



The Sustainability related opportunities and challenges with various transformer insulation fluids and business case on re-refining

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Abstract

Transformers are electrical devices used in practice to increase or decrease voltages. Transformers are of various sizes and used mainly in power distribution. To provide cooling and insulation, transformer oils are used together with cellulose that acts as a solid insulation.

The most common type of transformer oil is mineral oil and is a product derived from the refining of crude oil. Its low cost and good compatibility with cellulose are two factors that have led to its predominant position as the common transformer oil. There are also synthetic ester based transformer oils, and following an increased interest in environmentally friendly products, transformer oils made from natural esters such as sunflower, soybean and rapeseed.

Mineral oil is not biodegradable and is deemed as hazardous waste. The ester based oils are biodegradable and promoted as a more environmentally friendly alternative to mineral oil.

In this thesis, the possibility of re-refining used mineral transformer oil is assessed from a financial perspective in the form of a business case and an LCA study has been done to compare the environmental impacts between ester based transformer oils and mineral based transformer oil.

The results from the LCA study showed that from a cradle-to-gate perspective, mineral oil has a lower environmental impact than ester-based transformer oils. The re-refining of used mineral transformer oil further reduces the environmental impact. The results from the business case showed that a small scale re-refining facility is financially feasible but highly dependent on the supply and demand of used transformer oil.

It is recommended to pursue further studies before making any decision. There is lack of data regarding the re-refining market in Eastern Europe and the accuracy of the LCA study can be further improved by having emissions data from re-refining used mineral transformer oil.

Sammanfattning

Transformatorer är elektriska komponenter som tillämpas vid spänningsregleringar. Dessa transformatorer har olika storlekar och används i eldistribution. Transformatorolja tillsammans med cellulosa används som elektrisk isolering och kylning av transformatorer.

Den vanligaste typen av transformatorolja är mineralolja och är en produkt som erhålls vid raffinering av råolja. Dess låga kostnad och goda kompatibilitet med cellulosa är två faktorer som har lett till dess dominerande ställning. Det finns också syntetisk esterbaserad transformatorolja och efter ett ökat intresse för miljövänliga produkter så tillverkas även transformatoroljor av naturliga estrar så som solros, soja och raps.

Mineralolja är inte nedbrytbar och anses vara farligt avfall. De esterbaserade oljorna är nedbrytbara och anses vara ett mer miljövänligt alternativ till mineralolja.

I denna rapport utvärderades möjligheten till att återraffinera använd mineralolja ur ett ekonomiskt perspektiv i form av en affärsplan och en LCA-studie där esterbaserad olja och mineralolja har jämförts ur ett miljöperspektiv.

Resultaten från LCA-studien visade att mineralolja från ett "cradle-to-gate" perspektiv har en lägre miljöpåverkan än esterbaserade transformatoroljor. Återraffinering av använd mineralolja minskar dess miljöpåverkan ytterligare. Resultatet från affärsplanen visade att en småskalig återraffineringsanläggning är ekonomiskt hållbar men samtidigt väldigt beroende av utbud respektive efterfrågan på använd mineralolja.

Det rekommenderas att göra en djupare analys innan man fattar ett beslut. Det finns brist på information med avseende på återraffineringsmarknaden i Östeuropa. Noggrannheten på LCA-studien kan förbättras ytterligare genom att emissionsdata från en återraffineringsanläggning är tillgänglig.

Nomenclature

LCA – Life Cycle Assessment
DBPC – Ditertiarybutyl para-cresol
DBP – Ditertiarybutyl phenol
PCB – Polychlorinated biphenyl
VOC – Volatile Organic Ester
IEC – International Electrotechnical Commission
ASTM – American Society for Testing and Materials
DDF – Dielectric Dissipation Factor
IFT – Interfacial tension
HPLC – High Performance Liquid Chromatography
DP – Degree of Polymerisation
AC – Alternating Current
DGA – Dissolved Gas Analysis
CSIRO - Commonwealth Scientific and Industrial Research Organisation
EIA – Environmental Impact Assessment
ERA – Ecological Risk Assessment
LCI – Life Cycle Inventory
LCIA – Life Cycle Impact Assessment
EC-JRC – European Commission Joint Research Centre
ILCD – International reference Life Cycle Data system
BEES – Building for Environmental and Economic Stability
NIST – National Institute of Standards and Technology
EWC – European Waste Code
UNECE -United Nations Economic Commission for Europe
ADR – Agreement concerning the international carriage of Dangerous Goods
CAPEX – Capital Expenditure
OPEX – Operating Expenditure
UTO – Used Transformer Oil
MBtu – Million British thermal unit
MJ – Megajoules
SIGAUS - Sistema Integral de Gestión de Aceites Usados
SOGILUB – Sociedade de Gestão Integrada de Óleos Lubrificantes Usados
BVA – Bundesverband Altöl
ENDIALE – Alternative Waste Management for Lubricating Oils
CONOU – Consorzio Nazionale per la gestione, raccolta e trattamento degli oli minerali usati
ORA – Oil Recycling Association
NPV - Net Present Value

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Introduction

Transformers are essentially electrical devices used to either increase or decrease voltages. The main purpose of this is to reduce transmission losses by reducing the current for a given electrical power. There are several different types of transformers such as power transformers and distribution transformers. The transformers, besides their function, are divided further into two categories depending on what type of insulation they use. These are oil immersed and dry-type transformers. In the oil-immersed transformers, transformer oils are used to provide both insulation and cooling. Transformer oils are also used as impregnators of cellulose in transformers. The cellulose, which is wrapped around the coils of a transformer, can get oxidised when exposed to air, lowering its dielectric strength. The impregnation of the cellulose with oil drives away the air and other gases to prevent oxidation. The volumes of oil in the transformers vary from a few litres in distribution transformers to several thousand litres for power transformers [1].

In many applications, they are used to ensure both the electrical insulation and the heat transfer of a component or a system, as in the case of transformers. The transformer oil is also used because of its capability to extinguish electrical arcs within the transformer [1] [2].

The usage of oil as insulation material began in the end of the 19th century with the use of petrol oil and progressed later to mineral oil and other types of insulating oils. The main disadvantage of mineral oil is its weak resistance to fire. This led to the development of PCB in the 1930's and was used frequently due to its non-flammable nature. In the 1970's, PCB was banned because of its toxicity and persistence in the environment. As a reaction to this, new synthetic oils were developed with low flammability as silicone oil and synthetic esters. Following an increased interest in environmentally friendly products, insulating oil made from natural esters has been developed and becoming an increasingly common sight as an insulating oil in transformers [1].

Project objective

This thesis aims at assessing the possibility of re-refining used mineral oil for use in transformers. The assessment will be done in the form of an LCA where different alternatives to mineral-based transformer oil will be studied and a business case where the feasibility of re-refining used mineral oil at Nynas will be investigated. The thesis will focus on the following tasks:

1. Evaluating existing scrapping procedures and explore possible new venues for used mineral-based transformer oil
2. The environmental impact of re-refining used mineral-based transformer oil
3. Comparison between ester based transformer oil and mineral based transformer oil.
4. Market analysis of the re-refining market.

Transformer oils

Mineral oil

Mineral oil is the most frequently used insulating fluid in electrical equipment. It is used for its good dielectric ability, heat transfer properties, its compatibility with cellulose insulators and most importantly because of its low cost. Power transformers require between 40.000 to 80.000 litres of oil which makes cost the most important factor when considering transformer oils and makes mineral oil the most common insulator fluid [1]. The structure of the hydrocarbons determines the composition and the quality of the oil:

- Paraffinic structure: Saturated hydrocarbons that are linear in structure and the general formula for these structures are C_nH_{2n+2} . Hydrocarbons with this kind of structure, also known as waxes, have bad flow properties at low temperatures and is known to have lower thermal stability than naphthenic and aromatic molecules [2].
- Naphthenic structure: Molecules in this group have saturated cyclical structures with the general formula C_nH_{2n} . The cycloalkanes have better properties than paraffins at low temperatures [2].
- Aromatic structure: These molecules are unsaturated hydrocarbons with the general formula C_nH_{2n-6} . They are different from naphthenic and paraffinic molecules but play an important part in the properties of a mineral oil. There are two forms: the monoaromatics and the polyaromatics which are considered carcinogenic. The aromatic components allow the oil to have good resistance against oxidation and good absorption capacity of gases [2].

Mineral oils also contain a small percentage of hydrocarbons with heteroatoms in their structure such as nitrogen, sulphur, and oxygen [2]. Mineral transformer oils consist of mainly of naphthenic oils and not paraffinic. This is because of the better solvency power of the naphthenic structures and the previously mentioned low temperature properties. One of the main advantages of mineral transformer oil is that they have a low viscosity compared to other transformer oils which allows for good heat transfer and good impregnation of cellulose [1].

Mineral transformer oils are either uninhibited or inhibited. The purpose of the inhibitor is to prevent the oxidation of the oil and the solid insulation. The uninhibited oils contain natural compounds which destroys peroxides that are formed during oxidation. For inhibited oils, this is achieved by adding synthetic additives such as DBPC and DBP [3].

Mineral oils also have a low pour point. The pour point is the lowest temperature at which oil will flow. The main disadvantage of mineral transformer oil is its low flammability. The flash point, which is the ignition temperature when exposed to an ignition source, is at 140 - 150 C° which is relatively low in comparison to other transformer oils [4] [5].

Refining

The raw material for mineral oil is crude oil and it is refined to mineral oil through several processes. The type of crude oil is important for the possible amount of mineral oil produced. The crude oil, depending on where it is extracted from, has both different densities and compositions of naphthenes, paraffins and aromatics. The naphthenic crude oil is heavy and is usually rich in bitumen and heavy distillate. In oil refining, the first step is generally distillation [2].

There are mainly two types of distillation used, atmospheric and vacuum. Atmospheric distillation involves heating, vaporisation, fractionation, condensation and cooling. In the process, the crude oil is separated into distillates with different boiling point ranges by fractionation. For light crudes, only normal pressures are required which is why atmospheric distillation is used. The crude oil is heated to about 300-400 °C and fed to a vertical distillation column where most of the feed is vaporised and separated into its various fractions by condensing on fractionation trays. Each of the trays corresponds into different condensation temperatures. Vacuum distillation is done by inducing a vacuum in the distillation unit, lowering the boiling point of the crude oil (hydrocarbons) allowing fractionation of the heavier crude. The fractionated products from the distillation correspond to a different type of petroleum product. Mineral transformer oil is in the subcategory “base oils” which is a part of a larger category called lubricating oils and about 1 to 2% of a barrel of crude oil is suitable for refining into base oil [6]. The additional processes needed to derive mineral transformer oil depend on the type of refinery and the supply of crude oil [7] [2].

A common technique that is used currently to produce mineral oil is hydrogenation. Hydrogenation is based on the chemical reaction between molecular hydrogen and other molecules in the presence of a catalyst. Undesirable molecules from the crude oil refining process can be converted into more desirable ones. Typical reactor conditions vary but are typically 30 to 40 bar and 320-380°C. The catalyst itself can be described as a porous heterogeneous type of catalyst with catalytically active metals that has a large surface area. Nickel, palladium, platinum are common catalysts for this type of reaction [8].

