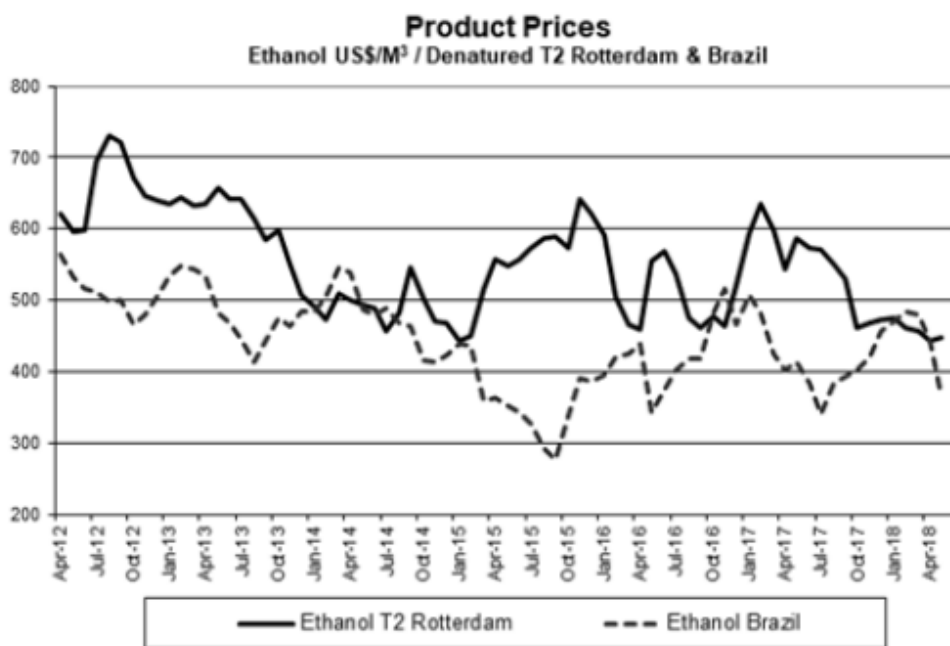
Figure 24. Bioethanol prices Source: Platts (T2) and CEPEA (Brazil)

Biomethanol

Figure 25 provides an overview of the historical methanol pricing in the world (MMSA, 2019). The methanol pricing is dependent on its feedstock, which is mostly natural gas (Inetrnational Energy Agency, 2017).
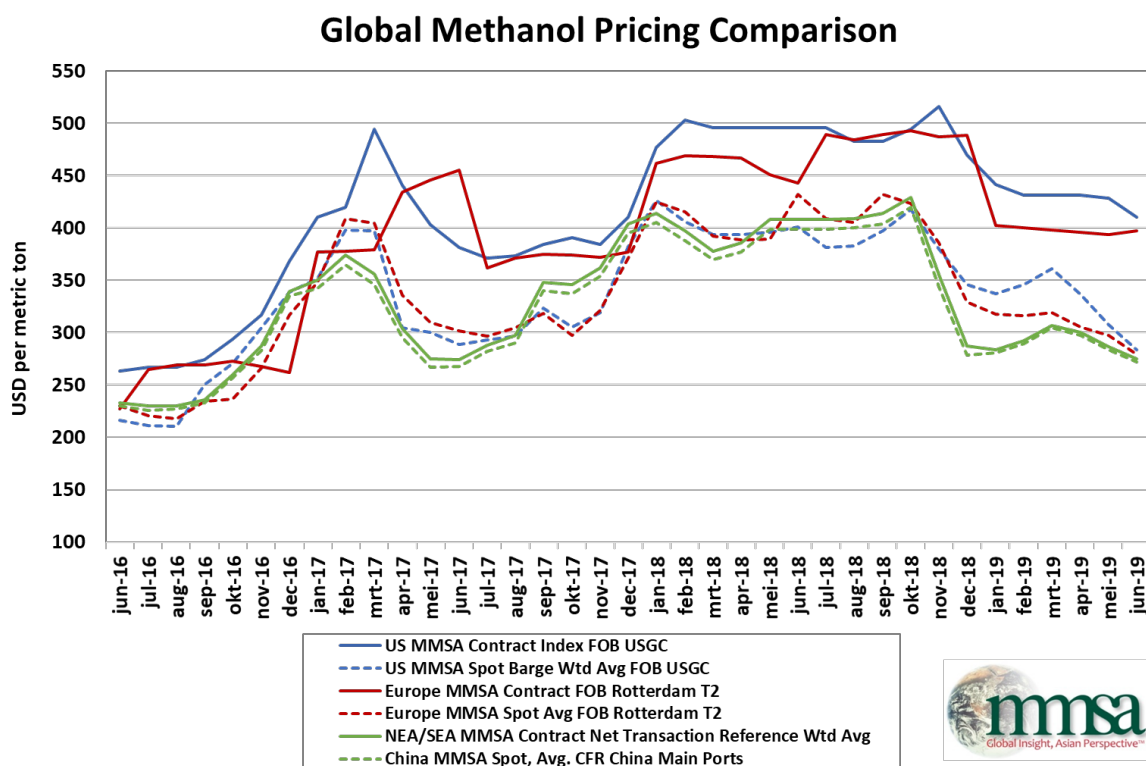
Figure 25. Methanol price comparison 2016-2019 (MMSA, 2019)

Table 14 gives an overview and comparison of different biofuel properties and prices, based on the previous information.

Table 14. Overview of the prices and properties of biofuels

	Price (USD/ton)	Density (kg/l)	Heating value (MJ/kg)	USD/m^3	USD/GJ
Biodiesel	800-1000	0.89	37.2		22-27
Ethanol	507-760	0.789	26.8	400-600	19-28
Methanol	300-500	0.792	19.9		15-25
	Euro/m^3		**MJ/m^3**		**Euro/GJ**
Natural gas	0.15		31.65		4.7
	USD/barrel	**l/barrel**	**MJ/kg**		**USD/GJ**
Gasoline	50-100	0.755	43		10-19

4 Options for decarbonisation

This study investigates the decarbonization options for the biofuel industries. A general classification of options is shown in Figure 26.

Figure 26. CO$_2$ reduction options

Most of the utility consumption in the biofuels industry is natural gas for heating. The options to decarbonise the biofuel industries include:

1. Alternatives for heat generation:
   - Hydrogen boilers
   - Biogas boilers
   - Electric boilers
   - Heat pumps
   - Ultra-deep geothermal energy
   - Other external heat supply options
2. CCUS (carbon capture, utilization and storage)
3. Alternative feedstocks
4. Alternative processes.

4.1 Heat generation

4.1.1 Hydrogen

Hydrogen could play an important role to reduce CO$_2$ emissions, using it as an alternative to natural gas to produce steam. Hydrogen is usually produced on large scale as an industrial

gas for many industrial applications, mostly produced by steam reforming of natural gas (Gigler & Weeda, 2018). Hydrogen to be considered as renewable option should be produced from electrolysis using renewable energy (green hydrogen). Direct electric heating is preferred if possible, as energy losses in electrolysis can be avoided. Natural gas in combination with CCS can also mitigate CO_2 emissions (blue hydrogen). Appendix B provides more information on types of hydrogen production.

Hydrogen can be applied in some of the existing boilers and furnaces, for high and low temperature processes, by implementing technical adjustments (Gigler & Weeda, 2018). There are no insurmountable technical obstacles for large-scale introduction of hydrogen to replace natural gas (van Wijk & Hellinga, 2018). Burners for existing boilers and furnaces have to be adjusted or replaced, to achieve similar temperature levels (Bertuccioli et al., 2014). The existing natural gas infrastructure can be used for supply of hydrogen (IEA, 2019b). The energy content of hydrogen (high calorific value) of hydrogen is 12 MJ/Nm^3, while that of natural gas is 40 MJ/Nm^3 (or approx. 35 MJ/Nm^3 for Groningen gas), thus the volume of hydrogen to be transported must be three times as of natural gas (van den Noort et al., 2017).

