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DECARBONISATION OPTIONS FOR THE DUTCH VEGETABLE OIL AND FAT INDUSTRY

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MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for the Dutch Vegetable Oil and Fat Industry
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MIDDEN project coordination and responsibility
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This report was reviewed by MVO, the industry organisation for oils and fats, and EproConsult. PBL and TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Contents

List of abbreviations and acronyms

ADM	Archer Daniels Midland Company
CIE	Chemical interesterification
CHP	Combined heat and power
EC	European Commission
EIE	Enzymatic interesterification
FFA	Free fatty acids
FOM	Fixed operation and maintenance
HT HP	High-temperature heat pump
IE	Interesterification
MF	Microfiltration
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
MVR	Mechanical Vapour Recompression
NBD	Neutralised, bleached, deodorised
NCV	Net calorific value
NF	Nanofiltration
TRL	Technology readiness level
UF	Ultrafiltration
VOM	Variable operation and maintenance

FINDINGS

Summary

In this report, four vegetable oil and fat companies in the Netherlands are studied: ADM, Bunge, Cargill and Sime Darby Unimills. These four companies, together, have 7 production sites that emit more than 10 kilotonnes (kt) CO_2 per year. Altogether, they were responsible for 0.36 megatonnes (Mt) CO_2 emissions in 2018 (NEa, 2019) and produced about 4.4 Mt in oils per year. The total steam use of the production processes at these companies is estimated to be 5.4 PJ and the total electricity use is estimated to be 1.3 PJ.

The main products of these companies are rapeseed, soybean and palm oil. The production process is divided in three process units: crushing, refining and modification, not necessarily all at the same location. Crushing involves the preparation steps before extraction and the oil extraction itself for obtaining crude oil, and is the most energy intensive of the three process units identified. In the Netherlands, crushing is only performed for rapeseed, sunflower and soybean oil. Palm fruits require processing into crude oil within 24 hours of harvesting and, therefore, processing takes place on or near the local plantation (Sridhar & AdeOluwa, 2009). Oil refining takes place in all Dutch vegetable oil companies. Refining consists of three main processes: neutralisation, bleaching and deodorisation (NBD). Oil modification is performed to obtain certain characteristics that are required for specific final products. Currently, there are three main modification technologies available in the vegetable oil industry: hydrogenation, interesterification and fractionation.

Decarbonisation options are divided into two categories: technology-specific options and alternative heating systems. The technology-specific decarbonisation options are only applicable for implementation in the vegetable oil and fat industry. The uses of membranes and enzymes are both technology-specific decarbonisation options. Furthermore, vertical ice condensing technology can be used as a substitute for the conventional deodorisation process in the vegetable oil and fat industry.

The alternative heating systems consist of options that partly or totally provide a substitute for the natural gas for combined heat and power (CHP) systems and steam boilers. An industrial heat pump (MVR, HT HP or chemical heat transformer) and ultra-deep geothermal energy can both reach temperatures of up to 120–140 °C, which is not sufficient to fully provide the energy required in vegetable oil processes. However, sustainable alternative heating systems, such as electric boilers, biomass boilers and hydrogen boilers, can fully replace the conventional natural gas for steam boilers and CHP systems.

Combinations of technology-specific options and alternative heating systems are interesting. The technology-specific options can reduce energy consumption, so that alternative heating systems with a lower capacity can be installed. When all stages (crushing, refining and oil modification) are completed, membrane solvent extraction can be combined with enzymatic degumming, vertical ice condensing technology and enzymatic interesterification. A biogas boiler, partly fed by leftover streams from the crushing stage, can supply the additional energy required.

Introduction

This report describes the current situation for the vegetable oil and fat sector in the Netherlands together with the options and preconditions for its decarbonisation. The study is part of the MIDDEN project (Manufacturing Industry Decarbonisation Data Exchange Network). The MIDDEN project aims to support industry, policymakers, 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

In the Netherlands, the vegetable oil and fat producers include:

- ADM
- Cargill
- Bunge Loders Croklaan
- Sime Darby Unimills.

These four companies represent the larger production facilities at seven production sites. There are more production facilities, but these are smaller and do not fall under the emission trade system of the European Union (EU ETS). Many other decarbonisation options may also be relevant for these facilities, but these were outside the scope of this study.

Production processes include cleaning, cracking, dehulling, threshing, conditioning, flaking, cooking, sterilisation, mechanical pressing, solvent extraction, degumming, neutralisation, bleaching, hydrogenation, desolventising and deodorisation. The processes are discussed in Section 2. The relevant products include palm oil, rapeseed and sunflower oil, soybean oil and other types of oil.

The main options for decarbonisation are membrane and enzyme technologies, together with the vertical ice condensing technology to improve energy efficiency. Furthermore, options for steam supply consist of hydrogen boilers, biogas boilers or electric boilers used to substitute natural-gas-fired steam boilers or CHP systems.

Reading guide

Section 1 introduces the Dutch vegetable oil and fat industry. Section 2 describes the current processes for palm oil, rapeseed and soybean oil production in the Netherlands. The relevant products of these processes and their prices are described in Section 3, while options for decarbonisation are systematically quantified and evaluated in Section 4. Lastly, the feasibility and requirements of the given decarbonisation options are discussed in Section 5.

1 Vegetable oil and fat production in the Netherlands

1.1 History of Dutch oil and fat industry

The Dutch oil and fat industry is one of the main players in the production and refining of oilseeds into fats and oils in Europe. Except from cultivation, all processes for the manufacturing of oil and fat occurs within the Netherlands. For this reason, the import of oilseeds and tropical oil sources is high, concerning 11.5 billion euros in 2018 (MVO, 2019). Subsequently, the Netherlands is one of the main exporters in oil and fat products worth 10.2 billion euros. More than 20% of the European import and export runs through the Netherlands (MVO, 2014). The main part of these products is used for the food industry, which is covered in this report. Other purposes of these oil and fat products are in the animal feed, oleochemical, and biofuel industries (MVO, 2014). However, this lies outside of the scope of this research. The decarbonisation of the Dutch biofuels industry is covered in another MIDDEN report (Khandelwal & Van Dril, 2020).

1.2 Dutch production sites

The oil and fat products are manufactured mainly in the areas around the ports of Rotterdam and Amsterdam, due to logistic reasons. However, in this report four different companies of which some consist of multiple production sites are considered, since these are the companies that emit more than 10 kt CO_2. In Table 1 below, an overview is given of these Dutch oil and fat companies, including their locations, production capacities and EU ETS CO_2 emissions.

In Table 2 we summarise the totals of the different types of oils produced by these companies. Data on individual companies is not available.

The total estimated production of oils of the companies in this report (Table 1) is estimated to be 4.4 million tonnes. Based on the energy flow analysis in Section 2.5, the total steam use of the production processes at these companies is estimated to be 5.4 PJ and the total electricity use is estimated to be 1.3 PJ.

Table 1 Overview of the Dutch oil and fat production sites with corresponding production capacities and emissions

	Crude oil capacity [Mt oil /year]	NEa[1] 2018 CO_2 emissions [kt/year]	Rapeseed /Sunflower	Soy-bean	Palm	Source
ADM	0.9	150.5	X	X		Kasper, 2018; Zande, 2011; Wachelder, 2017
Bunge Amsterdam	0.76	64.8		X		Kasper, 2018
Bunge Loders Croklaan Maasvlakte	0.75	19.0			X	Advocatie, 2017
Bunge Loders Croklaan Wormerveer	0.3[2]	16.6	X	X	X	assumption based on emissions
Cargill Amsterdam	0.22	32.9	X			Kuipers et al., 2015
Cargill Botlek	1	26.8			X	FoodIngredientsFirst, 2005; Industrielinqs, 2005
Sime Darby Unimills	0.45	51.2	X	X	X	Constandse, 2019; Unimills, 2011

Table 2 Types of oil produced in the Dutch vegetable oil sector

Crushing of oil seeds and refining of tropical oils in The Netherlands	
Rapeseed/sunflower oil produced	36%
Soybean oil produced	17%
Palm oil processed	47%

1.2.1 ADM

The Archer Daniels Midland (ADM) company was founded in 1902 at Minneapolis, United States. In 1986, ADM bought the company at Europoort in the Netherlands, which is their only location within Dutch borders where oil and fat products for the food industry are manufactured (ADM, 2019). It was reported that the company had a production capacity of 0.6 million tonnes oil in 2011 (Zande, 2011). However, ADM expanded their production in 2017 with 355,000 tonnes per year (Wachelder, 2017). Therefore, the annual oil production is estimated at 0.96 million tonnes per year. ADM Europoort processes both rapeseed and soybean oil (Kasper, 2018). The ratio of produced rapeseed and soybean oil is not known. Therefore, it is assumed that 50% of the production capacity is for rapeseed oil and the other 50% for soybean oil. The turnover of ADM Europoort is EUR 98.1 million, with 230 employees (Vainu.io, 2019). As shown in Table 1, ADM has the highest carbon emissions

[1] Dutch Emissions Authority (NEa)
[2] Estimated based on the CO_2 emissions reported by NEa (NEa, 2019). Actual production capacity is unknown.

noted in the ETS emission list of the oil and fat sector. In September 2019 an item appeared in the Dutch newspaper AD where ADM Europoort announced plans to rebuild the factory into a meat replacer manufacturer (AD, 2019).

1.2.2 Bunge Loders Croklaan

Bunge Loders Croklaan started in 1891 as the oil company Crok&Laan in Wormerveer. In 1970 it transformed to Croklaan which one year later again got changed when it was taken over by Unilever. The name got transformed to LodersCroklaan and was sold in 2002 to I.O.I. from Malaysia. After that, the company was producing as IOI Loders Croklaan. Recently in 2018 the company Bunge from the United States took 70% of the shares and 30% remained with IOI. The name changed to the current one: Bunge Loders Croklaan (Dekker, Bol, & Boom, 2019). Bunge Loders Croklaan operates at three different sites in the Netherlands: Amsterdam, Maasvlakte and Wormerveer. Bunge Loders Croklaan has in total 475 employees within the Netherlands.

Amsterdam

The soybean refinery in Amsterdam was built in 1968 and belonged initially to Cargill until they sold it to Bunge in 2016 (Bron, 2016). The current annual production capacity of the factory is 760,000 tonnes rapeseed and soybean oil which is produced mostly in the ratio of 90/10, respectively (Kasper, 2018). The Bunge Loders Croklaan company has 120 employers (Bron, 2016). This location emits the most CO_2 of the Bunge sites in the Netherlands, with an amount of 65 kt as is shown in Table 1.

Maasvlakte

After the takeover by IOI of Loders Croklaan, IOI soon started to build a big palm oil refinery at the Maasvlakte with an annual production capacity of 750,000 tonnes. This factory opened in 2010 and has an annual turnover of EUR 1.3 billion (Advocatie, 2017). Around 90 employees are working the palm refinery at the Maasvlakte and the corresponding CO_2 emissions are 18.3 kt in 2017 (Dekker, Bol, & Boom, 2019; Lalkens, 2017; InvestinHolland, 2010).

Wormerveer

Here the original Crok&Laan factory is located. The current exact amount of tonnes specialised oil is unknown. However, an estimation of 300,000 tonnes oil produced per year was made based on the NEa emissions which are equally divided on the three different types of oil. The Wormerveer site was responsible for 17 kt CO_2 emissions in 2018 (Table 1).

1.2.3 Cargill

Cargill was found in 1865 by William Wallace Cargill who owned a grain warehouse in Conover, the United States. The company grew very fast and in 20 years W.W. Cargill and his two brothers managed more than 100 grain warehouses within the country. In 1959 Cargill extended to the international market, with small offices in several countries including the Netherlands. From that moment Cargill expanded fast in the Netherlands by opening several new locations and taking over some Dutch companies. Nowadays, Cargill operates at 13 different sites in the Netherlands of which two, the multiseed firm in Amsterdam and the refined oils firm in Botlek, operate within the oil and fat food sector (Cargill, 2019). Cargill has 2200 employees at these 13 sites in the Netherlands.

Multiseed Amsterdam

This grain and seed processing firm was opened in 1980 and has a refinery capacity of 600,000 tonnes of seeds. Which means the multiseed firm produces 220,000 tonnes rapeseed and sunflower oil on annual basis (Kuipers, et al., 2015). The CO_2 emissions of the multiseed firm were 33 kt in 2018 (Table 1).

Botlek
Cargill took over the factory in Botlek from Brinkers in 1984 and, in 2005, expanded the annual production by an additional 575,000 tonnes of oil, which means the current total annual production capacity is around 1 million tonnes of oil. According to news items Industrielinqs and FoodIngredientsFirst, palm oil capacity was greatly expanded (FoodIngredientsFirst, 2005; Industrielinqs, 2005). According to Cargill, only palm, palm kernel and coconut oil are produced in Botlek. The Cargill Botlek company employs 100 people. The total in CO_2 emissions from the Cargill Botlek location was 27 kt in 2018 (Table 1).

1.2.4 Sime Darby Unimills

The company of Sime Darby Unimills originates from 1915, when Jurgens began a new oil refinery at Zwijndrecht in the Netherlands. With several mergers in time the name changed from Maatschappij der Vereenigde Oliefabrieken (MVO) to Unimills until eventually Sime Darby Unimills as it is recognised nowadays (Unimills, 2019). The company is still located in Zwijndrecht where it produces currently 450,000 tonnes oil per year of which 50% is allocated for palm oil production and the rest is divided in all other types of oil, depending on the price (Van der Klauw & De Ruiter, 2011; Constandse, 2019). There are 200 employees working in Zwijndrecht for Sime Darby Unimills (FNV, 2019). This oil refinery has the second highest ETS registered carbon emissions of the Netherlands in this sector, as can be seen in Table 1, with an amount of 51 kt in 2018.

2 Vegetable oil processes

The manufactured main products of the vegetable oil industry that are discussed in this report are rapeseed oil, soybean oil and palm oil. These three products can be considered to be representative for most processes occurring in this industry. Other production processes such as sunflower oil and coconut oil are similar to one of those or applied to a smaller extent. The chapter is divided in six sections; first, the crushing process is described. Subsequently, the refining processes are explained followed by the different oil modification processes available in the oil and fat industry. Then, the mass flows are given and lastly the energy flows and the related carbon emissions are presented.

