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Cost-effectiveness of decarbonisation options for the vegetable oil and fat industry in the Netherlands

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Abstract

Technologies for the reduction of the carbon dioxide emissions in the Dutch vegetable oil and fat industry are identified and characterised by their costs and carbon emission reduction potential. The Dutch vegetable oil and fat industry consists of seven companies each producing more than 10 kton CO_2 per year, emitting a total of 0.36 Mton CO_2 in 2018. In this study, Marginal Abatement Cost (MAC) curves are created to obtain an overview of the most cost-effective decarbonisation options. Both energy efficiency improvement technologies and alternative heating systems are required to achieve full decarbonisation of this industry. The energy consumption for the vegetable oil processing can be reduced by 44%, 45% and 57% for rapeseed oil, soybean oil and palm oil, respectively. The Vertical Ice Condensing technology is the most cost-effective decarbonisation option and a biogas boiler is the most-effective alternative heating system that can supply the energy in all stages of the vegetable oil processes. However, the energy substitution by a biogas boiler is limited by the biomass available from processing residues. Therefore, an electric boiler is required to deliver the residual energy supply to realise zero carbon emissions. The cost-effective decarbonisation options can abate cooperatively 38% and 40% of the total CO_2 emissions for 2020 and 2030 respectively.

Keywords: energy efficiency, vegetable oil and fat industry, marginal abatement costs, carbon emissions.

1. Introduction

In the Dutch Climate Agreement (‘*Klimaatakkoord’*), presented in June 2019, the main purpose is to reduce the national CO_2-emissions with 49% in 2030 and with 95% in 2050 relative to 1990 (Klimaatakkoord 2019). Every sector, including the industry, has to propose their measures and targets to collectively reach the goals of CO_2-emission reduction. The vegetable oil and fat industry in the Netherlands is one of these industry emitters, having seven companies participating in the European Union’s Emission Trading System (EU-ETS) producing more than 10 kton CO_2 per year responsible for a total of 0.36 Mton CO_2 in 2018 (NEa 2019).

The past few years a lot of research is done into more sustainable ways to process vegetable oils, particularly

rapeseed/soybean/palm oil. Not only processes that lead to an overall more efficient energy consumption have been explored but also extensive Life Cycle Assessments (LCA) on the production of both the separate oils and on all three together have been performed. (Li, et al. 2006, Nucci, et al. 2014, Schmidt 2007, Schneider and Finkbeiner 2013). The use of enzymes is one of these energy efficient process options in the vegetable oil industry. One of these applications is the degumming, the removal of phospholipids, in the refining stage of oil with enzymes, which is described by Hamm and in the AOCS (American Oil Chemists' Society) lipid library but also in other papers (AOCS 2019, Hamm 2013, Yang, et al. 2008, Jiang, et al. 2011). Enzymes can also be used for oil modification, to create a desired rearrangement of fatty acyl groups. This interesterification process can be both perfomed with chemicals and enzymes. Enzymatic interesterification was already researched in the 90's and is nowadays implemented on industrial scale (Hamm 2013, Holm 2008, Foglia, Petruso and Feairheller 1993, Xu, et al. 1998).
Another energy efficient applicable technology is the use of membranes in the vegetable oil and fat industry. Membrane technologies seem to have a high potential for a more sustainable and less energy intensive oil production process, since many conventional processes can be substituted by membranes (Cheryan 2005, Ladhe and Kumar 2010). Especially membrane degumming and the separation of solvent from oil with membranes in the solvent extraction process are currently in active development. However, both are not yet applied on a commercial scale (Cheryan 2005, Coutinhho, et al. 2009, ISPT, et al. 2016, Ladhe and Kumar 2010, Szekely, et al. 2014). One exception is a membrane degumming industrial plant that was implemented in the 1980s but got abandoned soon after because of underestimated fouling problems and the lack of proper cleaning methods (Hamm, 2013). Another way to decarbonise the vegetable oil and fat industry is to replace the currently used steam boilers and combined heat and power (CHP) plants by sustainable alternative heating systems like heat pumps, electric boilers and hydrogen boilers. The final energy consumption remains the same in most of these options while the CO_2 emissions decrease.

Despite the fact that several studies have looked into one of the aforementioned options, an overview of all possible decarbonisation options including their expenses does not exist for the edible oil and fat sector. Therefore, the research question is: how can the Dutch vegetable oil and fat industry decarbonise and what are the associated costs? For this study, the seven EU-ETS vegetable oil and fat companies in the Netherlands are considered to be representative for the whole Dutch industry. The ambition is to achieve zero scope 1 CO_2 emissions, which are the direct emissions that occur from owned or controlled sources (Greenhouse Gas Protocol, 2019). Moreover, the aim is to accomplish full decarbonisation of the industry in the most cost-effective way, whereby the decarbonisation options mentioned are all applicable on industrial scale in 2030. Therefore, this article investigates the possibilities and creates MAC (Marginal Abatement Cost) curves to show both the cost per unit of carbon dioxide abated as the reduction potential (Kesicki and Strachan 2011). A basis scenarios with fuel prices for 2020 and 2030 are used to observe the most relevant decarbonisation options in both years. Moreover, a high and low fuel price scenario for 2030 is created to analyse the fuel price sensitivity. Lastly, the influence of using a private discount rate instead of a social discount rate is investigated.

The remainder of this paper is structured as follows. The methods of data exploration and making MAC curves are discussed in Section 2. The oil processes are briefly described in Section 3 and the input of the data are noted in Section 4. The results and discussion are presented in Section 5 and 6. Lastly, the conclusions of this research can be found in Section 7.

2. Methodology

The general set-up of this research is as follows: first, a literature study is performed in order to understand the processes occurring in this industry. Specific data on the companies such as production capacity, produced end-product, etc. are used to identify the most common production processes in the Dutch vegetable oil and fat industry. Employing these findings, mass and energy balances are set up for these production processes. Subsequently, the carbon emissions are calculated. The obtained results are checked by experts from national research institutes which are part of the MIDDEN (Manufacturing Industry Decarbonisation Data Exchange Network) project initiated by PBL Netherlands Environmental Assessment Agency and Netherlands Organisation for Applied Scientific Research TNO. Field experts from the industry also examine these values.

The data is analysed to identify the critical control points: the processes which use most energy and/or involve most carbon emissions. Given these results, more sustainable processes that can potentially substitute the critical control points are explored in literature. In this way, a list of decarbonisation options is created. This list is then presented to field experts who can give feedback and suggest additional decarbonisation options which can replace the current processes with high energy consumption processes. Another method to decarbonise is to substitute the current heating systems, steam boilers and CHP plants. Sustainable alternative heating systems that reduce the CO_2 emissions are researched likewise in literature and added as decarbonisation option when they are applicable to this industry. It is investigated whether the combination of these sustainable technologies could result in decreased CO_2 emissions, aiming for 49% reduction in 2030 and/or zero carbon emissions in 2050. Lastly, the costs of the decarbonisation options are explored to analyse their feasibility. The expenditures are found in literature or via communication with experts. MAC curves are created for three different future scenarios to gain knowledge about the most cost-effective decarbonisation options.

1.1 Mass balance

Mass flow analysis is executed by setting up mass balances throughout the production chains of rapeseed, soybean and palm oil. Here the law of conservation of mass, which describes that no mass can be created nor destroyed, is expressed in the equation:

$$\sum\varphi_{x,in} = \sum\varphi_{x,out} \qquad (1.1)$$

Where $\varphi_{x,in}$ [kg] is the mass of the streams entering the process and $\varphi_{x,out}$ [kg] is the mass of the streams coming out of the process. No accumulation of materials is considered and therefore equation 1.1 is valid.

1.2 Energy balance

The energy requirement of the rapeseed, soybean and palm oil extraction processes are partially derived from literature. If not, the energy balances used rely on the first law of thermodynamics, which implies the conservation of energy. Energy does not get lost (equation 1.2). The energy flows (Q_j) were calculated with the use of equation 1.3:

$$Q_{in} = Q_{out} + Q_{losses} \qquad (1.2)$$

$$Q_j = \varphi_j * c_{pj} * (T_j - T_0) \qquad (1.3)$$

Q_j is calculated by multiplying the mass flow of the stream j (φ_j) with the corresponding specific heat (c_{pj}) and the temperature T_j of stream j. In case of a phase transition, equation 1.4 applies. The difference with equation 1.3 is the addition of $\Delta H_{phase,j}$, which is the energy required to change to another phase (Appendix C). In case of gaseous streams, ΔH is the heat of evaporation and in case of solids it is the heat of crystallisation.

$$Q_j = \varphi_j * cp_j * (T_j - T_0) + \Delta H_{phase,j} * \varphi_j \qquad (1.4)$$

1.3 Carbon emissions and decarbonisation options

The carbon emissions are related to the mass and energy balances for the manufacturing of the final oils. The carbon emitted in the processes is calculated using the generic national emission factors from Zijlema (Zijlema 2017). These calculated carbon emissions are subsequently compared to the reported ETS emissions for the different companies. This makes it possible to check the emissions and make satisfatory estimations for each of the product types and quantities manufactured at each production site. When the most energy consuming and carbon emitted processes are identified, decarbonisation options will be explored that could substitute the current technologies or could be added to the process chain in order to obtain zero emissions in the future. Therefore, the technical and theoretical potential is determined in order to understand what can be achieved by which decarbonisation technology in the present and what contribution this technology is expected to deliver in the future (Blok and Nieuwlaar 2016). For all the decarbonisation options the one-off initial investment costs, also known as capital expenditure (CAPEX), and the yearly costs which are the operational expenditures (OPEX) are determined per ton oil produced or per kW for the alternative heating systems.

1.4 Industry and data validation

First, a literature study is performed about the processing of vegetable oils and the available decarbonisation options. While researching the processes occuring in de vegetable oil industry, including the mass and energy balances of each process, the Dutch oil and fat branch organisation MVO was contacted. A meeting was arranged where the processes occuring for the production of rapeseed, soybean and palm oil were validated and adapted. Moreover, mass and energy balances were shared for possible feedback provision by industry experts. After exploitation of the decarbonisation options in literature, expertise from specialists at PBL and TNO both involved in the MIDDEN project was utilised, especially within the area of alternative heating systems. Due to the high amount of research performed within these institutes concerning various heating systems, sources and knowledge were provided. For sector specific decarbonisation options with enzymes, sufficient literature was available. For membrane technology within the vegetable oil and fat sector, SolSep BV, which is a membrane expert, was contacted for the required specific information. They provided additional feedback on the correlated numbers and text in this article.

1.5 Marginal abatement cost curves

In order to represent the outcome of the techno-economic analysis, Marginal Abatement Cost (MAC) curves are made for the decarbonisation technologies concerning the edible oil and fat industry in the Netherlands. These curves illustrate both the cost per unit of carbon abated and the reduction potential. Moreover, it can also be used to determine the average cost and total abatement cost (Kesicki & Strachan, 2011). The specific CO_2 mitigation costs $C_{spec,CO2}$ are calculated by using equation 1.7:

$$C_{spec,CO_2} = \frac{\alpha \cdot I + C - B}{\Delta M_{CO_2}} \quad (1.7)$$

which represents the marginal abatement cost (Blok and Nieuwlaar 2016). Where:

$\alpha \cdot I$ = annual capital costs
C = annual operation and maintenance costs
B = annual benefits
ΔM_{CO2} = annual amount of avoided CO_2 emissions

The capital recovery factor α in equation 1.7 is determined by the following calculation:

$$\alpha = \frac{r}{1-(1+r)^{-n}} \quad (1.8)$$

Where:

α = capital recovery factor
r = discount rate
n = life time or depreciation period of equipment

Three different future scenarios will be used in order to compare the different outputs: A business as usual where the fuel prices of the current year 2020 are used. A high fuel price scenario where 25% is added to the 2030 fuel prices; and a low price scenario where 25% is subtracted from the 2030 fuel prices.

For the making of the scenarios several assumptions are made:

a) The production of the Dutch oil and fat sector is assumed to increase each year with 0.95%. This is based on the 35% growth that is predicted by the branch organisation from 2013 until 2050 (MVO, 2013).
b) The baseline for the evaluation of the mitigation options is the frozen efficiency situation, since many decarbonisation options improve the process efficiency and would therefore be counted double.
c) The electricity costs are expected to be €43/MWh in 2020 and €60/MWh in 2030. However, since electricity prices fluctuate a lot, the electricity price is assumed to be in the range of €40-€80/MWh (PBL, et al. 2019)
d) The gasprice is €19.7/MWh in 2020 and is estimated to be €26/MWh in 2030 according to the Dutch "Klimaat en Energieverkenning" (KEV) 2019 (Climate and Energy Outlook). Similar to the electricity price, the gas price can fluctuate and is therefore overall estimated to be within the range of €21-€31/MWh (PBL, et al. 2019).
e) The price of green hydrogen for 2020 is estimated to be €156/MWh in the Netherlands (Elzenga and Lensink 2020). For 2030 IEA notes that the cost of producing hydrogen from renewable electricity can decline with 30% (IEA 2019), which means green hydrogen production will be €109/MWh in 2030.
f) For the biomass supply, the costs for using processed residue are considered, since waste of the vegetable oils can be used as feed in a biogas reactor. The upper range price from IRENA is assumed, which notes that 1 GJ processed residue costs €2.97 (IRENA 2014). The price of processed residues biomass in 2020 are assumed to be the same.
g) A social discount rate of 4% is assumed and used.

3. Vegetable oil processes

The processes of rapeseed, soybean and palm oil are researched and briefly described in this section. These three oil products are considered to be representative for most processes occurring within this industry. Other oil product processes are similar to one of them; sunflower oil undergoes the same production processes as rapeseed oil and coconut oil follows similar production processes as palm oil. While other product processes are applied to a smaller extent (MVO 2019). An accompanying report written in the context of the MIDDEN project substantiates this information in more detail (Altenburg and Schure 2020).

The production process is divided in three process units: crushing, refining and modification. Crushing involves the preparation steps before extraction and the oil extraction itself to obtain crude oil (CO). In the Netherlands, crushing is only performed for rapeseed and soybean oil. The palm fruits require processing into crude oil within 24 hours of harvest and therefore occurs on or near the local plantation (Sridhar, 2009). Moreover, not all companies in this sector execute crushing, several companies purchase crude rapeseed oil and crude soybean oil directly (MVO 2019, IPCC 2018). The refining of the oil is performed in all Dutch vegetable oil companies (Altenburg and Schure 2020). Refining consists of three main processes: neutralisation, bleaching and deodorisation. Neutralisation involves degumming and removes the free fatty acids (FFA) and lecithin from the oil. Bleaching is executed to remove 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 (IPCC 2018, Hamm 2013, Kasper 2018, Schmidt 2007). Oil modification is performed to obtain desired characteristics that are required for the specific end products. Currently, there are three main modification technologies available in the vegetable oil industry: hydrogenation, interesterification and fractionation. Hydrogenation improves the oxidative stability of polyunsaturated fatty acids and thus increases the shelf life of oils.