4.1.2 Biogas

Biogas can be used as a heating fuel in existing natural gas installations and infrastructure, depending on the specific characteristics. Biofuel producers already process organic feedstocks, which could make on site biogas generation an interesting option. The specific conditions per company are addressed in the last sections of this chapter. In general, biogas created by anaerobic fermentation is composed of methane and carbon dioxide, with small amounts of water vapour, hydrogen sulphide, hydrogen, nitrogen and oxygen (BioBased Economy, 2010; Morgan et al., 2018; Xie et al., 2018). The composition depends on the feedstock and the technology used for the extraction (Morgan et al., 2018). The biological production pathway (anaerobic digestion) for biogas uses microorganisms to break down the nutritional (digestible) content of biomass (Labatut & Pronto, 2018). The digester process includes a storage, mixing tank, digesters, pasteurisation tank and digestate and waste water treatment (Schulze et al., 2017). Biogas can be upgraded to green gas by removing carbon dioxide and contaminations (membrane technology), resulting in a gas which has similar properties as natural gas and can be fed into the natural gas network after compression (BioBased Economy, 2010). Reprocessing the gas entails capital costs and energy costs (approximately 10% of the combustion values of resulting green gas) (BioBased Economy, 2010). Table 15 includes the data on biogas used in this chapter.

Table 15. Overview of external biogas production data

Characteristic	Value	Source
Fuel	Biogas	
Emissions	Short cycle CO_2	
Capacity	5.5[10] MW_{th}	(Uslu, 2019)
Efficiency	90 %	Estimation
Lifetime	<25 years	
Investment cost	2.27-3.03 million €/MW_{th}	(Uslu, 2019)
Maintenance cost	0.11-0.28 million €/MW_{th}/yr	(Navigant, 2019)

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[10] The feed input consist of a mixture of pig manure and cattle manure, with a mix of slurry and thick fractions in a ratio of 80/20 producing biogas below 30 m^3 biogas per ton of feed (Uslu, 2019).

4.1.3 Electric boilers

An electric boiler uses electricity to produce hot water or steam. There are various types of electric boilers such as (Berenschot et al., 2017; Marsidi, 2019):
- Resistance element boilers and electrode boilers,
- Infrared and induction boilers (small scale systems).

Electric boilers and electrode boilers are mainly used for utility-related production (such as steam production). The implementation of this technology does not require complete redesign of the primary process. Also the boilers can be used as a flex option during low electricity prices period (Berenschot et al., 2017).

Electric boilers generally have lower thermal capacities than electrode boilers, with capacities up to 5 MW_e (Marsidi, 2019). Electrode boilers have capacities ranging from 3 MW_e to 70 MW_e, while a typical industrial boiler size is 10 to 30 MW_{th} (Navigant, 2019). Superheated steam with a temperature between 100 and 350 °C and >70 bar can be produced with commercially available electric/electrode boilers (Marsidi, 2019). Electric/electrode boilers usually have high efficiency (95-99.9%), and can be used in combination with gas-fired boilers to benefit from low power price intervals (Berenschot et al., 2015, 2017). Although emissions on site are avoided, the electrification itself is not CO_2 neutral, unless the electricity input is CO_2-neutral. Intermittent sources such as solar and wind are unlikely to satisfy the full industrial heat demand (Berenschot et al., 2015, 2017).

The equipment cost for an electric element boiler is in the range of 0.06 (Berenschot et al., 2015) to 0.140 €/MW_e (Marsidi, 2019). The equipment cost for an electrode boiler varies from 0.017 to 0.06 €/MW_e (Berenschot et al., 2017; Marsidi, 2019). In case of insufficient grid connection capacity, the cost of expanding the connection capacity, both the one-time connection cost as well as the yearly connection tariffs, can be substantial (Berenschot et al., 2015). The cost for the lower voltage grid to connect with the transmission grid vary in a range of thousand euros to several millions (Stedin, 2019) and are dependent on the distance of the site to the connection point. The fixed O&M costs for an electric boiler are 1.1 €/kW/y and the variable O&M costs are 0.5 €/MWh (Berenschot et al., 2017). Table 16 gives an overview of the electric boiler data used in this chapter.

Table 16. Overview of electric boiler data

Characteristic	Value	Source
Fuel	Electricity	
Emissions	0	
Capacity	0.4-5 MW_e (Electric boilers); 3-70 MW_e (Electrode boilers)	(Marsidi, 2019); (Navigant, 2019)
Efficiency	95-99.9%	(Berenschot et al., 2015; 2017)
Lifetime	10-30 years	(Navigant, 2019)
Investment cost	0.10-0.49 mln €/MW_{th}	(Marsidi, 2019)
Maintenance cost	0.01 mln €/MW_{th}	(Marsidi, 2019)

4.1.4 Industrial heat pumps

A heat pump uses energy to transfer heat from a lower temperature (source) to a higher temperature demand (sink) with use of additional energy. In the case of industrial heat pumps, the heat source is process waste heat. It is used for heating feedstock, enable chemical reactions and to drive separation processes (Spoelstra et al., 2017). Heat pumps

can play an important role to convert renewable and waste heat sources into end-use of heat. There are various types of heat pumps such as mechanical vapor recompression, reverse rankine cycles, gas cycles, steam ejectors and sorption systems (Spoelstra et al., 2017).

Bioethanol and biodiesel industry processes use steam with temperatures between 60 and 180 °C. Mechanical vapor recompression (temperature output range 60-180 °C) is an open heat pump system, in which pressure and temperature of the vapour with a corresponding saturation temperature are increased by compression (Marsidi, 2018b). Reverse Rankine cycle heat pumps can reach temperatures in the range of 90-100 °C. Heat pumps in the output range of 120-140°C are developed but thus far not applied in the industry (ECN, 2017; Spoelstra et al., 2017; Marina et al., 2017). Further research is needed to achieve temperatures around 200 °C to enable heat pump application in a larger group of industrial processes (ECN, 2017; Spoelstra et al., 2017). General data on heat pumps are included in Appendix C.

4.1.5 Ultra-deep geothermal energy

Ultra-deep geothermal (UDG) energy's main characteristic is the depth of the well, hot water is extracted from more than 4000 meters. An UDG project consists of two wells, a production and injection well, also called doublet. The wells which are drilled either fully vertically or vertically with a curvature deep below, and bottom of each well is situated in a water-holding limestone layer, around 4,000 metres below ground level. Brine (salty hot water), which is pumped up through the production well, goes through heat exchanger for cooling, and then injected into injection well. Since, there is no loss of water, however natural gas or oil needs to be separated from the brine. The estimated production temperature varies between 120 and 140ºC and makes this technology suited for low temperature steam supply for industry. The installation mostly consists of a production pump, and oil and/or gas separator, an above ground heat exchanger and an injection pump (PBL, 2018).

UDG is not yet applied in the Netherlands, and heat source occurrence is still unclear. More costly exploratory research is still needed before its viability can be assessed for the industry. PBL has included UDG as a category in its renewable energy subsidy advice. Table 17 gives an overview.

Table 17. Overview of Ultra-deep geothermal data, based on (PBL, 2018)

Characteristic	Value
Output	Steam
Emissions	No on-site emissions
Capacity	17 MW
Lifetime	15 years
Investment cost	2,509 EUR/kW$_{th}$
Fixed O&M cost	107 EUR/kW$_{th}$/yr
Variable O&M cost	0.0076 EUR/ kW$_{th}$ output

4.1.6 Other heat supply options

Using waste heat from external sources, or providing residual heat to external users depends on the specific situation of the site involved. The companies in this report may have opportunities to become part of a more optimized heat system, since they mostly do not

operate on high temperature levels. Heat pumps could be part of this system. A full analysis of these options is beyond the scope of this report.

4.2   Carbon Capture, utilization or storage (CCUS)

CCUS involves the capture of carbon dioxide (CO_2) from fuel combustion or industrial processes, followed by transport of CO_2 via ship or pipeline and storage in depleted gas fields or salt caverns. CO_2 can be used as a resource to create products or services or for permanent storage deep underground in geological formations (IEA, 2019a). It also provides the base for carbon removal or "negative emissions" (BECCS) when the CO_2 comes from bio-based processes or directly from the atmosphere (IEA, 2019a). CCUS technologies are expected to play a critical role in sustainable transformation of the industry sector (IEA, 2019c).