2.1 Crushing

The crushing processes of oilseeds and beans involve the preparation steps before extraction and the extraction itself for obtaining crude oil and oil seed meal. This is only performed for soybean oil and rapeseed oil in the Netherlands. The palm fruits require processing into crude oil within 24 hours of harvest and therefore occurs on or near the local plantation (Sridhar & AdeOluwa, 2009). The crude palm oil is then imported and shipped to the Netherlands for further processing. Below the rapeseed crushing process is shown and explained, followed by soybean crushing.

2.1.1 Rapeseed crushing

Before the rapeseed oil can be extracted, the rapeseeds from the field require some pre-processing steps. Moreover, the crude oil is obtained by both mechanical pressing and solvent extraction. The process flow of crushing the rapeseed oil can be seen in Figure 1 below (European Commission, 2018; Hamm, 2013; Kasper, 2018; Schmidt, 2007).

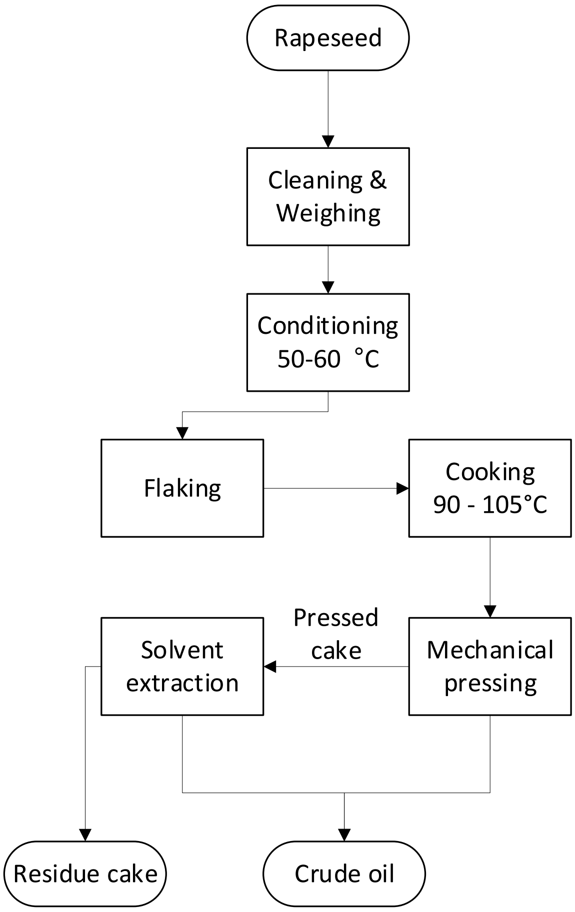

Figure 1 Crushing process flow of rapeseeds. Based on several sources (European Commission, 2018; Hamm, 2013; Kasper, 2018; Schmidt, 2007).

The rapeseeds are first cleaned and weighed before being preheated until 50–60 °C (Figure 1). This is done to soften the seeds before flaking, which generally improves the overall de-oiling. The seeds are fed into flaking mills which weakens the oil cells to make the oil more accessible for the solvent in the extraction. Then, the seeds are conveyed to the cooker for several reasons. Firstly, to decrease the oil viscosity making it easier to extract the oil. Secondly, to rupture the oil cells by flashing off the moisture that is captured inside the seeds as steam. Moreover, the proteins coagulate in the seeds and lastly sterilisation of the seed is required and executed in this step to destroy enzyme activity and to prevent the growth of bacteria and moulds. The cooking step is executed at temperatures of 90–105 °C in which the seeds are dried until a moisture content of between 3% and 5% (Hamm, 2013). After that, the rapeseed crude oil is extracted by mechanical pressing and solvent extraction. The flaked seeds contain approximately 40% oil content of which 2/3 is extracted by mechanical pressing. The remaining part is recovered by solvent extraction with hexane (Kasper, 2018). Solvent extraction results in an extraction cake and a miscella. Of the latter oil is obtained by heating, solvent removal, clarification, centrifugation and drying. The extraction cake on the other hand undergoes desolventisation and drying to gain rapeseed meal (Schmidt, 2007).

2.1.2 Soybean crushing

Soybeans are imported from North and South America. The soybeans coming from the storage require some pre-processing before the oil can be extracted. Like the rapeseed, soybean oil is also obtained by mechanical pressing and solvent extraction. The soybean crushing process flow is given in Figure 2 below.

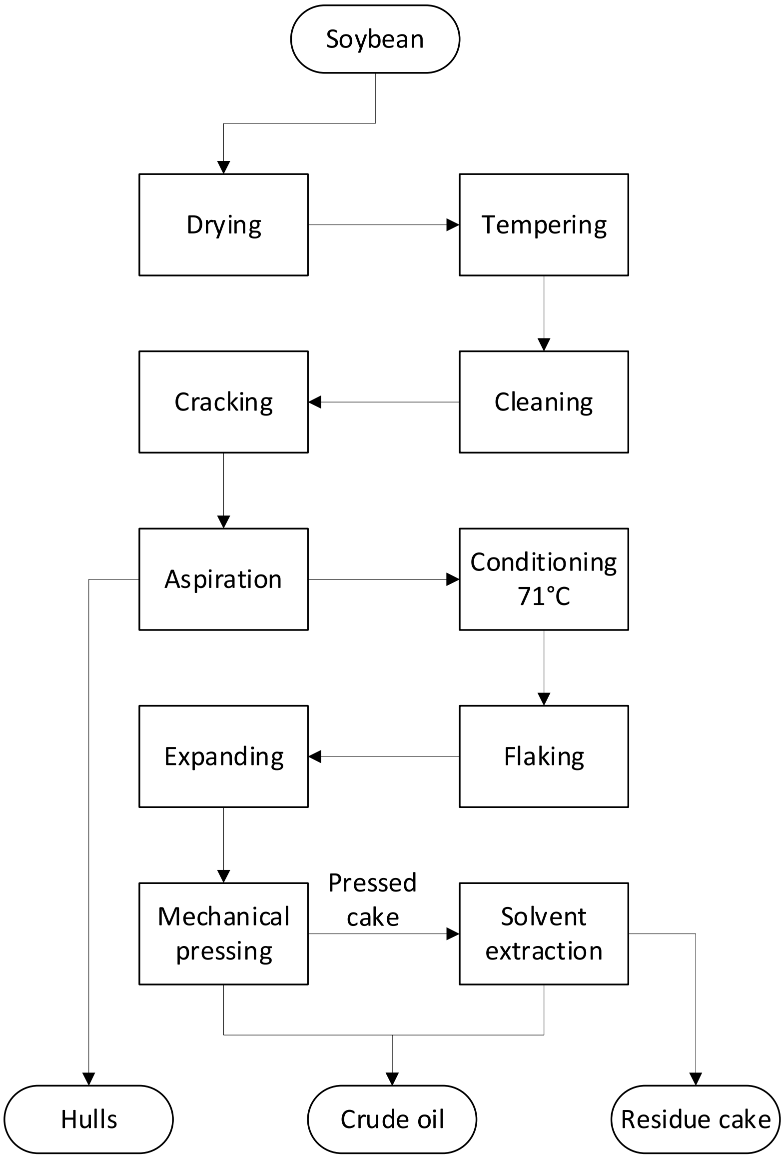

Figure 2 Crushing process flow of soybeans, Based on several sources (European Commission, 2018; Hamm, 2013; Kasper, 2018; Schmidt, 2007).

The incoming soybeans from the field are superficially dried (Schmidt, 2007) before being stored. For oil extraction, the stored soybeans are cleaned and cracked before dehulling takes place with the help of a current of air, known as aspiration (Figure 2). The dehulled soybeans are then heated until 71 °C in the conditioner before it enters the flaker which weakens the oil cells to make the oil more accessible for extraction. Finally, the dehulled soybeans go to the expander where the flakes are heated in a few seconds by mixing with steam and is pushed through the outlet section. In the outlet of the expander, flash evaporation of water in the product is occurring. This creates a sponge-like texture of the product, resulting in an increase in the capacity of an existing extraction plant. Expansion is an optional processing step, however it is assumed to be executed in most soybean oil manufacturing plants (European Commission, 2018; Hamm, 2013; Li, Griffing, Higgings, & Overcash, 2006).

The soybean oil is extracted in the exact same way as rapeseed oil, which is described in Section 2.1.1. With mechanical pressing, crude oil and a pressing cake of 12%–25% oil is obtained. The residual oil in the pressed cake is recovered by extraction using hexane as solvent. The other product of the solvent extraction is the residue cake or soybean meal that can be further processed for other applications (European Commission, 2018; Hamm, 2013). Vegetable oils from crushing of oilseeds and beans are usually refined at the same integrated plant.

2.2 Refining

Tropical oils from oil rich tropical fruits as palm and coconut are imported as crude oil to the EU for further processing like refining, because the fruits require crushing within 24 hours after harvesting. The refining process includes neutralisation, bleaching and deodorisation and is the same for all three oils. However, rapeseed and palm oil have a clarification step prior to refining due to the presence of phospholipids (Pan, Campana, & Toms, 2000). For rapeseed oil the clarification step is generally a two-stage process where most solids are removed by screening the oil over a static or vibrated screen. The screened oil is subsequently clarified by a filter before it is refined. For palm oil a decanter is used for this clarification step, which separates the various components by their difference in specific mass (Hamm, 2013). Two types of refining exist: chemical and physical refining which are shown in Figure 3. Chemical refining is the traditional and most commonly used one (AOCS, 2019; Schmidt, 2007). It has as advantage that it is flexible for all types of oil and that it uses lower deodorisation temperatures which prevents undesirable product formation (European Commission, 2018). Physical refining may be preferred for tropical oils since these are low in phospholipids but high free fatty acids (FFA) (European Commission, 2018). The purpose of neutralisation which involves degumming and neutralisation is to remove the FFA and lecithin. The bleaching process is executed to remove the undesired coloured particles and substances as a result of the physical and chemical interaction of the oil with the bleaching earth. Lastly, deodorisation is performed to remove undesired flavouring or odorous compounds (European Commission, 2018; Schmidt, 2007; AOCS, 2019).

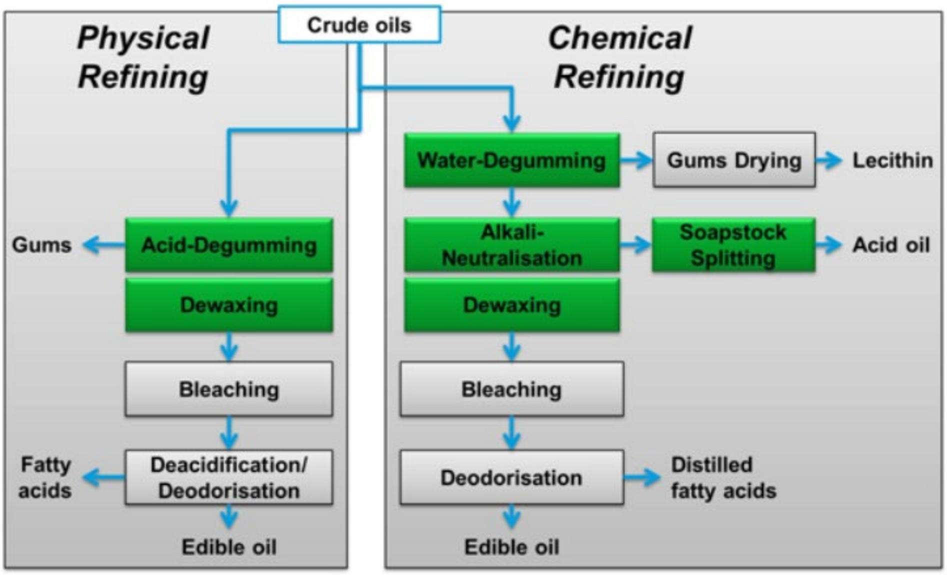

Figure 3 Physical and chemical refining process schemes (AOCS, 2019)

2.3 Oil modification

Depending on the application, the oil might need to be modified to obtain the desired characteristics that are required for the specific final products. With oil modification processes the physical behaviour and structural properties of an oil can be changed. Currently, there are three main modification technologies available in the vegetable oil industry: hydrogenation, interesterification and fractionation, which are more extensively explained below. For some oil modification processes, the crude oil must be neutralised but not bleached and deodorised before being modified. Since some colour can be formed during these modification steps, it is desired to bleach and deodorise the oil afterwards. Using neutralised, bleached and deodorised (NBD) oil as raw material in oil modification is therefore unnecessary and more expensive. Below, in Figure 4 an overview is given of the order the oil modification processes are performed.

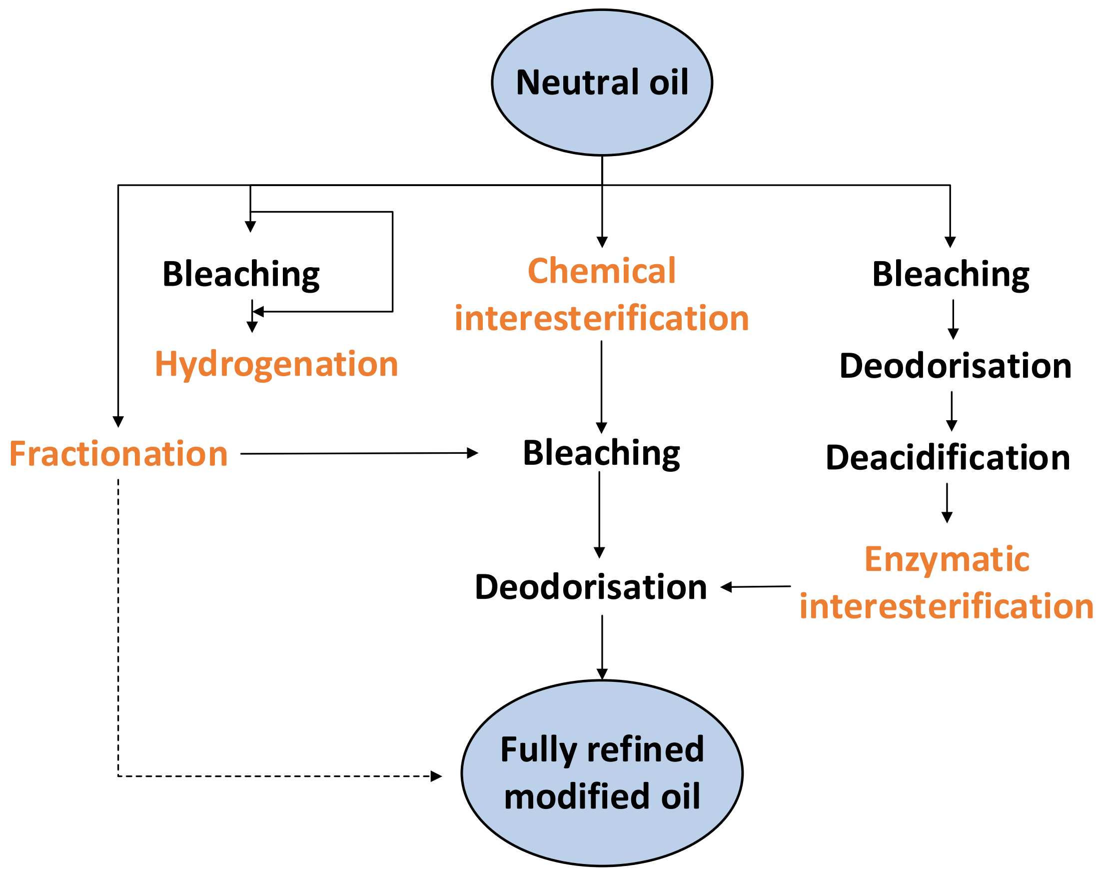

Figure 4 Oil modification process flow (Dijkstra, 2015)

2.3.1 Hydrogenation

Originally, hydrogenation was performed to improve the oxidative stability of oils that contained several polyunsaturated fatty acids, resulting in a longer shelf life. Hydrogenation makes an oil more stable and increases the melting point of the oil through the reduction in unsaturated fatty acids. In this process, supplied hydrogen atoms react with the unsaturated double bonds in the fatty acids by the presence of a catalyst. This process can allow the conversion of liquid oil to solid fat (Hamm, 2013; Gupta, 2017).