Moreover, this process is able to convert liquid oil into solid fat (Hamm 2013, Gupta 2017). Interesterification is performed to create a desired rearrangement of fatty acyl groups within and between different triglycerides for specific purposes in end products (AOCS 2019, Hamm 2013, Holm 2008). Fractionation is executed to generate two fractions, which can be dry and wet fractionised. In the Netherlands, the fractionation process only occurs for palm oil (MVO 2019).

The mass and energy flows for the three oils can be seen in Figure 1. The numbers in the mass and energy balances are largely based on the production of these oils at the AarhusKarlshamn company in Aarhus, Denmark in 2003 and 2004 (Schmidt 2007). The production of 1 tonne rapeseed and soybean oil requires 2500 kg rapeseeds and 5390 kg soybeans, which matches with the numbers given in the LCA commissioned by FEDIOL (Schneider and Finkbeiner 2013). The energy consumption of each process is subdivided into electricity and heat (steam), where both values are provided in MJ. From information of field experts it is known that both CHP as steam boilers are used in the Dutch vegetable industry. It is assumed that the CHP boilers used in this sector are small gas turbines, which have a thermal efficiency of 64% and an electrical efficiency of 25% (Hers and Wetzels 2009). The steam boilers on the other hand, are expected to have an efficiency of ~90%. The energy requirements of rapeseed and soybean oil for integrated crushing and refining and stand-alone refining do match with the numbers provided by the IPCC (IPCC 2018). More explanation and details of these processes can be found in the MIDDEN report (Altenburg en Schure 2020). Furthermore, it is known that energy can be saved by usage of residual heat that is released in higher temperature processes. For example, according to Li (Li, et al. 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 in the numbers used in this analysis.

4. Input data

The decarbonisation options found for the vegetable oil and fat industry are listed in Table 1 below. The decarbonisation options are split in two categories: the technology specific options and the alternative heating system options. The technology specific decarbonisation options are only applicable for implementation in the vegetable oil and fat industry.

In the crushing stage, traditional solvent extraction can be substituted with membrane solvent extraction where membranes are used to separate the solvent from the oil, which is less energy intensive than distillation only. Nevertheless, this technique is not yet applied on industrial scale, but it is highly developed having a Technology Readiness Level (TRL) of 6-8 (SolSep 2019, ISPT, et al. 2016). In the refining stage, the degumming step within neutralisation can be replaced with both membranes and enzymes, which both possess a lower energy consumption compared to the conventional process. Enzymatic degumming does already exist on industrial scale (AOCS 2019), membrane degumming is still in progress and has a TRL of 6 (SolSep 2019). EIE, in the oil modification stage, is also already applied on commercial scale. However, it can be applied to a higher extent to decrease the overall energy consumption and fully replace CIE (Holm 2008). The OPEX costs are high primary due to the cost of the enzymes (Hamm 2013).

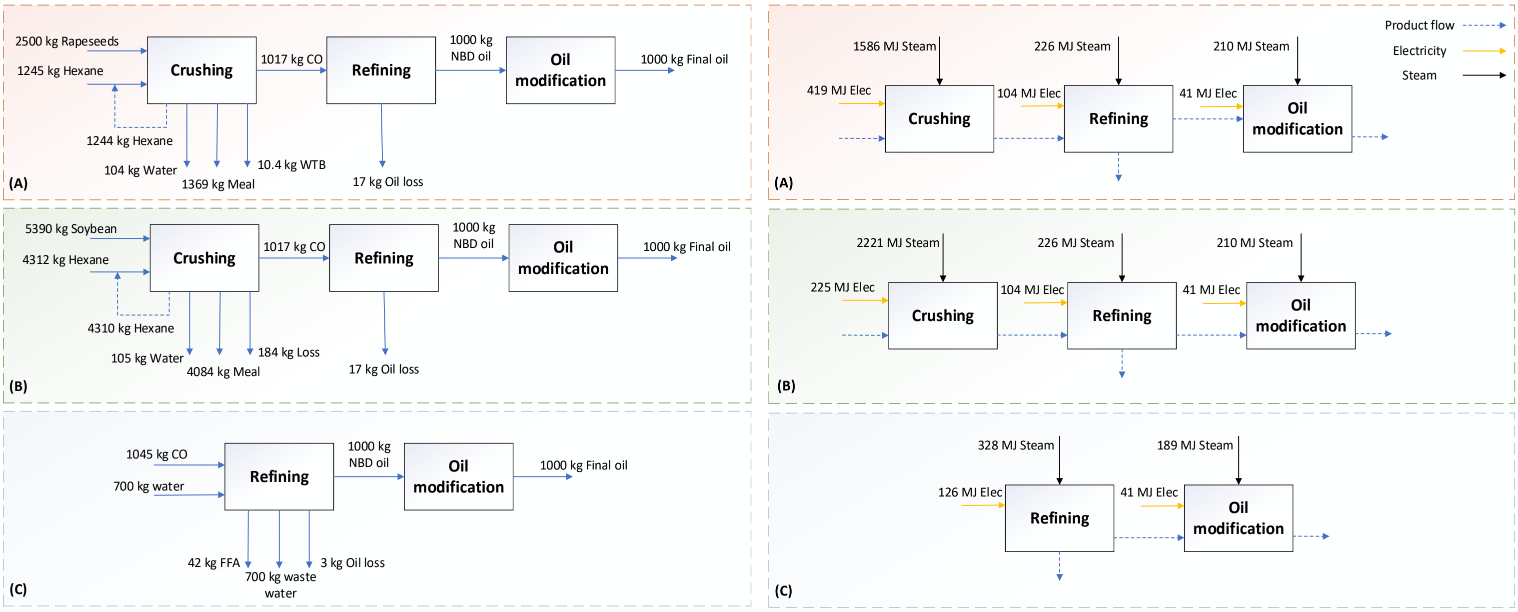

Figure 1 Left: mass balances and right energy balances of (A) rapeseed (B) soybean and (C) palm oil (Schmidt 2007, Hamm 2013, IPCC 2018)

The alternative heating systems consist out of options that can partly or totally substitute the gas or CHP boiler. A mechanical vapour recompression (MVR) industrial heat pump and ultra-deep geothermal energy can both reach up to 120–140°C, which is not sufficient for fully providing the energy required in the vegetable oil processes. The electrode boiler is the electric boiler that is most suitable in this industry. It can fully substitute the conventional boiler, but can only be considered as a decarbonisation option when the input electricity is produced by a renewable energy source. Besides, a biogas boiler is also a possibility to provide the energy requirements of the vegetable oil production.

Waste products from the rapeseed, soybean and sunflower oil crushing can be converted to heat and electricity. Lastly, the installed gas or CHP boiler can be converted into a hydrogen boiler. For a full decarbonisation option, the hydrogen fuel should be produced by electrolysis running on renewable energy sources. The energy (heat) and emissions savings of all decarbonisation options can be seen in Table 1.

Table 1 Characteristics of the decarbonisation options where CAPEX are the one-off investment costs and OPEX the yearly costs

Technology specific decarbonisation options	**Steam per ton product saved (MJ)**	**kg CO2 per ton product saved**	**Costs per ton product [EUR/tonne]**			**References**
			Rapeseed	*Soybean*	*Palm*	
Membrane solvent extraction	619 – 866	35 – 49	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	x	(ISPT, et al. 2016, Szekely, et al. 2014)
Membrane degumming	16	0.9	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	x	(SolSep 2019, ISPT, et al. 2016)
Enzymatic degumming	60	3.4	CAPEX 6 OPEX 0.2	CAPEX 6 OPEX 0.2	x	(Hamm 2013, Munch 2007)
Enzymatic interesterification	385[1]	7.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	(Hamm 2013)
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)
Alternative heating systems						
Industrial heat pumps (MVR)	0 – 724	0 – 41	CAPEX 8 OPEX 0.2	CAPEX 11 OPEX 0.3	x	(Kong, et al. 2017, ECN 2017)
Ultra-deep geothermal energy	0 – 724	0 – 41	CAPEX 51 OPEX 2.2	CAPEX 71 OPEX 3	x	Groen, 2018
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)
Biogas boiler	517 – 2657	29 – 150	CAPEX 4 OPEX 0.2	CAPEX 5 OPEX 0.2	CAPEX 1 OPEX 0.04	(Energy Matters 2015)
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)

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

5. Results

The MAC curves, calculated for 2020 and 2030 using a social discount rate as stated in the Methodology, can be seen in Figures 2 and 3. A total amount, including the yearly sector growth, of 369 kton in 2020 and 403 kton in 2030 needs to be abated to fully decarbonise this industry.

The technology specific decarbonisation options for this sector and the alternative heating systems are all shown in one graph. Membrane technology and ultra-deep geothermal energy are still in development in 2020 and therefore only considered as decarbonisation option in 2030. The ultra-deep geothermal energy decarbonisation option is phased out by the MVR heat pump. The MVR heat pump and ultra-deep geothermal energy can both deliver temperatures up to 120–140°C and therefore substitute the same part of energy in the crushing stage. Since the MVR industrial heat pump is cheaper, ultra-deep geothermal energy is not included in the MAC curves. The same applies for membrane degumming in 2030, which is phased out by the enzymatic degumming since the latter is less expensive and substitutes the same process. Ultimately, an electric boiler provides the last share of required energy. The alternative, a hydrogen boiler, is more expensive with a higher MAC of €764/tCO_2 and €477/tCO_2 for 2020 and 2030, respectively. The specific MAC of the other (phased out) technologies, can be found in Appendix A.

The cost-effective decarbonisation options can eliminate 141 kton CO_2 emissions in 2020 and 163 kton CO_2 emissions in 2030. This translates to 38% and 40% of the total carbon dioxide emissions for 2020 and 2030, respectively.

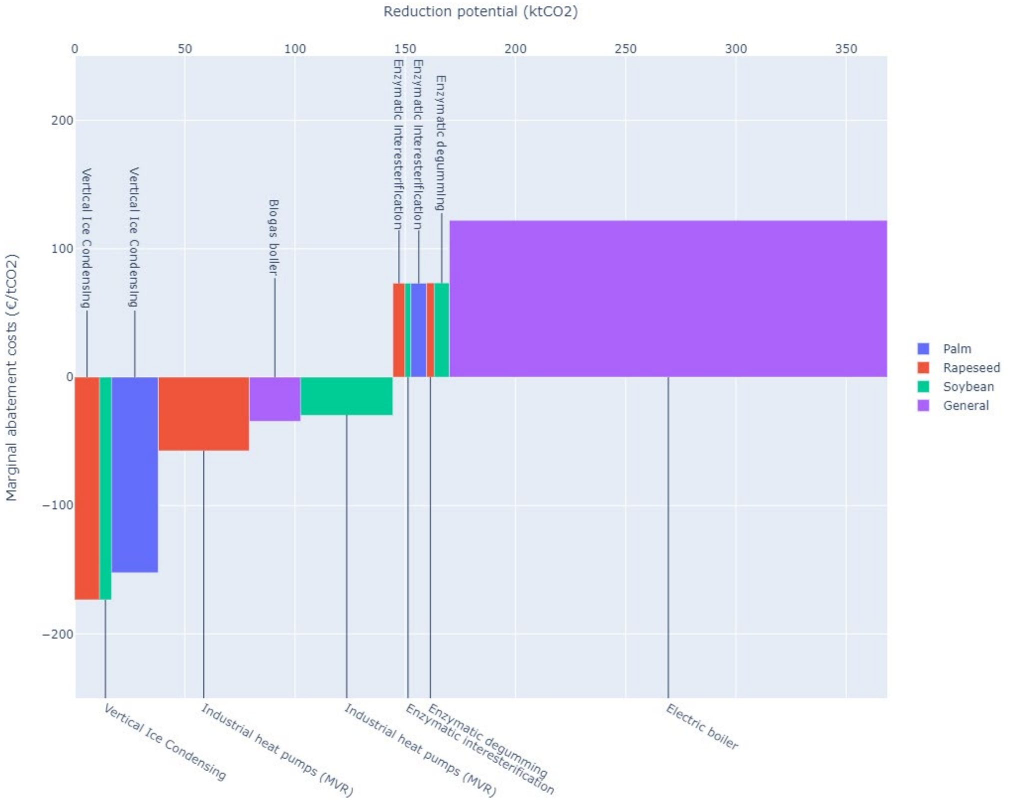

Figure 2 Decarbonisation options with 2020 fuel prices

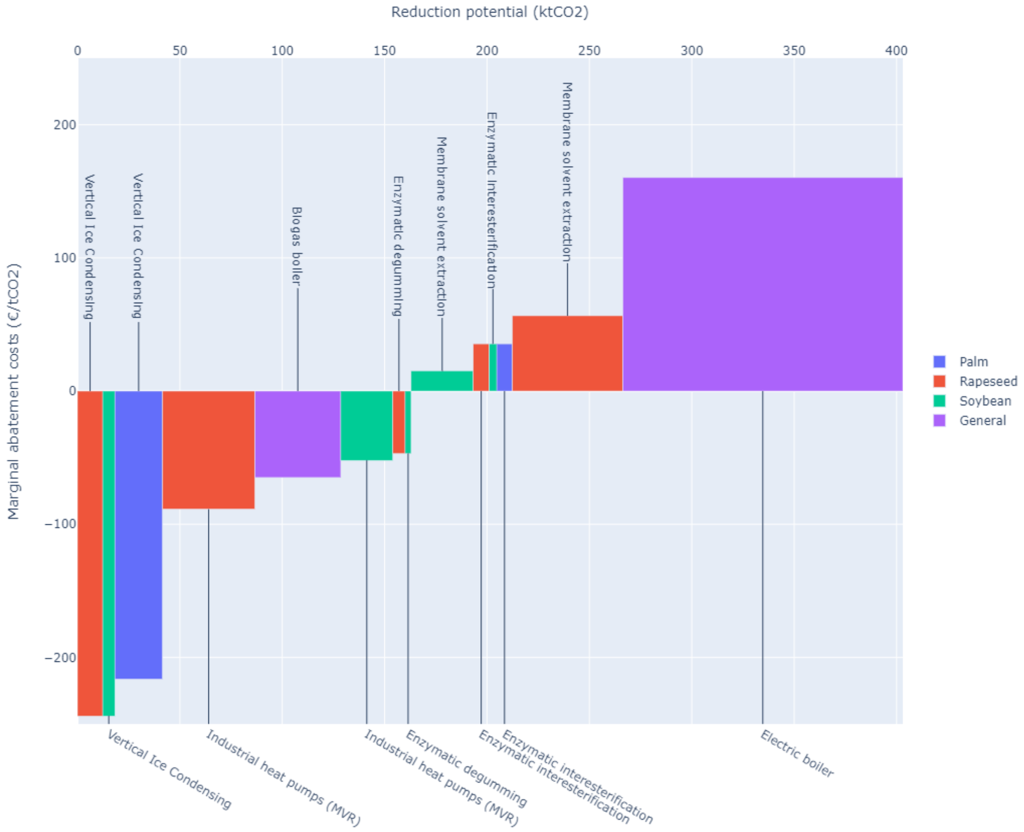

Figure 3 Decarbonisation options with 2030 fuel prices

Nevertheless, the cost benefits of the decarbonisation options are smaller in 2020 than 2030. This is due to higher predicted fuel prices for electricity and gas in 2030. The cost benefits of avoiding or substituting energy from electricity or gas become therefore higher. Hence, also the costs for the decarbonisation options above zero are less in 2030 than in 2020. Sorted on cost-effectiveness, the order of the decarbonisation options does not change except for enzymatic degumming, which transforms from a non -cost-effective decarbonisation option in 2020 to a cost-effective option in 2030. Lastly, replacing the currently used steam boilers or CHP's with an hydrogen boiler will be almost twice as expensive in 2020 than in 2030. The electric boiler will be, on the other hand, currently cheaper than in the future. Both observations can be explained by the change in fuel prices. The green hydrogen fuel price will become cheaper in 2030, in contrast to the electricity price which will increase in the future.