Four main carbon capture approaches are (IEA, 2019c):
- Post-combustion capture: CO_2 is separated from the mixture of flue gases at the end of the industrial or energy processes. With an absorptive or adsorptive substance or membrane, CO_2 is separated and captured.
- Oxy-fuel combustion and capture: In this process, pure oxygen is used instead of air to combust fuel, thus producing flue gas composed of CO_2 and water vapour. This simplifies separation of CO_2 to dehydration. Further, part of flue gas is recycled to the combustion chamber so as to control the combustion temperature and maintain purity.
- Pre-combustion capture: In case of a reforming or gasification process, fossil fuels or bioenergy can be processed with steam and/or oxygen to produce syngas (carbon monoxide and hydrogen). Carbon monoxide is reacted with more steam (water gas shift reaction) to yield additional hydrogen and convert carbon monoxide to CO_2. This CO_2 can be separated from the high pressure gas mixture, yielding raw syngas for combustion or chemical production.
- Inherent separation: Certain processes in industry and fuel production generate high purity CO_2 streams as an intrinsic part of the processes for e.g. gas processing and ethanol production. CO_2 produced is vented to atmosphere, and is available for CO_2 capture. This is for instance the case at Neste and Alco. Alco actually delivers CO_2 to horticulture. BioMCN uses pure CO_2 to produce methanol.

Case Studies - Port of Rotterdam

CCS is only feasible when transport and storage is available. In the Rotterdam area, there are plans for a CO_2-grid with offshore storage known as PORTHOS (Port of Rotterdam CO_2 Transport Hub and Offshore Storage). PORTHOS is expected to store 2 to 5 million tonnes of CO_2 in Rotterdam every year with an investment cost of EUR 400-500 million (Port of Rotterdam, 2019a, 2019b). The CO_2 is sent through a pipeline to an empty gas field that is located approximately 25 km off the coast under the North Sea (Port of Rotterdam, 2019b). Several configurations are possible for clustering oxygen production, syngas/hydrogen production, capture, purification and compression.

The case study of Botlek area by Berghout et al (2015) includes different CO_2 capture configurations[11] such as post combustion capture based on chemical absorption with MEA, oxy-fuel combustion and pre-combustion capture of SMR plant.

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[11]   The configurations of the post, oxy and pre-combustion capture can be found in the chapter 3 of the case study of Botlek area (Berghout et al., 2015).

CCS has been mostly applied on low cost opportunities such as gas processing rather than other industry sectors. The study by PBL (2019) estimates the investment cost for post combustion CO_2 capture capacity of 1 MtCO$_2$/yr at EUR 3.7 million.

For operation fixed O&M costs are EUR 0.1 million/yr and variable O&M costs 1.2 €/tCO$_2$. For the case of pre-combustion capture in SMR hydrogen production with capacity of 0.16 MtCO$_2$/yr, the investment cost for capture, compression and connection to a transport network is 75.3 million €, the fixed O&M is 1.5 million €/yr and the variable O&M is 23.3 €/tCO$_2$ (PBL, 2019).

Bio-CCS

Bio-CCS, where CO_2 originating from biomass is captured and stored, can also be considered as a CO_2 mitigation option (Berghout et al., 2015; ZEP, 2012). There are several routes for conversion of biomass into final energy products or chemicals in combination with CCS (Figure 27). They include bio-chemical biofuels production, thermo-chemical production of biofuels and biochemicals, and combustion of biomass for production of electricity and heat (ZEP, 2012).
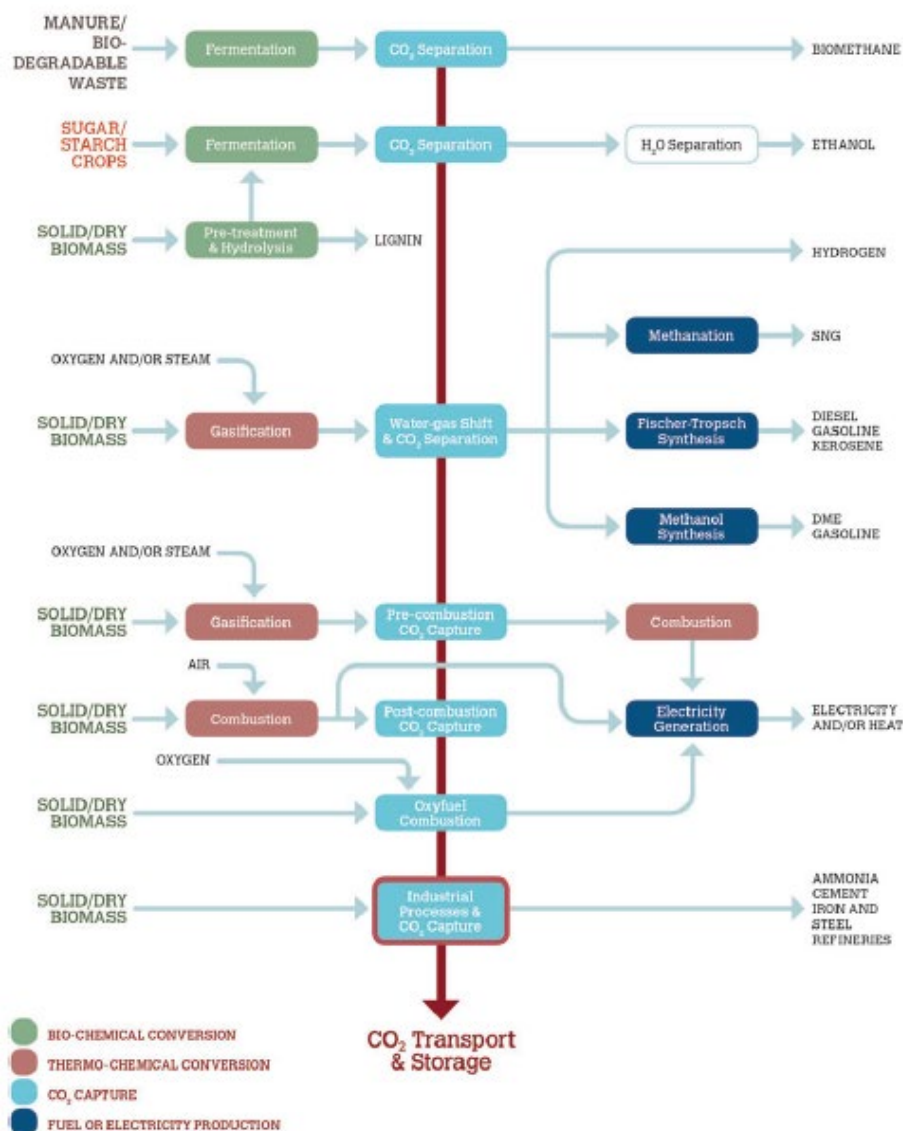

Figure 27. Schematic overview of biomass-based conversion routes with CCS *(ZEP, 2012)*

4.3 Alternative feedstocks and processes

In Chapter 3, different feedstock categories are defined and explained. With respect to the decarbonization, a chain analysis of the emission effect of alternatives is beyond the scope of this report. For the companies in this report alternative feedstocks may require complete overhaul of their current process. An illustration of alternatives is depicted in Figure 27. This is especially the case for Alco and Biopetrol. Decisions on alternative feedstocks depend largely on biofuels policies and sustainability criteria.

BioMCN is still aiming at a transition to biobased feedstocks, but is currently using mainly fossil feedstock (natural gas). So BioMCN can still enhance a switch to biobased methane feedstock, or source CO_2 and hydrogen from external sustainable sources to produce biomethanol. A major energy efficiency improvement for BioMCN could be a switch to improved production processes like autothermal reforming or partial oxidation. This would require a complete overhaul of the current reformer installation.

4.4 Summary of measures per company

Table 18 and following tables show a summary of decarbonization options for the production process involved in the specific industries along with capital and operational expenditures (CAPEX/OPEX). Actual values may differ substantially from literature sources depending on the characteristics of specific industry situations.

4.4.1 ALCO Energy Rotterdam B.V.

Alco is still optimising its site since the takeover from Abengoa, and sees potential to increase its material throughput by more than 25% with the same energy input. Alco Energy is already using part of its waste heat for evaporation purposes. Presently, Alco has cooling towers installed after the cooking section. Further analysis would be needed explore heat optimisation on the site, possibly including heat pumps.

