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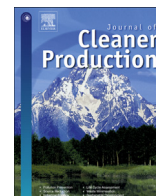
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Cost-effectiveness of decarbonisation options for the vegetable-oil and -fat industry in the Netherlands



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ABSTRACT

There is significant emission reduction potential in the Dutch vegetable oil and fat industry, which consists of seven companies each producing more than 10 kt CO₂ per year, emitting a total of 0.36 Mt CO₂ in 2018. Marginal Abatement Cost (MAC) curves are constructed to provide an overview of the most cost-effective decarbonisation options. Both energy efficiency technologies and alternative heating systems are combined in order to achieve technological configurations for full decarbonisation of this industry. Energy consumption for vegetable oil processing can be reduced by 44% for rapeseed oil, 45% soybean oil, and 57% for palm oil. Vertical Ice Condensing is the most cost-effective decarbonisation option, while biogas boilers are the most cost-effective alternative heating systems that can supply energy in all stages of production. However, the availability of processing residues limits the energy substitution possible with biogas boilers. Electric boilers are therefore required to deliver the residual energy necessary to realise zero carbon emissions. Together the cost-effective decarbonisation options can abate between 38% and 40% of the total CO₂ emissions by 2020 and 2030 respectively.

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1. Introduction

In the Dutch Climate Agreement ('Klimaatpakkoord'), presented in June 2019, targets for national CO₂-emission reduction were set to 49% in 2030 and 95% in 2050, relative to emissions in 1990 (Dutch Climate Agreement, 2019). Each sector, including industry, has been tasked to propose measures and targets to collectively reach the national targets for CO₂-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 kt CO₂ per year, responsible for a total of 0.36 Mt CO₂ in 2018 (NEa, 2019).

In recent years a lot of research has been done into more sustainable ways to process vegetable oils (Nucci et al., 2014), particularly rapeseed, soybean (Li et al., 2006) and palm oil. Not only the processes that impact energy efficiency have been explored, but also extensive Life Cycle Assessments (LCA) have been performed on the production of both the separate oils (Schneider and Finkbeiner, 2013), and on all three oils together (Schmidt, 2007). One of the energy efficiency options in the vegetable oil industry is

the use of enzymes, which can be applied in both degumming and oil modification. Degumming is the removal of phospholipids in the refining stage of oil (AOCS, 2019; Hamm, 2019), which is usually done thermally, but can also be done with enzymes (Jiang et al., 2011; Yang et al., 2008). Oil modification has traditionally been done using chemicals, but can also be performed using enzymes. This modification process, called interesterification, is applied in order to create a desired rearrangement of fatty acyl groups. Enzymatic interesterification was already researched in the 90's (Foglia et al., 1993; Xu et al., 1998) and is nowadays implemented on industrial scale (Hamm, 2013; Holm, 2008).

Another energy efficient 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 (ISPT et al., 2016) are currently in active development (Cheryan, 2005; Szekely et al., 2014). However, neither have been applied on a commercial scale (Coutinho et al., 2009; Ladhe and Kumar, 2010). One exception is a membrane degumming industrial plant that was implemented in the 1980s but was abandoned

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Nomenclature and units			
AOCS	American Oil Chemists' Society	MJA	Meerjaren Afspraak (long-term agreement)
CAPEX	Capital Expenditure	MSE	Membrane Solvent Extraction
CHP	Combined Heat and Power	MVR	Mechanical Vapour Recompression
CIE	Chemical Interesterification	OPEX	Operational Expenditures
CO	Crude Oil	TRL	Technology Readiness Level
ED	Enzymatic Degumming	VIC	Vertical Ice Condensing
EIE	Enzymatic Interesterification	c_p	specific heat, $J \cdot kg^{-1} \cdot K^{-1}$
EU-ETS	European Union's Emission Trading System	T	temperature, K
FFA	Free Fatty Acids	t	tonne
KEV	Klimaat en Energyverkenning (Climate and Energy Outlook)	Q	energy, J
LCA	Life Cycle Assessments	Δh_{phase}	energy phase transition, $J \cdot kg^{-1}$
MAC	Marginal Abatement Cost	B	annual benefits, €
MIDDEN	Manufacturing Industry Decarbonisation Data Exchange Network	C	annual operation and maintenance costs, €
		r	discount rate
		n	life time or depreciation period of equipment
		α	capital recovery factor
		ϕ	mass, kg

soon after because of underestimated fouling problems and the lack of proper cleaning methods (Hamm, 2013). Another way to reduce CO₂ emissions in 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 CO₂ 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 costs does not exist for the vegetable-oil and -fat sector. Therefore, this paper addresses the following question: How can the Dutch vegetable-oil and -fat industry fully 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 its branch in the Dutch industry. The ambition is to explore the route to zero scope 1 CO₂ 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, and the reduction potential of the technologies (Kesicki and Strachan, 2011). A base scenario with fuel prices for 2020 and 2030 is used to observe the most relevant decarbonisation options in both years. Moreover, a high and low fuel price scenario for 2030 is used to analyse the fuel price sensitivity. Lastly, the influence of using a private discount rate instead of a social discount rate is investigated. The innovative aspects of this article are: cost-effectiveness of GHG mitigation options are investigated for a light industrial sector; a marginal abatement cost curve is constructed, while providing uncertainty ranges; a trajectory to full decarbonisation is explored.