Synthetic ester

Synthetic ester oils are becoming increasingly common as insulating fluids for transformers. Ester oils for transformers are known as pentaerythritol esters. They were developed because the ban of PCB for the impregnation of the cellulose insulation. Pentaerythritol esters are also known as tetraesters because they are made from tetraalcohols and a mixture of monocarboxylic acids. The reaction scheme for the esterification is described below:

Pentaerythritol(tetraester) + monocarboxylic acids \Rightarrow pentaerythritol ester (tetraester) + water

The main benefit of this type of insulating oil compared to other alternatives is the high concentration of water it can contain. Humidity is a significant problem in transformers because the cellulose paper in a humid environment absorbs the water, decreasing its dielectric strength. Ester oils can absorb up to 20 or 30 times more moisture than mineral oil. This makes humidity less of a factor to consider but the high absorption also dries the paper which makes a trade-off between the increased longevity of the transformer and the increased care of handling due to higher solubility [9].

The other advantages synthetic ester oil has over mineral oil is that it has better fire resistance with a fire point higher than 300°C and that it is biodegradable [10].

There are however disadvantages with synthetic ester oils. The main point is its viscosity. The viscosity is high in comparison to other oils and becomes significant at low temperatures. Tetraesters such as pentaerythritol esters are generally used for “fire resistant” distribution transformers because of their high fire point. The use of synthetic esters in distribution transformers has become more common but in power transformers because of its high cost, they are 4-8 times more expensive than mineral oil [10].

Natural ester

Vegetable oils or natural esters are naturally synthesized from living organisms and usually from soy, sunflower and rapeseed. Natural esters are synthesized from a tri-alcohol such as glycerol with three monocarboxylic acids, otherwise known as fatty acids. The esterification reaction is described as following:

Glycerol + 3 monocarboxylic acids - triglycerides (natural esters) + water

The most significant advantage natural esters possess is that it has good biodegradability potential making it a “green” alternative to other insulating oils. Its biodegradable capabilities also make it more sensitive to oxidation, limiting its use and utilizing other non-green products such as antioxidants to compensate for the high sensitivity.

Similar to synthetic esters, natural esters have both a high fire point and high water solubility. This type of oil, just like its synthetic equivalent, has higher viscosity than mineral oil which limits its heat transferring capabilities and high pour point further limiting its use to regions where the climate is not cold. In the case of natural esters, the type of fatty acids used in the esterification process affect its properties significantly. Oils with a high percentage of unsaturated fatty acids have lower viscosities and lower pour points and vice versa for saturated acids [1] [10].

Refining of natural esters

Natural esters are refined in a different way from mineral-based transformer oil. The base material is not crude oil but oil seeds and the manufacturing of the oil is done in several stages and techniques. The initial step is to dehull or to “crack” all of the seed for the extraction of the crude vegetable oil, there are two primary techniques. For sunflower and rapeseed seeds, batch processing is used where the oil is extracted by applying hydraulic pressure. For harder seeds as soybean, the crude oil is obtained by crushing the seeds and extracted with a solvent, primarily hexane. A degumming step follows the crude oil extraction step. In the degumming step, materials other than oil such as seed particles and impurities are removed from the crude vegetable oil. After the degumming step, the oil is first neutralised if it is refined chemically or winterised right after the degumming if it is refined through pressing. Alkali neutralisation reduces the content of fatty acids and carbohydrates from the oil.

Winterisation is done to remove waxes from the oil through crystallisation and filtering of the crystallised waxes. Lastly, the oil is deodorised whereby VOCs are removed through steam. The oil produced after all of these processes is known as RBD oil and in order to make it into transformer oil, additives are added to enhance the oxidation stability and reduce the pour point [4] [11].

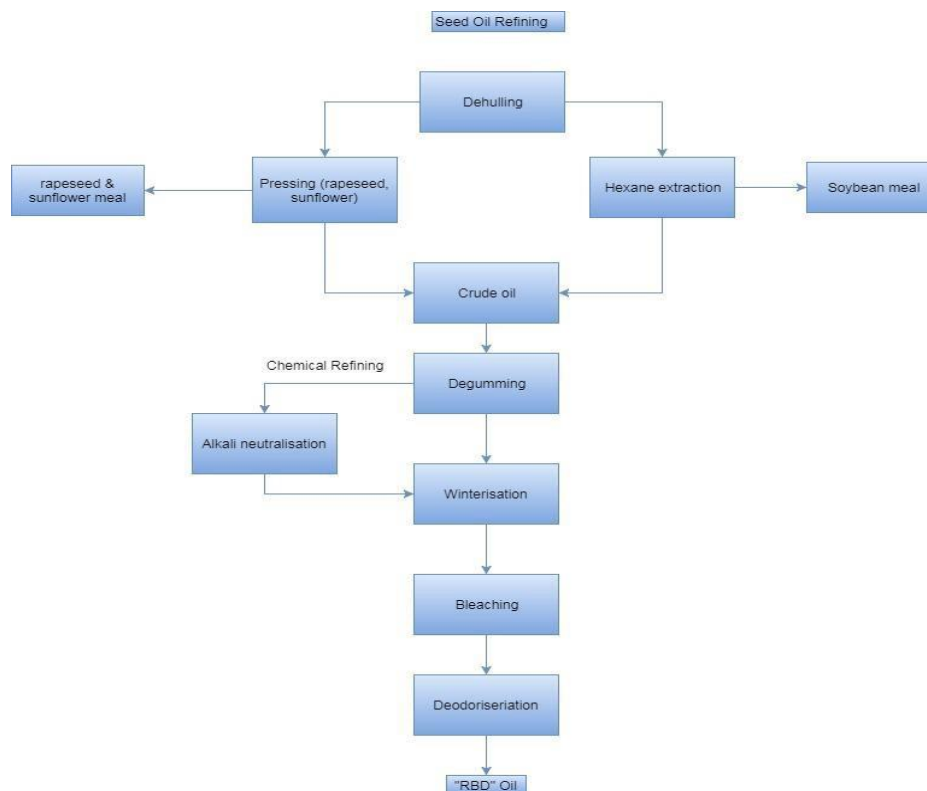


Figure 1 - Description of natural ester refining [11]

Requirements (IEC and ASTM)

In order for transformer oils to be used as insulation in transformers, they must fulfil certain requirements. These requirements are different depending on the type of insulating oil. The standards used internationally are set by two organisations called IEC and ASTM. For new mineral transformer oil, the most important regulations are IEC 60296 and ASTM D3487. They specify the necessary viscosity, pour point, flash point and other requirements of the oil. These requirements also involve tests to evaluate the condition of the oil after it has been in a transformer. For new and unused natural ester based transformer oil, IEC 62770 is to be followed and for synthetic esters IEC 61099. IEC and ASTM outline testing methods and requirements for every stage of a product's lifetime.

Solid insulation

The solid insulation in transformers is largely made of cellulose in the form of kraft paper, also known as electrotechnical paper, and pressboard. The paper provides important functions to the transformer in the form of electrical insulation, mechanical stability among others. The pressboard is used mostly in high-voltage equipment such as power transformers. The main reason for the use of cellulose is because of its good electrical properties, availability, and its interaction with mineral oil. Cellulose impregnated with mineral oil provides more electrical insulation than just the individual components. The dielectric strength of pressboard impregnated with oil is approximately three to four times greater than the dielectric strength of just oil [2].

Because of the accumulation of moisture inside the transformer, drying is an important process. Moisture in insulating material causes reduction in dielectric strength, acceleration of cellulose aging and an increase in dielectric losses. The aging of the solid insulation will affect the strength of the transformer. Water affects cellulose through hydrolysis. Hydrolysis is the breakdown of chemical bonds with the aid of water and although the cellulose is dried in the transformer, moisture can be picked up from the surrounding air through the oil and water is also formed from the degradation of cellulose and through the degradation of oil [2].

The DP is defined as the number of monomeric units per each individual molecule. It is the most useful parameter of evaluating the aging progress of cellulose. The DP value of new cellulose is in the range of 1200-1400. When the DP value reaches 200, it is considered not satisfactory for use in transformers and other electrical equipment [2] [12].

Analytical methods for transformer oil aging

To assess the health state of the transformer oil, a number of different physical, electrical and chemical methods are used. Continuous inspection of the state of the transformer oil is critical for it to last for long time.

Colour

The colour and appearance of the oil can serve as indicators for oil degradation and contaminants. The oil is compared to a spectrum of colours and generally oil that is contaminated can have a cloudy appearance while new transformer oil is clear [2].

Dielectric dissipation factor

The DDF measures the leakage current through the oil which assists in analysing the deterioration of the transformer within the oil. In practice, it can reveal the presence of moisture resin, varnish and other contaminants. An increase in DDF means loss of dielectric strength in the oil [13].

Interfacial tension

The IFT measures the tension at the interface of two immiscible fluids. It provides a means of detecting soluble polar contaminants and oil degradation. The IFT between oil and water varies during the initial stages of oil aging but stabilises when the deterioration is still moderate [14].

Acidity

Acids form in the oil due to the acidic products that form during oxidation. These acids cause damage as corrosion in the metallic parts of the transformer and degrade the solid insulation. Acidity tests are expressed in the unit KOH/g oil, the amount needed to neutralise the acid. An increase in acidity indicates an increased rate of deterioration, leading to the formation of sludge inside the transformer. This makes the acidity test useful in determining what should be done with the used oil [13] [14].

Furfural analysis

Furfural analysis is used when evaluating the aging condition of the insulation paper. Furfural (or 2-FAL) is a furan compound that is generated during the cellulose degradation and is released into the oil. It is analysed by using HPLC. It is said to be an indirect correlation between the DP and furfural values. Although it is not currently possible to establish a precise link between the furfural content and the DP-value, information about the thermal behaviour of the solid insulation can be obtained by analysing the trend of DP and furfural values [15].

Breakdown voltage

The dielectric strength of a transformer fluid is measured as its resistance to electrical stress. The method involves applying an AC current between two oil-immersed electrodes. The gap between the electrodes is specified before the test. When the current arcs between the gap, the voltage recorded is the dielectric breakdown voltage. The property is sensitive to physical contaminants in the oil [14].

Dissolved gas analysis

DGA is a common tool in which one can predict the internal health of a transformer or more specifically, the condition of the insulating oil. During the aging process, the transformer oil generates decomposition gases from various loads and stresses. DGA has three main objectives: To check if the equipment is in good condition, to prevent failure by localising possible faults and monitor the operating conditions. Depending on the type of error, different types of gases are formed. The gases that are of interest are H_2 , CH_4 , C_2H_2 , C_2H_4 , C_2H_6 , C_3H_8 and C_4H_{10} . In DGA, the change of the gaseous concentration is of interest. It can be evaluated with the IEC method by looking at the ratios $\frac{C_2H_2}{C_2H_4}$, $\frac{C_2H_2}{CH_4}$, $\frac{C_2H_4}{CH_4}$ or by using Duval's triangle where the types of fault are represented in a triangle with three percentages of relative concentration ($\%C_2H_4$, $\%C_2H_2$ and $\%CH_4$). Each zone in the triangle represents a type of fault [2] [16].

Oxidation stability

The oxidation stability refers to the resistance to oxidation by transformer oil without any change to its properties. Certain phenomena inside the transformer can be a cause to dissolved oxygen, temperature differences, moisture and other factors making the transformer oil more likely to undergo oxidation which may result in the production of peroxides and sludge products. The oxidation stability determines the quality of the transformer oil. [14] [17].