For further decarbonisation of the heat production, natural gas in the CHP plant and drying section could be replaced with sources such as hydrogen or biogas. These sources could be potentially available from:
- Hydrogen from external sources in the port of Rotterdam area, for instance with projects under the proposed H-vision programme. Apart from the infrastructure required, additional investment involves burner replacement, and redesign of a CHP.
- Biogas from an anaerobic digester or other source. Alco currently does not use its co products for energy because it can attain a higher market value than avoiding natural gas costs. This may well change in future, depending on economic and policy developments.

Another potential reduction option from a system perspective is feeding captured CO_2 in storage, which is possible under the proposed PORTHOS project. Alco prefers delivery of its biogenic CO_2 to horticulture, since it is valued by this sector for not having a fossil origin. Consequently, Alco would also need separate storage to accommodate seasonal demand fluctuations.

Switching to different second generation feedstocks such as lignocelluloses is a far reaching option since it requires changing the production process completely to hydrolysis and fermentation to produce bioethanol. Decarbonisation options relevant for Alco are summarised in Table 18.

Table 18. Overview of the decarbonisation options for Alco Energy Rotterdam B.V.

Option	CAPEX	OPEX	CO_2 emission	Remarks
Heat generation				
Hydrogen application in steam generation and drying to replace natural gas	SMR with CCS: 0.98-1.33 million €/MW (IEA, 2017). Electrolysis: AEL 0.75 mil €/MW (2017) PEM 1.2 mln €/MW (2017) (IRENA, 2018) Burners: minor additional costs CHP: turbine replacement is necessary.	SMR with CCS: Fixed O&M : 0.03-0.04 mln €/ MW/yr variable O&M: 0.24-0.26 mln €/ MW/yr (IEA, 2017) Electrolysis: 2% of initial CAPEX (IRENA, 2018)	100% reduction, applies to CHP and other natural gas combustion	Pm: Additional costs for natural gas and electricity to produce hydrogen (IEA, 2017)
Biogas application in steam generation and drying to replace natural gas	(5.5 MW$_{th}$): 2.27-3.03 mln €/ MW$_{th}$ (Uslu, 2019) Burners and CHP: no additional costs	0.11-0.28 mln €/MW$_{th}$/yr (Uslu, 2019)	100%, applies to CHP and other natural gas combustion	Based on anaerobic digestion of manure
Electric boilers to replace natural gas in CHP	(10-30 MWth): 0.1-0.5 M€/MW (Marsidi, 2019); (Navigant, 2019)	0.01 mln €/MW/yr (Marsidi, 2019)	For CHP (75%) reduction in CO_2 and natural gas combustion	For heat 100-350°C and pressure>70 bar. Additional cost involved in replacing CHP
Other options				
Further energy efficiency improvement	Minor investments in new equipment	Cost reductions per unit of output	No direct reduction, but 25% output increase	Potential is confirmed and acted upon by Alco
CCS on current biogenic process emissions	Alco is already capturing CO_2 CAPEX is extra connection and additional compression[12] 2 million € based on 0.3 Mton CO_2 (PBL, 2019);	Fixed O&M cost: 0.1 million €/yr and variable O&M cost: 1.2 €/tCO_2 (PBL, 2019)	100% biogenic CO_2/yr avoided (0.3 Mton)	For transport and storage, €20-40/tCO_2 has to be added, based on the PORTHOS project (Navigant, 2019; PBL, 2019; Port of Rotterdam, 2019b).

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[12] Reference based on industries where CO_2 is already captured and transported for use in greenhouses . Here, it is assumed the CO_2 (which is captured all year around) is not used and emitted, can be captured with help of second pipeline and additional compressor (PBL, 2019).

Option	CAPEX	OPEX	CO_2 emission	Remarks
Heat generation				
CCS on current CHP flue gases	CAPEX of CO_2 capture and connection (0.16 Mt CO_2/yr): 75.3 million € (PBL, 2019)	Fixed O&M: 1.5 million €/yr and variable O&M: 23.3 €/tCO_2 (PBL, 2019)	100% of CHP emissions	For transport and storage, €20-40/tCO_2 has to be added
Feedstock substitution: ligno-cellulosic biomass (2nd generation) based on (Poole, 2012)	For 8.4 Mton bioethanol/yr:100 million $ or $4/gallon bioethanol[13]	OPEX for 8.4 Mton/yr: $0.094/litre or range of $0.24-0.38/gallon bioethanol	NA	Production process and material flows change completely. Feedstock cost range (forest residues): 27-35 $/ton instead of current Alco feedstock
Feedstock substitution with CCS[14]	See above, connection costs can be included in plan			For transport and storage, €20-40/tCO_2

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[13] Reference based on case study of a bioethanol production plant in the USA with a capacity of 8.4 Mton/yr using lignocellulosic biomass as feedstock (Poole, 2012).
[14] Reference based on case study by IEA GHG (2011) on the bioethanol production along with CCS from 2nd generation feedstock.
     *1 gallon= 334.95 ton (Renewable fuels association, 2015)

4.4.2 Biopetrol Rotterdam B.V.

Biopetrol in the future could substitute natural gas with other renewable sources (such as hydrogen, biogas) to fuel its boiler (production capacity of 50 ton/hr; installed in 2017; heat produced around 195 °C and 13 bar). These sources could be potentially available from:

- Hydrogen, for example from the proposed H-vision programme in the port of Rotterdam.
- The use of biogas (from an anaerobic digester or other source) could be an alternative fuel.
- Furthermore, addition of an electric boiler can be applied along with the gas boiler or complete replacement of the gas boiler with electric boiler.

For the natural gas boiler, a potential option could be post combustion CO_2 capture and storage under the north sea. Relevant case studies for CCS include the proposed PORTHOS project in the port of Rotterdam and a study for the Botlek region by Berghout et al. (2015). The other possible option when advanced biofuels are favoured, is replacing the transesterification process with Fischer-Tropsch synthesis to produce biodiesel (Jarvis & Samsatli, 2018). This would require syngas supply, either from biomass gasification or origins. A total reinvestment for the whole plant would be required. Decarbonisation options relevant for the industry itself can be seen in Table 19.

Table 19. Overview of the decarbonisation options for Biopetrol Rotterdam B.V.

Option	CAPEX	OPEX	CO$_2$ emission	Remarks
Heat generation				
Hydrogen application in steam generation to replace natural gas in gas boiler	SMR with CCS: 0.98-1.33 million €/MW (IEA, 2017). Electrolysis: AEL 0.75 mil €/MW (2017) PEM 1.2 mln €/MW (2017) (IRENA, 2018) Burners: additional costs are minor	SMR with CCS: Fixed O&M: 0.03-0.04 mln €/MW/yr variable O&M: 0.24-0.26 mln €/ MW/yr (IEA, 2017) Electrolysis: 2% of initial CAPEX (IRENA, 2018)	100% reduction in CO$_2$ and natural gas combustion	Pm: Additional costs for natural gas and electricity to produce hydrogen (IEA, 2017)
Biogas application in steam generation to replace natural gas in gas boiler	(5.5 MW$_{th}$): 2.27-3.03 mln €/ MW$_{th}$ (Uslu, 2019) Burners: no additional costs	0.11-0.28 mln €/MW$_{th}$/yr (Uslu, 2019)	100% reduction in CO$_2$ and natural gas combustion	Based on anaerobic digestion of manure
Electric boilers to replace gas boilers	(10-30 MWth): 0.1-0.5 M€/MW (Marsidi, 2019); (Navigant, 2019)	0.01 mln €/MW/yr (Marsidi, 2019)	100% reduction in CO$_2$ and natural gas combustion	For heat 100-350°C and pressure>70 bar. Additional cost involved in replacing gas boiler
Other options				
CCS (for own Natural gas boiler)	CAPEX of CO$_2$ capture and connection (0.16 Mt CO$_2$/yr): 75.3 million € (PBL, 2019)	Fixed O&M: 1.5 million €/yr and variable O&M: 23.3 €/tCO$_2$ (PBL, 2019)	100% of gas boiler emissions	For transport and storage, €20-40/tCO$_2$ has to be added, based on the PORTHOS project (Navigant, 2019; PBL, 2019; Port of Rotterdam, 2019b)
Fischer-Tropsch synthesis[15] Based on syngas from external CO$_2$ and H$_2$ to replace the trans-esterification of oils	CAPEX: 308-322million € including syngas production, excluding H$_2$ production. Capacity range 97-123 kton fuel/yr (Jarvis & Samsatli, 2018)	OPEX: 87.20 €/t of fuel (Jarvis & Samsatli, 2018)(Jarvis & Samsatli, 2018)(Jarvis & Samsatli, 2018)(Jarvis & Samsatli, 2018)	100% reduction (Jarvis & Samsatli, 2018)	Complete change of the production process. High and low temperature hydrolysis deliver different fuel qualities, see (Jarvis & Samsatli, 2018) extra costs for H$_2$ and CO$_2$ inputs replacing oils

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[15] Based on the calculation done for the production of high temperature and low temperature Fischer-Tropsch diesel fuel (Jarvis & Samsatli, 2018).