The Vertical Ice Condensing technology, which replaces the conventional deodorisation process, is the most cost-beneficial decarbonisation option. It is therefore understandable that some companies in the Netherlands already invested in this system in the past few years (Eproconsult 2019, MVO 2013). The industrial heat pump (MVR) for rapeseed oil is the cheapest alternative heating system option. However, since it can only provide temperatures up to 120–140°C, it can only substitute the energy in the crushing stage. The biogas boiler is therefore the most cost-beneficial alternative heating system option that can supply energy of all temperature in all stages. This is in line with the report of Element Energy, where it is stated that biogas boilers are the most cost-effective fuel switching option for the steam and indirect heating in the Food & Drink industry among others (Lyons, Durusut and Moore 2018). However, the energy substitution by a biogas boiler is limited by the biomass available from processing residues in the Dutch vegetable oil and fat industry. In total, 38 kton and 42 kton CO_2 can be abated by the available processing residues, in 2020 and 2030, respectively. These numbers do not include the 3.8 kton CO_2 that is already substituted by an existing biogas plant (Appendix A).

The technology specific decarbonisation options together with the industrial heat pumps and biogas boiler cannot realise fully decarbonisation, as can be seen in Figure 3. Still 137 kton and 202 kton CO_2 emissions needs to be abated for 2020 and 2030, respectively. The electric boiler and hydrogen boiler can both achieve this, but as discussed above the MAC of a hydrogen boiler is higher than for an electric boiler. Therefore, the remaining energy supply should be delivered by an electric boiler.

5.2 Energy efficiency

The total reduction of energy use, involving both steam and electricity, that can be obtained for the production of rapeseed, soybean and palm oil can be seen in Figure 4.

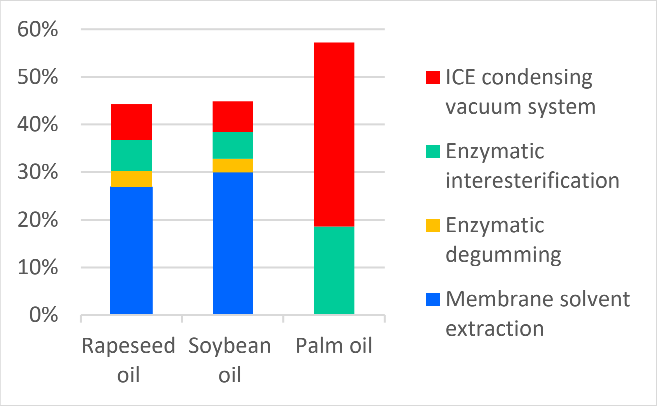

Figure 4 Energy reduction possible for the different types of oils

Figure 4 shows the savings of the four technology specific decarbonisation options of membrane solvent extraction, enzymatic degumming, enzymatic interesterification and Vertical Ice Condensing technology in percentage energy reduction of the total oil processes. Membrane degumming is not taken into account, since enzymatic degumming reduces the energy consumption to a larger extent and both substitute the same conventional degumming process.

When all the technology specific decarbonisation options are combined for the total production process for rapeseed and soybean oil, which means the crushing, refining and oil modification stages together. The energy consumption can in total be reduced by 44% and 45% for rapeseed oil and soybean oil, respectively. The energy requirements of the entire palm oil processing involving refining and oil modification can be reduced by 57% (Figure 4). Membrane solvent extraction relatively saves the most energy for rapeseed and soybean oil, whereas Vertical Ice Condensing technology saves the most energy for the palm oil production process.

6. Discussion

The production numbers of the 7 companies in the Dutch vegetable oil and fat industry are not fixed. For one manufacturing site the precise production capacity was unknown and is therefore estimated based on their CO_2 emissions. Moreover, the production amount of the different type of oils are dependent on the purchase price and demand. The quantities of the different types of oils produced can therefore vary over the years. However, since the factory with an unknown capacity is the smallest emitter of all ETS companies, no large variations are expected in the results.

6.1 Scenarios

Predicted fuel prices for the future come along with uncertainty. To include this uncertainty, a low and high fuel price scenario is made for 2030. In the low price scenario, -25% of the fuel prices for 2030 is used, whereas in the high price scenario +25% is added to the standardised fuel prices. The MAC belonging to the different decarbonisation options for the low and high price scenario can be found in Appendix A. For all decarbonisation options, except the electric boiler, the MAC are lower for the high price scenario than for the low price scenario. This is because of higher fuel cost benefits that are associated with avoiding or substituting the energy from electricity or natural gas. Only the MAC for the electric boiler is higher in the high price scenario than in the low price scenario. This is due to the fact that the MAC of the electric boiler is highly dependent on the electricity fuel price since an electric boiler does not avoid energy consumption but substitutes every MJ with electrical energy. The increasing electricity price in 2030 therefore leads to a higher MAC. The order of the decarbonisation options remains mostly the same. Only the enzymatic degumming processes become more advantageous than the biogas boiler and industrial heat pump (MVR) for soybean in the high price scenario. Moreover, enzymatic degumming, membrane solvent extraction and enzymatic interesterification change from a cost-effective option to a cost-beneficial option in the high fuel price scenario. The Vertical Ice Condensing technology remains the most cost-beneficial technology specific decarbonisation option in all scenarios. Another factor that plays a role in the uncertainty of the fuel prices is the difficulty of predicting the development of technologies. Fuel prices are dependent on this growth and evolve coherently. The fuel price development is especially important for the production of green hydrogen. The hydrogen boiler is the most expensive alternative heating system because of the high fuel prices. However, history has shown before that it is possible for a technology to develop rapidly and cut expenditures in half. This is what occurred for the PV-panels for instance, where costs declined with 5% per year in a time-period of 10 years (Hoffmann 2006). Lastly, the electricity prices can fluctuate a lot within a year. In summer, when a high amount of renewable energy is produced, the electricity prices can be much lower than in winter (PBL, et al. 2019). This price fluctuations are expected to occur even more in 2030, since the renewable energy share will be higher in the future. The electricity price is expected to be low for a larger time-period in a year (PBL, et al. 2019).

Additionally, to evaluate the influence of the discount rate, a scenario where a private discount rate r=0.15 in 2030 is analysed with a social discount rate of r=0.04 in 2030. The order remains the same with a higher discount rate, except for enzymatic degumming. This decarbonisation option moves from a cost-effective option to a decarbonisation option above zero. This is similar to the comparison of the 2020 and 2030 MAC curves and the high and low fuel price scenario, as elaborated elsewhere in the results and discussion. The reason for this change in the MAC of enzymatic degumming, is that per ton produced oil the amount of avoided CO_2 emissions is rather small (Table 1). Therefore, the MAC of enzymatic degumming is relatively prone to both discount rate changes as fuel price changes. Furthermore, the cost-effective decarbonisation options become slightly less effective with a higher discount rate. Likewise, the MAC for the decarbonisation options above zero increases as the discount rate increases. This is for the reason that with an inclining discount rate, the redemption of the capital expenditures become more expensive.

6.2 Decarbonisation options

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 therefore explains the choice to purchase a biomass boiler as some companies in the Dutch vegetable oil and fat industry did in recent years. The biomass fuel price for processing residue is taken from IRENA (IRENA 2014). Since it is known that factories can feed the biomass boiler with by-products from the oilseed processing (Schmidt 2007, Kuipers, et al. 2015). When the biomass feed consists mainly of these process residues, purchasing a biomass boiler becomes highly 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. The biomass fuel costs can therefore exceed the 2.97€/GJ. 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).

Next to the decarbonisation options, heat recovery is applicable in the vegetable oil and fat industry. It is known from the MJA (Meerjarenafspraak) (English: long-term agreement) reports (de Ligt 2018) that the companies within the vegetable oil and fat industry in the Netherlands increased their energy efficiency in the last 20 years every year with approximately 2%. This is partly achieved by the recirculation of residual heat (de Ligt 2018, MVO 2013). 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 more energy efficiency than shown in Figure 4 can be realised. Adding this heat recovery up to the technology specific decarbonisation options for the manufacturing of oils will lead to higher possible efficiencies.

The usage of membranes in the edible oil and fat industry seems to have a huge potential for a more sustainable and less energy intensive oil production process. Nevertheless, it is still hard to realise this technique on industrial scale. Firstly, because not many membranes stay intact when coming into contact with hexane. Additionally, various components in the oil can cause problems by fouling the pores in the membranes. For this reason, the oils 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 highly dependent on the oil type. Not all rapeseed, soybean and palm oil can use the same membrane process unit in a factory. Hence, membrane usage is very specific when it comes to application and implementation in the edible oil and fat industry. Lastly, what is observed is that converting an existing factory for adding a membrane process unit is rather costly and not chosen to implement. However, for newly built installations the purchase of membrane technology is more obvious (SolSep, 2019; Eproconsult, 2019).

6.3 Methods

Using the MAC curve as a method to obtain an overview of reduction potential and costs of the available decarbonisation options comes along with some limitations (Kesicki 2011). One of the concerns is the transparency of the assumptions. The MIDDEN project report (Altenburg and Schure 2020) is therefore added as supplementary resource which elaborates on used data and assumptions in more detail. Other aspects discussed in the paper of Kesicki are that the MAC curves represent the abatement cost at a single point in time. Moreover, the intertemporal dynamics of the emission pathways for the options are not included. Since the MAC are estimates for the future it is impossible to sketch the exact costs and technical development a decarbonisation option will follow. The farther an estimation lies in the future, the more uncertain these aspects are. Therefore, 2030 is chosen as future single timepoint and not later to restrict uncertainties. Lastly, MAC curves only focus on CO_2 abatement and do not represent the ancillary benefits of CO_2 emission reduction. Nevertheless, MAC curves still provide a clear overview on the MAC and reduction potential for the available decarbonisation options which makes them easy to understand. Expert-based MAC curves represent a fixed maximum abatement potential since behavioural aspects are not considered. Altogether, these disadvantages are listed for MAC curves that are used for policy making. The MAC curves presented in this report are not used to assess policy instruments (Kesicki 2011, Kesicki and Strachan 2011).

This research is performed for the Dutch vegetable oil and fat industry. However, the results can also be relevant for other countries or other vegetable oil and fat companies. Each decarbonisation option is globally implementable, although the effect of a decarbonisation option or the CO_2 abated could vary or should be differently interpreted. The energy consumption for the production of a type of oil can differ from the numbers stated here. Nevertheless, the CO_2 that can be saved can still be determined with the information provided in Table 1. Some decarbonisation options abate a set amount of CO_2, while the reduction of energy for other options are dependent on the current energy consumption. The latter options can save a certain part or percentage of the energy consumed in the traditional production process. The CO_2 reduction is therefore very dependent on the amount of energy the conventional process requires. Hence, the order and the price of some decarbonisation options will differ from the values given in this article. Furthermore, fuel prices can vary per country. In this article, mainly predicted prices for the Netherlands are used for 2030. But some fuels, such as for example green hydrogen, is much cheaper in North-Africa than in the Netherlands (IEA 2019).

6.4 Scope 2 emissions

Electricity consumption can bring along scope 2 emissions, which are the indirect emissions from sources that are not owned or controlled by the companies (Greenhouse Gas Protocol 2019). An example is electricity that is produced by non-renewable energy sources which is bought from an external party. Nevertheless, the indirect (scope 2) CO_2 emissions are disregarded in this paper, since the emissions that come along with electricity production have been strongly reduced in the last years within the Netherlands due to the increase of the imported electricity instead of producing electricity with coal. Moreover, it is expected that the electricity produced by renewable energy sources will further increase to more than two-third of the total electricity production in 2030 (PBL, et al. 2019).

The electricity consumption at companies with a CHP are counted as direct emissions (scope 1), since the electricity is produced on the site. On the other hand, the electricity used at companies with a steam boiler is bought and thus externally produced (scope 2). In this sector, the amount of indirect (scope 2) emissions comprises approximately 6% of the total energy consumption.

7. Conclusion

There are several decarbonisation options for the vegetable oil and fat industry in the Netherlands. The technology specific decarbonisation options can reduce the energy consumption by 44%, 45% and 57% for rapeseed oil, soybean oil and palm oil, respectively. The Vertical Ice Condensing technology is the cheapest decarbonisation option for all oils in all scenarios. The industrial heat pump (MVR) for rapeseed oil crushing is the most beneficial alternative heating system. However, since a heat pump can only provide temperature up to 120–140°C it cannot provide energy for the refinery and oil modification stages. A biogas boiler is the most beneficial alternative heating system that can supply energy at all temperatures, but is limited by the available processing residues from the Dutch vegetable oil and fat industry. Therefore, the remaining energy supply is delivered by an electric boiler, since this is less expensive than supplying the energy from a hydrogen boiler. In total, 38% and 40% of the total CO_2 emissions can be abated by cost-effective decarbonisation options, for 2020 and 2030 respectively.

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Appendix A

The MAC prices for all decarbonisation options and scenarios are provided in Table 2 below. No growth is included here, also all options are included so membrane technology with 2020 prices are stated here. When the membrane decarbonisation options are removed, the reduction potential of an electric or hydrogen boiler changes to 198.47 kton CO_2.