Aging

When in service, the transformer oil will be subjected to heat, electrical discharges and oxygen which may cause degradation. This is known as aging of the transformer oil. The aging processes involved depends on the operating conditions, the design of the electrical equipment and on the type of transformer oil [2]. The aging limits the oil from fulfilling its functions in terms of heat transferring and insulation since the aging products reduce both the electrical properties and cooling efficiency of the oil [18]. The aging is predominantly caused due to oxidation reactions when the mineral transformer oil is subjected to temperatures over 300 °C and electrical stresses form acids and sludge. The degradation also affects the solid insulation lowering its dielectric strength [18]. The rate of aging is a function of temperature and moisture. Moisture can be seen as the biggest problem in terms of the aging in transformers. Oil will age rapidly at high temperatures and moisture acts as a catalyst of the aging. There are also other materials in a transformer that can act as catalysts; among them are copper, paint, and other metals [2]. There are several techniques for monitoring and assessing the oil and the solid insulation.

During the oil's lifetime, its condition is monitored to make sure that it fulfils its functions. The oil condition tests for transformer oils can be divided into physical tests, electrical tests and chemical tests. In general, the monitoring of the colour, appearance, acidity, DDF and IFT will provide information about the oxidation of the oil. Oil can also be degraded by arcing [2]. Arcing is defined as the electrical discharge that is formed when current moves across a gap between two points and it causes formation of gases within the oil. This is usually monitored by DGA.

The aging process is different in synthetic esters and natural esters. It also affects the solid insulation differently.

Comparison of transformer oils

The performance of transformer oil is evaluated in how they handle ageing and under different types of stresses. As described earlier, aging of the transformer oil and the solid insulation is the largest issue in electrical insulation and that the aging affects almost all properties of both the solid insulation and the transformer oil. The ageing also affects the insulation in different ways depending on what type of transformer oil that is being used.

The moisture content in the oil-paper/pressboard insulation is affected differently whether it is a natural ester or a mineral oil. In a paper from Zhou et al. [19], the properties of pressboard under thermal aging was conducted and evaluated. The study compared mineral oil (Nytro Gemini X) and natural ester (Envirotemp FR3) and the tests were conducted at 130°C for 80 days and 100 °C for 220 days. The properties tested are moisture content in oil and pressboard, furfural content, viscosity, the AC breakdown voltage, acidity and dielectric loss of the oil.

Moisture content

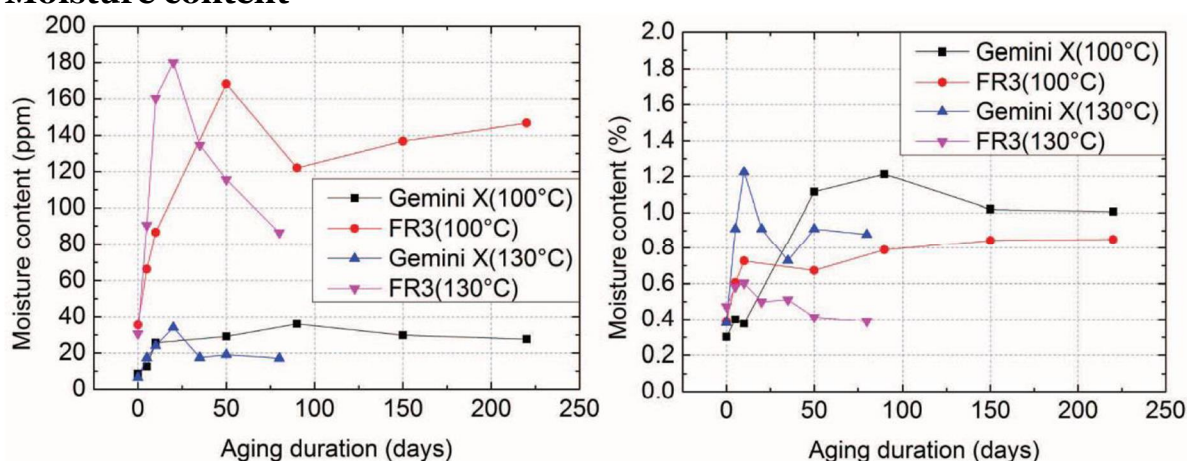


Figure 2 and 3 - Moisture content in pressboard [19]

The moisture content in the mineral oil is several lower than the natural ester based oil but when observing the moisture content in percentage in pressboard, the moisture content is higher in the mineral oil than in the natural ester. What is evident is that in mineral oil, moisture migrates from oil to pressboard during aging while the reverse phenomenon occurs in natural ester.

Acidity

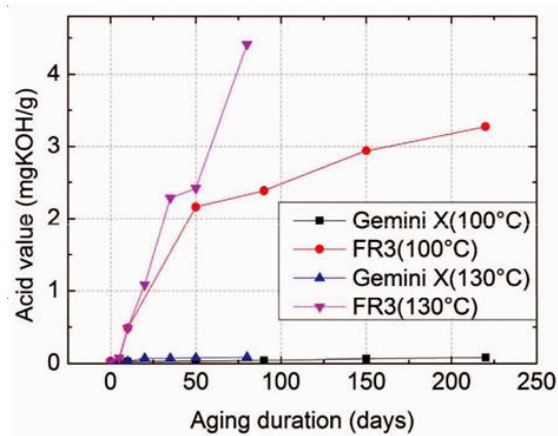


Figure 4 - Acidity content in pressboard [19]

There is no acidity increase for the mineral oil while in the natural ester, there is rapid increase in acidic products. This is caused by the hydrolysis in the natural ester because it releases fatty acids. The increased acidity appears to have no effect of the aging of pressboard.

Viscosity

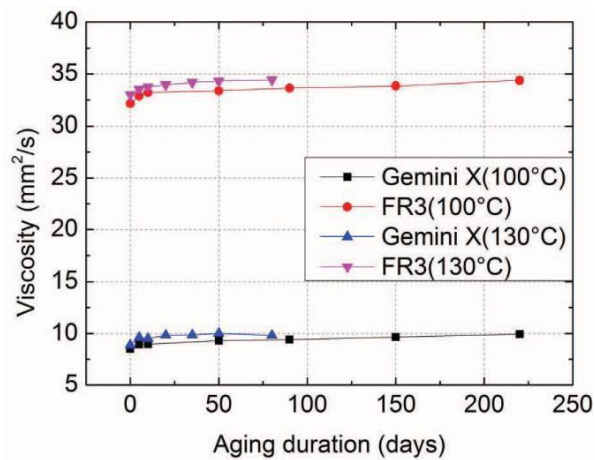


Figure 5 - Viscosity in different oils [19]

The viscosity of ester oils is higher than mineral oil and even more so when exposed to thermal aging. This is to be expected because of the viscosity of natural esters are higher naturally.

Furan content

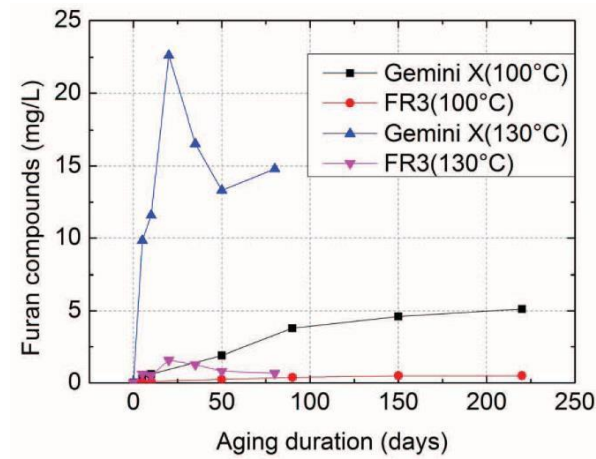


Figure 6 - Furan content in pressboard [19]

The furfural generated by the decomposition of the pressboard can indirectly give information on the DP-value. From the figure, there is a large increase in furan compounds in the mineral oil in high temperatures within the first 50 days. This result, with the significantly lower moisture content in the pressboard, show that the solid insulation lasts longer in the natural ester oil than in the mineral oil.

Dielectric loss and breakdown voltage

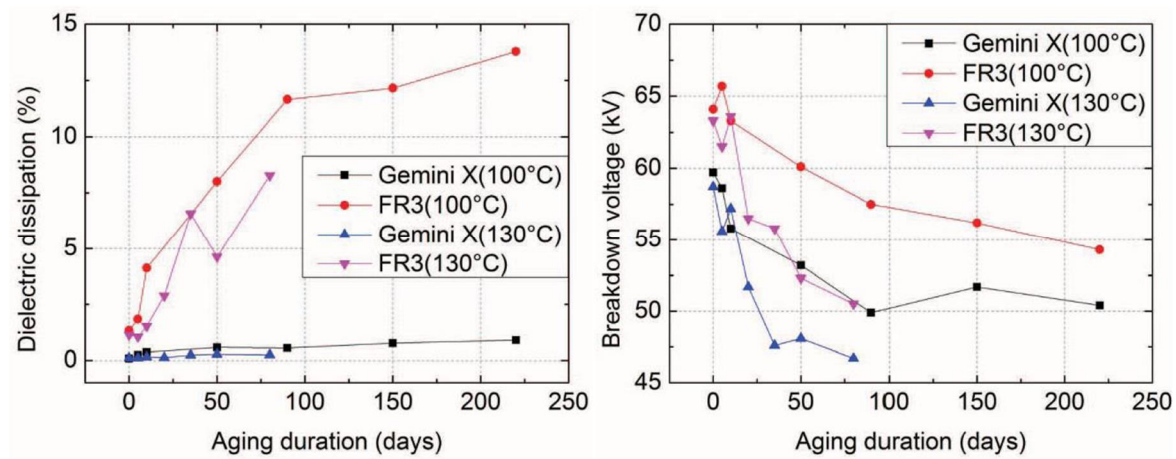


Figure 7 and 8 - DDF and breakdown voltage of different oils [19]

The dielectric loss is significant in the natural ester. This is thought to be caused by the large number of polar groups in the natural ester while the mineral oil remains principally unchanged. In terms of the breakdown voltage, both types of oils gradually decrease at the same rate but the breakdown voltage is higher in the natural ester.

For the synthetic ester, it behaves almost exactly as the natural ester oil in the same conditions. In studies from Coulibaly et al. [16] and Gasser et al. [20], the aging of pressboard and kraft paper were tested but under different conditions for both studies. Both studies showed that in the ester oils, there is an increase of water on the oil but a decrease of water in the solid insulation, reducing the rate of aging. This is due to the hydrolysis reaction in the ester oils while in the mineral oil, the reverse phenomenon occurs, leading to a faster degradation of the cellulosic insulation.

Reuse of transformer oil

Reuse of transformer oil is of high importance for manufacturer of the oil but also for electrical utility companies. This is of economic interest because of the cost of buying new transformer oil and for environmental reasons. For aged mineral oil, there are three main techniques for recovering the oil: reclamation, reconditioning and re-refining.

Reclamation

Reclamation is a process that removes soluble and insoluble contaminants through a chemical or physical process. Reclamation of oil usually involves treatment with clay or other adsorbents. In reclamation, the aged oil is passed through a bed of active adsorbent material to remove degradation products. There are several types of adsorbent material such as Fuller's earth, activated alumina or bauxite and molecular sieves. Fuller's Earth refers to natural adsorbent clays that have the properties to neutralise acids, adsorb polar compounds and decolourise into clear oil. The major advantage of oil reclamation is that it can be applied while the transformer is still in operation and the aging products are removed from the transformer. Typical Fuller's Earth reclamation systems use a mix of activated alumina and Fuller's earth [21] [22].