4.4.3 BioMethanol Chemie Nederland B.V.

BioMCN B.V., wants a large scale and steady supply of bio based feedstock for the production of biomethanol. The possible solutions include:

- Green hydrogen from the proposed Nouryon and Gasunie 20 MW electrolysis plant along with CO_2 imported from biogenic origin to produce methanol (Bilfinger, 2018). CO_2 from biomass could come from the neighbouring plants in Delfzijl or elsewhere.
- Constructing bio-digesters for processing manure in the area. This could generate biomethane to be used as feedstock.
- Biomass (wood) gasification producing syngas to be used for directly producing biomethanol, thus replacing the SMR, including its combustion emissions.

Currently, for heating the furnace, natural gas is used as a fuel. Decarbonisation options for this include replacement of natural gas by biogas or hydrogen. The possibility of electrification to the required temperatures needs to be further investigated. For the furnace emissions, also CCS could be considered, either pre- or post-combustion.

The other option for reducing combustion emissions is a complete change of the production process using ATR (autothermal reforming) or POX (partial oxidation). For the remaining combustion emissions, this can be combined with CCS. Decarbonisation options relevant for the industry itself can be seen in Table 20.

Table 20. Overview of decarbonisation option for BioMCN B.V.

Option	CAPEX	OPEX	CO_2 emission	Remarks
Feedstock replacement and heat generation				
Hydrogen and biogenic CO_2 to replace natural gas as feedstock and combustion fuel	Electrolysis: AEL 0.75 mil €/MW (2017) PEM 1.2 mln €/MW (2017) (IRENA, 2018) Avoided costs for SMR.	Electrolysis: 2% of initial CAPEX (IRENA, 2018)	Zero emissions and 100% natural gas reduction	BioMCN to buy green hydrogen from proposed 20 MW electrolysis plant (Nouryon, 2019) and to buy CO_2 Avoided fuel for SMR
Biogas application for biomethane feedstock and to use for combustion	(5.5 MW$_{th}$): 2.27-3.03 mln €/ MW$_{th}$ (Uslu, 2019)	0.11-0.28 mln €/MW$_{th}$/yr (Uslu, 2019)	100% reduction in CO_2 and natural gas as feedstock and for combustion	Based on anaerobic digestion of manure
Biomass gasification replacing SMR	CAPEX (32 MW capacity and >95% biogenic): 0.02 mln €/ MW (PBL, 2019a)	OPEX: 0.190 €/MW/yr (PBL, 2019a)	100% reduction in CO_2 and natural gas as feedstock and for combustion	Syngas produced by gasification used for producing biomethanol, replacing the SMR
Alternative processes, CCS				

Option	CAPEX	OPEX	CO_2 emission	Remarks
Partial oxidation (POX) replacing SMR	For capacity up to 0.15 mlnNM3/hr syngas: 10-100 million USD (Air Liquide, 2018)	NA	NA	Complete change of production process
POX with CCS	CAPEX of CO_2 capture and connection (0.16 Mt CO_2/yr): 75.3 million € (PBL, 2019)	Fixed O&M: 1.5 million €/yr and variable O&M: 23.3 €/tCO_2 (PBL, 2019)	100% reduction	Complete change of production process. Additional cost required for transport and storage of CO_2
Autothermal reforming (ATR) replacing SMR	For capacity up to 1 mln NM3/hr syngas: 160-280 million USD (Air Liquide, 2018)	NA	NA	Complete change of production process
ATR with CCS	CAPEX (capacity of 10228 MW):1.20 mln €/MW (Janssen, 2019)	OPEX: 0.04 mln €/MW/yr (Janssen, 2019)	100% reduction	Complete change of production process. Additional cost required for transport and storage of CO_2
CCS or the furnace)	CAPEX of CO_2 capture and connection (0.16 Mt CO_2/yr): 75.3 million € (PBL, 2019)	Fixed O&M: 1.5 million €/yr and variable O&M: 23.3 €/tCO_2 (PBL, 2019)	100% reduction in CO_2 emissions from furnace	Additional cost required for transport and storage of CO_2

Note: NA=Not Available

4.4.4 Neste Netherlands B.V.

Neste's fossil based emissions are small, only for the heating of the hot oil system and for start-up, natural gas is used. However, this natural gas for heating can be replaced by carbon neutral energy sources, including hydrogen, biogas or electricity. Biobased propane gas could also be sourced internally, but for Neste, this propane now has a higher value as product.

Neste imports both steam and hydrogen from fossil origin, which cause no direct emissions from the Neste site. In time, these imports may be replaced by steam and hydrogen from carbon free sources. In that case, the options for alternative heat generation and hydrogen may also apply to these imports.

BECCS can be applied to the biogenic CO_2 emissions. This 42 kton of purified CO_2 is currently emitted to the air. This purified CO_2 can be captured and recovered, the site is actually designed to allow for capture. Additional provisions will be needed to actually transport and store, possibly with a connection to PORTHOS or other destinations.

Alternative processes like Fischer Tropsch synthesis are not considered, since the NExBTL process is versatile in using different oil or fat feedstocks. Decarbonisation options relevant for the industry itself can be seen in Table 21.

Table 21. Overview of the decarbonisation option for Neste Netherlands B.V.

Option	CAPEX	OPEX	CO$_2$ emission	Remarks
Heat generation				
Hydrogen from Electrolysis	Electrolysis: AEL 0.75 mil €/MW (2017) PEM 1.2 mln €/MW (2017) (IRENA, 2018)	Electrolysis: 2% of initial CAPEX (IRENA, 2018)	Zero emissions and 100% natural gas reduction	Hydrogen could be also used for NExBTL process instead of H$_2$ and to replace steam imports
Biogas application to replace natural gas	(5.5 MW$_{th}$): 2.27-3.03 mln €/ MW$_{th}$ (Uslu, 2019)	0.11-0.28 mln €/MW$_{th}$/yr (Uslu, 2019)	100% reduction in CO$_2$ and natural gas for combustion	Based on anaerobic digestion of manure. Neste could also use its own generated bio propane
Electric boilers to replace natural gas	(10-30 MWth): 0.1-0.5 M€/MW (Marsidi, 2019); (Navigant, 2019)	0.01 mln €/MW/yr (Marsidi, 2019)	100% reduction in CO$_2$ and natural gas combustion	For heat 100-350℃ and pressure>70 bar.
CCUS				
CCS on current biogenic process emissions	Neste has infrastructure to capture CO$_2$ CAPEX is extra connection and additional compression[12] 2 million € based on 0.3 Mton CO$_2$ (PBL, 2019);	Fixed O&M cost: 0.1 million €/yr and variable O&M cost: 1.2 €/tCO$_2$ (PBL, 2019)	100% biogenic CO$_2$/yr avoided (0.3 Mton)	For transport and storage, €20-40/tCO$_2$ has to be added, based on the PORTHOS project (Navigant, 2019; PBL, 2019; Port of Rotterdam, 2019b).

5 Discussion

Biofuels have the potential to reduce greenhouse gas emissions and provide energy security while replacing fossil fuels in the existing transport fleet and infrastructure (Kazamia & Smith, 2014). The emissions from manufacturing biofuels are much smaller compared to their reduction potential in transport. However, this report focuses on the further decarbonisation options in manufacturing. The four industries analysed in this report have different processes and opportunities for further decarbonisation on site.