Table 1 Marginal abatement costs for all decarbonisation options in all scenarios

		2020	2030	2030 low	2030 high
Technology	**Total reduction potential kton CO2**	**MAC per ton CO2**	**MAC per ton CO2**	**MAC per ton CO2**	**MAC per ton CO2**
Membrane solvent extraction R	48.45	95.52	56.54	96.95	16.14
Membrane solvent extraction S	27.26	49.04	15.23	50.37	-19.90
Membrane degumming R	1.48	8027.85	7963.74	8029.72	7897.75
Membrane degumming S	0.71	8027.85	7963.74	8029.72	7897.75
Enzymatic degumming R	5.42	73.38	-46.95	17.09	-110.99
Enzymatic degumming S	2.61	73.38	-46.95	17.09	-110.99
ICE condensing vacuum system R	11.06	-173.37	-244.04	-171.38	-316.70
ICE condensing vacuum system S	5.32	-173.37	-244.04	-171.38	-316.70
ICE condensing vacuum system P	20.86	-152.34	-216.40	-150.47	-282.33
Enzymatic interesterification R	6.96	73.14	35.47	74.54	-3.59
Enzymatic interesterification S	3.35	73.14	35.47	74.54	-3.59
Enzymatic interesterification P	6.78	73.14	35.47	74.54	-3.59
Industrial heat pumps (MVR) R	40.51	-57.32	-88.69	-56.03	-121.35
Industrial heat pumps (MVR) S	22.79	-29.71	-52.13	-28.58	-75.68
Ultra-deep geothermal R	40.51	344.43	382.63	344.48	420.79
Ultra-deep geothermal S	22.79	345.17	383.36	345.22	421.51
Biogas boiler	37.66	-34.35	-64.94	-47.90	-81.99
Electric boiler	122.76	122.12	160.30	122.16	198.44
Hydrogen boiler	122.76	763.76	476.87	360.15	593.60

Table 3 below respresents the 2030 MAC with r=0.04 and including growth. The reduction potentials for the different technologies are therefore different than in Table 2.

	Total reduction potential kton CO2	**MAC per ton CO2**
ICE condensing vacuum system R	12.32	-244.04
ICE condensing vacuum system S	5.93	-244.04
ICE condensing vacuum system P	23.24	-216.40
Industrial heat pumps (MVR) R	45.13	-88.69
Biogas boiler	41.96	-64.94
Industrial heat pumps (MVR) S	25.39	-52.13
Enzymatic degumming R	6.04	-46.95
Enzymatic degumming S	2.91	-46.95
Membrane solvent extraction S	30.36	15.23
Enzymatic interesterification R	7.75	35.47
Enzymatic interesterification S	3.73	35.47
Enzymatic interesterification P	7.55	35.47
Membrane solvent extraction R	53.97	56.54
Electric boiler	136.76	160.30
Hydrogen boiler	136.76	476.87

Table 4 below represents the MAC for 2020 including growth and without the membrane technology options.

	Total reduction potential kton CO2	**MAC per ton CO2**
ICE condensing vacuum system R	11.27	-173.37
ICE condensing vacuum system S	5.43	-173.37
ICE condensing vacuum system P	21.25	-152.34
Industrial heat pumps (MVR) R	41.28	-57.32
Industrial heat pumps (MVR) S	23.23	-29.71
Biogas boiler	38.38	-19.53
Enzymatic degumming R	5.52	15.25
Enzymatic degumming S	2.66	15.25
Enzymatic interesterification R	7.09	73.14
Enzymatic interesterification S	3.41	73.14
Enzymatic interesterification P	6.91	73.14
Electric boiler	202.24	122.12
Hydrogen boiler	202.24	656.06

Biomass 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 ton rapeseed oil. For soybean oil this amount is 189 kg per ton 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 ton rapeseed oil and soybean oil this amount is 14 kg. The amount of MJ gas 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 kton CO_2 without growth of the vegetable oil and fat sector. A biomass boiler that produces 67 ton per day is already been used. This means that some part is already catched away. The biomass boiler produces 24.5 kton steam in a year which saves 3.8 kton CO2 emissions. Therefore, the total amount of CO2 emissions that can be avoided for the total sector decreases from 41.47 to 37.7 kton per year. This is 14% of the total carbon emissions of 2018. With the growth of the sector of 0.95% the biomass potential also increases. In 2020 the reduction potential of a biomass boiler increases with 1.9% to 38.4 kton and in 2030 with 11.4% to 42 kton relatively to 2018.

PBL Netherlands Environmental
Assessment Agency

DECARBONISATION OPTIONS FOR THE DUTCH VEGETABLE OIL AND FAT INDUSTRY

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MIDDEN

Manufacturing Industry Decarbonisation Data Exchange Network

Decarbonisation options for Dutch Oil and Fat Food Industry

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This report was reviewed by (MVO and Eproconsult). PBL and ECN part of TNO remain responsible for the content. The decarbonisation options and parameters are explicitly not verified by the companies.

Contents

List of abbreviations and acronyms

MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network
ADM	Archer Daniels Midland Company
FFA	Free Fatty Acids
NCV	Net Calorific Value
EC	European Commission
NBD	Neutralized, bleached, deodorized
CO	Crude oil
CHP	Combined heat and power
IE	Interesterification
NF	Nanofiltration
UF	Ultrafiltration
FOM	Fixed Operation and Maintenance
VOM	Variable Operation and Maintenance
TRL	Technology Readiness Levels

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Summary

In this report, four different vegetable oil and fat companies in the Netherlands are discussed: ADM, Bunge, Cargill and Sime Darby Unimills. These four companies have together seven production sites that emit more than 10 kton CO_2 emissions per year. Altogether, they are responsible for 0.36 Mton CO_2 emissions in 2018 (NEa 2019).

The main products of these companies involve the production of rapeseed, soybean and palm oil. The production process is divided in three process units: crushing, refining and modification. Crushing involves the preparation steps before extraction and the oil extraction itself for obtaining crude oil (CO). In the Netherlands, crushing is only performed for rapeseed and soybean oil. The palm fruits require processing into crude oil within 24 hours of harvest and therefore occurs on or near the local plantation (Sridhar, 2009). While the refining of the oil is performed in all Dutch vegetable oil companies. Refining consists of three main processes: neutralisation, bleaching and deodorisation. Oil modification is performed to obtain desired characteristics that are required for the specific end products. Currently, there are three main modification technologies available in the vegetable oil industry: hydrogenation, interesterification and fractionation.

The decarbonisation options are split in two categories: the technology specific options and the alternative heating system options. The technology specific decarbonisation options are only applicable for implementation in the vegetable oil and fat industry. The usage of membranes and enzymes are both technology specific decarbonisation options. Furthermore, the vertical ice condensing technology can substitute the conventional deodorisation process within the vegetable oil and fat industry.
The alternative heating systems consist out of options that can partly or totally substitute the gas or CHP boiler. An industrial heat pump (MVR) and ultra-deep geothermal energy can both reach up to 120–140°C, which is not sufficient for fully providing the energy required in the vegetable oil processes. However, sustainable alternative heating systems as the electric boiler, a biomass boiler and a hydrogen boiler can fully replace the conventional gas and CHP boilers.

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

Introduction

This report describes the current situation for 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 oil and fat food producers include:

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

These four companies represent the larger production facilities at 7 production sites. There are more production facilities, but these are smaller and are not participating in the emission trade scheme.

Production processes include Cleaning, Cracking, Dehulling, Threshing, Conditioning, Flaking, Cooking, Sterilization, Mechanical Pressing, Solvent Extraction, Degumming, Neutralisation, Bleaching, Hydrogenation, Desolventisation and Deodorisation.
products include: Palm oil, Rapeseed (and sunflower) oil and Soybean oil and other types of oil.
The main options for decarbonisation are membrane and enzyme technology together with the vertical ice condensing technology for improvements in the energy efficiency. Furthermore, an hydrogen boiler, biogas boiler or electric boiler for substitution of the steam boiler or CHP.

Reading guide

Section 1 introduces the Dutch oil and fat food industry. Section 2 describes the current processes for the palm oil, rapeseed and soybean oil production in the Netherlands. The relevant products of these processes are described with the prices 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 Edible 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, 2018). 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, 2013, MVO, 2017). The main part of these products are used for the food industry, which is covered in this report. Other purposes of these oil and fat products are used in the animal feed, oleochemical, and biofuel industries (MVO, 2013). However, this lies outside of the scope of this research.

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 kton CO_2. In Table 1 below, an overview is given of these Dutch oil and fat companies including their locations, production capacities and ETS CO_2 emissions.

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 CO2 emissions [kt/year]	Rapeseed /Sunflower	Soybean	Palm	Source
ADM	0.96	150.5	X	X		Kasper, 2018; Zande, 2011; Wachelder, 2017
Bunge Amsterdam	0.76	64.8	X	X		Kasper, 2018
Bunge Maasvlakte	0.75	19.0			X	Advocatie, 2017

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[1] Nederlandse Emissieautoriteit

Bunge Wormerveer	0.3[2]	16.6	X	X	X	no source, 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

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

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

Crushing of oilseeds 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 found in 1902 at Minneapolis, USA. In 1986 ADM bought the company at Europoort in the Netherlands, which is their only location within the 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 ton oil in 2011 (Zande, 2011). However, ADM expanded their production in 2017 with 355,000 ton per year (Wachelder, 2017). Therefore, the annual oil production is estimated at 960,000 ton 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 €98.1 million, with 230 employees (vainu.io, 2019). As shown in Table 1, ADM has the highest carbon emissions noted in the ETS emission list of the oil and fat food sector. In September 2019 an item appeared in the Dutch newspaper 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, 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.

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[2] Estimated based on the CO_2 emissions reported by NEa (NEa, 2019)

Amsterdam

The soy 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 tons rapeseed and soy oil which is produced mostly in the ratio of 90/10, respectively (Kasper, 2018). The Bunge Loders Croklaan company in has 120 employers (Bron, 2016). This company emits the most carbon of the Bunge Loders Croklaan sites, with an amount of 65 kton as is shown in Table 1.

Maasvlakte

After the take-over of IOI of Loders Croklaan, IOI started soon to build a big palm oil refinery at the Maasvlakte with a production capacity of 750,000 tons palm oil per year. This factory opened in 2010 and has a yearly turnover of €1.3 billion euros (Advocatie, 2017). Around 90 employees are working the palm refinery at the Maasvlakte and the corresponding carbon emissions are 18.3 kton in 2017 (Dekker, 2019; Lalkens, 2017; InvestinHolland, 2010).

Wormerveer

Here the original Crok&Laan factory is located. The current exact amount of tons specialized oil is unknown. However, an estimation of 300,000 tons 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 kton carbon 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 ton of seeds. Which means the Multiseed firm produces 220,000 ton rapeseed and sunflower oil on annual basis (Kuipers, et al., 2015). At this site 70 employees are working for Cargill (ddh, 2019). The CO_2 emissions of the multiseed firm were 33 kton in 2018 (Table 1).

Botlek

The Cargill company in Botlek was taken over from Brinkers in 1984 and was expanded with an extra 575.000 ton oil per year in 2005 which makes the total production capacity now around 1 million ton oil per year. According to news items Industrielinqs and foodingredientsfirst (2005), the capacity of palm oil got greatly expanded (FoodIngredientsFirst, 2005; Industrielinqs, 2005). According to Cargill, only palm, palmkernal and coconut oil are produced in Botlek. At the Cargill Botlek company work 100 employees. The total CO_2 emission for the Cargill Botlek location is 27 kton 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 recognized nowadays (Unimills, 2019). The company is still located in Zwijndrecht where it produces currently 450,000 ton 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 (Unimills, 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 kton in 2018.

2 Edible oil processes

The manufactured main products of the oil and fat food industry that are discussed in this report are: rapeseed oil, soybean oil and pam oil. These three products can be considered to be representative for most processes occurring in this industry and 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, 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 (IPCC, 2018; Hamm, 2013; Kasper, 2018; Schmidt J. , 2007).

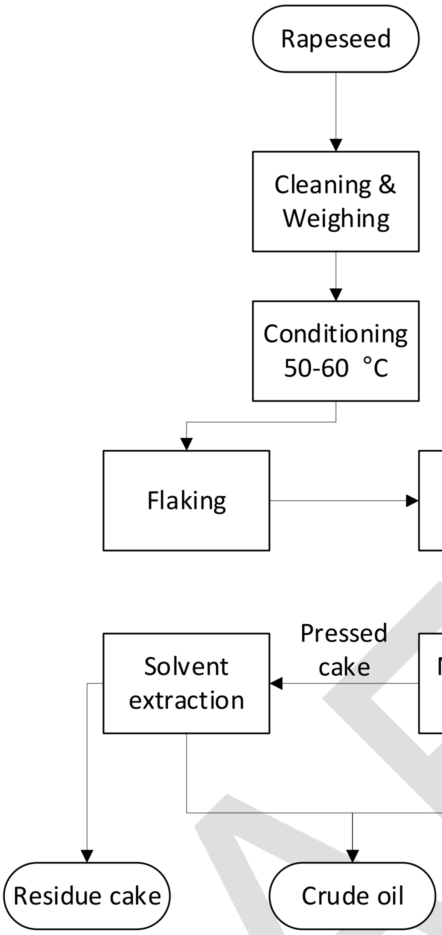

Figure 1 Crushing process flow of rapeseeds

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 sterilization 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 the temperature of 90-105 °C and dries the seeds until 3-5% moisture content (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 which 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 J. , 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.

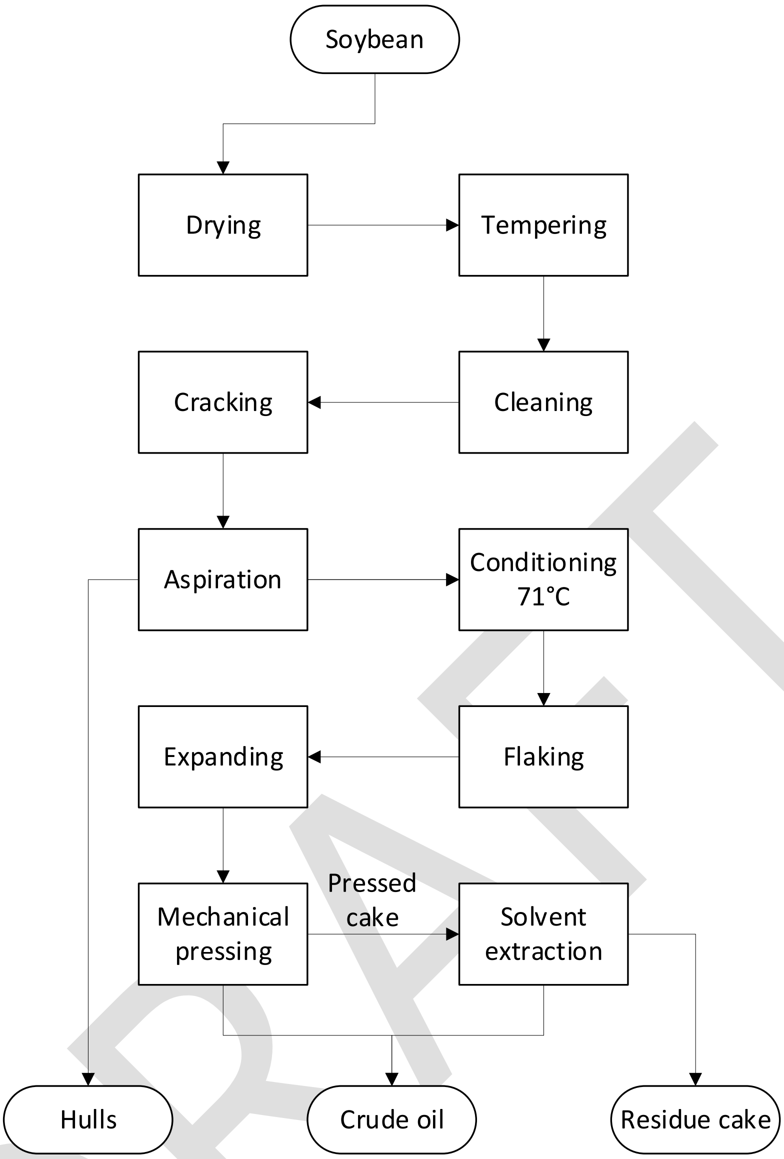

Figure 2 Crushing process flow of soybeans

The incoming soybeans from the field are superficially dried (Schmidt J. , 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 which results in an increase of 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 (IPCC, 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 with 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 (IPCC, 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 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 J. , 2007). It has as advantage that it is flexible for all types of oil and that it uses lower deodorization temperatures which prevents undesirable product formation (IPCC, 2018). Physical refining may be preferred for tropical oils since these are low in phospholipids but high free fatty acids (FFA) (IPCC, 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 (IPCC, 2018; Schmidt J. , 2007; AOCS, 2019).