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, end-products, 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 have also reviewed these values.

The remainder of this paper contains the following structure. The methods of data exploration and constructing MAC curves are discussed in Section 2, including the oil processes and the input of the data. The results and discussion are presented in Section 3. Lastly, the conclusions of this research can be found in Section 4.

2. Methodology

To start with, the mass and energy balances were analysed to identify the critical control points: the processes which use most energy and/or involve the most carbon emissions. Given these results, more sustainable processes that can potentially substitute the conventional processes are explored based on a literature survey. In this way, a list of decarbonisation options is created. This list was complemented by suggestions from field experts. Additionally, methods to decarbonise the existing heating systems, steam boilers and CHP plants, were explored. Sustainable alternative heating systems that reduce the CO₂ emissions were taken from literature research and added as decarbonisation options when they are applicable to this industry. It is investigated whether the combination of these sustainable technologies could result in decreased CO₂ emissions, aiming for 49% reduction in 2030 and/or zero carbon emissions in 2050. Lastly, the costs of the decarbonisation options are explored to assess 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 (Fig. 1). The MAC curves provide a quick and clear overview on the cost per unit of carbon abated and the reduction potential. The marginal abatement methodology has its limitations, which will be discussed in Section (3.4).

2.1. Mass balance

Mass flow analysis is executed by setting up mass balances throughout the production chains of rapeseed, soybean, and palm oil. Assuming that no material is accumulated in the process, the conservation of mass is expressed in Equation (1) as:

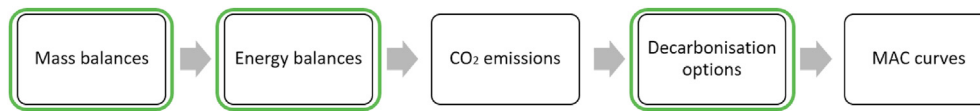


Fig. 1. Framework of the overall methodology. Green: data verified by experts.

$$\sum \phi_{x,in} = \sum \phi_{x,out} \quad (1)$$

where $\phi_{x,in}$ [kg] is the mass of the streams entering the process and $\phi_{x,out}$ [kg] is the mass of the streams exiting the process.

2.2. 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 can neither be created or destroyed (Equation (2)). The energy flows (Q_j) were calculated using Equation (3):

$$Q_{in} = Q_{out} + Q_{losses} \quad (2)$$

$$Q_j = \phi_j * c_{pj} * (T_j - T_0) \quad (3)$$

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 (4) applies. The difference with Equation (3) is the addition of $\Delta H_{phase,j}$, which is the energy required to change phase. In the case of gaseous streams, $\Delta H_{phase,j}$ is the heat of evaporation, and in the case of solids it is the heat of crystallisation.

$$Q_j = \phi_j * C_{pj} * (T_j - T_0) + \Delta h_{phase,j} * \phi_j \quad (4)$$

2.3. 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 (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 satisfactory estimations for each of the product types and quantities manufactured at each production site. When the most energy consuming and carbon emitting 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 initial investment costs, also known as capital expenditure (CAPEX), and the yearly costs indicated as operational expenditures (OPEX) are determined per tonne of oil produced for the end-use technologies or per kilowatt for the alternative heating systems.

2.4. Industry and data validation

First, a literature study is performed on the processing of

vegetable oils and the available decarbonisation options. While researching the processes occurring in the 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 occurring 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 were consulted, especially regarding the area of alternative heating systems. For sector specific decarbonisation options with enzymes, sufficient literature was available. For membrane technology within the vegetable-oil and -fat sector, SolSep BV, a membrane expert, was contacted for the required specific information. They provided additional feedback on the correlated numbers and text in this article.

2.5. Marginal abatement cost curves

In order to represent the outcome of the techno-economic analysis, MAC curves are made for the decarbonisation technologies concerning the vegetable-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 and Strachan, 2011). The specific CO₂ mitigation costs C_{spec,CO_2} are calculated using Equation (5):

$$C_{spec,CO_2} = \frac{\alpha \cdot I + C - B}{\Delta M_{CO_2}} \quad (5)$$

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_{CO_2} = annual amount of avoided CO₂ emissions

The capital recovery factor α in Equation (6) is determined by the following calculation:

$$\alpha = \frac{r}{1 - (1 + r)^{-n}} \quad (6)$$

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 scenario 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 in 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 (PBL et al., 2019).
- d) The natural gas price 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 natural 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 €3 (IRENA, 2014). The price of processed residues biomass in 2020 and 2030 are assumed to be the same.
- g) A social discount rate of 4% is assumed.
- h) The indirect (scope 2) emissions, which are the indirect emission from sources that are not owned or controlled by the companies (Greenhouse Gas Protocol, 2019) of electricity consumption are not included in this research. The electricity sector is on a pathway to rapid decarbonisation, and that will have already been implemented by 2030 to a large extent (more on this in Section 3.5)