Biofuels production remains policy dependent. In 2016, the transport sector, including international aviation and navigation, contributed 27% of total EU greenhouse gas emissions (EEA, 2018). The low emission mobility strategy includes improving the efficiency of the transport system and low-emission alternative energy for transport. These include biofuels, renewable electricity, renewable synthetic fuels and hydrogen. (European Commission, 2016). Because of this policy dependence, the future share of biofuels in this transport strategy is uncertain. In light vehicles, electricity is expected to grow fast, while for aviation, biofuels get a strong focus. For freight transport, biofuels and various other options are considered.

The "Blend wall", the extent to which biofuel molecules can be added to fossil based fuels in current vehicles is a limiting factor. According to the petroleum refining industry, the fuel providers, original equipment manufacturers (OEM) and regulators need to work hand-in-hand to overcome the "Blend Wall" and enable the use of higher bio-blends in road transport to decarbonize the transport sector (Fuels Europe, 2018). Another important limitation on biofuels is the supply of sustainable feedstocks. However this supply may be further increased by developing advanced biobased sources like algae. Alternatives like electricity, synthetic fuels and hydrogen in new vehicles also have a large potential for decarbonisation of the transport sector. This may be a factor for future investment in the biofuels industry.

Combining biogenic CO_2 emissions with CCS (BECCS) is a relevant further decarbonisation option for the atmospheric system. The biofuels industry could apply this combination of technologies. BECCS is included in EU and IPCC scenario's but has still to be integrated in policy instruments like the European emissions trading system (ETS).

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Appendices

Appendix A Biofuel industries in the Netherlands

Table 22. Biofuel industries in the Netherlands *(GAVE, 2015)*

Name	Location	Product	Production Process	Production capacity	ETS Emission 2018 [kton CO$_2$ eq.]	Feedstock
Alco Energy Rotterdam B.V.	Rotterdam	Bioethanol	Dry milling and fermentation	379 kton	340	Maize
ACCRES		Bioethanol		71 kton		
BioPetrol Rotterdam B.V.	Rotterdam	Biodiesel	Trans-esterification	400 kton	36	Rapeseed and sunflower oil
BioMCN BV	Delfzijl	Bio methanol and methanol	Steam Methane Reforming	450 kton	217	Natural gas and biogas
Cargill	Bergen op zoom	Bioethanol		31 kton	34	Maize
Cargill	Rotterdam	Bioethanol	-	40 million litres	27	Maize
Eco fuels Netherlands BV	Eemshaven	Biodiesel	-	50 kton	-	UCO
Ecoson/Vion	Son	Biodiesel	FAME	5 kton		Animal fat
Electrawinds Greenfuel BV	Sluiskil	Biodiesel		250 kton		
Greenmills	Amsterdam	Biodiesel and Biogas		99 kton and 20 mln Nm^3		
HarvestaGG BV	Lelystad	Bioethanol	-	6.5 kton	-	Grass
SABIC	Geleen	MTBE and ETBE	-		-	
Sime Darby Unmills	Zwijndrecht	Biodiesel	-	200 kton	51	Rapeseed oil
Lyondell Chemie Netherlands B.V.	Rotterdam	Bio-ETBE	-	-	327 (whole site)	-
Neste oil B.V.	Rotterdam	Biodiesel (HVO)	NExBTL	1000 kton	8 (not ETS)	UCO
Royal Nedalco B.V.	Sas van gent	Bioethanol	1st generation	7 kton		Cereals
Royal Nedalco B.V.	Sas van gent	Bioethanol	2nd generation	173 kton		
Sunoil Biodiesel BV	Emmen	Biodiesel	-	88 kton	-	Frying fats and animal fats

Appendix B Hydrogen production

In recent studies from FCHJU, there are 11 other options to produce hydrogen[16]. Some of the potential pathways are (Gigler & Weeda, 2018):

- SMR (Steam methane reforming)
- Partial oxidation and autothermal reforming
- ALK (Alkaline electrolysis) and PEM (Proton exchange membrane)
- SOEC (Solid oxide electrolysis cell)
- Biomass pyrolysis and gasification
- Fermentation of biomass flows to biogas, combined with biogas reforming
- Thermochemical water splitting
- Photo-catalysis (using photo-electrochemical cells, PECs).

Steam methane reforming

Steam methane reforming (SMR) includes reforming through a reaction with steam. Pure water vapour is used as the oxidant and the reaction requires heat (endothermic). A case study by IEA (2017) includes a standard plant which has capacity of 100,000 m^3 or 9 ton of hydrogen per hour[17]. The process consumes 14.21 MJ of NG and emits about 0.81 kg CO_2 per Nm^3 of H_2 produced and in combination with CCS could be a decarbonisation option with zero emission (IEA, 2017).

Alternatives for SMR are partial oxidation and autothermal reforming. For partial oxidation, oxygen or air is used and the process releases heat (Exothermic). Autothermal reforming is a combination of both SMR and partial oxidation using a mixture of air and water vapour. In this process the ratio of two oxidants is adjusted, thus no heat needs to be introduced or discharged. Other options are SMR with CCS, partial oxidation with CCS and ATR with CCS which includes pre-combustion capture units.

Hydrogen produced from the use of renewable electricity is called green or CO_2 neutral hydrogen(van Wijk & Hellinga, 2018). In electrolysis, water is split into hydrogen and oxygen[18] using energy input and heat (Hydrogen Europe, 2017). The current electricity mix used for electrolysis, is still largely based on fossil fuels (Gigler & Weeda, 2018). The electrolysis processes are differentiated by electrolyte materials and operating temperatures. Low temperature electrolysis includes alkaline electrolysis (AEL) and, proton exchange membrane (PEM) electrolysis and alkaline exchange membrane (AEM) operating at 60-70 °C (Gigler & Weeda, 2018; Hydrogen Europe, 2017). High temperature electrolysis includes solid oxide electrolysis cells (SOEC) works at temperatures of 600-800°C, where it has highest electrical efficiency (Gigler & Weeda, 2018; Hydrogen Europe, 2017).

The production cost of hydrogen depends heavily on the natural gas prices, natural gas account for 70-80 % of the costs in large scale production, is in range of €1- €1.50 per kilo of H_2 (Gigler & Weeda, 2018). For the production of small scale (100-300 Nm^3/hour), where efficiency is 60-65 %, the prices could be €4-5 per kilo (in 2020) and further drop to €3-4 per kilo (in 2030) (Gigler & Weeda, 2018).

The H-vision project in port of Rotterdam proposes large-scale hydrogen production from natural gas with output capacity of 1,460 MW (700 kton) in combination with CO_2 capture

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[16] http://www.fch.europa.eu/publications/study-hydrogen-renewable-resources-eu

[17] Reference based on the case study of SMR plant of 100,000 Nm^3/hr capacity (IEA, 2017).

[18] Along with each m^3 of hydrogen an amount of 0.5 m^3 of oxygen is produced; this translates to roughly 8 kg of oxygen for each kg of hydrogen. When production takes place at a limited scale, the market value of hydrogen is outweighed by the investments required for capture, purification and storage. Large-scale production could change this and offer interesting opportunities in combination with biomass gasification or natural gas reforming with full CO2 capture. (Gigler & Weeda, 2018)

and storage (also known as blue hydrogen). The hydrogen could be used by industries as an energy source for high temperature and power generation (Port of Rotterdam, 2019c). The CO_2 emission reduction potential from project is 2.2 Mt per year in 2026 to 4.3 Mt/yr in 2031 (TNO, 2019). The cost for CO_2 avoidance is 86-146 €/ton, and cost for compression, transport and storage of CO_2 is 17-30 €/ton (TNO, 2019). In H-vision project, biomass sources such as waste streams and sewage sludge can be used for H_2 production. However, due to the nature of these streams being residual, the availability and scalability of these options is limited (TNO, 2019).