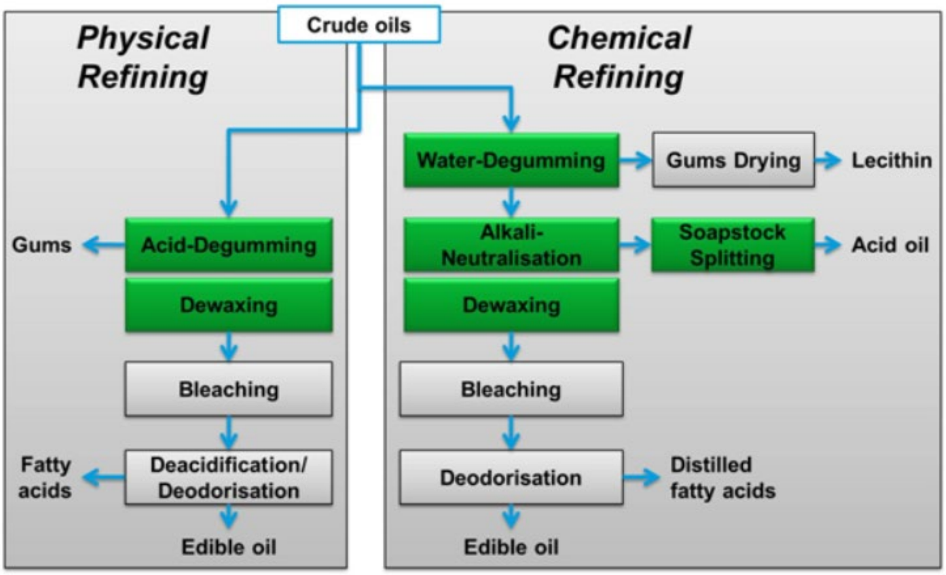

Figure 3 Physical and chemical refining process schemes (AOCS, 2019)

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 end 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 edible oil industry: hydrogenation, interesterification and fractionation, which are more extensively explained below. For some oil modification processes, the crude oil must be neutralized but not bleached and deodorized 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.

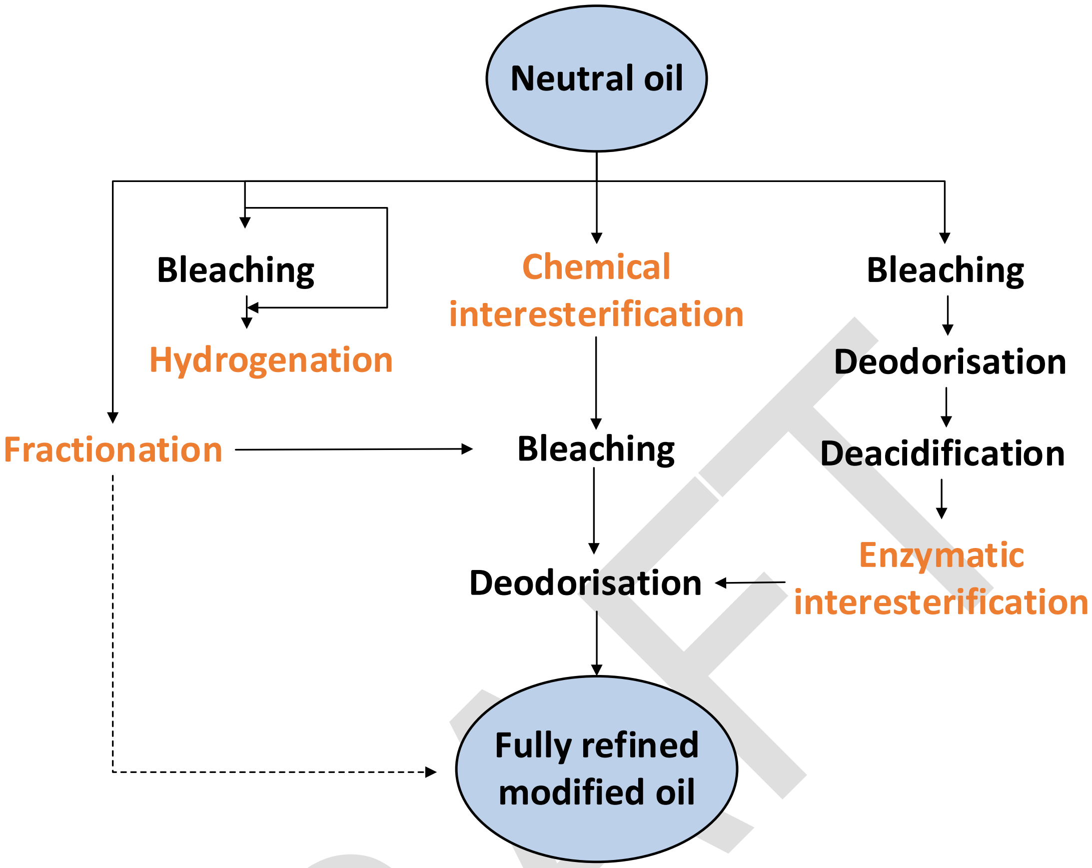

Figure 4 Oil modification process flow (Dijkstra, 2015)

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 with the reduction of 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 edible oils is performed to create a desired rearrangement of fatty acyl groups within and between different triglycerides for every specific purpose in an end 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 crystallizing 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, 2019).

2.3.4 Energy requirement

In Hamm (2013), an overview is given for each oil modification process with the electricity and steam usage per ton oil, which are 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/ton]	30	150	12	40
Electricity [Kwh/ton]	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 high-pressure steam is used. 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%	72%	0%
Refining	100%	100%	100%
Oil modification	50%	50%	50%

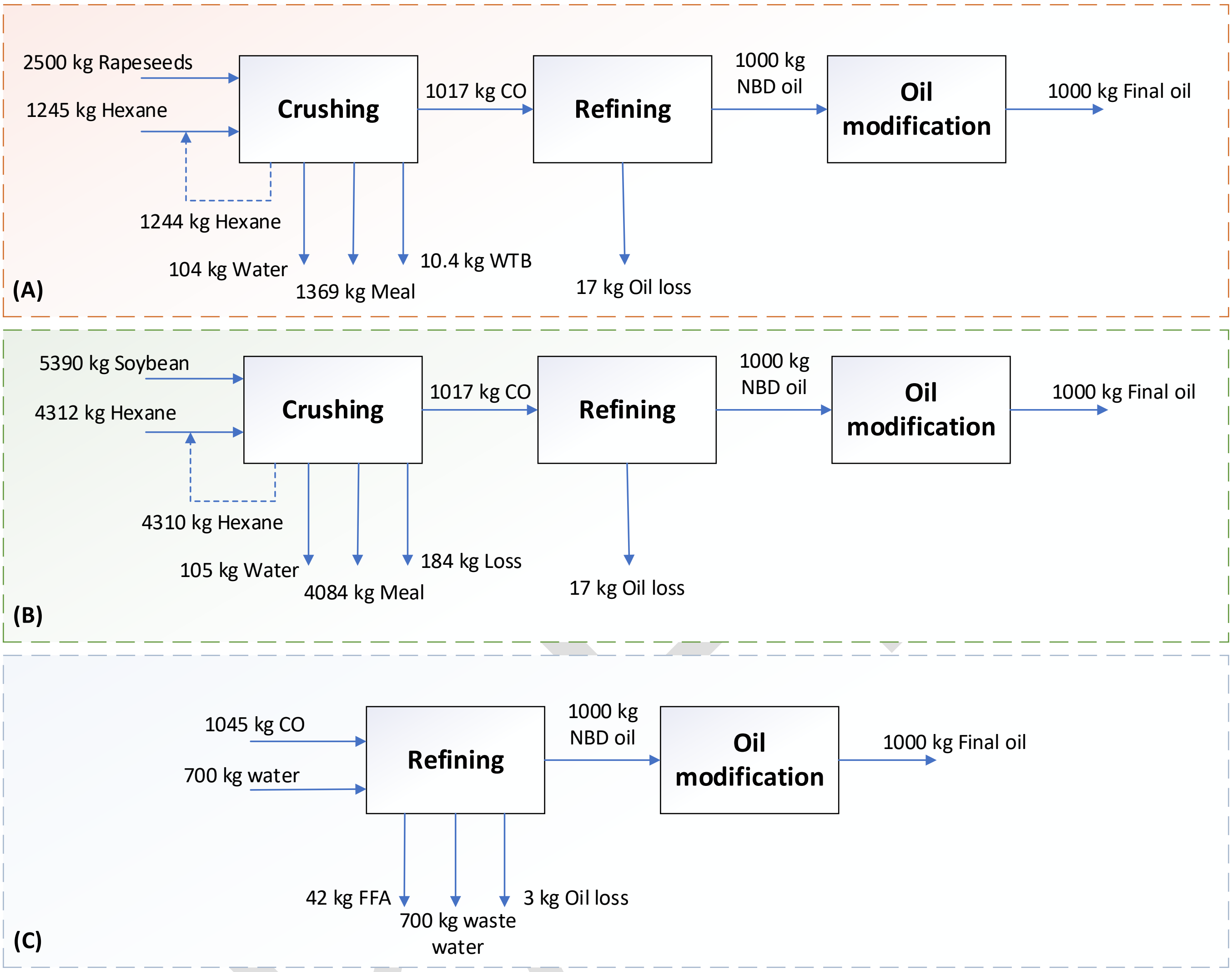

Figure 5 Mass balances of the production of (A) rapeseed oil (B) soybean oil and (C) palm oil

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 2013 and 2014. For the production of one ton rapeseed oil, 2500 kg rapeseeds is required (Figure 5). With the production of one ton rapeseed oil, 1369 kg rapeseed meal is produced which consists of 87.5% dm. Moreover, 104 kg water is used in 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 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 J. , 2007). Moreover, little amount 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 end product, depending on the demand and factory.

For the production of one ton 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 J. , 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 in total produced (Schmidt J. , 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, 2019). The mass balances of all three oils are similar with the numbers provided in the FEDIOL report (Schneider and Finkbeiner 2013).

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, Cargill Amsterdam, Bunge Maasvlakte and Bunge Wormerveer make use of steam boilers. Whereas ADM, Bunge Amsterdam and Sime Darby Unimills possess a CHP. However, frequently companies also have a small steam boiler next to the CHP to be able to produce different pressure steam or to have a buffer. Though, what type of steam boiler and how much they use these boilers is unknown. It is assumed that the CHP boiler used in the edible oil and fat sector are the small gas turbines, which have a thermal efficiency of 64% and an electrical efficiency of 25% (Hers & Wetzels, 2009). The steam boilers are assumed to have an efficiency of ~90%.
Furthermore, the used CO2 emission factor is 56.6 kg/GJ and is 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.

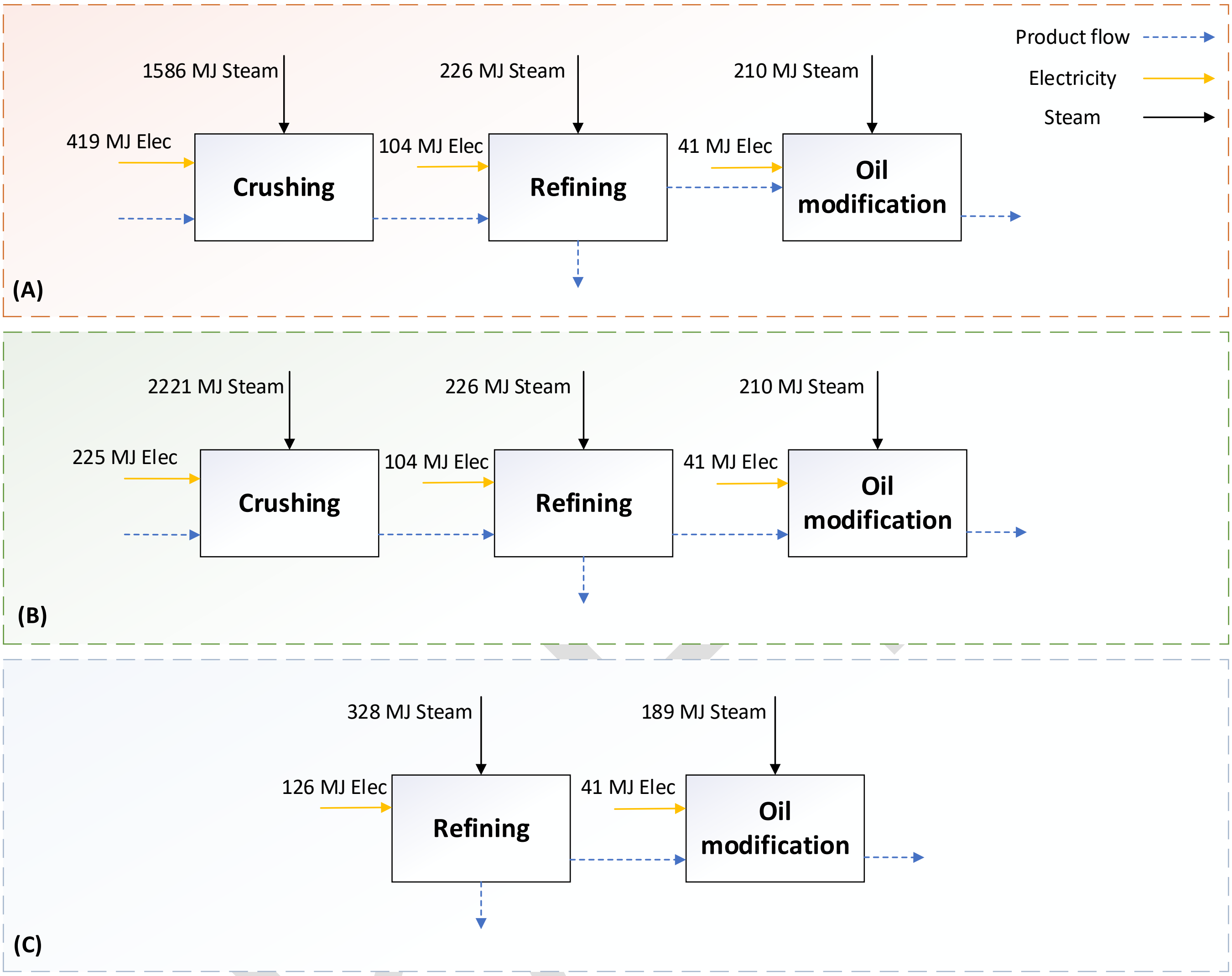

Figure 6 Energy balances for (A) rapeseed oil (B) soybean oil and (C) palm oil per tonne of oil produced