2.6. 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 of 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 to palm oil. Other oil inputs are only used to a very small 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 h of harvest and therefore such processing occurs on or near the local plantation (Sridhar and AdeOluwa, 2009). Moreover, not all companies in this sector execute crushing, several companies purchase crude rapeseed oil and crude soybean oil directly (MVO, 2019; IPPC, 2019). 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 the removal of free fatty acids (FFA) and lecithin from the oil. Bleaching is executed to remove undesired coloured

particles and substances (Schmidt, 2007). This is achieved through physical and chemical interaction of the oil with the bleaching earth (IPPC, 2019). Lastly, deodorisation is performed to remove undesired flavouring or odorous compounds (Hamm, 2013). Oil modification, finally, 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 and -fat 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 (Gupta, 2017; Hamm, 2013). 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). Fractionation is executed to generate two fractions, which can be dry or wet fractionised. In the Netherlands, the fractionation process only occurs for palm oil (MVO, 2019).

The mass and energy flows for the three oil types are shown in Fig. 2. 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 2.5 tonne rapeseed and 5.4 tonne 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. The amount of steam added is the net amount of heat (in the form of steam) required for the process. From information of field experts, it is known that both CHP plants and steam boilers are used in the Dutch vegetable-oil and -fat industry. It is assumed that the CHP boilers used in this sector are small gas turbines with waste heat boilers, 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 (IPPC, 2019). More explanation and details of these processes can be found in the MIDDEN report (Altenburg and Schure, 2020).

2.7. 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: *i*) the technology specific options and *ii*) the alternative heating system options. The technology specific decarbonisation options are only applicable for implementation in the vegetable-oil and -fat industry.

- i) In the crushing stage, traditional solvent extraction can be substituted with membrane solvent extraction (MSE) where membranes are used to separate the solvent from the oil, which is less energy intensive than distillation only. This technique has not been applied on an industrial scale, nevertheless it is in an advanced stage of development, having a Technology Readiness Level (TRL) of 6–8 (ISPT et al., 2016; SolSep, 2019). 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 (ED) does already exist on an industrial scale (AOCS, 2019), whereas membrane degumming is still in progress and has a TRL of 6 (SolSep 2019). Enzymatic interesterification (EIE), in the oil modification stage,

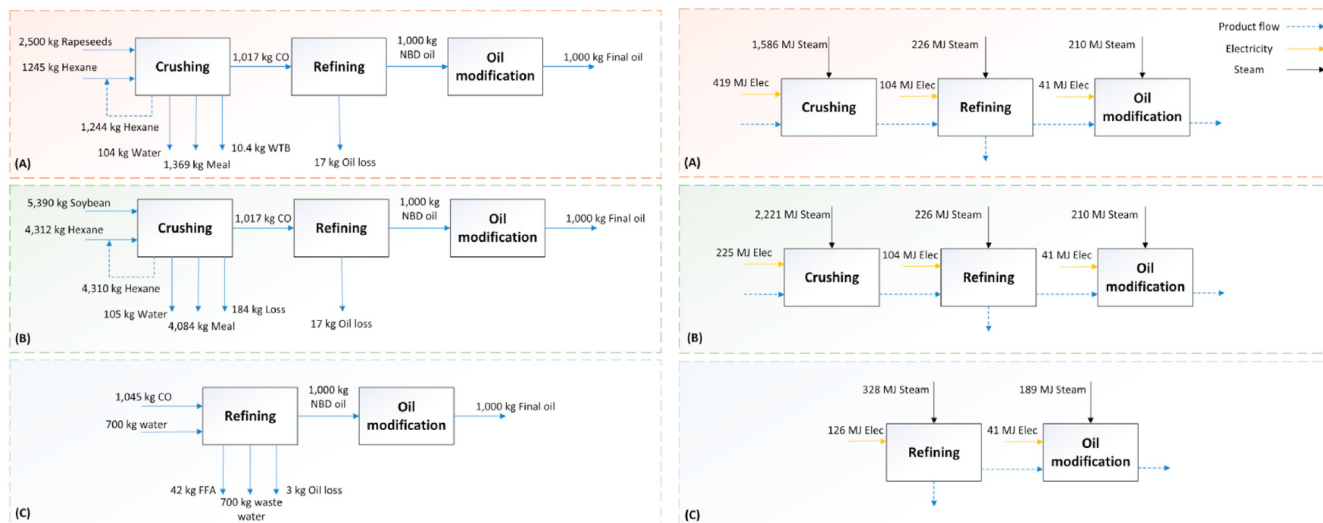


Fig. 2. Left: mass balances, and right: energy balances of (A) rapeseed (B) soybean and (C) palm oil (Schmidt, 2007; Hamm, 2013; IPPC, 2019).

is also already applied on a commercial scale. However, it can be applied to a larger extent to decrease the overall energy consumption and fully replace chemical interesterification (CIE) (Holm, 2008). The OPEX costs are high primarily due to the cost of the enzymes (Hamm, 2013).

- ii) The alternative heating systems consist of options that can partly or totally substitute the natural gas boiler or the CHP plant. A mechanical vapour recompression (MVR) industrial heat pump and ultra-deep geothermal energy can both reach temperatures up to 120–140 °C, which is not sufficient for fully providing the energy required in the vegetable oil processes. The electrode boiler is an 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.