Table 23. Overview of hydrogen production from SMR

Characteristics	Value	Source
Fuel	Natural gas	
Emissions	Depends on SMR with CCS	
Capacity	100000 Nm^3/hour; 300 MW (SMR) with CCS[19] (50-90% capture rate); 1460 MW (H-vision)	(Gigler & Weeda, 2018); (IEA, 2017; Janssen, 2018b); (TNO, 2019)
Efficiency	60-65%; 96%	(Gigler & Weeda, 2018); (Janssen, 2018b)
Lifetime	15-25 years	(Janssen, 2018b)
Investment cost	• 1.16-1.33 mln €/ MW (SMR w/d CCS using flue gas); 1-1.16 mln €/MW (SMR w/d burner gas & syngas carbon capture); 1.05-1.16 mln €/ MW (SMR w/d CCS from PSA tail gas using CMS); 0.98-1.16 (SMR w/d CCS from PSA tail gas using MDEA); • EUR 1.3 billion (H-vision)	(IEA, 2017; Janssen, 2018a, 2018b, 2018c, 2018d); (TNO, 2019)
Maintenance cost	0.3 mln €/MW (SMR w/d CCS using flue gas); 0.29 mln €/MW (SMR w/d burner gas & syngas carbon capture); 0.27 mln €/MW (SMR w/d CCS from PSA tail gas using CMS); 0.27 mln €/MW (SMR w/d CCS from PSA tail gas using MDEA)	(IEA, 2017; Janssen, 2018a, 2018b, 2018c, 2018d)

Partial Oxidation and Autothermal reforming

For partial oxidation (POX) (see Figure 28) feed gas (desulfurized natural gas or refinery off gas) is mixed with steam and pre-heated in a fired heater (Air Liquide, 2015). The feed gas is then fed into a furnace along with oxygen and steam at 1,400 – 1,450°C with an operating pressure of 55 – 60 bar (Arthur, 2010). This process causes partial oxidation of feed gas, to produce a mixture of hydrogen, carbon monoxide and carbon dioxide. The reformed gas is cooled down to produce high pressure steam and CO_2 is removed in an amine wash unit (Air Liquide, 2015). For partial oxidation with CCS, the CCS connection cost as 1 €/tCO_2 and the cost of feeding the CO_2 to CCS pipeline is 10-20 €/tCO_2 (Navigant, 2019).

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[19] Reference based on case 1B;2A;2B and 3 of Techno-Economic evaluation of SMR based Hydrogen plant with CCS (IEA, 2017)
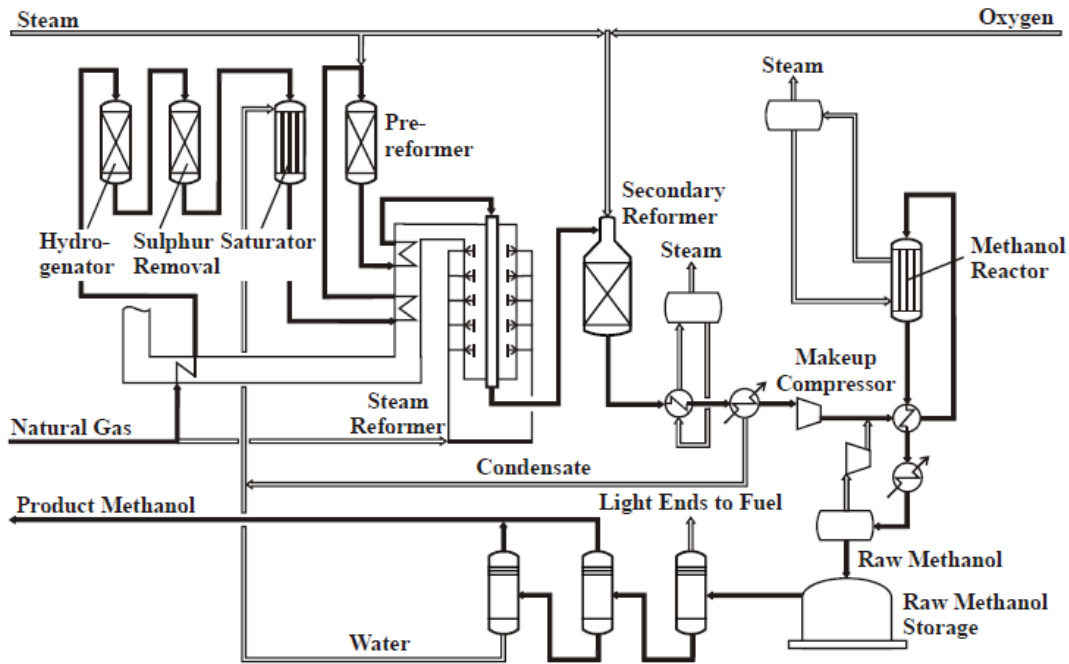
Figure 28. Partial oxidation process *(Aasberg-Petersen et al., 2008)*

Autothermal reforming (ATR) is the combination of both SMR and POX in a single reactor with temperature range of 900-1,150°C with less energy efficiency than SMR. The pre-reformed natural gas is fed to an ATR reformer, where hydrocarbons undergo combustion in the presence of oxygen (see Figure 29). Without a tubular reformer, the steam addition to the feed streams can be reduced significantly (Juuhl Daal et al., 2014). The emission reduction of ATR with CCS 15.60 Mt CO_2 (Janssen, 2019).
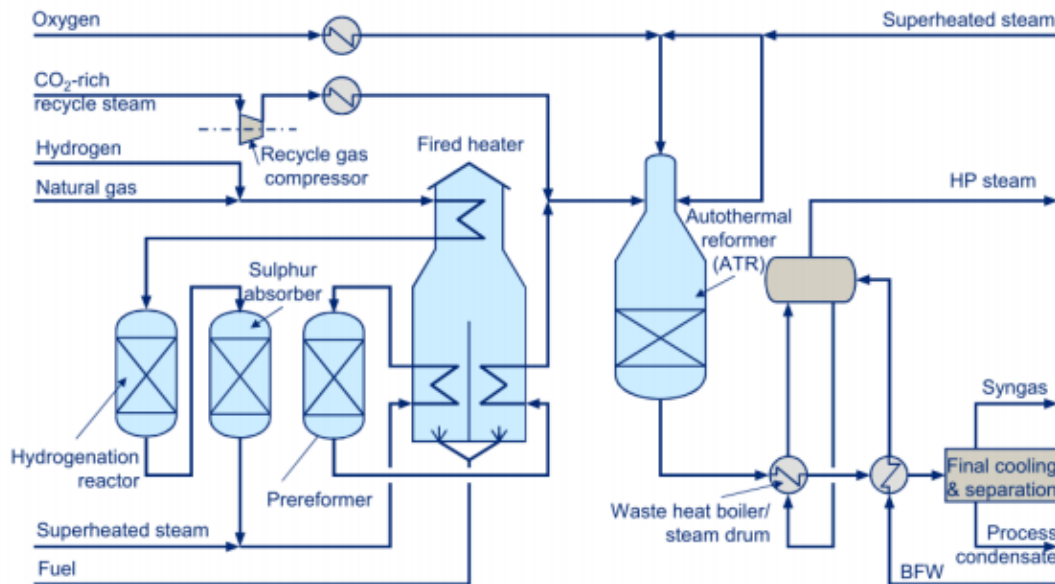

Figure 29. Autothermal reforming (ATR) *(Juuhl Daal et al., 2014)*

Table 24. Overview of Hydrogen production from POX and ATR

Characteristics	Value	Source
Fuel	Natural gas	
Emissions	Depends on production process	
Capacity	150,000 Nm^3/hour (POX); 1 mln Nm^3/hour (ATR); 10228 MW (ATR with CCS)	(Air Liquide, 2018); (Janssen, 2019)
Efficiency	79-82 %	(Janssen, 2019)
Lifetime	10 years	(Janssen, 2019)
Investment cost	10 mln USD (POX);160 mln USD (ATR); 50-100 €/tCO$_2$ (POX with CCS); 1.2 mln €/MW (ATR with CCS)	(Air Liquide, 2018); (Navigant, 2019); (Janssen, 2019)
Maintenance cost	1-5 % of CAPEX (POX with CCS); 0.04 million €/MW/yr (ATR with CCS)	(Navigant, 2019); (Janssen, 2019)

Electrolysis (ALK and PEM)

ALK and PEM are available at a scale of 1-5 MW (Lymperopoulos, 2017). There is an expected increase in the efficiency of the system from the average of 61% (55 kWh/kg) to a minimum of 67% (50 kWh/kg) (Gigler & Weeda, 2018). The electricity consumption of PEM is 60 kWh/kg, slightly better than AEL, with a further reduction in 2030 of less than 50 kWh/kg (Gigler & Weeda, 2018). The current hydrogen production cost are estimated at 5-5.5 €/kg for AEL and 6-6.5 €/kg for PEM, assuming maximum operating hours and electricity cost €70-80 per MWh (Gigler & Weeda, 2018). Table 25 gives overall techno economic characteristics of AEL and PEM in 2017 and 2025.