Not all used oils are suitable for reclamation. Oils that contain PCB cannot be reclaimed because of the risk of contaminating other equipment.

Reconditioning

Reconditioning is the removal of contaminants and dissolved gases through mechanical means. This is usually through filtering, vacuum degassing to remove the dissolved gases and other methods [21].

Re-refining

Re-refining is the use of refinery processes to re-refine used mineral oil into products that are suitable for reuse. While reconditioning and reclamation are in essence physical and molecular filtration techniques, re-refining restores the molecular structure of the used mineral oil, leading to principally new mineral transformer oil. Typical processes involved are the same processes found at a refinery which include hydrotreatment, solvent extraction and others. It is also the only method where there is a possibility to treat mineral transformer oil containing PCB. PCB can be removed through the use of catalytic hydrotreatment. CSIRO developed the process using catalysts based on metal sulphides which are tolerant to most catalyst poisons. They were able to reduce the amount of PCB to less than 15 ng/m³ [23]. Hydrodec is a re-refining company utilizing the technology developed by CSIRO and is using it to refine all used mineral transformer oil to re-refined oil [24].

Life Cycle Assessment

Definition of Life cycle assessment

It is known that in order to assess or to evaluate the environmental consequences of an activity or product, the impact from all parts of its life cycle, from raw material to eventual disposal, must be considered. This type of analysis is called a Life Cycle assessment. In LCA terms, it means that a product is followed from raw material acquisition ("cradle") to disposal ("grave"). Not all LCA's are done by looking at every step. Some are done by something known as "cradle-to-gate" which leaves out the use phase and the waste management. There are other tools to evaluate environmental impacts such as EIA and ERA [23]. There is an international standard for LCA in terms of an ISO standard called ISO 14040 that lists the following application: Identification of improvement possibilities, decision making, choice of environmental performance indicators and market claims [25]. These offer uniform assessment guidelines for how to perform an LCA.

An LCA study contains four main phases: goal and scope definition, inventory analysis, impact assessment and interpretation. In the goal and scope, the product and the purpose of the study is decided upon. The system boundaries, i.e. which processes to include in the study are also made during the goal and scope definition. These in turn govern the system boundaries needed for the inventory analysis. An LCA relates environmental impact to a function of the product system which necessitates a way to express the function in measurable terms, as a functional unit. The functional unit is a measure of the function of the studied system and it provides a reference to which the inputs and outputs can be related. This enables comparison of two different systems that are part of the assessment. The inventory analysis is a description of the actual systems model according to the defined goal and scope. Only the environmentally relevant flows should be included in the model [25].

The LCI consists of construction of the flow model according to system boundaries, data collection for all the processes and transports in the product system and calculation of the amount of resource use and emissions in relation to the functional unit. In the LCI, allocation is necessary to account for processes which have multiple outputs. The inventory analysis is then followed up by the LCIA. The purpose of the LCIA is to describe the information obtained in the inventory analysis into indicators showing the impact of the environmental loads and in a sense to rewrite the information into more relevant environmental information and to aggregate the information from the LCI in fewer parameters. The final phase known as the Life Cycle interpretation aims to evaluate the impact assessment [25].

Most LCA can be categorized into two types, accounting LCA and change-oriented LCA. Accounting LCAs are focused on answering the question "What environmental impact can this product be responsible for" while change-oriented or consequential LCAs focus more on exploring how different alternative courses gives different outputs/consequences [25].

System boundary and functional unit

The system boundaries for this LCA are set from the extraction and cultivation of the raw material to the production of the oils at the respective refinery. For the mineral oil, the system boundary differs for the two cases. In the first case, the system boundary will be, as for the vegetable oils, from extraction of raw material to the refinery and in the second case, the system boundary will be extended to include a disposal scenario in the form of re-refining the mineral oil. The functional unit is “Production of one tonne of oil”.

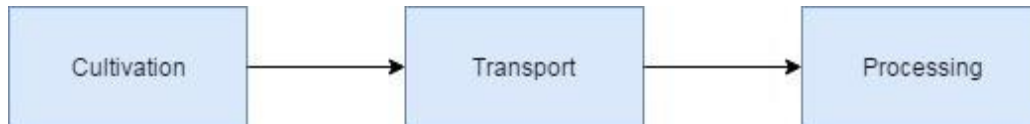


Figure 9 - Diagram of cradle-to-gate model

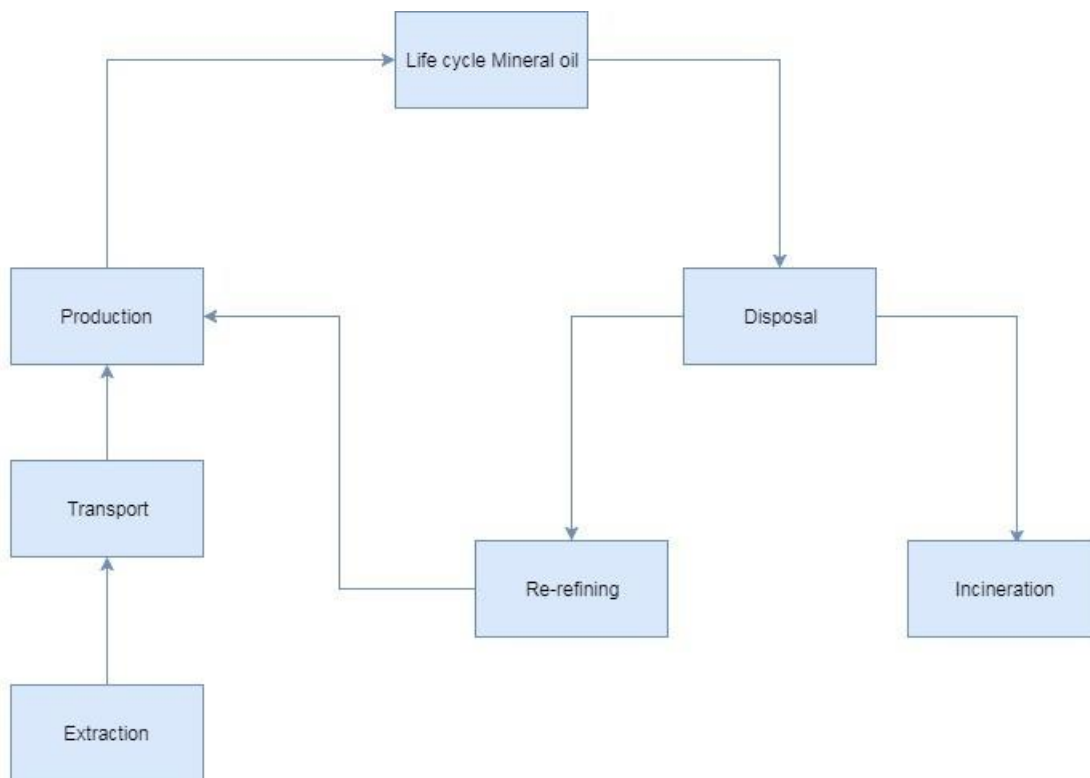


Figure 10 - Diagram of cradle-to-grave model for mineral oil

Modelling with Simapro

Since there is no possibility of only using directly obtained data, primary data, we used the predefined datasets in Simapro. The databases used were Ecoinvent for the modelling of the mineral oil and Agri-footprint for the vegetable oils. Ecoinvent was developed by a Swiss organisation and is among the most developed databases for LCA studies covering over 10000 processes [26].

Processes are divided between unit and system processes. Unit processes include upstream processes in the production of a product whereas system processes do not so. System processes compile the data and only give the result of a product, simplifying the data but giving no insight to the inputs or outputs [26].

In Ecoinvent, there is also a further distinction of the processes into market and transformation processes. Transformation processes contain all of the inputs for a product including the associated emissions and resource extractions but exclude transport inputs. Market processes also include the environmental impact of transportation from different regions and countries making a dataset contain the average transportation data for a specific product.

Agri-footprint is a database solely focused on agricultural products. It was developed by Blonk consultants and contains approximately 3500 products and processes. The database contains data on primary processes for example crops, feed compounds and background processes such as transportation and fertilizers. The database has three pre-defined allocation systems; mass, energy and economic allocation and for different locations in the world.

In this thesis, mass allocation is used for the vegetable oils and a mixture of transformation and market processes for the mineral oil.

To do the LCA, we used the software Simapro. Simapro is the leading software used in LCA studies and the Classroom Edition 8.2.0.0 was applied. In Simapro, the models of the mineral oil production process and the vegetable oil production processes were built in line with the previously defined system boundaries. Simapro distinguishes seven process types (materials, energy, transport, processing, use, waste scenario and waste treatment) each of which can be a unit process or a system process where a set of unit processes are described as one process. To form a product in Simapro, product stages are used. Product stages describe how a product is produced, its usage and disposal. The product stage contains the flow data from the unit and system processes. Simapro has five product stages:

- Assembly: The assembly which defines the production stage of the product.
- Disposal scenario: The disposal scenario which describes the end-of-life scenario of the product.
- Disassembly scenario: The disassembly scenario which describes which parts of a product should be disassembled and where the disassembled parts will go.
- Reuse: The reuse stage which describes the process needed for reusing a product.
- Life cycle stage: The life cycle stage describes the total life cycle of the product. Depending on the type of LCA study, it can include the assembly or more stages.

Each process in Simapro consists of three sections; documentation, input/output and system descriptions. The first section, documentation, contains information regarding the particular dataset such as the name for the dataset and general comments regarding the application of the dataset. The second section, input/output, contains all of the flows in and out of the processes. There are three types of inputs in Simapro: Inputs from nature, inputs from the technosphere in the form of materials

and fuels and inputs from the technosphere in the form of electricity and heat. The outputs are divided into the categories emissions to air, emissions to water, emissions to soil and final waste flows. The third section, system description, contains detailed information and references of a process system. Once all of the data has been entered and is part of a life cycle of a product, the environmental impact of the product can then be evaluated with the selected impact assessment method.

To evaluate the environmental loads of different production methods and products in Simapro, an impact assessment method must be chosen. As defined in ISO 14040, any impact assessment method contains the elements classification and characterization. They can also include the optional elements normalization and weighting [26]. The LCI contains information on the emissions, land use and other information caused by the life cycle of the products and the emissions and resources are assigned different impact categories. This step is called classification and it is important to point out that different emissions can be assigned to the same impact category and one emission can be assigned to several impact categories.

| Elementary flow | Climate change | Ozone layer depletion | Eutrophication |
|---------------------------|----------------|-----------------------|----------------|
| 1 kg CH ₄ | x | | |
| 100 gram N ₂ O | x | | |
| 1 gram CFC142b | x | x | |
| 5 gram NH ₃ | | | x |

Table 1 - Example of classification of emissions

Once the emissions have been separated into different categories, the emissions are multiplied with a characterisation factor to obtain the same unit. For example, CH₄ has a 25 times higher impact on global warming than N₂O and therefore, CH₄ must be multiplied with a factor of 25 to obtain the unit N₂O-equivalents. This is known as the characterisation step [26].