Additionally, a biogas boiler is also a possibility to provide the energy requirements for 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 are presented in Table 1. The values that are provided in range mean that the natural gas savings are different for the various types of oil. For example, Vertical Ice Condensing (VIC) technology saves 122 MJ natural gas in rapeseed and soybean oil, but 178 MJ for the production of palm oil.

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

Technology specific decarbonisation options	Natural gas saved per tonne product (MJ/t)	kg CO ₂ saved per tonne product	Costs per tonne oil capacity [EUR/t] ^a			References
			Rapeseed	Soybean	Palm	
<i>Membrane solvent extraction</i>	619 – 866	35 – 49	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	X	ISPT et al., 2016; Szekeley et al. (2014)
<i>Membrane degumming</i>	16	0.9	CAPEX 25 OPEX 0.8	CAPEX 25 OPEX 0.8	X	ISPT et al. (2016); SolSep (2019)
<i>Enzymatic degumming</i>	60	3.4	CAPEX 6 OPEX 0.2	CAPEX 6 OPEX 0.2	X	Hamm (2013); Munch (2007)
<i>Enzymatic interesterification</i>	385 ^b	7.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	CAPEX 9 OPEX 2.5	Hamm (2013)
<i>Vertical Ice Condensing technology</i>	122 – 178	7 – 10	CAPEX 3.5 OPEX 0.1	CAPEX 3.5 OPEX 0.1	CAPEX 5.1 OPEX 0.15	DesmetBallestra (2015); GEA (2019); Körting (2019); Schmidt (2007)
Alternative heating systems						
<i>Industrial heat pumps (MVR)</i>	0 – 724	0 – 41	CAPEX 8 OPEX 0.2	CAPEX 11 OPEX 0.3	X	ECN (2017); Kong et al. (2017)
<i>Ultra-deep geothermal energy</i>	0 – 724	0 – 41	CAPEX 51 OPEX 2.2	CAPEX 71 OPEX 3	X	In 't Groen et al. (2018)
<i>Electric boiler</i>	517 – 2657	29 – 150	CAPEX 13 OPEX 0.1	CAPEX 16 OPEX 0.1	CAPEX 3 OPEX 0.02	Berenschot et al. (2015, 2017)
<i>Biogas boiler</i>	517 – 2657	29 – 150	CAPEX 4 OPEX 0.2	CAPEX 5 OPEX 0.2	CAPEX 1 OPEX 0.04	Energy Matters (2015)
<i>Hydrogen boiler</i>	517 – 2657	29 – 150	CAPEX 10 OPEX 0.3	CAPEX 11 OPEX 0.4	CAPEX 2.2 OPEX 0.07	E4tech (2014); VNP (2018)

^a The unit for OPEX is EUR/t.y; CAPEX is EUR/t.

^b This is the amount of energy saved of 1 tonne oil that is modified by EIE instead of CIE. Not all oil is interesterified.

3. Results and discussion

The MAC curves, calculated for 2020 and 2030 using a social discount rate as stated in the Methodology, are shown in Figs. 3 and 4. Considering the annual sector growth, a total of 368 kt CO₂ in 2020 and 403 kt CO₂ in 2030 needs to be abated to fully decarbonise the vegetable-oil and -fat 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 are only considered as a decarbonisation option in 2030. 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 not selected since enzymatic degumming 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/tCO₂ and €477/tCO₂ for 2020 and 2030, respectively. The specific MAC of the other (not selected) technologies, can be found in Appendix A.

The cost-effective decarbonisation options (options with negative MAC) can eliminate 141 kt CO₂ emissions in 2020 and 163 kt CO₂ emissions in 2030. This translates to 38% and 40% of the total carbon dioxide emissions for 2020 and 2030, respectively. 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 natural gas therefore become higher. Hence, 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, but enzymatic degumming 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 plants with a hydrogen boiler will be almost twice as expensive in 2020 than in 2030. The electric boiler, on the other hand, will be cheaper in 2020 than in 2030. 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 is expected to 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 have already invested in this system (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 sufficient energy for all stages. This is in line with the report of Element Energy, which stated that biogas boilers are the most cost-effective fuel switching option for steam and indirect heating in the food & beverages industry among others (Lyons et al., 2018). However, the energy substitution by a biogas boiler is limited by the availability of biomass from processing residues in the Dutch vegetable-oil and -fat industry. In total, 38 kt and 42 kt CO₂ can be abated by the available processing residues, in 2020 and 2030, respectively. These numbers do not include the