Table 25. Techno-economic characteristics of ALK and PEM electrolysers *(IRENA, 2018)*

Technology		ALK (Alkaline Electrolysers)		PEM (Proton Exchange Membrane)	
	Unit	2017	2025	2017	2025
Efficiency	kWh of electricity/kg of H$_2$	51	49	58	52
Efficiency (LHV)	%	65	68	57	64
Lifetime stack	Operating hours (h)	80,000	90,000	40,000	50,000
CAPEX-total system cost (incl. power supply and installation cost)	EUR/kW	750	480	1,200	700
OPEX	% of Initial CAPEX/year	2%	2%	2%	2%
CAPEX-stack replacement	EUR/kW	340	215	420	210
Typical output pressure*	Bar	Atmospheric	15	30	60
System lifetime	Years		20		20

*Higher output pressure leads to lower downstream cost to pressure the hydrogen for end use

Challenges for hydrogen

Figure 30 illustrates the key challenges and potential measures for scaling up hydrogen. Hydrogen is not economically competitive at present, thus significant reduction in cost of production and distribution need to take place for decarbonising the relevant sector.
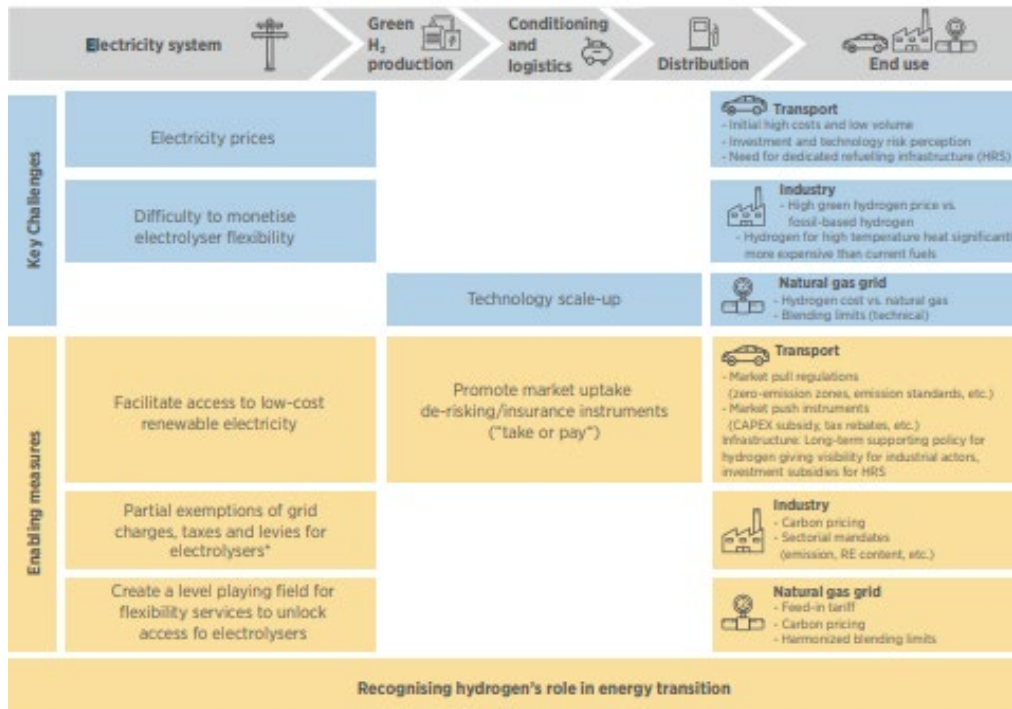

Figure 30. Key challenges and measures for power-to-hydrogen *(IRENA, 2018)*

Appendix C Heat pumps

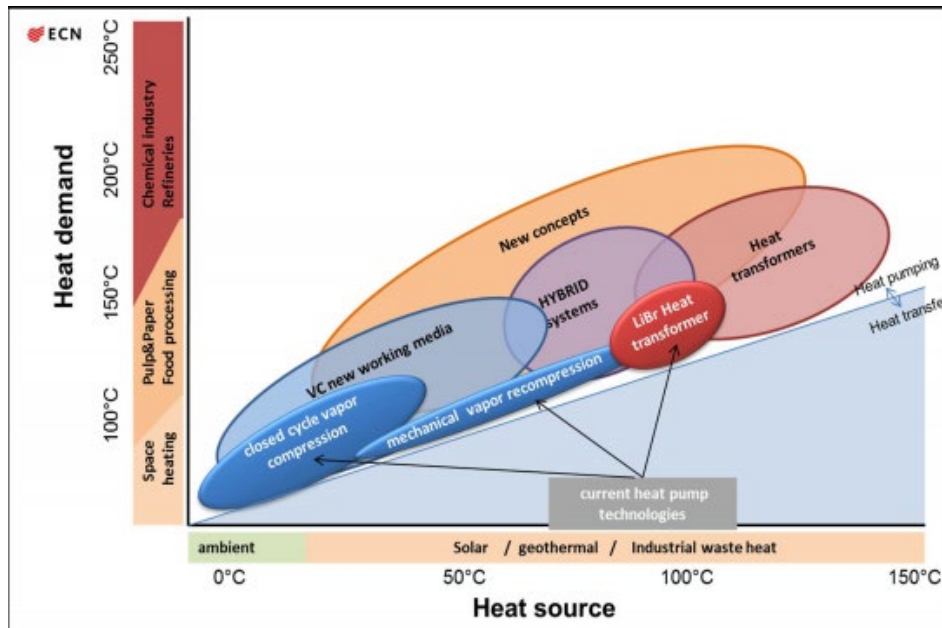Figure 31 gives an overview of the current and future heat pump technologies.

Figure 31. Current and future heat pump technologies with source heat on the x-axis and temperature range on y-axis *(RVO, 2016)*

For heat pumps up to 90°C the TRL is 9. They are commercially available, although there has not been a substantial roll-out. For the skid-mounted compression heat pumps above 160°C of around 2 MW$_{th}$, TRL is about 4-5 (Marsidi, 2018a). The installation cost and potential grid connection cost can vary significantly for heat pumps, depending on the site and current available grid connection. The installation costs for grid connection are EUR 1.5 mln for a 110 kV and 150 kV line, while for a 220 kV and 380 kV line is EUR 3 mln (Marsidi, 2018a).

Table 26. Overview of heat pump data

Characteristic	Value	Source
Energy output	Steam	
Energy input	Electricity, waste heat	
Emissions	No on-site emissions	
Capacity	20 MW$_{th}$	(Marsidi, 2018a);
Efficiency	3.5-4 COP;	(Marsidi, 2018a);
Lifetime	10-15 years	(Navigant, 2019)
Investment cost/ CAPEX	• 0.40-5 mln €/MW$_{th}$ (upto 90 ℃); • 800-2000 €/kW$_{th}$ (upto 90 ℃); 2000-5000 €/kW$_{th}$ (upto 140 ℃) including installation cost and grid connection cost	(Marsidi, 2018a); (Navigant, 2019)
Maintenance cost/ OPEX	• 0.06 mln €/ MW$_{th}$	(Marsidi, 2018a);

Mechanical vapour recompression

Table 27. Overview of Mechanical vapour recompression

Characteristic	Value	Source
Output	Steam	
Input	Electricity, Waste heat	
Emissions	No on-site emissions	
Capacity	4-20 MW$_{th}$	(Navigant, 2019)
Efficiency	9.8 COP (4.4 MW$_e$); 10.3 COP (0.25 MW$_e$)	(Blue Terra, 2018; Spoelstra et al., 2017)
Lifetime	10 years	(Marsidi, 2018b)
Investment cost	CAPEX: 260-600 €/kW$_{th}$	(Marsidi, 2018b)
Maintenance cost/OPEX	0.01-0.02 mln €/MW$_{th}$	(Marsidi, 2018b)