Normalisation is used to see the environmental impact compared to a reference value and weighting is to show the relative importance of different impact categories. The information from the weighting can be used to produce a Single score which shows the total environmental impact for a product. The Single Score is used in comparative LCAs [26]

The impact assessment method chosen in this thesis is "ILCD 2011 Midpoint +". The ILCD method is developed by the EC-JRC and the midpoint method offers the following 16 impact categories [27] [28]:

- **Climate Change:** The category Climate change measures the GWP of a product in kg CO₂-equivalents. GWP is defined as a relative measure of how much heat a greenhouse gas traps in the atmosphere. All gases affect the environment but to a different degree and CO₂ is set as the reference number 1 to which all other gases are compared.
- **Ozone Depletion:** The impact category for ozone layer depletion accounts for the destruction of the stratospheric ozone layer over a time – horizon of 100 years. The unit is kg CFC-11 equivalents.

- **Human toxicity, cancer and non-cancer effects:** the impact category for the human toxicity expresses the estimated increase in morbidity by cases per kilogramme of a chemical emitted. The model was developed by USEtox and for the cancer effects, the unit CTUh is used and for the non-cancer effects CTUe.
- **Terrestrial eutrophication:** The impact category for the terrestrial eutrophication accounts for the emissions of nitrogen dioxide and ammonia to the air. The unit is mole N-equivalents.
- **Marine eutrophication:** The impact category for the marine eutrophication accounts for the environmental fate of the emission of nitrogen containing nutrients. The unit is kg N to freshwater equivalents.
- **Freshwater eutrophication:** The impact category of freshwater eutrophication accounts for the environmental fate of the emission of phosphate containing nutrients. The unit is kg P to freshwater equivalents.
- **Ionising radiation:** The impact category of ionising radiation accounts for the level of exposure to radiation bodies. The unit is kBq ^{235}U - equivalents.
- **Photochemical ozone formation:** the impact category for photochemical ozone formation is defined as the potential contribution to the formation of ozone from emissions of NO and it is expressed in the unit kg NMVOC – equivalents.
- **Water resource depletion:** The impact category for water resource depletion accounts for the abstraction of water from the ground and from rivers. The unit is m³ water equivalents.
- **Acidification:** The impact category of acidification accounts for the flows contributing to acidification such as ammonia, nitrogen oxide and sulphur dioxide. The unit is moles H⁺.
- **Particulate matter formation:** The impact category of particulate matter formation accounts for the formation of particulate matter such as PM_{10} , $\text{PM}_{2.5}$, $\text{PM}_{10-2.5}$ and others. The unit is kg $\text{PM}_{2.5}$ equivalents.
- **Freshwater ecotoxicity:** The impact category for the freshwater ecotoxicity accounts for the emissions to freshwater based on the same model for the human toxicity. The unit is CTUe.
- **Land use:** The impact category for land use accounts for both land occupation and land transformation. Land occupation is defined as the actual occupation of a square meter of land for one year and land transformation as the conversion of land from one use to another expressed in square meters of land converted. The unit is kg C deficit.
- **Resource depletion- minerals and fossil:** The impact category for the resource depletion accounts for the mineral and fossil depletion and it is expressed in kg Sb –equivalents per kg extraction.

Choice of oils and assumptions for LCA

The oils that will be studied is the natural ester based oils and mineral oil. This is because there is a lack of data on the synthetic ester transformer oil. The additives required to make transformer oil are not included in the LCA and are assumed to be negligible. The vegetable oils that will be part of the LCA are rapeseed, soybean and sunflower oil. This is because of previous studies from BEES where LCA's on different types of transformer oils have been made. BEES is a software developed by NIST where the environmental performance of building products are measured. It combines the LCA approach from the specified ISO 14040 and an economic performance evaluation to give an overall performance of a product [27]. The studies that are of interest are named after the products "ABB BIOTEMP" and "Cooper Environtemp FR3" and the study "Generic biobased transformer oil".

In the models from the BEES software, carbon sequestration is included. Carbon sequestration is defined as the long-term storage and capture of carbon dioxide. Capture can occur either through natural processes as photosynthesis or at the point where it is emitted [28]. In the case of vegetable oils, the carbon sequestration occurs during the cultivation of the crops and the amount of sequestration depends on the cultivation method [29]. The amount of carbon sequestration for the LCA will be based on the LCA prepared for the interest organisation United Soybean Board from Omni Tech International [30].

In the report, they stated that for one tonne of lubricant soy oil, 2955 kg of CO_2 is sequestered. Due to lack of data, the carbon sequestration for the rapeseed and sunflower oil will be assumed to be 80% of that amount. The reason for this is that an estimate was required for the comparison of the oils and no studies were found that specifically studied the amount of carbon sequestration of rapeseed and sunflower. The disposal scenario in the Simapro model will be divided into two cases, 80 % re-refining with 20% incineration and 75% re-refining with 25% incineration. As there was no information on the emissions emitted by incinerating one tonne of waste mineral oil, the pre-defined dataset "waste mineral oil" from Ecoinvent was used.

Life cycle inventory

Mineral oil

The LCI data for the mineral oil was given to us from Nynas and accounts for the cradle-to-gate data for the production of one tonne of mineral base oil including the bulk transportation to Nynäshamn.

Soybean oil

| Production of 1 tonne of refined soybean oil | Unit | Cradle-to-gate |
|--|------|----------------|
| Known inputs from technosphere(materials and fuels) | | |
| Crude soybean oil | kg | 1038 |
| Water | kg | 540 |
| Bleaching earth | kg | 5,4 |
| Phosphoric acid | kg | 1,13 |
| Sulfuric acid | kg | 2 |
| Activated carbon | kg | 0,2 |
| Sodium hydroxide | kg | 2,8 |
| Known inputs from nature | | |
| Carbon dioxide, in air | kg | -2955 |
| Emissions to water | | |
| Unsaponifiable matter | kg | 15 |
| Oils, unspecified | kg | 18 |

Table 2 – LCI of soybean oil

The data for the soybean oil was taken from the Agri-footprint database in Simapro. The carbon sequestration of the soybean oil has been added to the data as “Carbon dioxide, in air”. The crude soybean oil is derived from crushing of soybeans with the use of hexane as a solvent and is based on a soybean refining process in The Netherlands. A small portion of the crude soybean oil is allocated for the soap stock that is formed as a by-product when refining the crude oil but its impact is considered to be negligible.

Rapeseed oil

| Production of 1 tonne of refined rapeseed oil | Unit | Cradle-to-gate |
|--|-------------|-----------------------|
| Known inputs from technosphere (materials and fuels) | | |
| Crude rapeseed oil | kg | 1032 |
| Water | kg | 500 |
| Bleaching earth | kg | 4 |
| Phosphoric acid | kg | 0,791 |
| Sulfuric acid | kg | 2 |
| Nitrogen | kg | 0,5 |
| Activated carbon | kg | 0,2 |
| Sodium hydroxide | kg | 3 |
| Known inputs from technosphere (electricity and heat) | kg/t | 6 |
| Steam from natural gas | MJ | 467,5 |
| Electricity | kWh | 27 |
| Known inputs from nature | | |
| Carbon dioxide, in air | kg | -2364 |

Table 3 – LCI of mineral oil

The data for the rapeseed oil was taken from the Agri-footprint database in Simapro. Just as for the soybean oil, a small portion of the crude rapeseed oil is allocated for the soap stock produced during refining. The crude rapeseed oil is derived through pressing and is based on a rapeseed oil refining process in Germany. The carbon sequestration has been added to the data.

Sunflower oil

| Production of 1 tonne of refined sunflower oil | Unit | Cradle-to-gate |
|--|-------------|-----------------------|
| Known inputs from technosphere (materials and fuels) | | |
| Crude sunflower oil | kg | 1032 |
| Activated carbon | kg | 5,05 |
| Bleaching earth | kg | 3,03 |
| Energy from diesel | MJ | 342,45 |
| Known inputs from technosphere (electricity and heat) | | |
| Steam from natural gas | MJ | 731,5 |
| Electricity | kWh | 54,8 |
| Known inputs from nature | | |
| Carbon dioxide, in air | kg | -2634 |

Table 4 – LCI of sunflower oil

The production data for one tonne of refined sunflower, just as in the two other oils, is taken from the Agri-Footprint database. The crude sunflower has been derived through physical refining (pressing) and the dataset is based on a sunflower refining process in Ukraine. The carbon sequestration has also been added.

| Re-refining of 1 tonne of waste mineral oil | | Unit |
|--|----|--------|
| Known inputs from technosphere (electricity and heat) | | |
| Electricity | MJ | 94 |
| Process steam | MJ | 600 |
| Process heat | MJ | 440 |
| Energy from diesel | MJ | 342,45 |
| Emissions to air | | |
| Carbon dioxide | kg | 36 |
| Carbon monoxide | kg | 0,02 |
| NO_x | kg | 0,013 |
| Sulfur dioxide | kg | 0,13 |
| Particulates | kg | 0,004 |

Table 5 – LCI of re-refining

For the re-refining of the mineral transformer oil, the data is taken from a report commissioned by GEIR from IFEU institute where the re-refining of base oils was evaluated with an LCA [29] and the emissions data from the EC-JRC reference document for the refining of mineral oil and gas [7]. The emissions from the hydrotreatment are based on a naphtha hydrotreater because of lack of data concerning the waste mineral oil.

Case study

This case study has been divided in four sections. The first section is about scrappers, the second section is about legislation and licenses, the third about waste oil management in Europe and the last section about the business model that is based on the previous sections.

Scrappers

Scrappers collect all types of waste including transformers. Not all scrappers can handle transformers because of the oil. Waste oil is classified as a hazardous waste and special certification is needed for its disposal. This means that there is considerable amount of waste oil that can be gathered from these sites.

Legislation and licenses

PCB

When it comes to the disposal of waste oils, there is legislation that must be considered. The EU has published the European waste oil directive which all European countries must apply in their national legislation. The directive places duty on member states to ensure that the collection and disposal of waste oil do not harm citizens and the environment and that member states are required to give priority to regeneration of oils “where technical, economical and organisational structures so allow”. The waste oil that is not regenerated is to be burnt. That also includes used transformer oil that contains PCB but special regulations are in place for the disposal of PCB in each member state. A limit of 50 ppm is allowed for the content of PCB in regenerated transformer oil [30].

Transportation

Of interest for this case study is the legislation regarding transportation of waste across EU states. Shipments of waste entering or passing through EU countries must follow regulation 1013 from 2006 which stipulates the conditions of the transport of waste within the EU. The legislation encompasses all types of waste that in some way is removed from the site of use. The law applies for mainly four types of movement of waste: Waste shipped between EU countries, Waste imported into the EU from non-EU countries, Waste exported from the EU to non-EU countries and waste transiting through the EU. The law has annexes that contain the classification of waste into different waste types and codes. The waste codes consist of six digits and are called EWC-codes. Each type of waste has its own EWC-code [31].

For the shipment of hazardous waste such as waste mineral oil, prior written notification and consent is necessary. When the notifier intends to ship waste, a written notification must be submitted to the competent authority in the country from which the waste is dispatched from. In the case of Sweden, for example, Naturvårdsverket is the competent authority.

The starting point for the notification or application is firstly to identify the type of waste and find the correct EWC-code, specify to what country the waste should be sent to and how the waste should be handled. In the written application, a contract for the waste must be specified, a financial guarantee, overall process description of how the waste should be handled in the receiving country, description of how the waste will be transported, information from where it will be sent and on what country and company to which the waste should be sent [31].