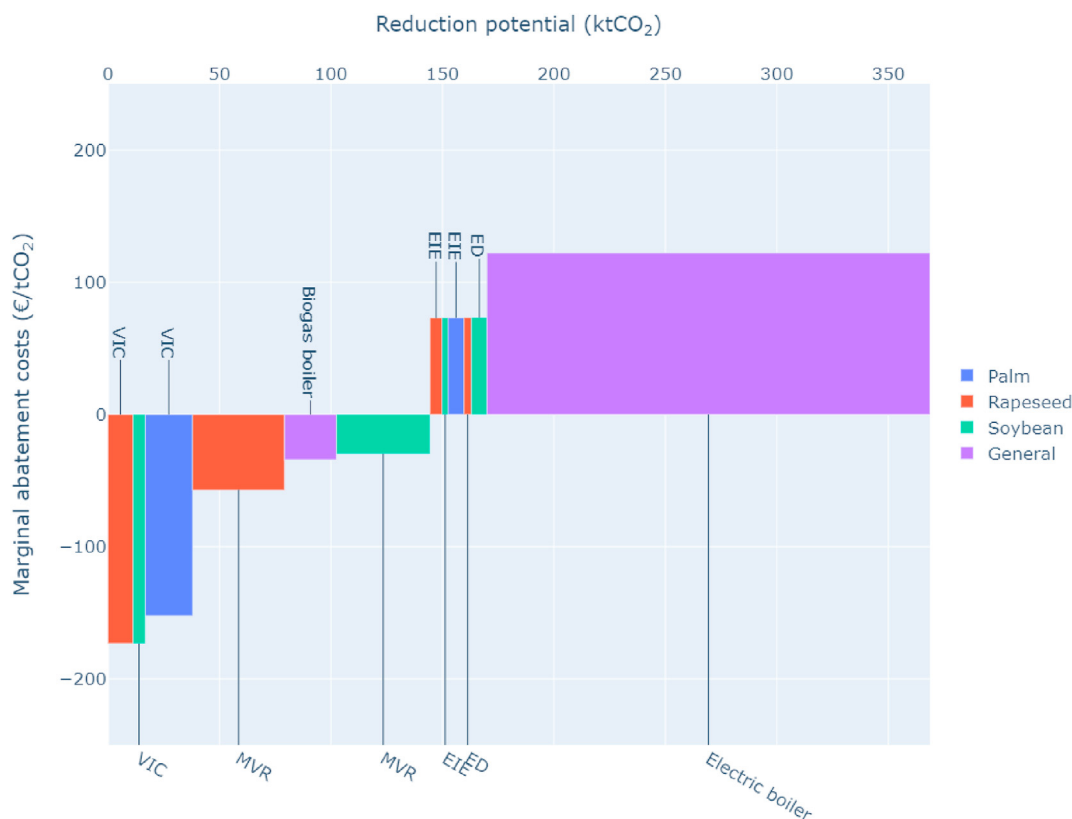


Fig. 3. Decarbonisation options with 2020 fuel prices. The technology-specific options from Table 1 are presented for the different oil categories. The alternative heating system from Table 1 are presented as 'General'. (Where VIC: Vertical Ice Condensing, MVR: Mechanical Vapour Recompression industrial heat pump, EIE: Enzymatic Interesterification and ED: Enzymatic Degumming).

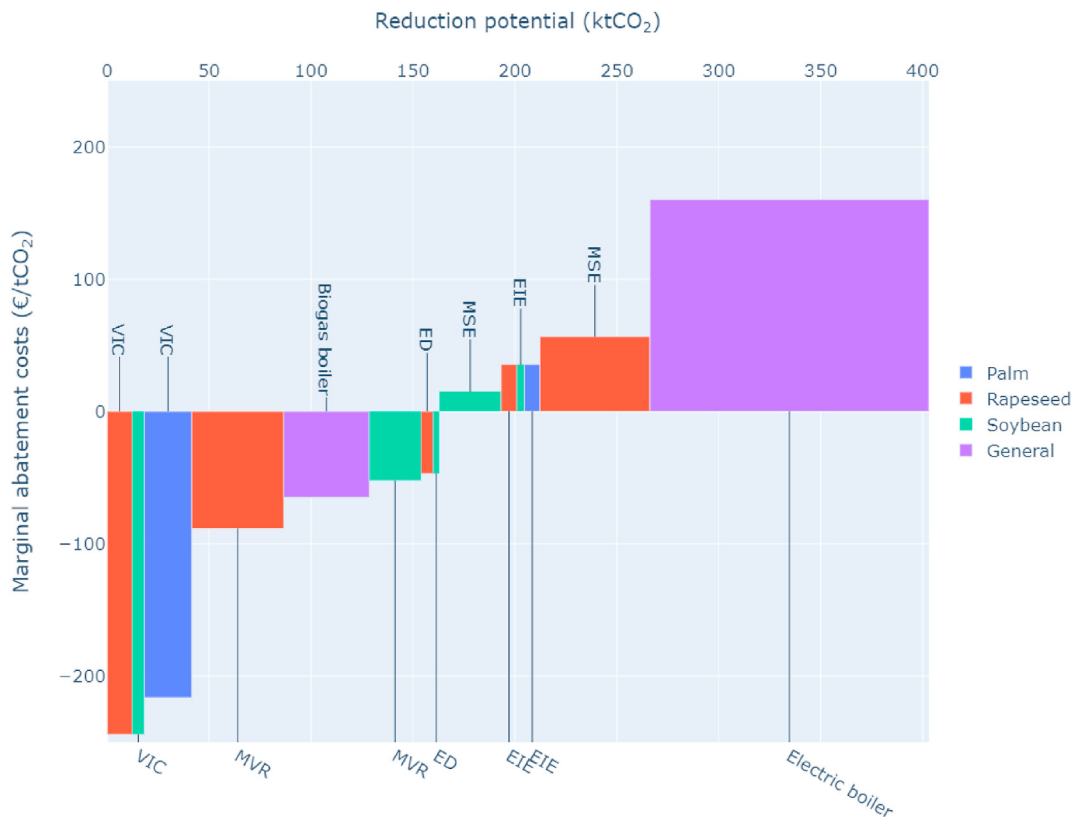


Fig. 4. Decarbonisation options with 2030 fuel price. See further explanation in the caption of Fig. 3.