2.3.2 Interesterification

The interesterification of all vegetable oils is performed to create a desired rearrangement of fatty acyl groups within and between different triglycerides for every specific purpose in an final product. For example, a fat used in a cookie requires a different arrangement of fatty acyl groups than a fat in chocolate. The interesterification normally requires very high temperatures in the range of 140–250 °C, but can also be performed in milder conditions when using catalysts. Moreover, next to chemical interesterification also enzymatic interesterification exists where enzymes are used to catalyse the exchange of fatty acids attached to the glycerol backbone (AOCS, 2019; Hamm, 2013; Holm, 2008).

2.3.3 Fractionation

Fractionation is executed to generate two fractions, which can be dry fractionised or wet fractionised. Dry fractionation is the simplest method performed by crystallising the fraction with the lower melting point. Wet fractionation is also known as solvent fractionation. Solvent fractionation allows the higher-melting point components to crystallise in very low-viscous organic solvents as hexane or acetone (Hamm, 2013). In the Netherlands, the fractionation process only occurs for palm oil (MVO, Personal communication with Frans Bergmans and Eddy Esselink, 2019).

2.3.4 Energy requirement

Hamm (2013) gives an overview for each oil modification process with the electricity and steam usage per tonne oil, which is shown in Table 3. For both high-pressure hydrogenation and chemical interesterification (IE) post-treatment is included. As mentioned before, fractionation is only performed for palm oil in the Netherlands. Moreover, Hamm (2013) also only gives values for the energy consumption on fractionation of palm oil.

Table 3 Energy requirement of the oil modification processes (Hamm, 2013)

	Hydrogenation	Chemical IE	Enzymatic IE	Fractionation
Steam [kg/t]	30	150	12	40
Electricity [kWh/t]	10	15	4	10

Chemical IE has both the highest steam requirement as the highest electricity consumption. A reason for this is the high temperature at which the process is executed (Section 2.3.2). The values of hydrogenation are relevant for high-pressure hydrogenation, for this process medium-pressure steam is used (deodorisation requires high-pressure steam). For chemical/enzymatic IE and fractionation low-pressure steam is used (Hamm, 2013).

2.4 Mass balances

The mass balances of the processing of rapeseed oil, soybean oil and palm oil are shown in Figure 5 and discussed in this section. The balances are subdivided in three sections; crushing, refining and oil modification of which the processes are explained in the previous sections of this chapter. The mass balances involve only the processes that are occurring in the Netherlands. In Table 4 below it can be seen which process stages are applied to what extent to the different types of oil within the Netherlands.

Table 4 Percentages of the processes applied to each oil

Process applied to different types of oil	Rapeseed/sunflower	Soybean	Palm
Crushing	87%[3]	72%[3]	0%
Refining	100%	100%	100%
Oil modification	50%[4]	50%[4]	50%[4]

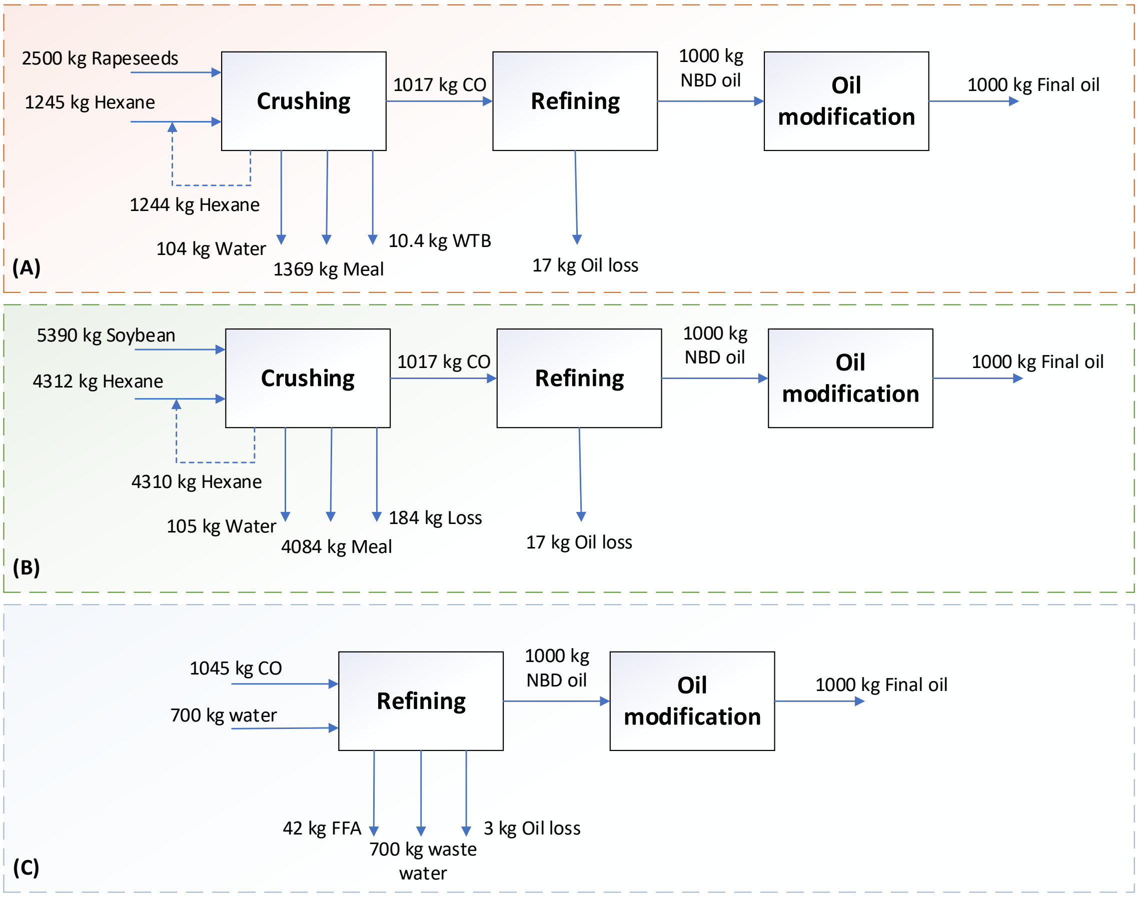

Figure 5 Mass balances of the production of (A) rapeseed oil (B) soybean oil and (C) palm oil. CO = crude oil; NBD = neutralised, bleached and deodorised.

The mass balance for the production of 1000 kg final rapeseed oil can be seen in part (A) of Figure 5. The numbers in this mass balance are obtained from Schmidt (2007) who based the numbers on the production of rapeseed oil at AarhusKarlshamn company in Aarhus, Denmark in 2003 and 2004. The mass balances of all three oils are similar with the numbers provided in a report commissioned by the FEDIOL (the EU vegetable oil and protein meal industry association) (Schneider & Finkbeiner, 2013).

For the production of 1 tonne rapeseed oil, 2500 kg of rapeseeds is required (Figure 5). With the production of 1 tonne rapeseed oil, 1369 kg rapeseed meal is produced which consists of 87.5% dm. Moreover, 104 kg water leaves the crushing step and 10.4 kg is by-product that goes to biomass (WTB). The crude oil is obtained by mechanical pressing and solvent

3 Calculated based on several sources.
4 Actual numbers unknown. Oil modification is applied to some of the oil but not all. 50/50 is an assumption.

extraction where 498 kg hexane is used per 1000 kg rapeseed (Pehnelt, 2012). In the refining stage 17 kg of rapeseed oil losses occur (Schmidt, 2007). Moreover, small amounts of excipients are used in the NBD processes. These materials (mainly acids, lye and bleaching earth) are not displayed here, since the amounts are small. Nevertheless, the exact materials quantities can be found in Appendix A. The same accounts for the oil modification stage; hydrogenation and chemical/enzymatic IE consumes as well few other materials. Therefore, this material stream is also left out in the mass balance but can be found in Appendix A. The final oil output refers to the required typical oil, since with oil modification lots of different oil and fat types can be produced. Moreover, it is good to keep in mind that not all NBD oil produced in every factory will go through the oil modification stage. The NBD oil can also be the final product, depending on the demand and factory.

For the production of 1 tonne soybean oil 5390 kg soybeans are required as shown in part (B) of Figure 5. For every kg soybeans 0.8 kg hexane is used (Potrich, 2020). An amount of 105 water is used and 4084 kg soybean meal is produced, next to 184 kg material losses (Schmidt, 2007). For the refining of soybean oil applies the same as for rapeseed oil. The material usage of soybean is the equal to the refining step of rapeseed and can be seen in Appendix A together with the inputs and outputs of the oil modification processes.

For the production of final palm oil, only the refining and oil modification stage are executed within the Netherlands. The crude palm oil is imported and shipped from abroad. The mass balance of 1000 kg final palm oil can be seen in part (C) of Figure 5. In the palm oil refining, 45 kg of FFA and oils are produced in total (Schmidt, 2007). For the oil modification step accounts the same as for rapeseed and soybean oil. The materials used here are shown in Appendix A. Nevertheless, palm oil is the only oil that is fractionated in the Netherlands (MVO, Personal communication with Frans Bergmans and Eddy Esselink, 2019).

2.5 Energy balance and carbon emissions

The energy consumption of each process is subdivided in electricity and heat (steam), both values are provided in MJ. According to the sector experts, Cargill Botlek, Bunge Loders Croklaan Maasvlakte and Bunge Loders Croklaan Wormerveer make use of steam boilers, whereas ADM, Bunge Amsterdam, Cargill Amsterdam and Sime Darby Unimills possess a combined heat and power (CHP) plant. However, frequently companies also have a steam boiler next to a CHP system to be able to produce steam at a different pressure or instead or in addition to the CHP. It is however unknown what type of steam boiler is used and to what extent. It is assumed that the CHPs used in the vegetable oil and fat sector are steam boilers with gas turbines, which typically have a thermal efficiency of about 67% and an electrical efficiency of about 26% (R. Ongenae, personal communication). The steam boilers are assumed to have an efficiency of ~90%.

Furthermore, the used CO_2 emission factor is 56.6 kg/GJ obtained from Zijlema (2017). The energy balances of rapeseed oil, soybean oil and palm oil and the correlated carbon emissions are shown in Figure 6 and discussed in this chapter.

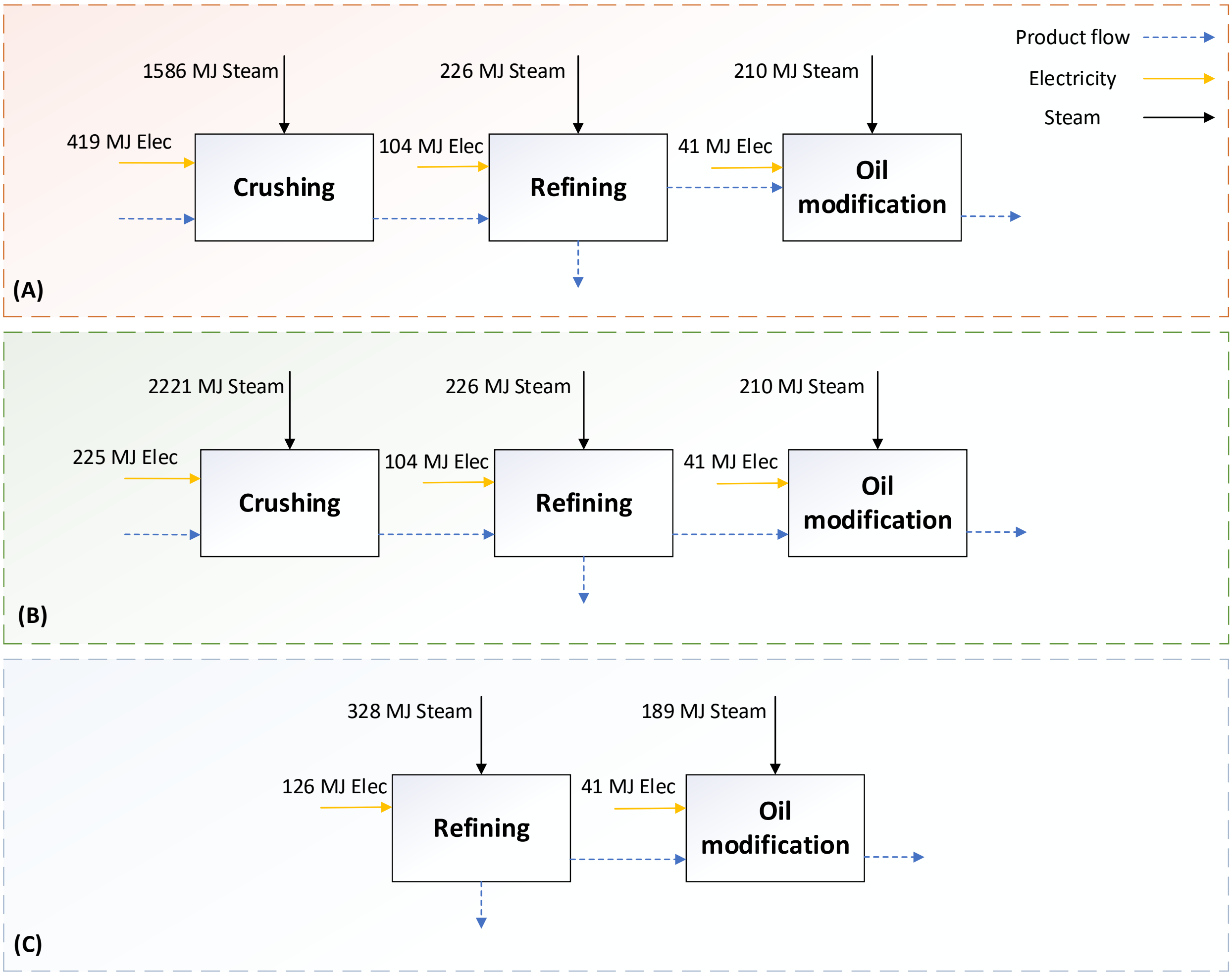

Figure 6 Energy balances for (A) rapeseed oil (B) soybean oil and (C) palm oil per tonne of oil produced.