To transport the used oil in vehicles, special certification is required. The license needed is called ADR licence and is issued by UNECE.

Excise duty

Excise duty must be paid for energy products in the EU. Energy product is an umbrella term for different types of fuels such as natural gas, gas oil and mineral oil. Each energy product is sorted into a tax category.

Any energy product is liable to tax when it is manufactured within the EU and when it is imported. Certain energy products such as mineral oil is covered by an excise duty suspension and be stored in a tax warehouse. This allows for manufacturing, processing and storage of energy products without paying the excise duty. The excise duty is paid when it is no longer part of the excise duty suspension. This occurs when it leaves its tax warehouse, when it is destroyed or is received by a consignee. The excise tax will be then paid in the member state where this has occurred with its national tax rate [32].

The movement of excise goods is regulated by the EU directive No 684/2009 which states that the movement can only happen when a number of conditions is fulfilled. The goods can only be moved between authorised actors and locations and an electronic administrative document must be submitted to EMCS which is a computerised system for monitoring the excise goods that are under duty suspension.

Waste oil management

The Waste Framework Directive is the principal EU legislation concerning the reuse of waste oil. It essentially stipulates that member states should take the necessary steps to make sure that waste oils are collected separately and to encourage the best environmental outcome, prioritising the re-use of waste through recycling [34]. The directive does not state any specific way how to recycle the waste oil but allows each member state to apply measure leading to different ways of managing the waste oil.

Poland

Poland has a closed loop system where only four recovery organisations are allowed to handle all waste oil on the Polish market. Oil producers which include manufacturers, sellers and importers are required to keep records on the amount of oils they put on the market and report the data. The collective data is reported to the Ministry of Environment. One out of the four recovery organisations is a re-refiner. In Poland, oil producers and importers have an obligation to handle the generated waste oil. This can be done individually or collectively through established consortiums. There are currently six consortiums that take care of the entire management of the waste oil and are funded by their members.

A fee is paid by the producers and importers that is supposed to cover the cost of collection and treatment of the waste oil. Once the used oil has been regenerated, the producers sell them to the market as re-refined oil. PCB- contaminated oils are not treated in the same facility as other waste oils and subject to thermal treatment. Only two facilities in Poland can handle PCB-contaminated oil. [33] [34] [35].

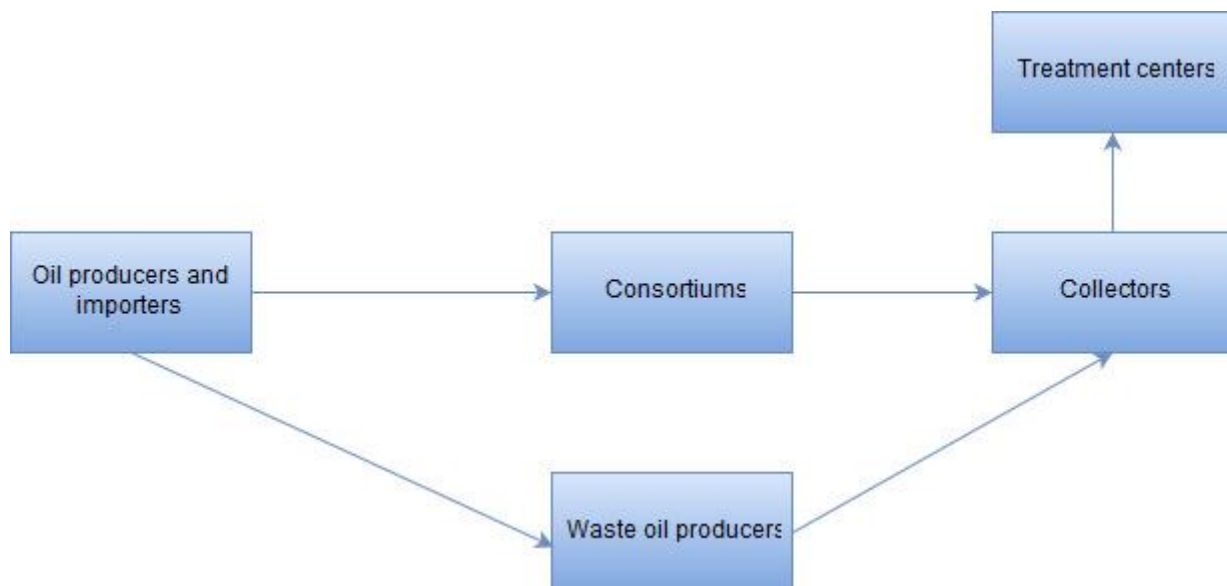


Figure 11 - Diagram of waste oil management in Poland [33]

Spain and Portugal

Spain has since 2006 created an integrated oil management system called SIGAUS that handle all waste oils in the country. This includes collection, transportation and regeneration of the waste oil. SIGAUS is a joint venture between the major oil companies present in the Spanish market and more than 90 firms representing 90 % of the Spanish lubricant market are a part of the organisation which includes transformer oil producers. To make this integrated system, SIGAUS has signed contracts and agreements with waste oil management companies which handle the following: collection, analysis, transportation, pre-treatment and regeneration. Three companies handle the re-refining and regeneration of the waste oil and there are multiple companies that work with energy recovery in the form of incineration.

SIGAUS is financed through financial contributions of its members. The collection and management of waste oil in SIGAUS is free of charge.

The fee that is meant to cover the collection and management costs is passed from the producer onto the final consumer by placing the fee on the invoice in each step of the sales process. This is also meant to compensate waste oil managers for eventual operating deficits. Regarding PCB-contaminated oils, the collection of such oils is also free as long as they contain a PCB content that is less than 50 ppm. Oils that do not meet the specifications pay for the collection of the oil [33] [36].

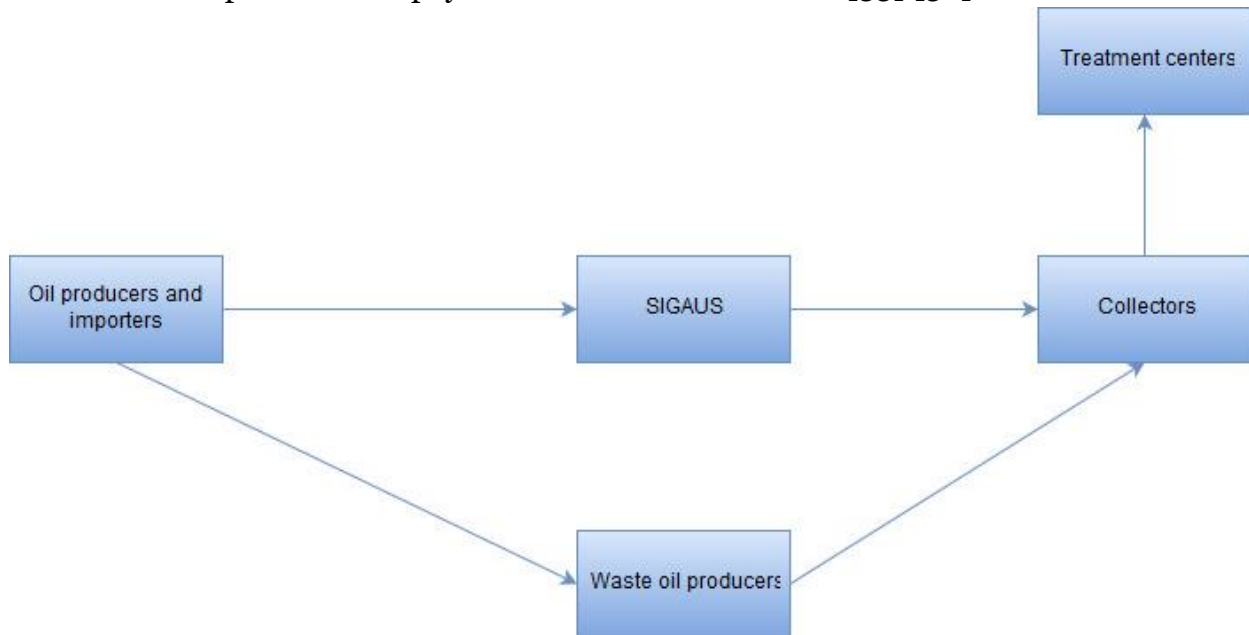


Figure 12 - Diagram of waste oil management in Spain [33]

Portugal operates in an almost identical system and their waste oil organisation is called SOGILUB. The fee in Portugal is higher than Spain. In Portugal, unlike Spain, all oil producers are required to have a contract with SOGILUB and it is financed from the levy and from the sale of waste oils. SOGILUB handles the collection, analysis, pre-treatment and disposal. Portugal also has two re-refiners that handle all of the oil recycling in the country [35] [38].

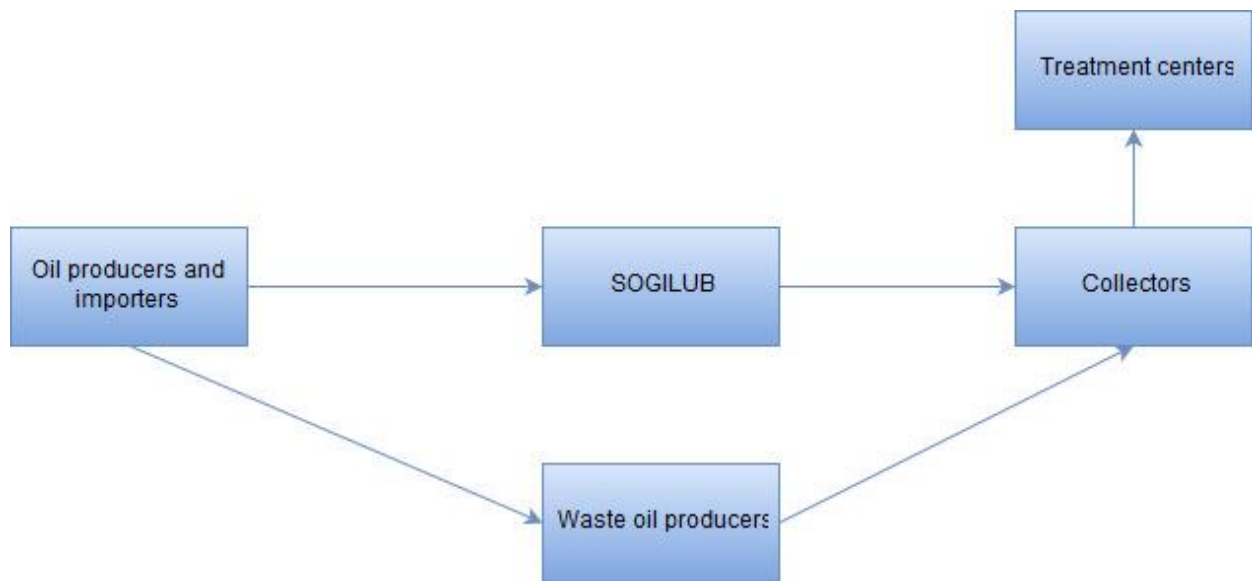


Figure 13 - Diagram of waste oil management in Portugal [33]

Germany

Germany has a free market system where all collectors and re-refiners compete for the available waste oil. Private end consumers dispose of their oil free of charge at their local lubricant dealer and industries pay a fee for the disposal of their waste oil. In Germany, the waste oil companies have formed an organisation called BVA and it includes all of the re-refiners, regeneration companies in the country and many collectors that operate in the country. It is meant to support the waste oil industry in the country by means of information. There is no excise duty on lubricants in Germany and the re-refining industry is highly subsidised when it comes opening new facilities and re-refined products.