3.8 kt CO₂ that is already substituted by an existing biogas plant (Appendix B).

The technology specific decarbonisation options together with the industrial heat pumps and biogas boiler cannot realise full decarbonisation (Fig. 3). Still 137 kt and 202 kt CO₂ emissions need to be abated for 2020 and 2030, respectively. Both the electric boiler and hydrogen boiler can achieve this, but as discussed above the MAC of a hydrogen boiler is higher than that of an electric boiler. Therefore, the remaining energy is likely to be delivered by an electric boiler.

3.1. 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 Fig. 5.

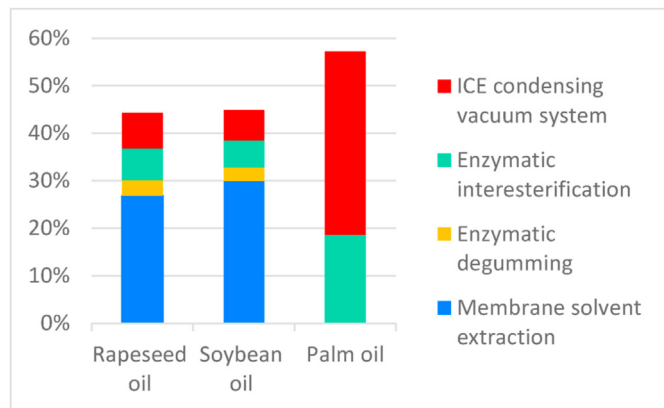


Fig. 5. Energy reduction possible for the different types of oils.

This figure shows the energy savings of the four technology specific decarbonisation options: membrane solvent extraction, enzymatic degumming, enzymatic interesterification and Vertical Ice Condensing technology. 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 decarbonisations options are combined for the total production process (crushing, refining, and oil modification stages together) for rapeseed and soybean oil, the energy consumption can be reduced by 44% and 45% respectively. The energy requirements of the entire palm oil production involving refining and oil modification can be reduced by 57% (Fig. 5). Membrane solvent extraction saves the most energy for rapeseed and soybean oil production, whereas Vertical Ice Condensing technology saves the most energy for palm oil production.

The production of the seven companies in the Dutch vegetable-oil and -fat industry can vary from year to year. The production quantities of the different types of oil are dependent on the purchase price and demand. Note also that for one manufacturing site the precise production capacity was unknown and is therefore estimated based on their CO₂ emissions. However, since this is the smallest emitter of all seven companies, no large impact is expected on the results.

3.2. Price scenarios

Predicted fuel prices for the future are uncertain. To deal with this uncertainty, a low and a high fuel price scenario are created for 2030. In the low price scenario, the fuel prices for 2030 are reduced by 25%, whereas in the high price scenario +25% is added to the 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. These reduced costs arise from 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, due to the fact that the MAC of the electric boiler depends on the electricity fuel price. An electric boiler does not avoid energy consumption but rather substitutes natural gas with electricity. Therefore, the increasing electricity price in 2030 results in higher MAC. The order of the decarbonisation options in the MAC curve remains largely the same. Only the enzymatic degumming processes become more advantageous than the biogas boiler and industrial heat pump (MVR) for soybean oil in the high price scenario. In addition, enzymatic degumming, membrane solvent extraction and enzymatic interesterification change from a non-cost-effective option to a cost-effective option in the high fuel price scenario. The Vertical Ice Condensing technology remains the most cost-effective technology specific decarbonisation option in all scenarios. A factor that plays a role in the uncertainty of the energy prices is the difficulty of predicting the development of costs and performance of technologies. Fuel prices are dependent on such development and 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 halve expenditures in a short period of time. An example of unexpected rapid development of technologies are PV-modules, where the costs declined by more than 80% between 2009 and 2017 ([IRENA, 2018](#)). Lastly, the electricity prices can fluctuate much within a year. In summer, when a large amount of renewable energy is produced, the electricity prices can be much lower than in winter ([PBL et al., 2019](#)). These price fluctuations are expected to be stronger in 2030, since the renewable energy share will be much higher. Therefore, the electricity price is expected to be low for a longer 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, that moves from a cost-effective option to a decarbonisation option above zero. This effect is similar to the comparison of the 2020 and 2030 MAC curves and the high and low fuel price scenario, as elaborated previously in the Results and Discussion section. This shift in the MAC of enzymatic degumming occurs because the amount of avoided CO₂ emissions per tonne produced oil is rather small ([Table 1](#)). Therefore, the MAC of enzymatic degumming is relatively prone to both discount rate changes and fuel price changes. Another effect of the higher discount rate is that the cost-effective decarbonisation options become slightly less cost-effective. Likewise, the MAC for the decarbonisation options above zero increases as the discount rate increases, as a result of increased capital charges with increasing discount rates.