The electricity and heat required for the crushing, refining and oil modification steps for 1000 kg rapeseed oil are displayed in part (A) of Figure 6. The values for the steam and electricity consumption of crushing and refining are subtracted from Schmidt (2007). Crushing requires most energy both in terms of electricity and steam, because of the conditioning and cooking steps where the seeds are heated up. The refining stage consisting of neutralisation, bleaching and deodorisation consume 20 MJ, 0 MJ, and 84 MJ electricity and 41 MJ, 41 MJ and 144 MJ heat per tonne, respectively (Schmidt, 2007). For the oil modification energy consumption, it is assumed that 50% is hydrogenated, 40% is chemical interesterificated and 10% enzymatic interesterificated. The exact energy consumption of each oil modification step can be found in Table 3. The total energy consumption of the rapeseed oil production is 2335 MJ/t if NBD oil is the final product and no oil modification occurs, and 2586 MJ/t if the oil is modified. Both values are in line with the specific energy consumption range of rapeseed provided by the IPCC (European Commission, 2018). However, the latter seems a bit higher than the average value of specific energy consumption of all evaluated rapeseed oil producers whereas 2335 MJ/t seems equal to the average. The specific energy consumption graph for rapeseed and sunflower oil can be found in Appendix B.

An energy balance for the production of 1000 kg soybean oil is also made and is shown in part (B) Figure 6. For crushing 225 MJ/t electricity is needed and 2221 MJ/t steam (Schmidt, 2007). According to Li (2006), the drying of raw soybeans is the most significant consumption of energy, followed by conditioning of soybeans. The third largest consumer in the crushing stage is the expander. The refining is considered to be similar to rapeseed oil (Schmidt, 2007). For the oil modification, again it is assumed that 50% is hydrogenated, 40% undergoes chemical IE and 10% enzymatic IE. Therefore, the energy consumption of refining and oil modification is exactly the same as for rapeseed oil. The total energy consumption for manufacturing soybean oil is 2776 MJ/t excluding oil modification, and 3027 MJ/t including oil modification. The latter is close to the value provided in the paper by Li (2006). However, these values seem a bit lower than the average specific energy consumption for soybean oil producers, but are within the given range (Appendix B).

Since the crushing of palm oil is performed abroad, the energy balance of palm oil only consists of refining and oil modification (Part (C) Figure 6). The refining of 1000 kg palm oil requires more energy than for rapeseed and soybean oil (Schmidt, 2007). Moreover, refining consumes more energy than the oil modification of palm oil. The palm oil can be hydrogenated, interesterificated or fractionated in the oil modification stage. It is assumed that these three processes are equally performed. For interesterification, 90% is chemical IE and 10% enzymatic IE. The total energy consumption of refining is 453 MJ per tonne and of refining and modification 684 MJ per tonne. These values are much smaller than the energy consumption of rapeseed and soybean oil, due to the fact that no crushing is occurring for palm oil in the Netherlands. This energy consumption lies within the range of the specific energy consumption of a stand-alone refining given by the IPCC (2018), but seems a bit lower than the average (Appendix B).

Combining the production numbers with the energy numbers, the calculated CO_2 emissions present 102% of the real carbon dioxide emissions in 2018 of (NEa, 2019). For the companies with a CHP system, the combined electricity and heat energy requirement for the production of the oils are used for these four companies. Therefore, the electricity consumed in these companies is included in the scope 1 emissions. For the companies with a steam boiler, the electricity used is bought and produced externally by energy producers. Therefore, the emissions related to this amount of electricity are indirect (scope 2) emissions and are not included. For both CHP systems and steam boilers, a total efficiency of ~90% is used.

To provide a clear overview the numbers for the different processes and oils are summarised in Table 5. Furthermore, it is known that energy can be saved by usage of residual heat that is released in the higher temperature processes. For example, according to Li (Li, Griffing, Higgings, & Overcash, 2006), approximately 35% of the energy consumption in the traditional soybean crushing process can be reduced by potential heat recovery. However, this is not yet taken into account.

Table 5 Energy consumption of each stage for the production of one tonne of oil.

	Rapeseed oil	Soybean oil	Palm oil
Crushing Electricity [MJ]	419	225	-
Crushing Heat [MJ]	1586	2221	-
Refining Electricity [MJ]	104	104	126
Refining Heat [MJ]	226	226	328
Oil modification Electricity [MJ]	41	41	41
Oil modification Heat [MJ]	210	210	189
Total Electricity [MJ]	564	370	167
Total Heat [MJ]	2022	2657	517
Total [MJ]	**2586**	**3027**	**684**

The energy numbers from the FEDIOL report (Schneider & Finkbeiner, 2013) appear valuable as they represent information from more than 20 oil and fat production sites, but they are not used in the overview above, for several reasons. The energy numbers for heat in this process could not be derived from these numbers, since no conversion numbers are provided. It is thus unknown at what temperature the water is fed in for the production of steam and what part of the heat really transferred to the process. Still, with the FEDIOL energy numbers a calculation was made to estimate the MJ required in the process (assuming the equivalent of 85 Nm^3 of natural gas/tonne steam (2690 MJ/t steam).

However, the results of this calculation did not match closely with the CO_2 emissions pictured in graph 3–4 in the FEDIOL report, which made it difficult to draw definite conclusions about the energy consumption. Furthermore, the FEDIOL report did not present the distribution of the energy consumption over all processes whereas Schmidt does (Schmidt, 2007). These numbers were needed to know which processes are energy intensive and for knowing how much energy a decarbonisation option can save. Lastly, as mentioned before, the numbers of Schmidt are considered representative since it matches with energy consumption provided by the IPCC (European Commission, 2018; Schmidt, 2007).

3 Oil and fat products and application

The total vegetable oil and fat sector in the Netherlands is responsible for 11.8 million tonnes of imported goods and exports 6 million tonnes of products in 2013 (MVO, 2014). These products are oilseeds, oils or fats. Of the total vegetable oil and fat sector, 54% is for food purposes, 23% is destinated for animal feed, 17% goes to the energy sector and 6% is for the (oleo)chemical industry as is also shown in Figure 7 (MVO & Atos Consulting, 2012).

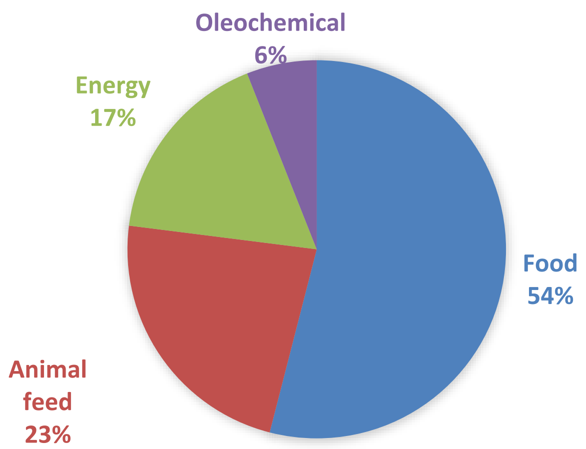

Figure 7 Vegetable oil and fat products used for sectors.

3.1 Products

Food products

The most widely used oils and fats in food products are palm oil, soybean oil, rapeseed oil and sunflower oil. Other oils, like corn oil, coconut oil, olive oil and palm kernel oil, can also be found in food products. Next to full fat products like margarine, frying oil and olive oil, there is a wide range of products used in for example bakery products for the manufacturing of cookies, donuts, cremes and powders. Moreover, the oil and fat is used in the confectionary industry where it can substitute the cacao butter or milk fat to obtain other required characteristics. Fat is also an important ingredient in ice cream, where it determines the structure but also the taste and mouthfeel. Lastly, it is used for fried products like crisps and fries where oil is taken up during frying but also in meat snacks where fat is added as an ingredient (MVO, 2019).

Since the oil is used for many different purposes, which each require other characteristics the oil is modified to obtain the required oil structures. With oil modification, the oil is hardened (hydrogenated), interesterification or fractionated. These processes change the fat structure which ensures that the melting temperature is adapted or the saturated fats are transformed to unsaturated fats in such way that they become suitable for the specific application.

Animal feed
The most used oils and fats in animal feed are crude palm oil, crude soybean oil and distillates of these fats. Fats are usually added to animal feed, to provide enough energy, since fat has a very high energy content. Besides being an energy source, some fatty acids are essential for the animals and are required to be contained in the feed as well (De Haan, 2008). With soybean oil extraction, soybean meal is also produced. This protein-rich fraction is also mainly used in animal feed production.

Energy industry
The plant-based oils can also be used for the production of biofuels. Specifically, biodiesel and biokerosene are manufactured with these oils as a substitution of fossil fuels (MVO, 2019).

Oleochemical products
Last, oil and fat is also used in shampoo, cosmetics, cleaning agents and paint. The oleochemical industry processes the oils into intermediate products which serve as feedstocks in other industries (MVO, 2019).

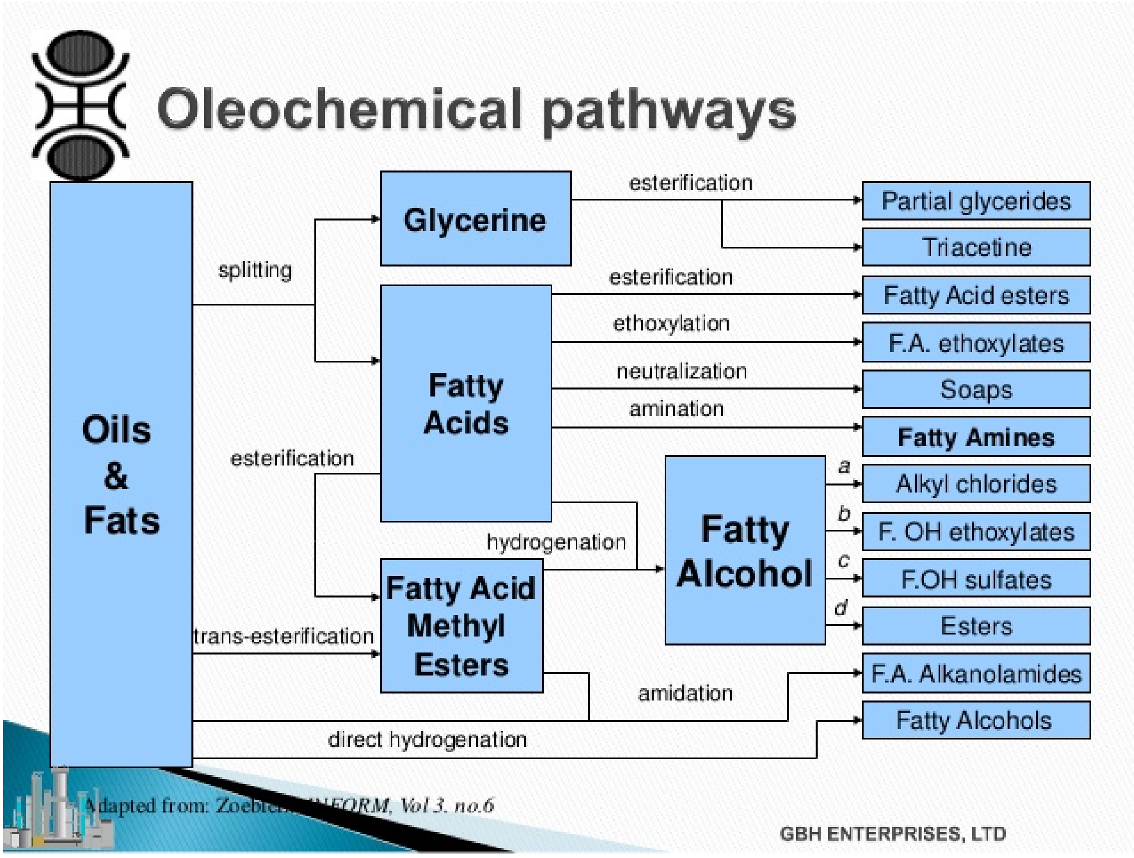

Figure 8 Oleochemical pathways for different final products.

3.2 Oilseed meal

Oilseed crushing produces oil and meal as main products. Nowadays, this protein meal is mainly used in animal feed. However, this protein-rich stream could also be processed further to be suitable for the production of meat replacers. Especially for soy, it is interesting since soybean protein is widely used in the plant-based meat products. Recently, in September 2019 ADM announced already plans to rebuild the factory into a meat replacer manufacturer (AD, 2019). The protein meal side stream can therefore be upgraded from animal feed to human consumption.

Other side streams are from the seed processing, such as hulls and sunflower, soybean, and palm waste can also be used to produce energy. However, this is only a good alternative when the streams are not suitable as food or feed for human and animals. This could be fed into a bioreactor to produce biogas for the production of steam used in the oil processes.