There are many collectors present in the country and all of them must be authorised by each German state. There is only one re-refiner in Germany that specialises on used transformer oil but there are other companies that work with the reuse of used transformer oil [33] [37].

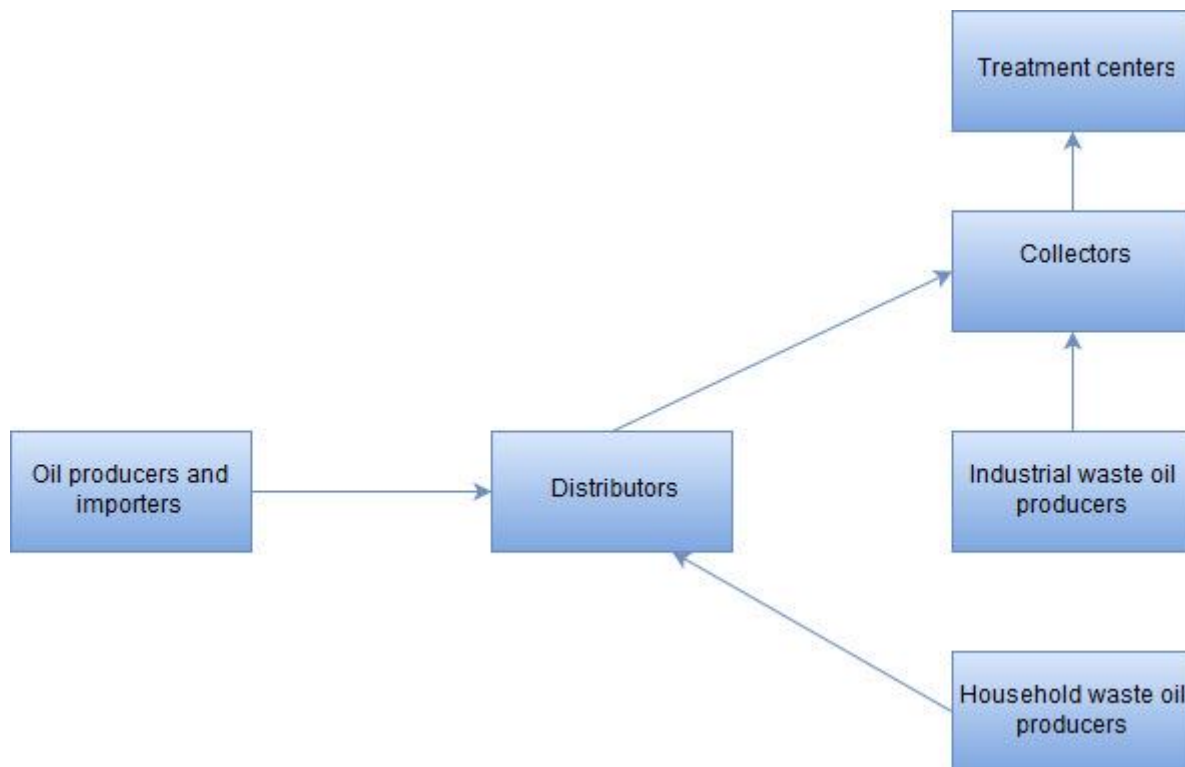


Figure 14 - Diagram of waste oil management in Germany [33]

Belgium

Belgium is a country split into the regions Wallonia, Brussels and Flanders. Each region has its own waste oil legislation but all of them prioritise the reuse of waste oil after the EU directive either through regeneration, incineration or other means. In Belgium, producers or importers of oil have a take-back obligation where they have to take back used lubrication oil from private end users free of charge while industrial end users pay for their collection. All producers and importers must also have a waste control plan that is compliant with the regulations in the three regions. This can be done by each company or through an organisation called VALORLUB.

VALORLUB is a non-profit organisation and the only organisation recognised by the Belgian government that is allowed to handle the take-back obligation from the importers and producers. To finance this system, VALORLUB takes out several different fees.

There are currently a number of collectors and facilities where the waste oil is treated. VALORLUB signs contracts with these collectors and facilities and reimburse them for their services with the fees collected.. Two facilities are in Belgium but the rest in Netherlands, Germany and France [38].

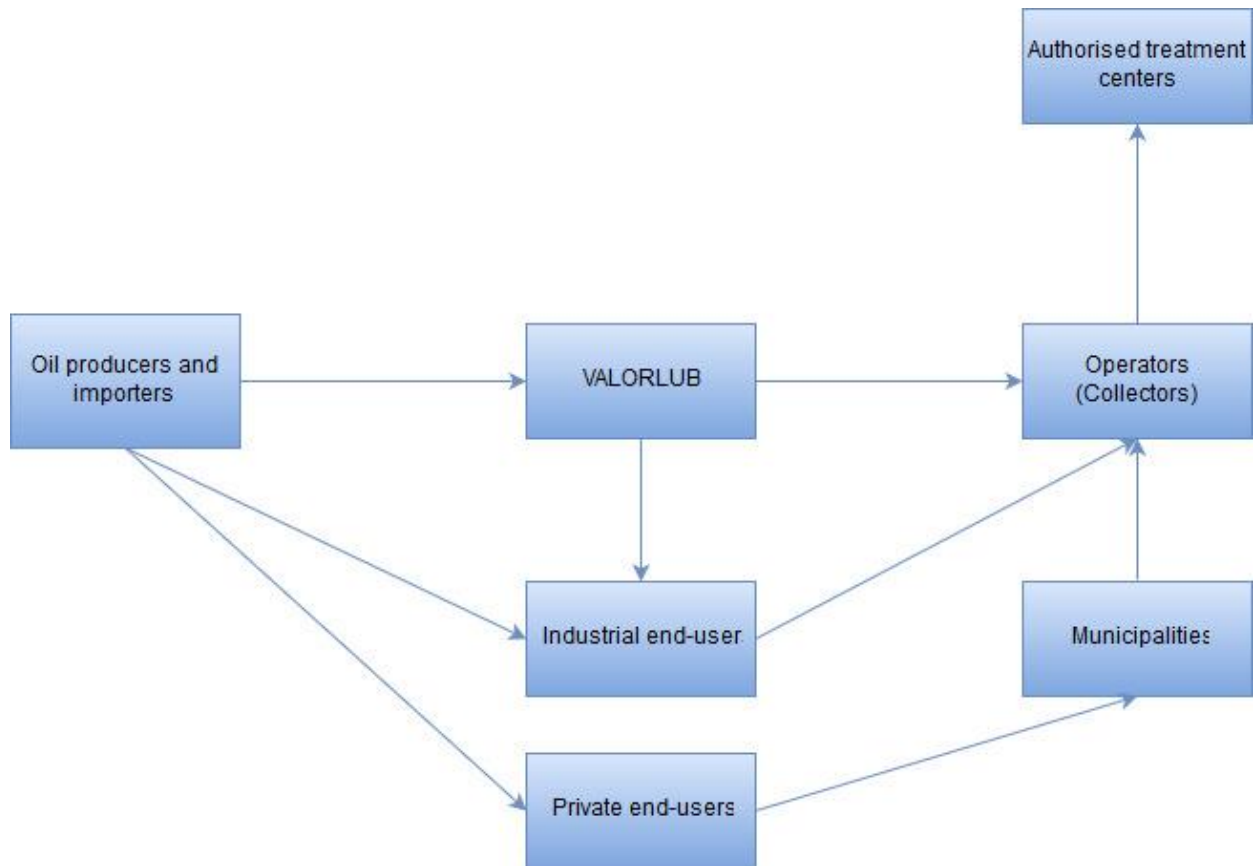


Figure 15 - Diagram of waste oil management in Belgium [38]

Finland

Finland has a state-run system where importers and producers of lubricants pay a tax on placed on the Finnish market to finance its oil collection. Priority is placed on the regeneration of waste oil according to Finnish law. The management of waste oil disposal lies at the Ministry of Environment and the company responsible for the collection of waste oil in the country is called Ekovoima Oy and is a part of Ekokem Group. The collection is done directly by Ekovoima in certain municipalities and in the rest of the country by companies that have a contract with Ekovoima. For companies that have larger volumes and the waste oil is of sufficient quality in terms of the technical requirement, the collection is free of charge. For companies with smaller amounts, they pay for the collection.

The oil tax not only finances the waste oil collection but also the transport, storage and eventual pre-treatment of the waste oil. Ekovoima is funded by this tax and a state-granted subsidy as long as it is making a loss. No subsidy is granted to Ekovoima when it generates profits and this is re-evaluated each year. Ekovoima is also financed by the sale of re-refined oils. They have three facilities for the treatment of waste oil, the Jämsänkovski plant that carries out the treatment of waste oil with high quantities of impurities, L&T Recoil plant which handles the re-refining of waste oils and Riihimäki plant which incinerates the oils that couldn't be regenerated [33].

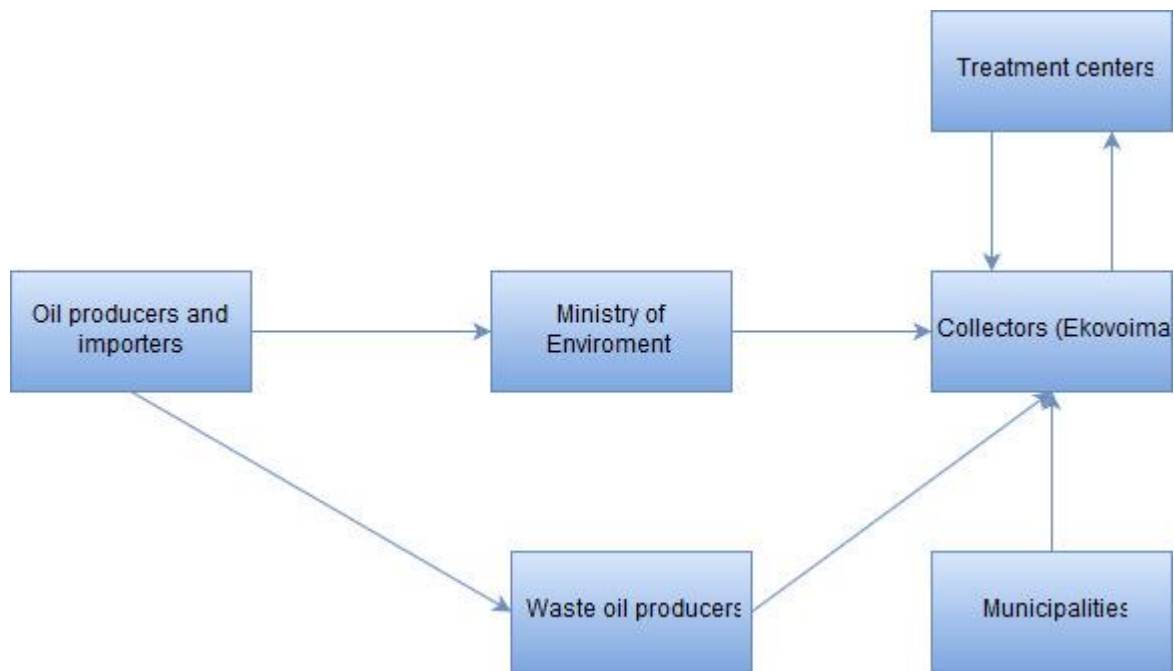


Figure 16 - Diagram of waste oil management in Finland [33]

Greece

The waste oil management in Greece is handled by the Ministry of Environment and by the organisation ENDIALE. In Greece, importers and producers of lubricant oils must organise a system in which the used waste oil is recovered and processed either through regeneration or some other means. This responsibility can be fulfilled by each importer or producer individually or participate in an already approved management system, most commonly the one provided by ENDIALE. ENDIALE (formerly ELTEPE) has existed since 1998 and is a non-profit organisation that is approved from the Ministry of Environment to collect waste oil. ENDIALE has contracts with a significant number of collectors throughout the country and cover the majority of the Greek market.