3.3. Decarbonisation options

The cheapest alternative heating system option is the biomass boiler, due to the low expenses for the biomass fuel. Biomass fuel expenses are much lower than fuel expenses for a hydrogen or electric boiler. This 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 that we used is valid for processing residue taken from [IRENA \(2014\)](#), since factories can feed the biomass boiler with by-products from the oilseed

processing ([Kuipers et al., 2015](#); [Schmidt, 2007](#)). When the biomass feed consists mainly of these process residues, purchasing a biomass boiler becomes highly cost effective. However, if insufficient processing residue biomass is produced for the energy required, other biomass sources should be fed in. Most of these alternative options are more expensive than the processing residues. The biomass fuel costs can therefore exceed 3€/GJ. Additionally, biomass fuel prices are also regionally dependent due to the variation of biomass availability ([IRENA, 2014](#)).

In addition to the decarbonisation options, heat recovery is applicable in the vegetable-oil and -fat industry. The MJA (Meerjarenspraak) (English: Long-Term Agreement) reports ([de Ligt, 2018](#)) show that companies within the vegetable-oil and -fat industry in the Netherlands improved their energy efficiency in the last 20 years by approximately 2% per year. This is partly achieved by the recirculation of residual heat ([de Ligt, 2018](#); [MVO, 2013](#)). Moreover, according to [Li et al. \(2006\)](#), approximately 35% of the energy consumption in the traditional soybean crushing process can be reduced by potential heat recovery. However, as the exact numbers regarding the amount of heat recovery achieved and heat recovery to be realised are still unknown, these are not taken into account in this analysis. Therefore, it is possible that even more energy efficiency than currently shown in [Fig. 4](#) can be realised.

The usage of membranes in the vegetable-oil and -fat industry seems to have a huge potential for a more sustainable and less energy intensive oil production process. Even though working prototypes already exist, the adaption of membranes in the vegetable-oil and -fat industry is perceived as problematic, partly because of negative experiences in the distant past. Firstly, few membranes stay intact when coming into contact with hexane. Secondly, various components in oil can cause problems by fouling the pores in the membranes. For this reason, the oils need to undergo additional preparation processes to remove the components that cause fouling before it can run through the membranes. Membrane technology is also highly dependent on the oil type. Not all rapeseed, soybean, and palm oils 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 vegetable-oil and -fat industry. Lastly, modifying an existing factory to add a membrane process unit is rather costly and therefore not implemented in practice ([Solsep, 2019](#)). However, for newly built installations the purchase of membrane technology is more favourable ([Eproconsult, 2019](#); [ISPT et al., 2016](#)).

3.4. Limitation of methods

Using the MAC curve as a method to obtain an overview of the emission reduction potential and costs of the available decarbonisation options comes with several limitations ([Kesicki, 2011](#)). One of the concerns is the transparency of the assumptions. Although this article is written with full transparency in mind, the MIDDEN project report ([Altenburg and Schure, 2020](#)), which elaborates on used data and assumptions in more detail, is added as supplementary resource. Another aspect discussed in the paper of [Kesicki \(2011\)](#) is 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 determine the exact costs and technical development for a specific decarbonisation option. The further an estimation lies in the future, the more uncertain these aspects are. Therefore, 2030 is chosen as the only future point in time, and no later years are considered to restrict uncertainties. Lastly, MAC curves only focus on CO₂ abatement and do not represent the ancillary benefits of CO₂ 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 specifically apply when MAC curves 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), but are nevertheless policy relevant as they indicate what the potential impacts of CO₂ abatement measures could be.

This research is performed for the vegetable-oil and -fat industry in the Netherlands. 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 impact of a decarbonisation option or the CO₂ emissions abated could vary. The energy consumption for the production of a type of oil can differ from the numbers stated in this analysis. Nevertheless, the CO₂ emissions that can be prevented can still be determined with the information provided in Table 1. Some decarbonisation options abate a set amount of CO₂, while the reduction of energy for other options are dependent on the current energy consumption. The latter options can save a certain share of the energy consumed in the traditional production process. The CO₂ emission reduction is therefore very much dependent on the amount of energy the existing processes in a country or a company require. Hence, the order and the cost of some decarbonisation options will differ from the values given in this article. Furthermore, fuel prices can vary per country. In this article, predicted 2030 fuel prices for the Netherlands are used. However, some fuels might be much cheaper in other countries, for example green hydrogen in North-Africa (IEA, 2019).

3.5. Scope 2 emissions

Electricity consumption can have associated 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 produced by non-renewable energy sources bought from a third party. Nevertheless, the indirect (scope 2) CO₂ emissions are disregarded in this paper, since emissions related to Dutch electricity production have been strongly reduced over the last years due to the increase of imported electricity instead of producing electricity with coal. Moreover, it is expected that the share of 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).