4 Options for decarbonisation

This chapter describes the decarbonisation options for the vegetable oil and fat industry in the Netherlands. The chapter is split in two sections; The first section discusses all sector-specific technology decarbonisation options, so more efficient/sustainable alternatives for the vegetable oil and fat production processes in the Netherlands. The last section focuses on CHP alternatives and other decarbonised heat producing technologies that are not only suitable for this sector, but can also be applied to others. Additionally, in Appendix E, one can find a summarising table with used data, sources and comments.

4.1 Technology-specific decarbonisation options

4.1.1 Membrane technologies

Membrane technologies have an high potential for the application in the oil and fat industry, since many processes can be substituted with a membrane technology as is shown in Figure 9. Nanofiltration (NF), Ultrafiltration (UF) and Microfiltration (MF) are membrane technologies that are applicable in this sector. Membranes used for solvent extraction, degumming are only described in this section, since these techniques are most extensively researched and can save energy consumption. Both are promising techniques for application at industrial scale. Still, complications as selectivity, productivity and unknown lifetime of membranes hinder industrial application of this practices (Coutinhho, et al., 2009; Ladhe & Kumar, 2010). Additionally, a short description of the other techniques; bleaching, dewaxing and deacidification with membranes can be found in Appendix C.

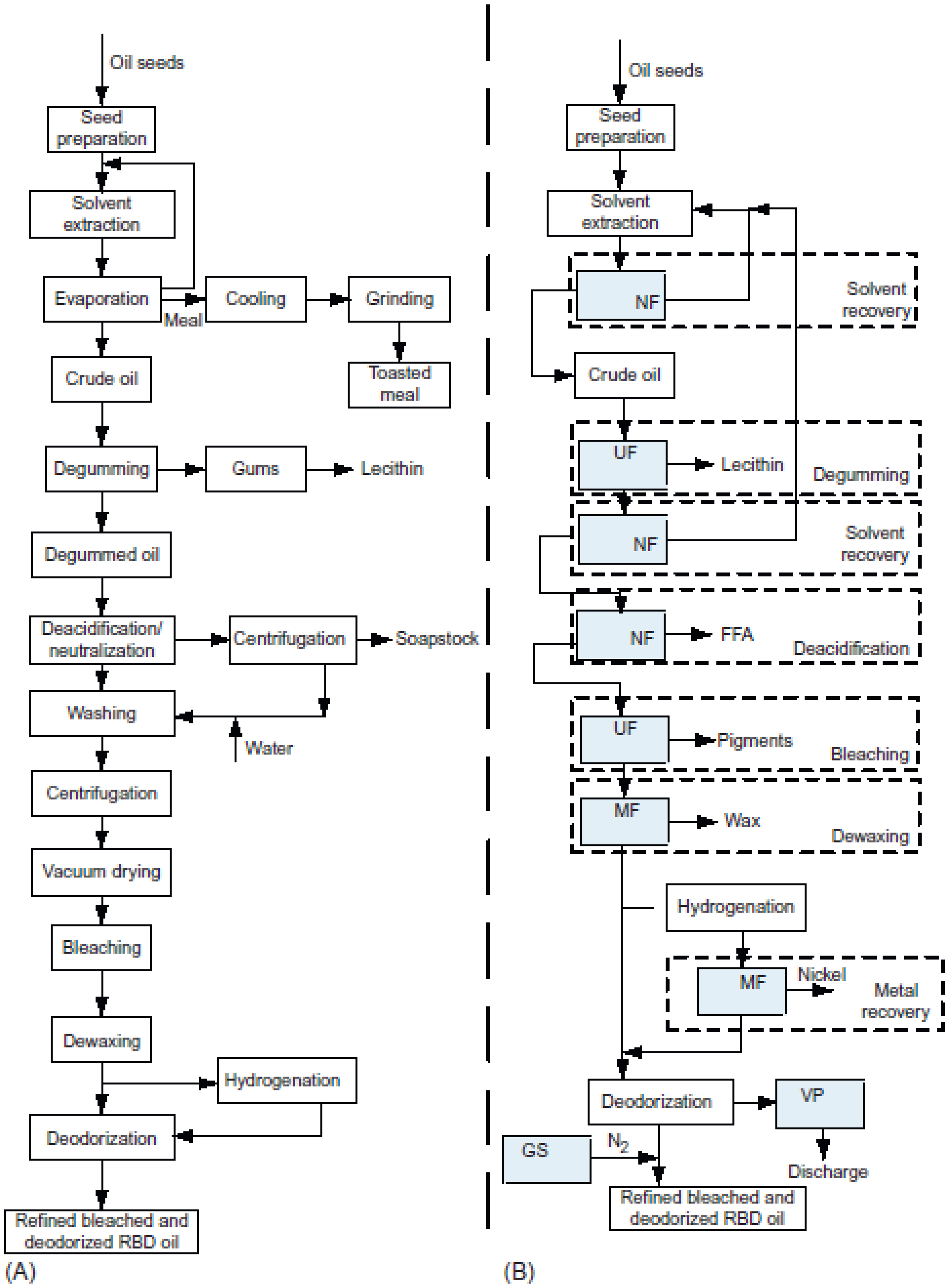

Figure 9 Vegetable oil processing. (A) Conventional Process. (B) Possibilities of substituting conventional processes by membrane-based processes (Ladhe & Kumar, 2010)

Solvent recovery with membranes

The traditional crushing of vegetable oil includes a solvent extraction process, where the most commonly used solvent hexane is removed from the oil. This is an extensive and expensive process which consumes a lot of energy to evaporate all hexane from the oil. Membranes have a good potential to decrease this energy consumption. This is mainly because the separation of hexane from the oil can be performed at room temperature and evaporation energy is thus only partly necessary. Secondly, it is reported that operating, maintenance and manufacturing costs are lower than those of heat processes. Nanofiltration (NF) is the membrane technique most suitable to use for solvent separation. In the research of Firman (2013) the polyvinylideenefluoride-12SI (PVDF) membrane achieved both a high permeate flux and oil recovery for soybean oil. Moreover, the membrane structure did not undergo significant changes in its structural and functional properties during processing (Firman, 2013). However, membrane specifications depend very much on the typical solvent and oil used. Still some hexane would be left in the feed after UF, therefore it should be complemented with conventional distillation. In this manner, first UF is performed to decrease the hexane content, followed by distillation to recover the rest of the hexane (Coutinhho, et al., 2009).

A similar recovery strategy can be used for acetone (RVO, 2019). This is being evaluated by a tech-consortium in the Netherlands. In this context, lifetime estimates and final recovery values are main items of research.

Using membrane technology for the solvent extraction can reduce energy consumption by 30% to 50% (Szekely, Jimenez-Solomon, Marchetti, Kim, & Livingston, 2014) while the pilot plant in the project EEMBAR showed 50% energy reduction (ISPT, SolSep, VITO, IOI Loders Croklaan, & Hogeschool Rotterdam, 2016). This is a general figure that counts for a lot of evaporation processes (Bruinsma & Spoelstra, 2010). Furthermore, Cordis (2019) even reports that membrane-based solvent technology only requires 25% of the heat consumption, 20% of the size of the conventional unit and can reduce process costs by 50% to 85%, compared to the conventional method (CORDIS, 2019). Moreover, the capital investments for an membrane filtration for acetone recovery from vegetable oil is 500 kEUR (ISPT, Energy Efficient Membrane Based Acetone Recovery (EEMBAR) poster, 2016). The payback period of using a membrane for the solvent recovery is >2 years according to research of EEMBAR (ISPT, SolSep, VITO, IOI Loders Croklaan, & Hogeschool Rotterdam, 2016).

Table 6 Membrane solvent extraction specifications.

Characteristics	Value	Source
Plant Capacity	20 kt	Calculated[5]
Lifetime	3–5 years[6]	(SolSep, 2019)
Investment cost	500 kEUR	(ISPT, Energy Efficient Membrane Based Acetone Recovery (EEMBAR) poster, 2016)
Maintenance cost	3% of CAPEX	Assumed
TRL level	6–8	(SolSep, 2019)

[5] See the calculation and assumptions for the plant capacity in Appendix D

[6] This is what can be realised nowadays in solvent recoveries; however, longer lifetimes could occur also for specific applications and in future perspective. Moreover, it also depends on the solvent that is used in the application.

Table 7 Input and output when membranes are used for solvent extraction in the crushing stage of the production of 1 tonne oil.

	Material or energy flows	Processing rapeseed	Processing soybean
INPUT			
	Rapeseeds	2500 kg	5390 kg
	Hexane	1245 kg	1242 kg
	Steam	968 MJ[7]	1355 MJ[8]
	Electricity	344 MJ[9]	185 MJ[10]
OUTPUT			
	Crude oil	1017 kg	1017 kg
	Hexane	1244 kg	1240 kg
	Meal	1369 kg	4084 kg
	Water	104 kg	105 kg
	WTB	10.4 kg	
	Losses		184 kg

Membrane degumming

The degumming process, which is the removal of phospholipids can also be performed using membranes. In the conventional degumming process, crude oil is treated with water, salt solutions or dilute acid to remove the phospholipids. This traditional method produces a considerable loss of neutral oil and a large amount of wastewater. Moreover, the energy consumption is fairly large. Alternatively, separation of phospholipids can also be achieved by the membrane involving technique of UF. Phospholipid molecules tend to form micelles when being in non-polar media, such as hexane or neutral oil. The formed micelles get an average molecular weight (MW) of at least 20,000 dalton. Because the micelles attain this MW, it enables the usage of UF with suitable membranes for the separation of phospholipids. This technology is simple and can be performed on ambient temperatures, therefore it requires less energy. Furthermore, no (less) chemicals are needed for the separation which results in no created waste water. The membrane degumming technique functions better on crude oil/hexane mixtures than for crude oil only. Membranes that can be used for this application are polyvinylidenefluoride (PVDF) and polyimide (PI) of which PVDF is more suitable for industrial usage since it gives higher permeate fluxes (Pagliero, 2001). Moreover, the applicability of a membrane is less oil depending as for solvent extraction. One membrane type can therefore be used for different oils. However, a drawback of using membranes with degumming can be irreversible membrane fouling. A first industrial implementation of degumming was quickly abandoned (in the 1980s) because of underestimated fouling problems and the lack of proper cleaning methods (Hamm, 2013).

Using membrane degumming instead of the conventional degumming process is also be estimated to reduce energy consumption by 30% to 50% (SolSep, 2019). The new input and output flows for the refinery stage when membrane degumming is executed are shown in Table 9.

[7] 50% of energy reduction of conventional solvent extraction taken
[8] Same proportion of energy reduction (~39%) for the crushing stage assumed as for rapeseed since no specific heat energy data on solvent extraction only is known for soybean
[9] Average of 50% reduction used
[10] Same proportion of energy reduction (~18%) for the crushing stage assumed as for rapeseed since no specific electric energy data on solvent extraction is known for soybean

Table 8 Membrane degumming specifications.

Characteristics	Value	Source
Plant Capacity	20 kt	Assumption, same as for solvent extraction
Lifetime	3–5 years[11]	(SolSep, 2019)
Investment cost	500 kEUR	Assumption, same as for solvent extraction
Maintenance cost	3% of CAPEX	Estimation
TRL level	6	(SolSep, 2019)

Table 9 Input and output when using membrane degumming in the refining stage of the production of 1 tonne oil.

	Material or energy flows	Processing rapeseed/soybean
INPUT		
	Crude oil	1017 kg
	Steam	210[12] MJ
	Electricity	94[13] MJ
OUTPUT		
	NBD oil	1000 kg
	Oil losses	17 kg

4.1.2 Enzyme applications

Enzymatic Degumming

Oil degumming, which is a reduction in phospholipids occurring in the neutralisation step of the refining stage, can also be performed with enzymes. The main advantage of using enzymes instead of the conventional physical degumming methods is that it provides an higher oil yield (Hamm, 2013). The process flow of enzymatic degumming can be seen in Figure 10. Enzymatic degumming already exists on industrial scale and the roadmap of MVO states that the whole Dutch oil and fat sector optimised the degumming process and therefore reduced the energy consumption (Bergmans, 2012). However, how this energy saving is accomplished is not mentioned.

The usage of enzymatic degumming can overall reduce CO_2 by 3.4 kg per tonne produced oil and, therefore, decreases energy consumption by 60 MJ per tonne produced oil (Hamm, 2013). It is good to keep in mind that the degumming process is only needed for rapeseed and soybean oil (also sunflower oil), but not for palm oil, since already high quantities of water is involved in the palm oil production process (AOCS, 2019). The investment costs and variable costs are shown in Table 10. Material and energy input for the refinery stage of rapeseed and soybean oil when using enzymatic degumming can be seen in Table 11.

11 This is what can be realized nowadays, however, longer lifetime could occur also for specific applications and in future perspective. Moreover, it depends also on the solvent that is used in the application.
12 Average of 40% energy reduction used
13 Average of 40% energy reduction used

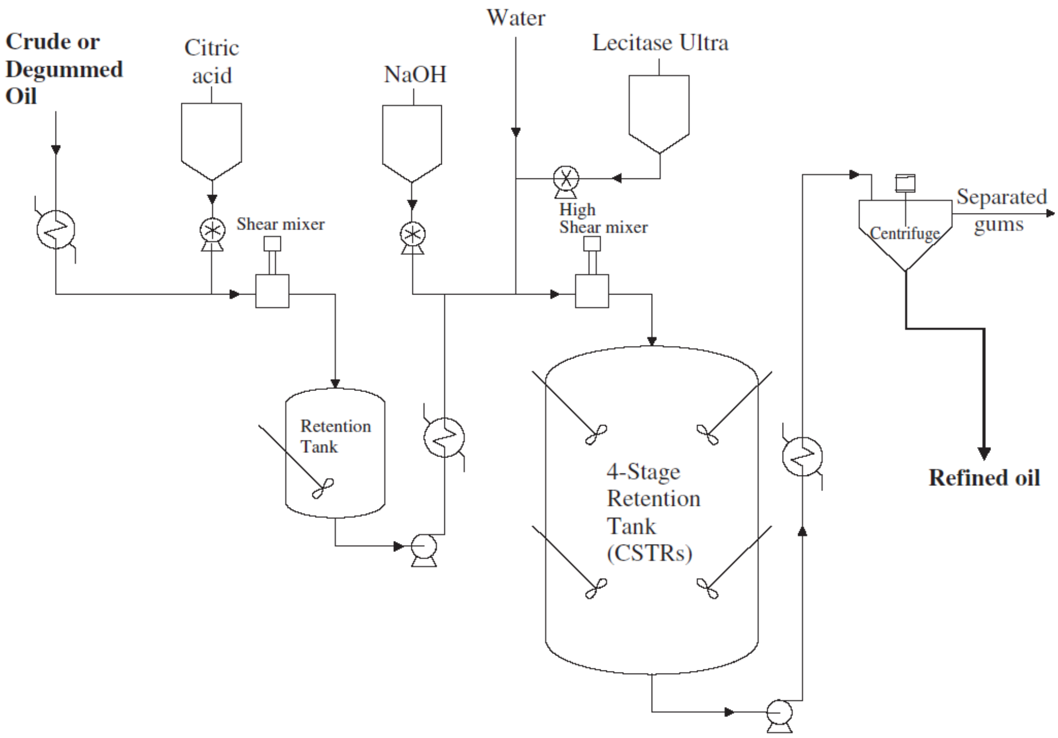

Figure 10 Enzymatic degumming flow sheet (Hamm, 2013).