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 neutralization, bleaching and deodorisation consume 20 MJ, 0 MJ, and 84 MJ electricity and 41 MJ, 41 MJ and 144 MJ heat, respectively (Schmidt J. , 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, if NBD oil is the final product and no oil modification occurs, and 2586 MJ if the oil is modified. Both values are in line with the specific energy consumption range of rapeseed provided by the IPCC (IPCC, 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 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 electricity is needed and 2221 MJ steam (Schmidt J. , 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 J. , 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 excluding oil modification, and 3027 MJ 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 J. , 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 and of refining and modification 684 MJ. 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, the combined electricity and heat energy requirement for the production of the oils are used for these three 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 by external companies. Therefore, the emissions related to this amount of electricity are indirect (scope 2) emissions and are not included. For both CHP and the steam boiler an 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 ton 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	**2586**	**3027**	**684**

The energy numbers from the FEDIOL report (Schneider and Finkbeiner 2013) appear valuable as they represent information from more than 20 oil and fat production sites, but they are not used for several reasons. The energy numbers for heat in this report are provided in terms of kg steam. However, the amount of energy required in the process could not be derived from these numbers, since no conversion numbers are provided. It is thus unknown what the temperature of the water was 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 85 MJ/kg 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. Furthermore, the FEDIOL report did not present the distribution of the energy consumption over all processes whereas Schmidt does (Schmidt J. , 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 (IPCC, 2018; Schmidt J. , 2007)

3 Oil and fat products and application

The total oil and fat sector in the Netherlands is responsible for 11.8 million ton of imported goods and exports 6 million ton of products in 2013 (MVO, 2013). 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, 2012).

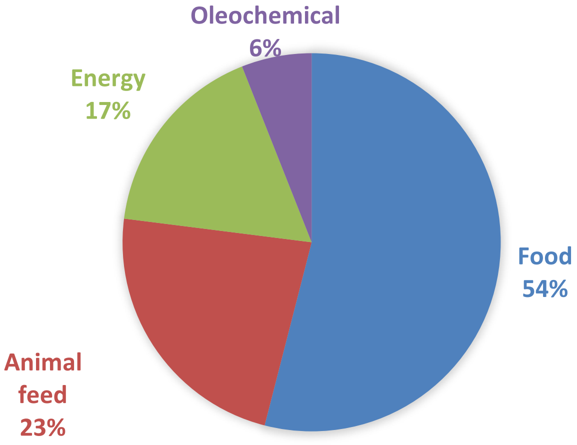

Figure 7 Oil and fat products used for sectors

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. Also other oils like: corn oil, coconut oil, olive oil and palmkernel oil can 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, crème 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 soy oil and distillates of these fats. Fats are usually add 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 (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).

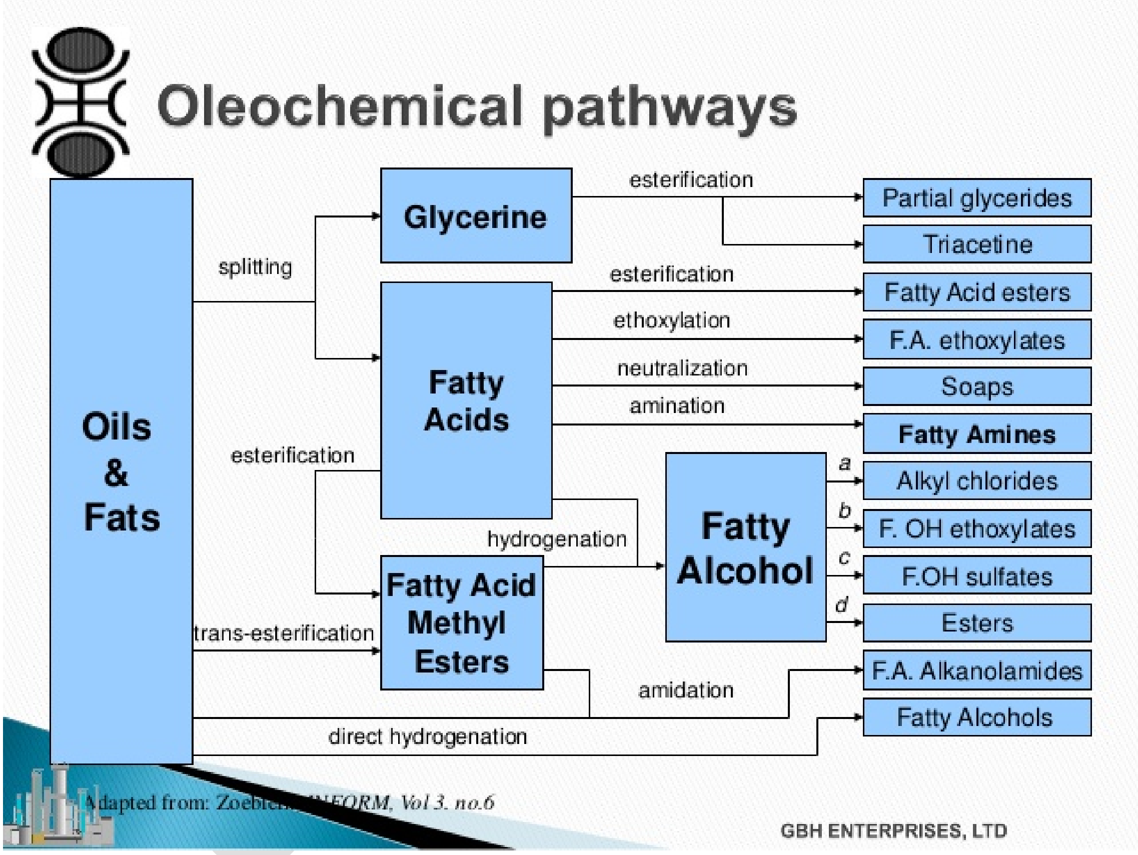

Figure 8 Oleochemical pathways for different end-products

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 soy protein is widely used in the plant based meat products. Recently, in September 2019 ADM announced already plans to rebuild the factory into also a meat replacer manufacturer (AD, 2019). The protein meal side stream can therefore be upgraded from animal feed to human consumption.

Other side streams is from the seed processing, such as hulls and sunflower-, soybean-, and palm waste can also be used to produce energy. Only 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 edible oil and fat production processes in the Netherlands. Whereas, the last section focusses on CHP boiler alternatives and other sustainable heat winning technologies that are not only suitable for this sector but can also be applied to others. Additionally in Appendix E, one can find a summarizing 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 8 below. Nanofiltration (NF), Ultrafiltration (NF) 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 life-time 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.

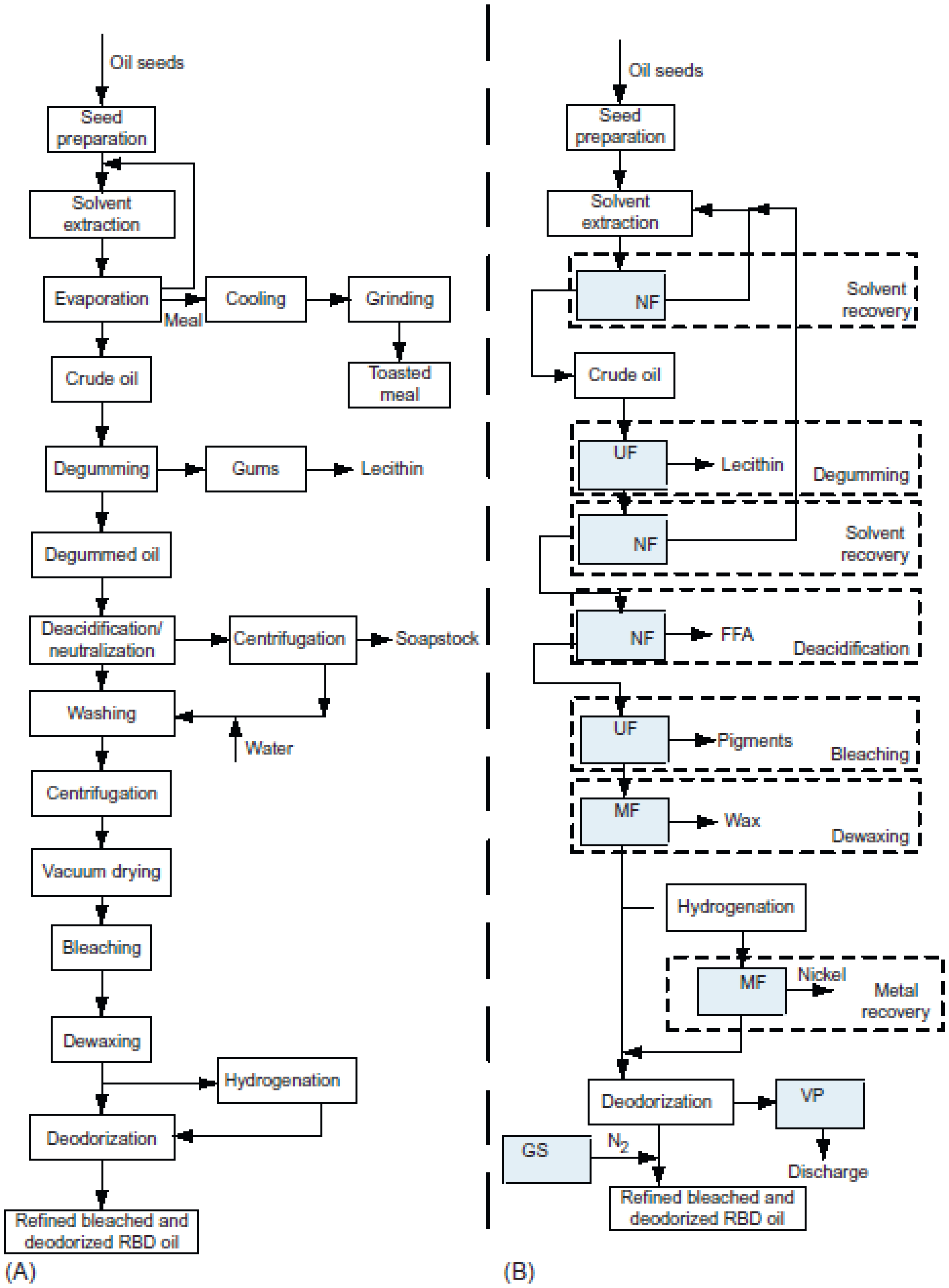

Figure 9 Vegetable oil processing. (A) Conventional Process. (B) Possibilities of substituting conventional processes by membrane-based processes (Ladhe & Kumar, 2010)

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 firstly, because the separation of hexane from the oil can be performed at room temperature and evaporation energy is 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). Though, it is good to keep in mind that membrane specifications required 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 . So that 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. Also, here life-time estimates and final recovery values are main items of research.

Using membrane technology for the solvent extraction can reduce the energy consumption by 30-50% (Szekely, Jimenez-Solomon, Marchetti, Kim, & Livingston, 2014) where 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 the process costs by 50-85% compared to the conventional method (CORDIS, 2019). Moreover, the capital investments for an membrane filtration for acetone recovery from vegetable oil is 500 k€ (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 kton	Calculated[3]
Lifetime	3-5 year[4]	(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)

Table 7 In- and outputs when membrane are used for solvent extraction in the crushing stage for the production of 1 ton oil

	Material or energy flows	Processing rapeseed	Processing soybean
INPUT	Rapeseeds	2500 kg	5390 kg
	Hexane	1245 kg	1242 kg
	Steam	968 MJ[5]	1355 MJ[6]

---

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

[4] This is what can be realized nowadays in solvent recoveries, 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.

[5] 50% of energy reduction of conventional solvent extraction taken

[6] 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

	Electricity	344 MJ[7]	185 MJ[8]
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 by using membranes. In the conventional degumming process, crude oil is treated with water, salt solutions or dilute acid to obtain the removal of 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 obtained 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 1980's) 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 the energy consumption with 30-50% (SolSep, 2019). The new input and output flows for the refinery stage when membrane degumming is executed are shown in Table 10.

Table 8 Membrane degumming specifications

Characteristics	Value	Source
Plant Capacity	20 kton	Assumption, same as for solvent extraction
Lifetime	3-5 year[9]	(SolSep, 2019)
Investment cost	500 k€	Assumption, same as for solvent extraction
Maintenance cost	3% of CAPEX	Estimation
TRL level	6	(SolSep, 2019)

---

[7] Average of 50% reduction used

[8] 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

[9] 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.

Table 9 In- and outputs when using membrane degumming in the refining stage for production of 1 ton oil

	Material or energy flows	Processing rapeseed/soybean
INPUT	Crude oil	1017 kg
	Steam	210[10] MJ
	Electricity	94[11] MJ
OUTPUT	NBD oil	1000 kg
	Oil losses	17 kg

4.1.2 Enzyme applications

Enzymatic Degumming

Oil degumming, which is the reduction of the 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 9. Enzymatic degumming already exists on industrial scale and the routemap of MVO states that the whole Dutch oil and fat sector optimized the degumming process and therefore reduced the energy consumption (Bergmans, 2012). However, how they exactly accomplished this energy saving is not mentioned.