Electricity consumption at companies with a CHP plant is counted as direct emissions (scope 1) since the electricity is produced on site. On the other hand, electricity used at companies with a steam boiler is purchased and thus externally produced (scope 2). In this sector, the amount of indirect (scope 2) emissions comprises approximately 6% of the total energy consumption. We have assumed that electric boilers are used throughout the year, however, in an electricity system with a large amount of intermittent renewable sources, the electric boilers may be used for balancing purposes, alternatively with biogas or hydrogen. This may lead to cheaper solutions than the ones discussed here.

3.6. Barriers

This study shows that a cost-effective pathway to decarbonisation consists of both demand-side and supply-side options. Policy makers should provide a balance of incentives that stimulate both. One should be aware of the non-economic barriers to implementing the cost-effective technologies. Why are these cost-effective technologies not widely implemented in the industries? In

the literature, a variety of barriers are described. For the non-energy-intensive industries Rohdin and Thollander (2006) describe barriers such as costs of production disruptions, lack of time, other priorities, and lack of sub-metering. In addition, in our research, we have encountered the hesitation to adopt new technologies, such as membrane-based technologies. Also, private sector discount rates may be higher than social discount rates. These barriers should be taken into account to develop adequate policies that should stimulate the adoption of the cost-effective potential. Further research should clarify the precise role of these barriers in the vegetable-oil and -fat industry.

4. Conclusion and future prospects

There are several decarbonisation options for the vegetable-oil and -fat industry in the Netherlands. Energy efficiency options alone can reduce CO₂ emissions by 44% for rapeseed oil, 45% for soybean oil, and 57% for palm oil. 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 the MVR 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. For full decarbonisation, the remaining energy supply could be delivered by an electric boiler since this is less expensive than a hydrogen boiler. In total, 38% and 40% of the total CO₂ emissions can be abated by cost-effective decarbonisation options, for 2020 and 2030, respectively.

As mentioned in the discussion, more research is needed into the non-economic barriers to implementing cost-effective technologies. Moreover, it would be interesting to have similar research performed on other small industrial sectors. Most information is available for large industrial energy-consuming sectors such as the steel, cement and petrochemical industry. However, all the smaller industrial sectors together are contributing substantially to the world's CO₂ emissions and are therefore also in need of research.

CRedit authorship contribution statement

Marte D. Altenburg: Main author of all parts. **Klara M. Schure:** Writing – review & editing. **Kornelis Blok:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2021.127270>.

Appendix A

The MAC prices for all decarbonisation options and scenarios are provided in Table 1 below. No sector growth is included in this table. Moreover, the MAC in 2020 is also given for decarbonisation options that are only available in 2030 (as membrane technology and the hydrogen boiler). When the membrane decarbonisation options are removed, the reduction potential of an electric or

hydrogen boiler changes to 198 kt CO₂. The R, S and P represent rapeseed, soybean and palm, respectively.

Table 1
Marginal abatement costs in the different scenarios

Technology	Total reduction potential kt CO ₂	2020	2030	2030 low	2030 high
		MAC per tCO ₂	MAC per tCO ₂	MAC per tCO ₂	MAC per tCO ₂
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	15.25	-46.95	17.09	-110.99
Enzymatic degumming S	2.61	15.25	-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 2 below represents the 2030 MAC with $r = 0.04$ and includes growth of the vegetable-oil and fat sector. The reduction potentials for the different technologies are therefore different than in Table 1.

Table 2
MAC 2030 prices with $r = 0.04$ and including growth sector

	Total reduction potential kt CO ₂	MAC per tCO ₂
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 3 below represents the MAC for 2020 including growth and without the membrane technology and hydrogen boiler options.

Table 3
MAC 2020 with $r = 0.04$ and including growth sector

	Total reduction potential kt CO ₂	MAC per tCO ₂
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
Biogas boiler	38.38	-34.35
Industrial heat pumps (MVR) S	23.23	-29.71
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

Appendix B. Available biogas capacity

Waste biomass streams become available as a by-product of rapeseed and soybean crushing. The waste streams amount to 10.4 kg per tonne rapeseed oil and 189 kg per tonne soybean oil. From (Schmidt, 2007) it is known that, in addition, the bleaching earth used in the refining stage can be fed into the biomass boiler. For every tonne of rapeseed oil and soybean oil this amount is 14 kg. The amount of biogas produced from rapeseed waste is 4.2 MJ per kg waste, the same is assumed for the waste of soybeans. The bleaching earth delivers 10.2 MJ biogas per kg. The biomass boiler has an efficiency of 88.5%.

The total energy that can be produced replaces 41.5 kt CO₂ without growth of the vegetable-oil and -fat sector. A biomass boiler that produces 67 tonnes steam per day is already in use; this boiler produces 24.5 kt steam in a year which already saves 3.8 kt of CO₂ emissions per year. Therefore, the total amount of CO₂ emissions that in addition can be avoided for the total sector decreases from 41.5 to 37.7 kt 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. The CO₂ emission reduction potential of a biogas boiler increases to 38.4 kt in 2020 and to 42 kt in 2030, both relative to 2018.

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