Table 10 Enzymatic degumming investment specifications.

Characteristics	Value	Source
Plant Capacity	800 t/day	(Munch, 2007)
Yield	Rapeseed 97.7% Soybean 97.1%	(Munch, 2007)
Lifetime	15 years	Estimation
Investment cost	EUR 1.4 million	(Munch, 2007)
Maintenance cost	VOM 6.16 EUR/t; costs do not include oil losses with a value of 19.96–24.56 EUR/t[14]	(Munch, 2007)

Table 11 Input and output when using enzymatic degumming in the refining stage of the production of 1 tonne oil.

	Material or energy flows	Processing rapeseed/soybean
INPUT		
	Crude oil	1017 kg
	Steam	166 MJ
	Electricity	104 MJ
OUTPUT		
	NBD oil	1000 kg
	Oil losses	17 kg

[14] Considering 0.1% in oil losses cost EUR 0.6. So, for rapeseed oil, the total degumming costs result in 19.96 EUR/t and for soybean oil in 24.56 EUR/t

Enzymatic interesterification

As mentioned in Section 2.3.2, oil interesterification can also be executed with enzymes. In the oil modification stage, interesterification is applied to create a desired rearrangement of fatty acyl groups within and between different triglycerides. This can be performed with chemical interesterification (CIE) and enzymatic interesterification (EIE), both applied at industrial scale. The difference between these two processes can be seen in Figure 11 where the process steps and temperatures for CIE and EIE are exposed. The advantages of EIE over CIE is that defines a much simpler process which runs at mild conditions. This leads to less colour formation in the process as well. Moreover, EIE obtains a higher oil yield and therefore less oil is lost than with CIE (Holm, 2008).

The energy consumption of CIE is much higher than for EIE, as is discussed and shown in Section 2.3.4. With the total substitution of EIE for CIE 138 kg steam and 11 kWh electricity per tonne modified oil produced can be saved (Table 3) (Hamm, 2013). The investment and maintenance cost for ana EIE plant with an annual capacity of 34,000 tonnes per year can be seen in.

Table 12. Followed by the material and energy in and output in Table 13 when EIE substitutes the main part of CIE.

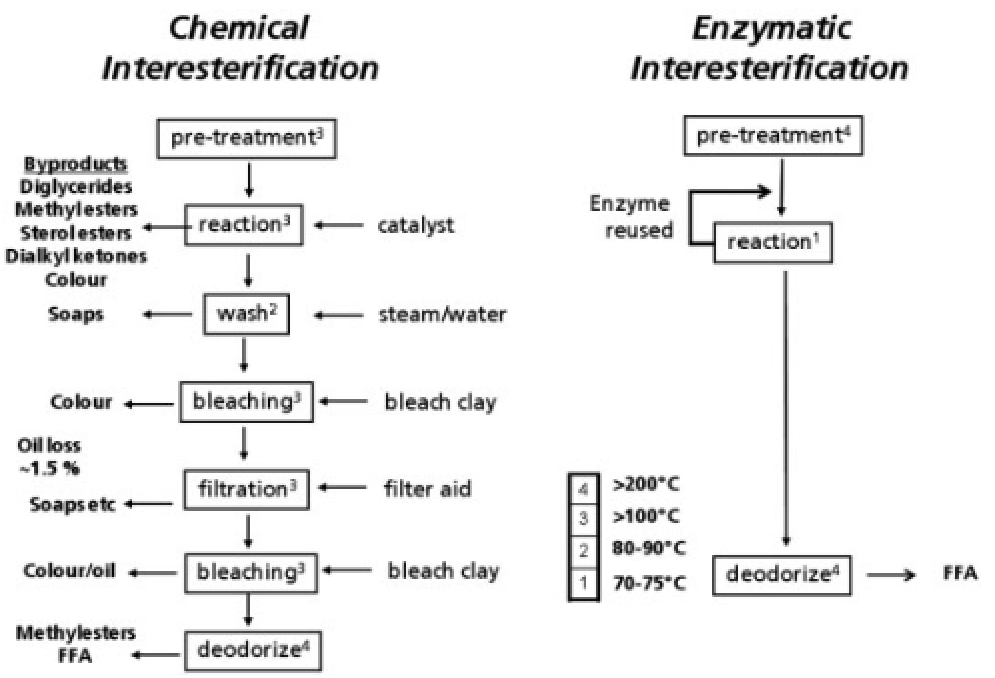

Figure 11 Comparison of process steps and temperatures for CIE and EIE (Holm, 2008).

Table 12 EIE investment specifications.

Characteristics	Value	Source
Plant Capacity	34,000 t/year	(Hamm, 2013)
Lifetime	6 years[15]	(Hamm, 2013)
Investment cost	1.85 MEUR	(Hamm, 2013)
Maintenance cost	OPEX[16] 2.46 EUR/t oil	(Hamm, 2013)

15 Calculated by given costs in Table 6.9 of (Hamm, 2013)
16 OPEX compared to OPEX (Hamm, 2013)

Table 13 Input and output where CIE is replaced with EIE in the oil modification stage of the production of 1 tonne refined oil

	Material or energy flows	Processing rapeseed/soybean	Processing palm oil
INPUT			
	NBD oil	1000 kg	1000 kg
	Steam	59 MJ	76 MJ
	Electricity	25 MJ	29 MJ
OUTPUT			
	Final oil	1000 kg	1000 kg

4.1.3 Vertical ice condensing technology

Vertical ice condensing technology can substitute the conventional deodorisation process. In the refinery stage, deodorisation consumes the most energy as described in Section 2.5. Therefore, energy savings could be obtained explicitly within this process. Deodorisation is performed to remove undesired flavour and/or odorous compounds. The conventional process of doing this is by a stripping process. The stripping agent is usually steam which passes the hot oil for a certain amount of time at low pressure. The volatile compounds are removed in this way at high temperatures of >200 °C (AOCS, 2019). The vertical ice condensing technology of Desmet Ballestra is known to be applied in the Dutch edible oil and fat sector (EproConsult, 2019). This Sublimax ice condenser technology works with ammonia as a refrigeration agent at -30 °C and an under pressure of 1–3 mbar. At this pressure water can only exist in two forms, water and ice. The (odorous) vapour including most of its impurities immediately sublimises (from vapour phase immediately to ice) on the cold surface when it enters the ice condenser. This is subsequently being captured by melting the ice and then disposed as polluted condensate.

There are a lot of advantages of this dry condensing vacuum system compared to the conventional deodorisation method. Firstly, it only consumes around 10–20% of the energy in the traditional method. This is also partly due to the fact that residual heat can be recovered step by step and be reused somewhere else in the oil manufacturing process. Moreover, less steam is needed in the process and a small steam generator is already sufficient. This reduces the investment costs for a steam boiler. Another benefit from the process is that a reduced effluent water flow is created compared to the conventional system (DesmetBallestra, 2015; GEA, 2019; Körting, 2019). Other characteristics can be found in Table 14.

Table 14 Vertical ice condensing technology specifications.

Characteristics	Value	Source
Plant Capacity (Steam)	200 kg/h	(DesmetBallestra, 2015)
Lifetime	>25 years[17]	Estimation
Investment cost	0.72 MEUR	(DesmetBallestra, 2015)
Maintenance cost	3% of CAPEX	Estimation

[17] First installation is installed ~1995 and still running (EproConsult, 2019)

Table 15 Input and output when using vertical ice condensing technology for deodorisation in the refining stage of the production of 1 tonne oil.

	Material or energy flows	Processing rapeseed/soybean	Processing palm oil
INPUT			
	Crude oil	1017 kg	1000 kg
	Steam	104 MJ[18]	150 MJ[19]
	Electricity	33 MJ[20]	40 MJ[21]
OUTPUT			
	Refined oil	1000 kg	1000 kg

4.2 Alternative heating systems

4.2.1 Industrial heat pumps

A suitable industrial heat pump for the vegetable oil and fat industry is the Mechanical Vapour Recompression (MVR). The MVR heat pump can be used for the crushing stage since the temperature range is between 80–150 °C (FME & HighEFF, 2017). The combination of membrane separation with the usage of MVR is proven to be able to save 73% of the conventional energy consumption for the production of rice bran oil (Kong, Miao, Qin, Baeyens, & Tan, 2017). The characteristics of an MVR heat pump can be seen in Table 16.

For the refinery and oil modification stages, higher temperatures are needed than 150 °C and therefore the MVR heat pump should be complemented by another heating system for reaching these temperatures. Other types of heat pumps may be applicable as well, e.g. high temperature heat pumps (HT HP) or chemical heat transformers.

Table 16 Characteristics of an MVR heat pump.

Characteristics	Value	Source
Energy source	Electricity, waste heat	
Capacity	0.25–60 MW	(ECN, 2017)
Efficiency	3.5–10 COP	(Klop, 2015)
Lifetime	10 years	(Walmsley, et al., 2017)
Investment cost	EUR_{2015} 1,300 and 3,100 per kW_e (for a 43 MW_{th} and 2.6 MW_{th} installation respectively)	(Klop, 2015)
Maintenance cost	3% of CAPEX	(ECN, 2017)

18 Average taken of 15% of the traditional energy consumption for deodorisation

19 54.16% steam energy savings in total refining process (same reduction proportion assumed as for rapeseed/soybean oil since no specific deodorisation energy data is available)

20 Average taken of 15% of the traditional energy consumption for deodorisation

21 68.65% electrical energy savings in total refining process (same reduction proportion assumed as for rapeseed/soybean oil since no specific deodorisation energy data is available)

4.2.2 Electric boiler

There are two main types of electric steam boilers that are used at industrial scale for the food and chemical industry: the electrode boiler and the electric boiler. The electrode boilers are available with capacities of up to 70 MWe and can produce saturated steam with temperatures up to 350 °C. Electric boilers have resistance elements instead of electrodes and can therefore heat up air or other gasses to 600 °C. However, the capacity of an electric boiler is typically much smaller with a max of 5 MWe. Since the processing temperatures of the oil production does not exceed 350 °C and higher capacities than 5 MWe are required, the electrode boiler is more suitable for this sector.

The electrode boiler can thus produce saturated steam with temperatures up to 350 °C and 70 bar. The efficiency of these boilers run up to 99.9%, they are robust and are flexible in capacity, and offer a 100% availability. The CAPEX and OPEX of electrode boilers are shown in Table 17.Table 17 It should be stated that the electrode boiler only counts as a decarbonisation when the electricity is produced by a renewable energy source.

Table 17 Characteristics of electrode boilers.

Characteristics	Value	Source
Energy source	Electricity	
Emissions	0	
Capacity	3–70 MWe	(Berenschot, CE Delft, Industrial Energy Experts, & Energy Matters, 2017)
Electrical efficiency	Up to 99.9%	
Lifetime	10–15 years	
Investment costs/CAPEX	150–190 EUR/kW$_{e,2017}$ (incl. installation)[22]	
Maintenance costs/OPEX	1.1 EUR/kW/yr FOM and 0.5 EUR/MWh VOM	

4.2.3 Biogas boiler

Biogas can be used instead of natural gas for the production of steam and/or electricity to achieve CO_2 reduction. The composition of biogas is depending on the exact feedstock and technology used for extraction. Feedstock undergoes anaerobic digestion by microorganisms whose break down the nutritional part of the feedstock into biogas. This biogas can then be used to fire a boiler for the production of steam and/or electricity. A biogas boiler is especially interesting for this sector when it can use the waste streams of the oil and fat processes as feedstock.

Since 2009 Cargill possessed a biomass boiler where agricultural waste streams like cacao hulls and rapeseed and sunflower oil waste is converted to heat and electricity. On a daily basis, 13.2 tonnes biomass can here be converted in 67 tonnes steam (Kuipers, et al., 2015). This biomass boiler in Amsterdam is taken over by Bunge. This facility will be expanded in the future to a production capacity of 25–30 tonnes steam per hour (CE Delft, Studio Marco Vermeulen, & SEO Economisch Onderzoek, 2018).

[22] Note that the electricity connection costs are site specific and can therefore vary significantly

Table 18 Characteristics of a biogas boiler.

Characteristics	Value	Source
Fuel	Biogas	
Emissions	CO_2 (short cycle)	
Capacity	50 to >300 MWth	For gas-fired boilers (IEA, 2010)
Efficiency	87%–90% (LHV)	Estimation
Lifetime	<25 years	For gas-fired boilers (IEA, 2010)
Investment cost	50 EUR_{2015}/kWth	For gas-fired boilers (Energy Matters, 2015)
Maintenance cost	1.5–2.5 EUR/kWth/yr	Estimation

4.2.4 Hydrogen boiler

Hydrogen could be used as an alternative for natural gas for the production of steam. However, the hydrogen fed in the combustion boiler requires to be 'green' before it can be considered as a decarbonisation option. This means that the hydrogen should be produced by electrolysis with renewable electricity with for example Alkaline electrolysis or Proton Exchange Membrane (PEM). Alternatively, the hydrogen can be produced as 'blue' hydrogen, for instance by means of autothermal reforming (ATR) with carbon capture and storage (CCS).

Hydrogen usage in a general industrial boiler is feasible and requires only adaptation of the burner. Therefore, a hydrogen boiler does not require major investments but it does change to a more expensive fuel (E4tech, 2014; VNP, 2018). The characteristics of a hydrogen boiler can be found in Table 19, together with the investment and maintenance costs.