The usage of enzymatic degumming can overall reduce the CO_2 with 3.4 kg per ton produced oil and therefore decreases the energy consumption with 60 MJ per ton 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 11. Whereas, the material and energy input for the refinery stage of rapeseed and soybean oil when using enzymatic degumming can be seen in Table 12

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[10] Average of 40% energy reduction used

[11] Average of 40% energy reduction used

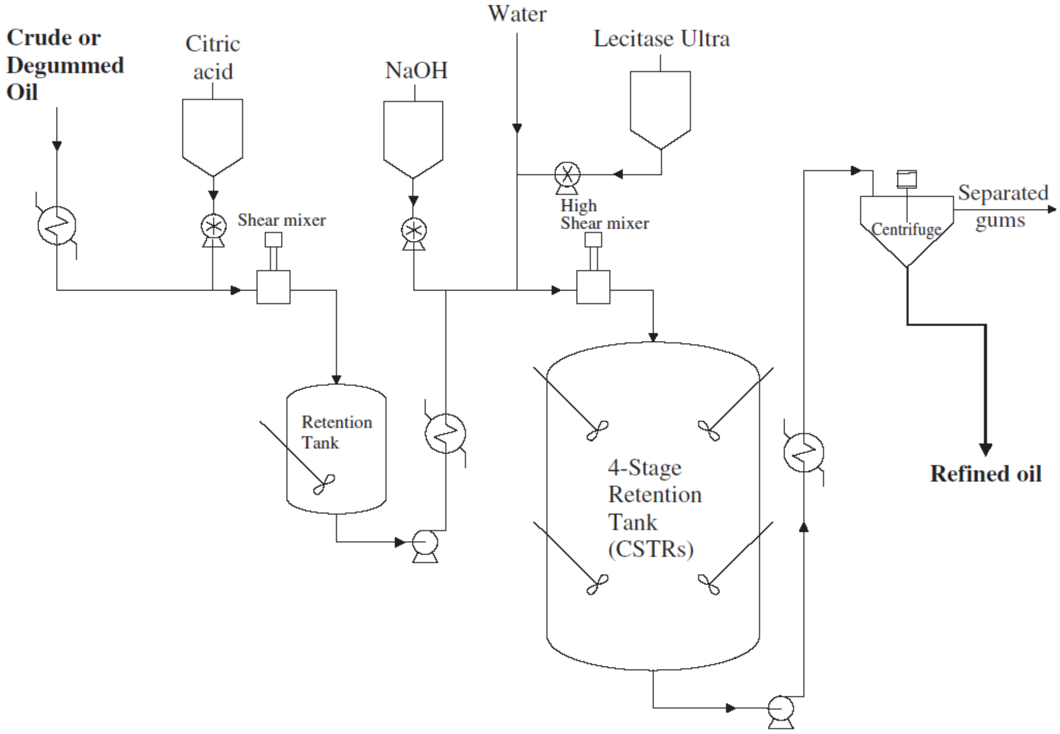

Figure 10 Enzymatic degumming flow sheet (Hamm, 2013)

Table 10 Enzymatic degumming investment specifications

Characteristics	Value	Source
Plant Capacity	800 ton/day	(Munch, 2007)
Yield	Rapeseed 97.7% Soybean 97.1%	(Munch, 2007)
Lifetime	15	Estimation
Investment cost	EUR 1.4 million	(Munch, 2007)
Maintenance cost	VOM 6.16 EUR/ton costs including oil losses 19.96-24.56 EUR/ton[12]	(Munch, 2007)

Table 11 In- and outputs when using enzymatic degumming in the refining stage for production of 1 ton 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

---

[12] Considering 0.1% oil losses costs 0.6 EUR. So for rapeseed oil the total degumming costs results in 19.96 EUR/ton and soybean oil 24.56 EUR/ton

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 10 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 an higher oil yield and therefore less oil is lost than with CIE (Holm, 2008).

The energy consumption of CIE is much higher than for CIE, 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 ton modified oil produced can be saved (Table 3) (Hamm, 2013). The investment and maintenance cost for a EIE plant with an annual capacity of 34,000 ton per year can be seen in Table 13. Followed by the material and energy in and output in Table 14 when EIE substitutes the main part of CIE.

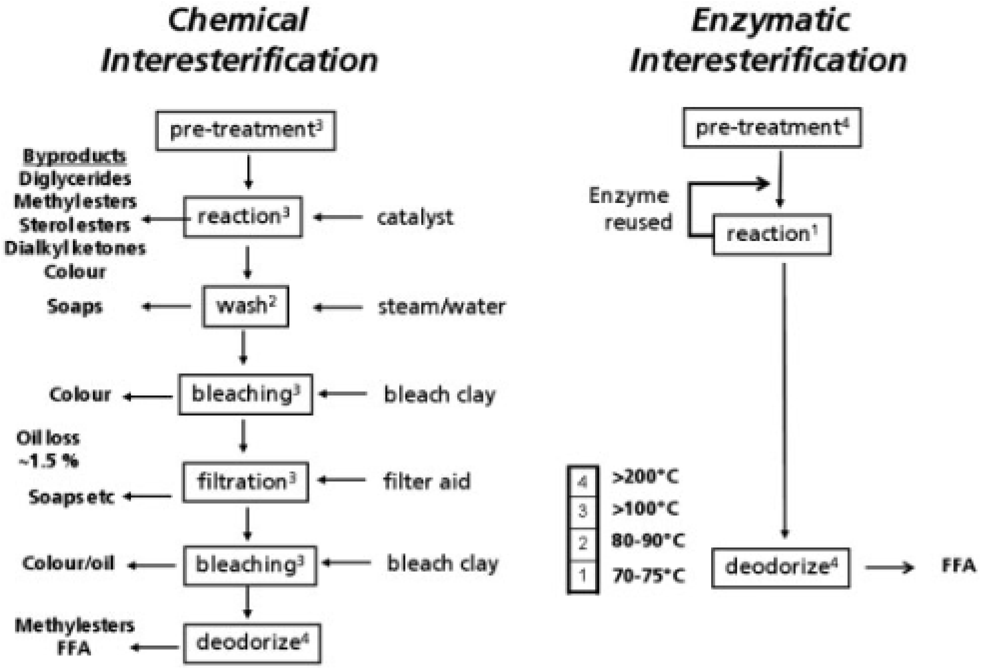

Figure 11 Comparison of process steps and temperatures for CIE and EIE (Holm, 2008)

Table 12 EIE investment specifications

Characteristics	Value	Source
Plant Capacity	34,000 t/year	(Hamm, 2013)
Lifetime	6[13]	(Hamm, 2013)
Investment cost	ROI 1.85 M EUR	(Hamm, 2013)
Maintenance cost	OPEX[14] 2.46 EUR/ton oil	(Hamm, 2013)

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[13] Calculated by given costs in table 6.9 of (Hamm, 2013)

[14] OPEX compared to OPEX (Hamm, 2013)

Table 13 In- and outputs where CIE is replaced with EIE in the oil modification stage for production of 1 ton 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 sublimizes (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 re-used 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 15.

Table 14 Vertical ice condensing technology specifications

Characteristics	Value	Source
Plant Capacity	200 kg/h	(DesmetBallestra, 2015)
Lifetime	>25 years[15]	Estimation
Investment cost	0.72 MEUR	(DesmetBallestra, 2015)
Maintenance cost	3% of CAPEX	Estimation

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[15] First installation is installed ~1995 and still running (Eproconsult, 2019)

Table 15 In- and outputs when using vertical ice condensing technology for deodorisation in the refining stage for production of 1 ton oil

	Material or energy flows	Processing rapeseed/soybean	Processing palm oil
INPUT	Crude oil	1017 kg	1000 kg
	Steam	104 MJ[16]	150 MJ[17]
	Electricity	33 MJ[18]	40 MJ[19]
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 edible 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 a MVR heat pump can be seen in Table 17.

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.

Table 16 Characteristics of a MVR heat pump

Characteristics	Value	Source
Fuel	Electricity, waste heat	
Emissions		
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)

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

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[16] Average taken of 15% of the traditional energy consumption for deodorisation

[17] 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)

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

[19] 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)

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 are 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 18. 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
Fuel	Electricity	
Emissions	0	
Capacity	3 – 70 MWe	(Berenschot, CE Delft, Industrial Energy Experts, & Energy Matters, 2017)
Electrical efficiency	Up to 99.9%	(Berenschot, CE Delft, Industrial Energy Experts, & Energy Matters, 2017)
Lifetime	10 -15 years	(Berenschot, CE Delft, ISPT, 2015) (VNP, 2018)
Investment costs/CAPEX	150-190 EUR/kWe$_{2017}$ (incl. installation)[20]	(Berenschot, CE Delft, ISPT, 2015)
Maintenance costs/OPEX	1.1 EUR/kW/yr FOM and 0.5 EUR/MWh VOM	(Berenschot, Energy Matters, CE Delft, Industrial Energy Matters, 2017)

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-, sunflower oil waste is converted to heat and electricity. On a daily basis, 13.2 ton biomass can here be converted in 67 ton 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 ton steam per hour (CE Delft, Studio Marco Vermeulen, & SEO Economisch Onderzoek, 2018).

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[20] 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[21]	(IEA, 2010)
Efficiency	87-90% (LHV)	Estimation
Lifetime	<25	(IEA, 2010)
Investment cost	50 EUR_{2015}/kWth[22]	(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 decarbonization option. This means that the hydrogen should be produced by electrolysis with renewable electricity with for example Alkaline electrolysis or Proton Exchange Membrane (PEM).
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 (Berkel, 2018 (E4tech, 2014)). The characteristics of an hydrogen boiler can be found in Table 20 together with the investment and maintenance costs.

Table 19 Characteristics of hydrogen boilers

Characteristics	Value	Source
Fuel	Hydrogen	(Johansson K. , 2005)
Emissions	Water vapour, NOx	(Johansson K. , 2005)
Capacity		
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 to be reached which can be thus useful for heating purposes in the vegetable oil and fat industry (Groen, Vries, Mijnlieff, & Smekens, 2018; IRENA, 2019).

To observe if geothermal energy is an option for the Dutch oil and fat sector, the map in Figure 11 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

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[21] 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.

[22] Assume same as gas-fired boiler

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 21.

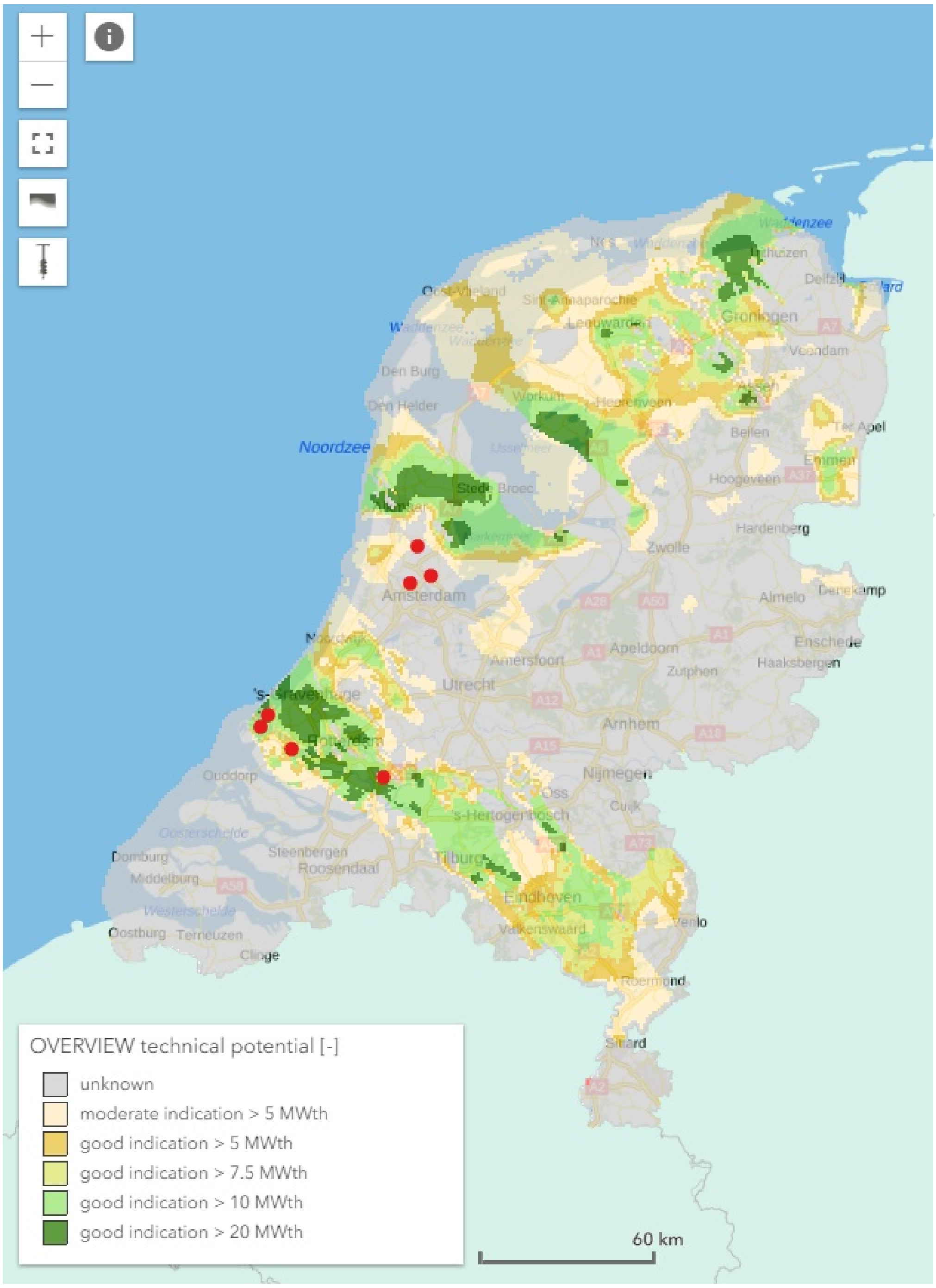

Figure 12 Technical geothermal energy potentials (ThermoGIS, 2019)

Table 20 Characteristics of geothermal energy

Characteristics	Value	Source
Fuel	Electricity, heat	
Emissions	0	
Capacity	17 MW	(Groen, Vries, Mijnlieff, & Smekens, 2018)
Efficiency		
Lifetime	15 years	(Groen, Vries, Mijnlieff, & Smekens, 2018)
Investment cost	2,509 EUR/kWth	(Groen, Vries, Mijnlieff, & Smekens, 2018)
Maintenance cost	107 EUR/kWth/yr FOM & 0.0076 EUR/kWhth output	(Groen, Vries, Mijnlieff, & Smekens, 2018)

5 Discussion

The Dutch edible oil and fat industry can 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 carbon emissions. Since a temperature of 280°C is required in the edible oil processing using only a MVR heat pump or ultra-deep geothermal energy is not enough. Therefore, this technologies should be complemented with another sustainable energy supply that can provide these elevated temperatures. Furthermore, cooperation between different companies can also help by purchasing a new sustainable energy supply unit. Especially for ultra-deep geothermal technology, companies in the same area can corporate to realise a geothermal unit and share the costs and the energy that is exploited.

The usage of membranes in the edible oil and fat industry seems to have an huge potential for a more sustainable and less energy intensive oil production process. Nevertheless, it is still hard 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 very 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 edible oil and fat industry. Lastly, what is observed is that converting an existing factory for adding a membrane process unit is rather costly and not chosen to implement. While for new build 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 therefore explains the choice to purchase a biomass boiler as some companies in the Dutch vegetable oil and fat industry did in recent years. The biomass fuel price for processing residue is taken from IRENA (IRENA 2014). Since it is known that factories can feed the biomass boiler with by-products from the 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. The biomass fuel costs can therefore exceed the 2.97€/GJ. 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).

Next to the decarbonisation options, also heat recovery is applicable in the vegetable oil and fat industry. It is known from the MJA (Meerjarenafspraak) (English: long-term agreement) reports (de Ligt 2018) that the companies within the vegetable oil and fat industry in the Netherlands increased their energy efficiency in the last 20 years every year with approximately 2%. This is partly achieved by the recirculation of residual heat (de Ligt 2018, MVO 2013). 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 more energy efficiency can be realised. Adding this heat recovery up 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 when the consumer perception of an high quality oil changes from a clear oil towards a more turbid oil.

Last but not least, decarbonisation of all industries depend on what kind of energy infrastructure the Netherlands get. The decarbonisation options given for the edible oil and fat industry rather intent to a more electrified process. However, usage of hydrogen or other green gas (or biogas) could also be an option as fuel input for the boiler. The choices taken should be realistic and able to be actual executed. Because if a company choses to electrify their whole industry, while later it will be decided that hydrogen is first supplied to all industries. All hydrogen should then be converted to electricity before it can be used for the electrical process changes. This goes along with a lot of energy conversion losses, and is thus costly and less sustainable.

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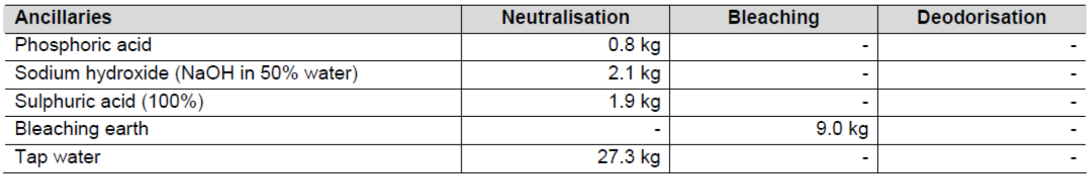
6 Appendix

6.1 Appendix A

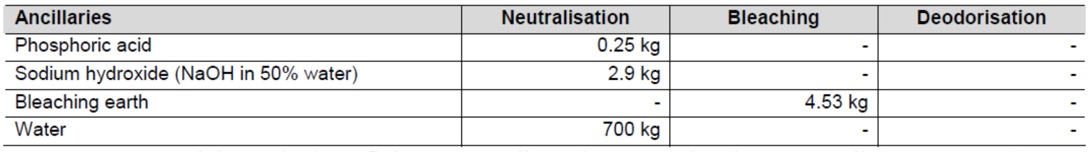
The material usage of rapeseed oil and soybean oil refining are shown in the table 13.1 below (Schmidt, 2007).



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	-	-

Table 13.1: Material uses in the refining stage. All numbers are related 1 t NBD oil. (Hansen 2006)

For refining palm oil, slightly other material and material qualities are used, which can be shown in Table 14.1.



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

Table 14.1: Material uses in the refining stage. All numbers are related 1 t NBD oil. (UPRD 2004)

The materials in the oil modification processes are subtracted from Hamm (2013) and shown in Table 6.9 below.

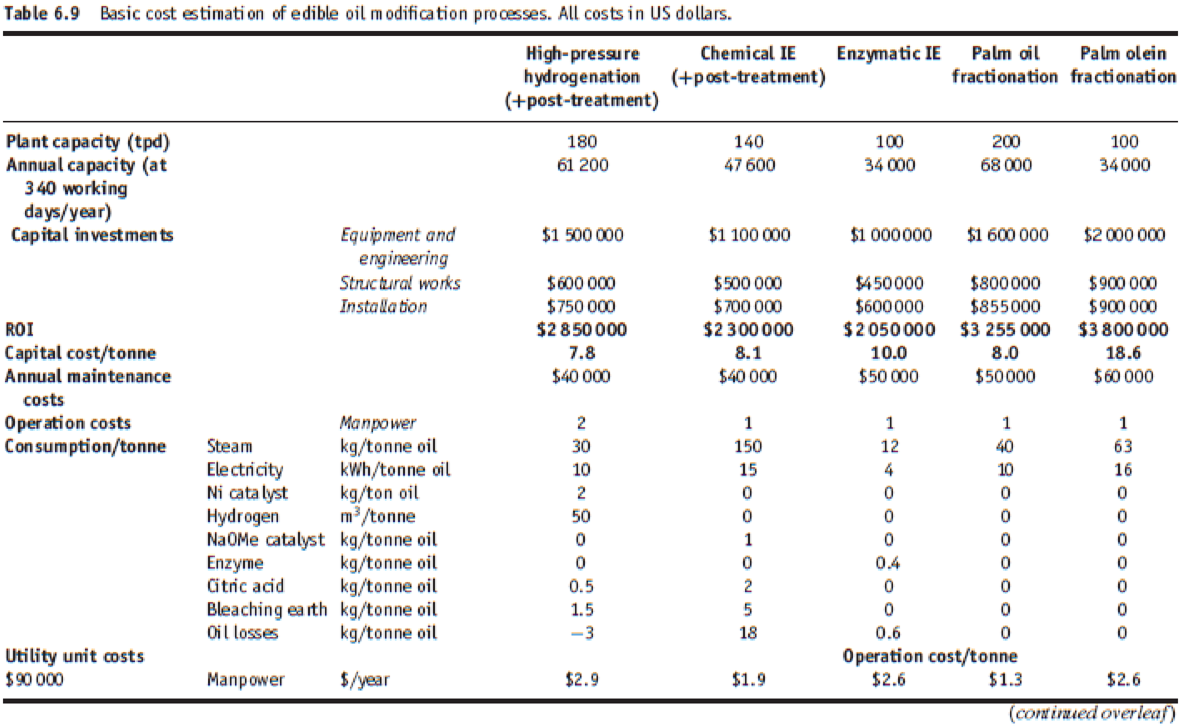
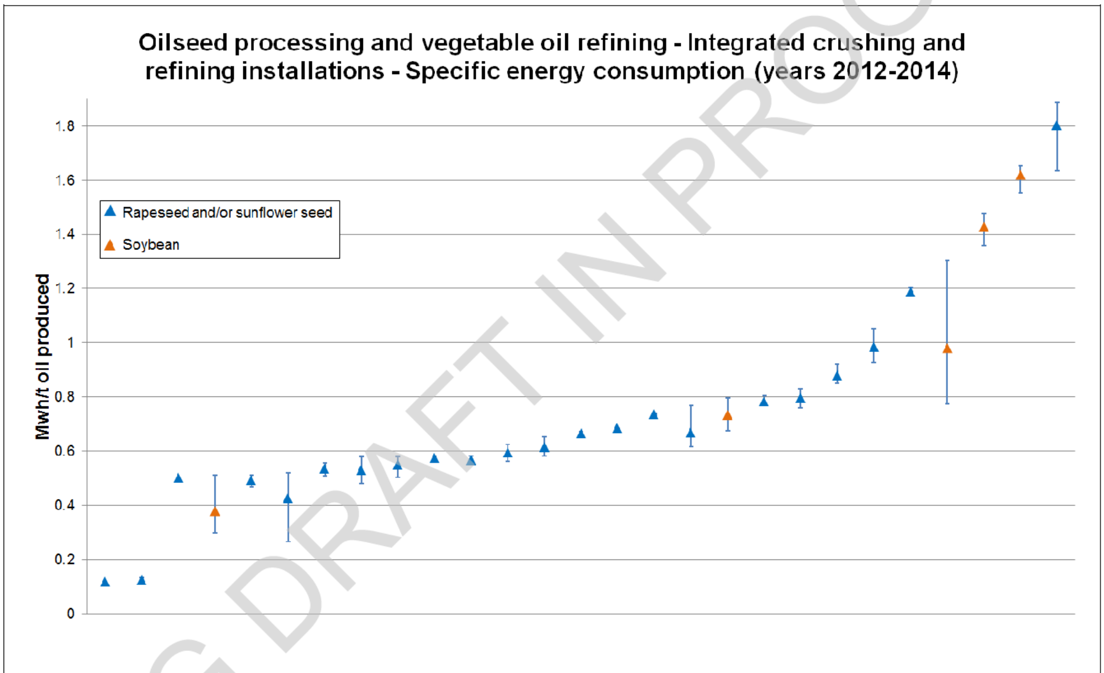


Table 6.9 Basic cost estimation of edible oil modification processes. All costs in US dollars.

			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 investments		*Equipment and engineering*	$1 500 000	$1 100 000	$1 000000	$1 600 000	$2 000 000
		Structural works	$600 000	$500 000	$450000	$800000	$900 000
		Installation	$750 000	$700 000	$600000	$855000	$900 000
ROI			**$2 850 000**	**$2 300 000**	**$2 050000**	**$3 255 000**	**$3 800 000**
Capital cost/tonne			**7.8**	**8.1**	**10.0**	**8.0**	**18.6**
Annual maintenance costs			$40 000	$40 000	$50 000	$50000	$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
	NaOMe 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	0
Utility unit costs					**Operation cost/tonne**		
$90 000	Manpower	$/year	$2.9	$1.9	$2.6	$1.3	$2.6

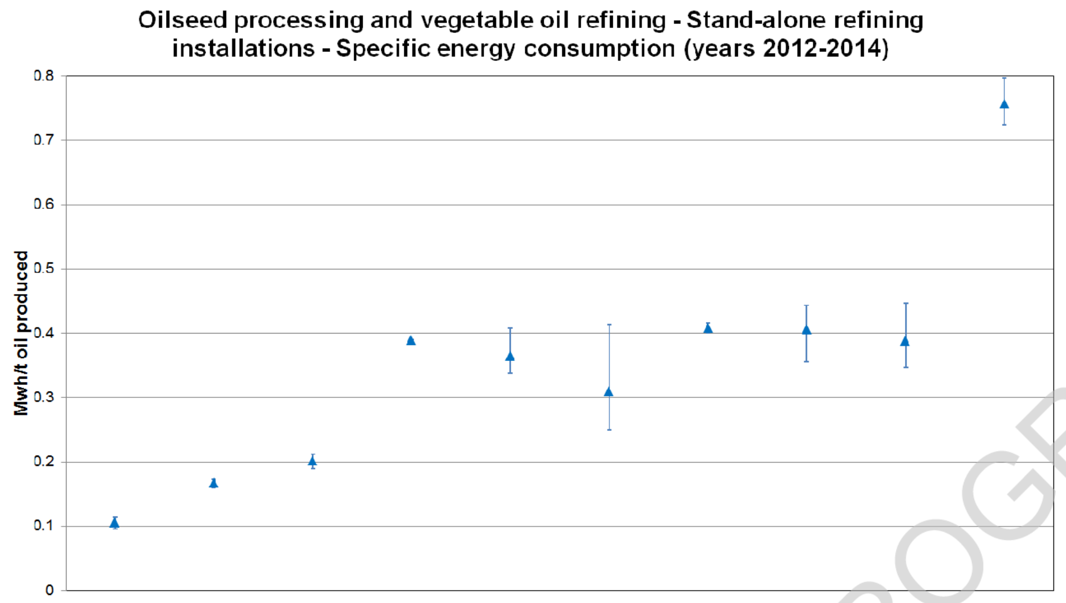
(*continued overleaf*)

6.2 Appendix B



Source: [193, TWG 2015]

Figure 11.6: Specific energy consumption (MWh/tonne of oil produced) in integrated crushing and refining



Source: [193, TWG 2015]

Figure 11.7: Specific energy consumption (MWh/tonne of oil produced) in stand-alone refining

6.3 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 pretreatment by breaking the cell walls and facilitate the oil extraction which will lead to higher oil yields. As a consequence of this, using enzymes can lead to 20-30 min reduction in the 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 color 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, Techno-Economic Analysis of Integrated Enzyme Assisted Aqueous Extraction of Soybean Oil, 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, Environmental Impact Analysis of Soybean Oil Production from Expelling, Hexane Extraction and Enzyme Assisted Aqueous Extraction, 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 Physical and chemical refining process schemes (AOCS, 2019)Figure 3. Using membranes for the dewaxing process is already executed on industrial scale. In Japan, an 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 be 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).

6.4 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 the energy consumption with 50%. The poster says that it reduces the energy consumption with 12.4 TJ/year so the 50% is 12.4 TJ. Based on the findings in Smith (2007), solvent extraction requires 1238 MJ heat for rapeseed oil (for soy there is not specified data). The total energy requirement according to the EEMBAR poster should than be 2x12.4 = 24.8 TJ/year divide this number by 1238 MJ and one gets ~20 kton/year. So the investment costs are calculated to be relevant for a plant of 20 kton 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 ton rapeseed oil. For soybean oil this amount is 189 kg per ton soybean oil. From (Schmidt J. , 2007) it is also known that the bleaching earth used in the refining stage can be fed into the biomass boiler. For every ton rapeseed oil and soybean oil this amount is 14 kg. The amount of MJ gas 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 kton CO2. A biomass boiler that produces 67 ton per day is already been used. This means that some part is already catched away. The biomass boiler produces 24.5 kton steam in a year which saves 3.8 kton CO2 emissions. Therefore, the total amount of CO2 emissions that can be avoided for the total sector decreases from 41.47 to 37.7 kton per year. This is 14% of the total carbon emissions of 2018.

EIE the difference in OPEX between CIE en EIE without the fuel costs is 2.1 dollar. However, the difference in yearly maintenance costs needs also to be added and this is 0.63$ In total the OPEX is 2.73 dollar which is €2.46 per ton oi

6.5 Appendix E

Technology specific decarbonisation options	Steam per ton product saved (MJ)	kg CO2 per ton product saved	Costs per ton product [EUR/tonne]			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, et al. 2016, Szekely, et al. 2014)	Using membrane technology reduces energy consumption with ~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 k€ for calculated capacity of 20 kton so 25 €/ton OPEX assumed 3% of CAPEX
Membrane degumming	16	0.9	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	x	(SolSep 2019, ISPT, et al. 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 ton 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 ton/day €1.4 M assuming 90% of the year producing with additionally 90% utilization factor when used 236520 ton/year and OPEX estimated 3% CAPEX

Enzymatic interesterification	385[23]	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 ton oil that is EIE instead of CIE	$10 capital cost/ton $23.5 operation cost/ton converted to €
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 rapseed/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)	$800.000 capital costs for production of 200 kg/h steam 21.6 MJ heat for rape/soy and 31.35 MJ heat for palm oil. 2789 kJ/kg gives 7.74 kg and 11.24 kg steam per ton 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, et al. 2017, ECN 2017)	32.61% steam energy saved in production of Rice bran crude oil (only crushing) Same assumed for rapeseed/soybean	CAPEX average 2200 €/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, 2018	Same energy saving assumed as for Industrial heat pumps, since it produces same temperatures 32.61% steam energy reduced	CAPEX 2509 €/kW OPEX 107 €/kW assumed efficiency of 90%
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 ton oil/year a boiler capacity of 9,11-

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

								46,81 MW is needed 150-190 €/kWe (€170 is taken) CAPEX and 1.1 €/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 €/kW OPEX average 2 €/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 €110/kW OPEX 3.5 €/kWth/yr