Table 19 Characteristics of hydrogen boilers.

Characteristics	Value	Source
Fuel	Hydrogen	(Johansson, 2005)
Emissions	Water vapour, NO_x	(Johansson, 2005; E4tech, 2015)
Capacity	Same as gas boiler[23]	(E4tech, 2015)
Efficiency	100% (LHV) 85% (HHV)	(VNP, 2018)
Lifetime	15–25 years	(VNP, 2018; E4tech, 2015)
Investment cost	110 EUR/kW	(E4tech, 2015)
Maintenance cost	3.5 EUR/kWth/yr	(E4tech, 2015)

4.2.5 Ultra-deep geothermal

Ultra-deep geothermal energy is another technique that could be used for the production of steam in the edible oil and fat industry. With this technology heat is extracted from hot water and/or steam at the sub-surface of the earth. Geothermal energy is considered ultra-deep when below 4000 meters depth. With this depth, temperatures of 120–140 °C are expected

23 It is not specified in the available literature what the typical size is for a hydrogen boiler. It is assumed that any steam boiler of any size can be converted into a hydrogen boiler by retrofitting the burner. Therefore, the size of industrial H_2 boilers is assumed to range from 50 to > 300 MWth.

to be reached which can thus be useful for heating purposes in the vegetable oil and fat industry (In 't Groen, De Vries, Mijnlieff, & Smekens, 2018; IRENA, 2019). This heat range only covers part of the required temperature levels. Heat will also be needed at temperatures above 150 °C and might be required up to about 250 °C.

To observe if geothermal energy is an option for the Dutch oil and fat sector, the map in Figure 12 is made. The red dots on the map represent the 7 concerning oil and fat companies. In the area around Rotterdam lies theoretically some good technical geothermal potential. This means that Sime Darby Unimills, Cargill Botlek, ADM Europoort and Bunge Botlek could consider geothermal energy as a decarbonisation option, whereas for the other companies this renewable energy supply has less or unexplored potential. The costs and lifetime specification for ultra-deep geothermal energy are shown in Table 20.

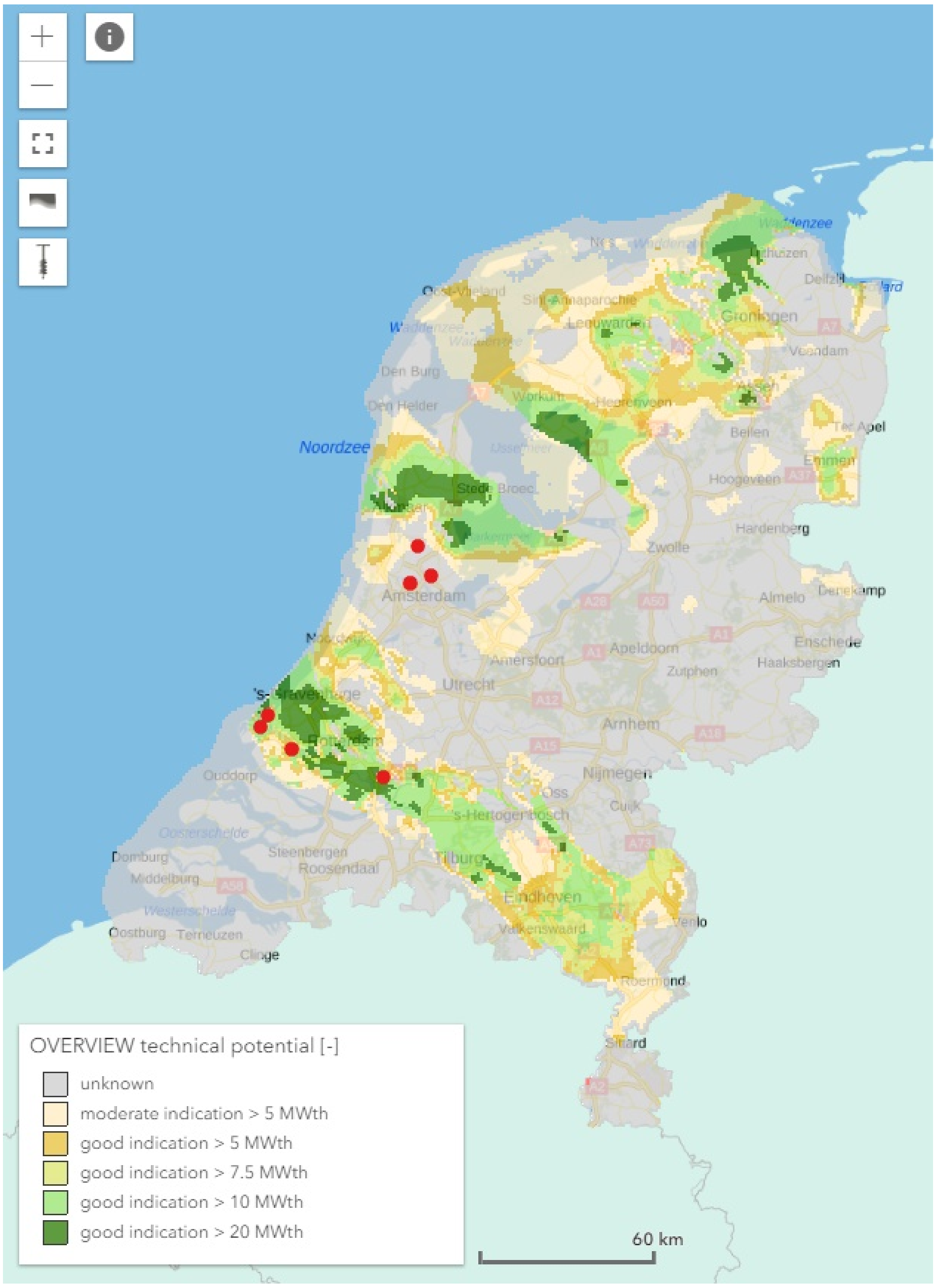

Figure 12 Technical geothermal energy potentials (ThermoGIS, 2019). Red dots indicate vegetable oil production sites.

Table 20 Characteristics of geothermal energy.

Characteristics	Value	Source
Energy source	Electricity, heat	
Emissions	0	
Capacity	17 MW	(In 't Groen, De Vries, Mijnlieff, & Smekens, 2018)
Full load hours	7000	
Electricity use	6063 MWh/yr	
Lifetime	15 years	
Investment cost	2,509 EUR/kWth	
Maintenance cost	107 EUR/kWth/yr FOM & 0.0076 EUR/kWhth output	

5 Discussion

The Dutch vegetable oil industry can technically combine decarbonisation options for achieving zero emissions. A combination energy efficiency improvement, by membrane processes, enzyme technologies and the vertical ice condensing technology, with sustainable energy supply with e.g. electric boiler, heat pumps, biogas, hydrogen or ultra-deep geothermal can lead to potential zero fossil carbon emissions. Since a temperature of 280 °C is required in the vegetable oil processing, it is not enough to use only an MVR heat pump or ultra-deep geothermal energy. Therefore, these technologies should be complemented with another sustainable energy supply that can provide these elevated temperatures. Furthermore, cooperation between different companies can be advantageous when implementing a new sustainable energy supply unit. Especially for ultra-deep geothermal technology, companies in the same area could cooperate to realise a geothermal energy unit and share the costs and the harvested energy involved.

The usage of membranes in the vegetable oil and fat industry seems to have a huge potential for a less energy intensive oil production process. Nevertheless, it is still difficult to realise this technique on industrial scale. Firstly, because not many membranes stay intact when coming into contact with hexane. Additionally, fat particles are a dense substance which can cause problems by fouling the pores in the membranes. For this reason, the fat needs to undergo additional preparation processes to remove the components that cause fouling, before it can run through the membranes. Moreover, the membrane technology is also depending on the oil type. Not all rapeseed, soybean and palm oil can use the same membrane process unit in a factory. Therefore, membrane usage is very specific when it comes to application and implementation in the vegetable oil and fat industry. Lastly, what is observed is that converting an existing factory for adding a membrane process unit is rather costly and thus often not attractive. For newly built installations the purchase of membrane technology is more obvious (SolSep, 2019; EproConsult, 2019).

The cheapest alternative heating system option is the biomass boiler. This is due to the low expenses for the biomass fuel, which are much lower than the fuel price for a hydrogen and electric boiler. It explains why some companies in the Dutch vegetable oil and fat industry purchased a biomass boiler as they did in recent years. Factories can feed the biomass boiler with by-products from oilseed processing (Schmidt 2007, Kuipers et al. 2015). When the biomass feed consists mainly of these process residues, purchasing a biomass boiler becomes very cost effective. However, if not enough processing residue biomass is produced for the energy required, other biomass fuel sources should be fed in. Most of these alternative options are more expensive than the processing residues. Additionally, biomass fuel prices are also region dependent. Some countries do have much more biomass than others and the supply of these biomass fuels (for example wood) can therefore fluctuate in prices among regions (IRENA, 2014). Future prospects regarding limited supply and large demand to biomass products may complicate the business case.

Next to the decarbonisation options, also heat recovery is applicable in the vegetable oil and fat industry. The MJA reports (Meerjarenafspraak, English: multi-annual agreement) (RVO, 2018) indicate that the companies within the vegetable oil and fat industry in the Netherlands have increased their energy efficiency over the past 20 years, each year by approximately 2%. This was partly achieved by the recirculation of residual heat (MVO, 2014; RVO, 2018). However, exact numbers on the amount of heat recovery that has been reached and what still can be realised is unknown. Therefore, it is expected that even higher energy efficiencies can be realised. Adding this heat recovery to the technology-specific decarbonisation options for the manufacturing of oils will lead to higher possible efficiencies.

Another discussion point is whether the consumer perception can be changed. The consumers expect that a clear vegetable oil is of high quality. While actually a more turbid oil could for some applications be suitable and even have better properties. Nevertheless, companies execute refining processes to obtain this clearer oil to fulfil the consumer demands. These oil clearing processes could be avoided if consumer perception of high-quality oil changes from a clear oil to a more turbid oil.

Last but not least, decarbonisation of all industries depend on what kind of energy infrastructure will be developed in the Netherlands. The decarbonisation options given for the vegetable oil and fat industry rather intend to a more electrified process. However, use of hydrogen or other green gas (or biogas) could also be an option as fuel input for the boiler. Uncertainty may be detrimental in the decision-making process. Certainty about the kind of infrastructure that is developed will likely lead to choosing the most efficient solution for a given situation, and avoid future inefficiencies in (in hindsight) unnecessary energy conversion.

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Appendix

Appendix A

The material usage of rapeseed oil and soybean oil refining are shown the table below (Schmidt, 2007).

Table 21 Material uses in the refining stage. All numbers are related l t NBD oil. (Hansen, 2006)

Ancillaries	Neutralisation	Bleaching	Deodorisation
Phosphoric acid	0.8 kg	-	-
Sodium hydroxide (NaOH in 50% water)	2.1 kg	-	-
Sulphuric acid (100%)	1.9 kg	-	-
Bleaching earth	-	9.0 kg	-
Tap water	27.3 kg	-	-

For refining palm oil, slightly other material and material qualities are used, which are shown below.

Table 22 Material uses in the refining stage. All numbers are related l t NBD oil. (UPRD, 2004)

Ancillaries	Neutralisation	Bleaching	Deodorisation
Phosphoric acid	0.25 kg	-	-
Sodium hydroxide (NaOH in 50% water)	2.9 kg	-	-
Bleaching earth	-	4.53 kg	-
Tap water	700 kg	-	-

The materials in the oil modification processes are subtracted from Hamm (2013) and shown below.

Table 23 Basic cost estimation of edible oil modification processes. All costs in US dollars.

			High-pressure hydrogenation (+post-treatment)	Chemical IE (+post-treatment)	Enzymatic IE	Palm oil fractionation	Palm olein fractionation
Plant capacity (tpd)			180	140	100	200	100
Annual capacity (at 340 working days/year)			61 200	47 600	34 000	68 000	34 000
Capital investment		*Equipment and engineering*	$ 1 500 000	$ 1 100 000	$ 1 000 000	$ 1 600 000	$ 2 000 000
		Structural works	$ 600 000	$ 500 000	$ 450 000	$ 800 000	$ 900 000
		Installation	$ 750 000	$ 700 000	$ 600 000	$ 855 000	$ 900 000
ROI			**$ 2 850 000**	**$ 2 300 000**	**$ 2 050 000**	**$ 3 255 000**	**$ 3 800 000**
Capital cost/tonne			**7.8**	**8.1**	**10.0**	**8.0**	**18.6**
Annual maintenance cost			$ 40 000	$ 40 000	$ 50 000	$ 50 000	$ 60 000
Operation costs		*Manpower*	2	1	1	1	1
Consumption/tonne	Steam	kg/tonne oil	30	150	12	40	63
	Electricity	kwh/tonne oil	10	15	4	10	16
	Ni catalyst	kg/ton oil	2	0	0	0	0
	Hydrogen	m^3/tonne	50	0	0	0	0
	Na0Me catalyst	kg/tonne oil	0	1	0	0	0
	Enzyme	kg/tonne oil	0	0	0.4	0	0
	Citric acid	kg/tonne oil	0.5	2	0	0	0
	Bleaching earth	kg/tonne oil	1.5	5	0	0	0
	Oil losses	kg/tonne oil	-3	18	0.6		0
Utility unit costs						**Operation cost/tonne**	
$ 90 000	Manpower	$/year	$2.9	$1.9	$2.6	$1.3	$2.6

Appendix B

The Figures below are copied from the Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries (European Commission, 2018).

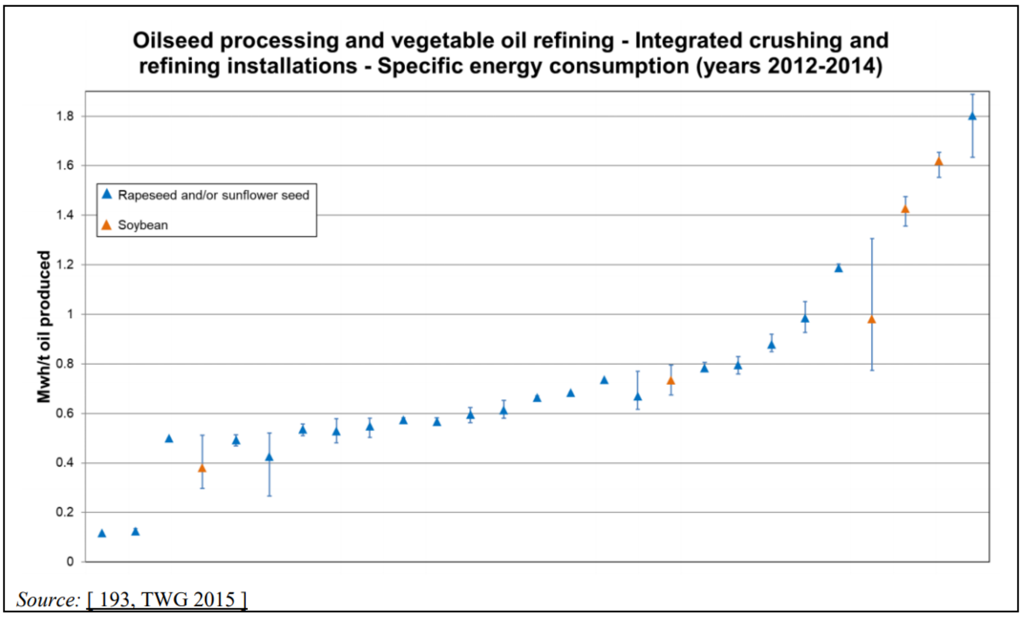

Figure 13 Specific energy consumption (MWh/tonne of oil produced) in integrated crushing and refining. The different crushing and refining installations are shown next to one another and sorted based on specific energy consumption.

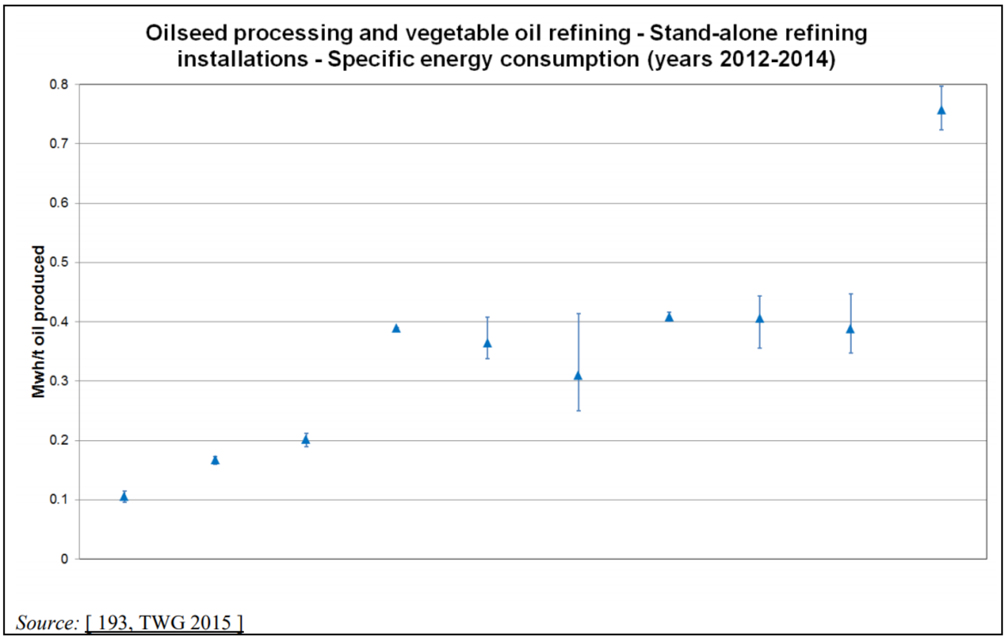

Figure 14 Specific energy consumption (MWh/tonne of oil produced) in stand-alone refining. The different refining installations are shown next to one another and sorted based on specific energy consumption.

Appendix C

Enzyme-assisted extraction processing (EAEP)

Enzyme technologies can be used in the oil crushing stages. The oil can be extracted by enzyme-assisted extraction processing (EAEP) but enzymes can also play a role in the pre-treatment by breaking the cell walls and facilitate the oil extraction which will lead to higher oil yields. As a consequence, using enzymes can lead to a 20–30 minute reduction in oil extraction time (Liu, Gasmalla, Li, & Yang, 2016). Additionally, enzymes can avoid the usage of hexane, which is better for environmental and safety reasons. Enzymes can thus substitute the mechanical and solvent extraction process steps in the crushing stage. Furthermore, oil that is extracted by EAEP have a better quality than oils extracted by these traditional methods in terms of FFA content, iodine value, saponification number, fatty acid composition, peroxide value, refractive index, density colour etc. at moderate conditions (Liu, Gasmalla, Li, & Yang, 2016). EAEP is already widely used on industrial scale but is has also already made the transformation to industrial processes. However, more research is needed to press the costs and obtain the right products when applying EAEP at industries (AOCS, 2019). Nevertheless, a techno-economic analysis is performed and presents the investments costs and O&M costs for upscaling EAEP (Cheng, Zhang, Rosentrater, Sekhon, & Wang, 2016). However, in terms of energy usage, more energy in terms of steam and electricity is required for EAEP compared to solvent extraction and expelling (Cheng, Zhang, Rosentrater, Sekhon, & Wang, 2016).

Membrane bleaching

In the conventional bleaching process, colouring compounds are removed by usage of an active bleaching clay or carbon at elevated temperature. Usage of UF membrane technology can also reduce the colouring compounds in the vegetable oil processing. It comes along with several advantages as less energy consumption and less costs since no expensive clay is involved. However, this technique is only applied on laboratory scale but could be effective also on industrial scale. Nevertheless, the membrane bleaching should get a boost in the coming years for realistic commercial application (Ladhe & Kumar, 2010; Reddy, Kawakatsu, & Nakajima, 2001)

Membrane dewaxing

Dewaxing is a step during the refinery stage before bleaching and deodorisation as can be seen in Figure 3. Using membranes for the dewaxing process is already executed on industrial scale. In Japan, a hollow fibre MF membrane is used for the dewaxing of sunflower oil. The fouling of these membrane is avoided by periodic backflushing of nitrogen under high pressure (Ladhe & Kumar, 2010).

Membrane deacidification

A lot of research has also been performed for the usage of membranes in the deacidification step, which is also known as neutralisation. In the conventional method, this is mostly performed by alkali refining but it can also be done by physical refining. The relatively small molecular weight between FFA and triglycerides makes it hard to separate them by membrane technology. However, it is possible to separate the FFA and triacylglycerols by the usage of polyamide membranes. In this way less chemicals are required which results in less waste water (Szekely, Jimenez-Solomon, Marchetti, Kim, & Livingston, 2014). Although, a lot of research is executed on this topic, the development of industrial viable membrane deacidification process is still challenging (Ladhe & Kumar, 2010).

Appendix D

Plant capacity and costs for membrane solvent extraction are based on the report and the poster of EEMBAR (ISPT, Energy Efficient Membrane Based Acetone Recovery (EEMBAR) poster, 2016; ISPT, SolSep, VITO, IOI Loders Croklaan, & Hogeschool Rotterdam, 2016). In the report it is stated that the membrane technology reduces energy consumption with 50%. The poster says that it reduces energy consumption by 12.4 TJ/year, so 50% corresponds to 12.4 TJ. Based on the findings in Smith (2007), solvent extraction requires 1238 MJ heat for rapeseed oil (for soy, there is no specified data). The total energy requirement according to the EEMBAR poster should than be 2 x 12.4 = 24.8 TJ/year. Dividing this number by 1238 MJ gives ~20 kt/year. So, the investment costs are calculated to be relevant for a plant of 20 kt capacity.

Biomass is calculated by the amount of rapeseed and soybean that is crushed. It is known that 10.4 kg biomass can be used to produce biogas per tonne rapeseed oil. For soybean oil this amount is 189 kg per tonne soybean oil. From Schmidt (2007) it is also known that the bleaching earth used in the refining stage can be fed into the biomass boiler. For every tonne of rapeseed oil and soybean oil, this amount is 14 kg. The amount of energy in biogas produced from rapeseed waste is 4.2 MJ per kg waste, same is assumed for the waste of soybeans. The bleaching earth delivers 10.2 MJ gas per kg. The biomass boiler has an efficiency of 88.5% so the total energy that can be used in the system is 41.47 kt CO_2. A biomass boiler that produces 67 tonnes per day is already been used. This means that some part is already caught away. The biomass boiler produces 24.5 kt steam in a year which saves 3.8 kt CO_2 emissions. Therefore, the total amount of CO_2 emissions that can be avoided for the total sector decreases from 41.47 to 37.7 kt per year. This is 14% of the total carbon emissions of 2018.

For EIE, the difference in OPEX between CIE and EIE without fuel costs is USD 2.10. However, the difference in annual maintenance costs also needs to be added, which is USD 0.63. In total, the OPEX is USD 2.73 which equals EUR 2.46 per tonne oil.

Appendix E

Technology-specific decarbonisation options	Steam per tonne product saved (MJ)	kg CO_2 per tonne product saved	Costs per tonne product [EUR/t]			References	Comments Energy	Comments costs
			Rapeseed	***Soybean***	***Palm***			
Membrane solvent extraction	619–866	35–49	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	x	(ISPT, SolSep, VITO, IOI Loders Croklaan, & Hogeschool Rotterdam, 2016; Szekely, Jimenez-Solomon, Marchetti, Kim, & Livingston, 2014)	Using membrane technology reduces energy consumption by ~50% taken 618.5 MJ steam saved in rapeseed oil which is 39% steam energy reduction in crushing stage -> also assumed for soybean Same reduction and method for electricity energy savings	CAPEX 500 kEUR for calculated capacity of 20 kt so 25 EUR/t OPEX assumed 3% of CAPEX
Membrane degumming	16	0.9	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	x	(SolSep, 2019; ISPT, SolSep, VITO, IOI Loders Croklaan, & Hogeschool Rotterdam, 2016)	40% reduction energy assumed which is 16.4 MJ steam and 8 MJ electricity for degumming	Same costs assumed as for membrane solvent extraction
Enzymatic degumming	60	3.4	CAPEX 6 OPEX 0.2	CAPEX 6 OPEX 0.2	x	(Hamm, 2013; Munch, 2007)	decreases energy consumption overall with 60 MJ per tonne produced oil (due to less crude oil is needed for the production of 1 tonne refined oil) same proportion electricity reduction assumed	for a plant of 800 t/day MEUR1.4 assuming 90% of the year producing with additionally 90% utilisation factor when used 236520 t/year and OPEX estimated 3% CAPEX

Technology-specific decarbonisation options	Steam per tonne product saved (MJ)	kg CO_2 per tonne product saved	Costs per tonne product [EUR/t]			References	Comments Energy	Comments costs
			Rapeseed	*Soybean*	*Palm*			
Enzymatic interesterification	385[24]	7.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	(Hamm, 2013)	100% substitution of EIE for CIE saves 384.9 MJ steam and 39.6 MJ elec per tonne oil that is EIE instead of CIE	USD10 capital cost/t USD23.5 operation cost/t converted to EUR
Vertical Ice Condensing technology	122–178	7–10	CAPEX 3.5 OPEX 0.1	CAPEX 3.5 OPEX 0.1	CAPEX 5.1 OPEX 0.15	(Schmidt, 2007; DesmetBallestra, 2015; GEA, 2019; Körting, 2019)	Only consumes 15% of traditional deodorisation process -> saves 122,4 MJ steam in rapeseed/soybean oil and 71.4 MJ electricity and 177.6 MJ steam and 86.5 MJ for palm oil (same proportion energy savings assumed for palm)	USD800,000 capital costs for production of 200 kg/h steam 21.6 MJ heat for rapeseed/soybean and 31.35 MJ heat for palm oil. 2789 kJ/kg gives 7.74 kg and 11.24 kg steam per tonne, so 26 t/h rape/soy and 18 t/h palm. OPEX estimated to be 3% of CAPEX
Alternative heating systems								
Industrial heat pumps (MVR)	0–724	0–41	CAPEX 8 OPEX 0.2	CAPEX 11 OPEX 0.3	x	(Kong, Miao, Qin, Baeyens, & Tan, 2017; ECN, 2017)	33% steam energy saved in production of Rice bran crude oil (only crushing) Same assumed for rapeseed/soybean	CAPEX average 2200 EUR/kW OPEX 3% of CAPEX assuming a COP of 5
Ultra-deep geothermal energy	0–724	0–41	CAPEX 51 OPEX 2.2	CAPEX 71 OPEX 3	x	Groen et al., 2018	Same energy saving assumed as for Industrial heat pumps, since it produces same temperatures 33% steam energy reduced	CAPEX 2509 EUR/kW OPEX 107 EUR/kW assumed efficiency of 90%

[24] This is the amount of energy saved of 1 tonne oil that is modified by EIE instead of CIE. Not all oil is interesterificated.

Technology-specific decarbonisation options	Steam per tonne product saved (MJ)	kg CO_2 per tonne product saved	Costs per tonne product [EUR/t]			References	Comments Energy	Comments costs
			Rapeseed	***Soybean***	***Palm***			
Electric boiler (Electrode)	517–2657	29–150	CAPEX 13 OPEX 0.1	CAPEX 16 OPEX 0.1	CAPEX 3 OPEX 0.02	(Berenschot, CE Delft, ISPT, 2015; Berenschot, Energy Matters, CE Delft, Industrial Energy Matters, 2017)	Natural gas completely substituted	With a company that produces 500000 tonne oil/year a boiler capacity of 9.11–46.81 MW is needed 150–190 EUR/kWe (EUR170 is taken) CAPEX and 1.1 EUR/kWe OPEX efficiency of 99.9%
Biogas boiler	517–2657	29–150	CAPEX 4 OPEX 0.2	CAPEX 5 OPEX 0.2	CAPEX 1 OPEX 0.04	(Energy Matters, 2015)	Natural gas completely substituted	Average efficiency 88.5% CAPEX 50 EUR/kW OPEX average 2 EUR/kW
Hydrogen boiler	517–2657	29–150	CAPEX 10 OPEX 0.3	CAPEX 11 OPEX 0.4	CAPEX 2.2 OPEX 0.07	(E4tech, 2014; VNP, 2018)	Natural gas completely substituted	Efficiency averaged 90% LHV CAPEX EUR110/kW OPEX 3.5 EUR/kWth/yr