The re-refining and regeneration companies buy the waste oil directly from ENDIALE and in Greece, seven plants carry out this service including Cyclon Hellas which also re-refines used transformer oil. Regarding the financing of ENDIALE, the collection and processing costs are financed by the oil producers and by the sale of waste oil. The cost that is placed on the producers depends on the volumes of new oils placed on the Greek market [33] [39].

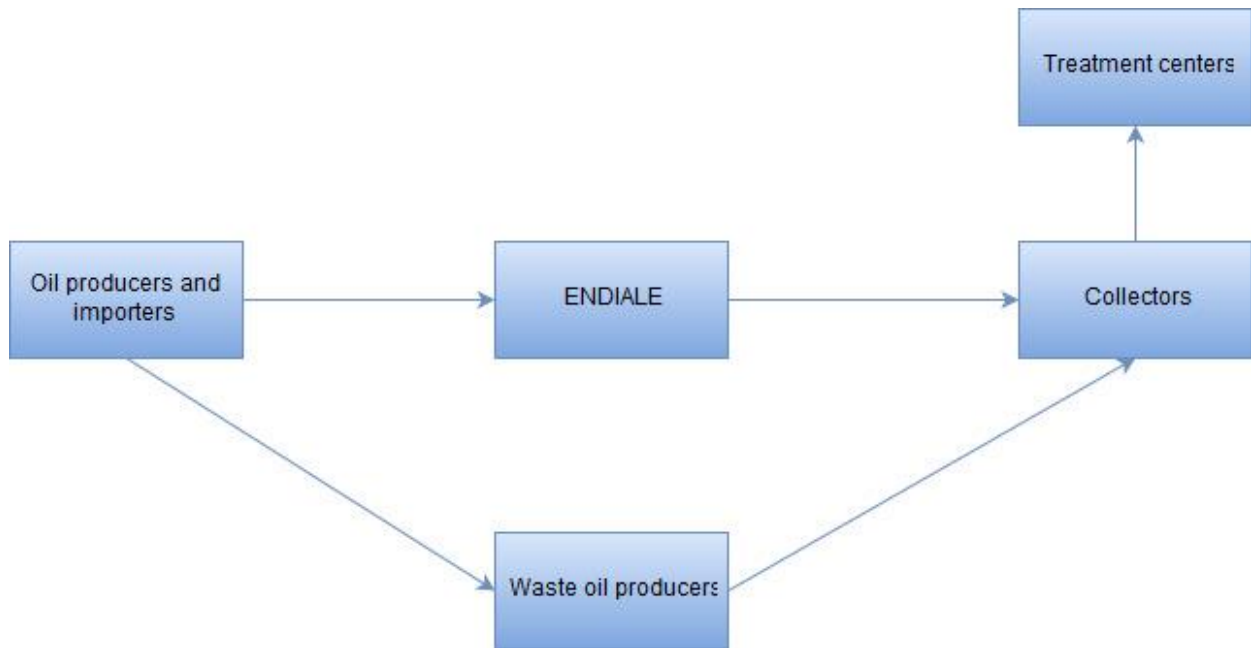


Figure 17 - Diagram of waste oil management in Greece [33]

Italy

In Italy, The National consortium for the management, collection and treatment of used mineral oils (CONOU) manages all of the collection and treatment of waste oils in Italy. The CONOU, similar to many national waste oil organisations, is a non-profit organisation that takes care of the collection, storage, analysis and treatment of the waste oil. It is obligatory for oil producers and importers to be a part of the organisation and the member companies are shareholders in the organisation. The collection of waste oil from private end users are handled by municipalities and provided free of charge. Industrial end users contact COOU to handle their collection. Once stored, the CONOU determines whether the oil upholds the requirements for regeneration or whether it is incinerated.

The CONOU is financed by the sale of waste oils and by contributions from producers and importers that are part of the organisation. Oil producers and importers pay a contribution fee for the service but the amount vary because of an annual reassessment based on the expected sale of the waste oil to the various treatment centres. The majority of CONOU's budget goes to the payment of collectors. The payment consists of a fixed part and a premium which they receive if they recover regenerable oil. The payment is also annually re-evaluated depending on several factors including inflation and oil prices [40] [41].

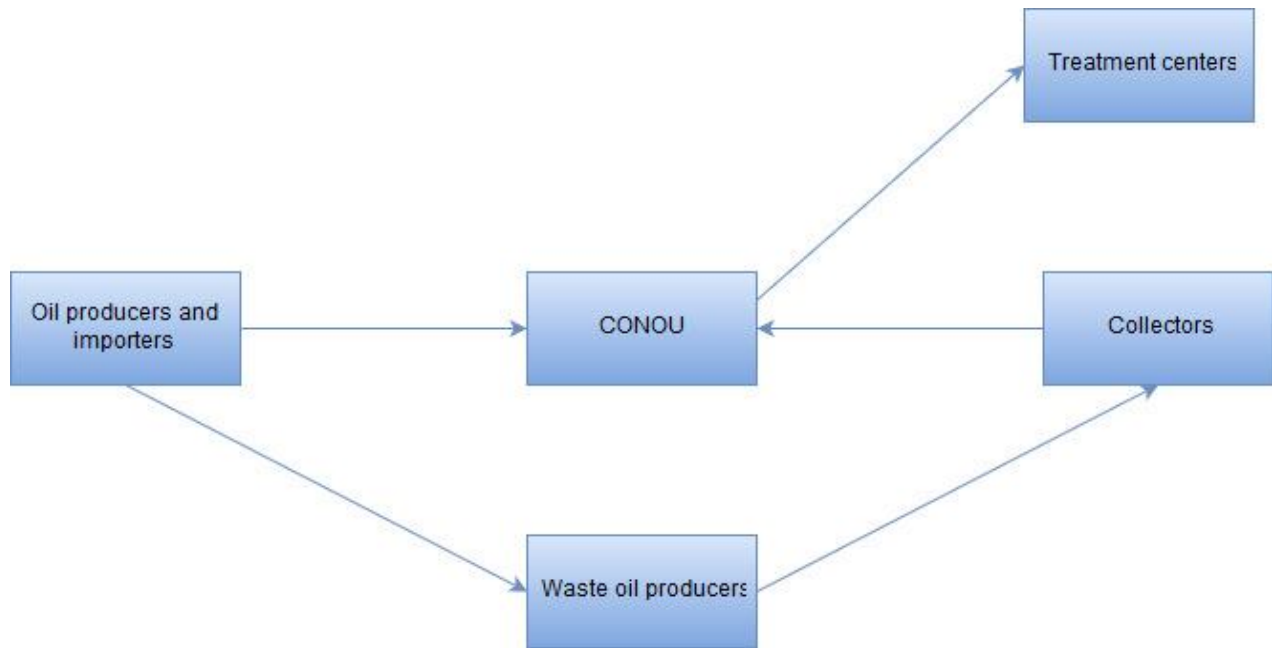


Figure 18 - Diagram of waste oil management in Italy [33]

The Netherlands

In the Netherlands, the management of waste oils is a free market system where it is financed by the holders of waste oils and from the sale of waste oil. There is no organisation that deals with waste oil management such as Belgium and Spain. The collection from private households, similar to other countries, is free of charge and handled by the municipalities in the country. Industrial end users must use one of the collectors that are authorised by the Ministry of Environment and the companies pay the costs of collecting and processing of waste oil. The Netherlands has one facility that handles all of the regeneration of the waste oil but it is unclear whether it is still functioning (North Refinery Refining & Trading Holland NV). For oils that cannot be regenerated are treated through incineration. Some quantities are also sent to other countries [33].

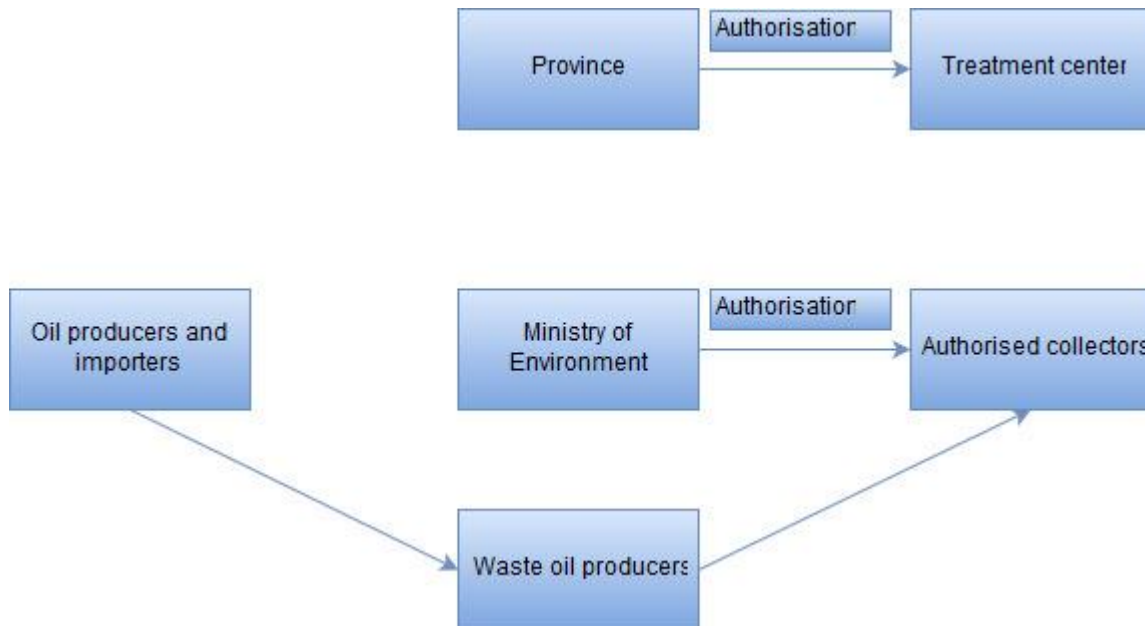


Figure 19 -- Diagram of waste oil management in The Netherlands [33]

United Kingdom

The UK does not have any unified organisation for the reuse of waste oil. Companies that produce large quantities of waste oil have a “Duty of Care” which obliges them to entrust the waste oil to approved collection and treatment providers. The British waste collectors and oil regeneration companies have formed a member association called ORA where the majority of the licensed waste oil collectors and oil recycling companies are a part of. There are currently no re-refining company in the UK but the company Hydrodec is under way to build a facility that can re-refine used lubricant oil, it is unclear whether this applies to UTO. The largest oil regeneration company that takes used transformer oil is Electrical Oil Service where they recondition and regenerate the oil [33].

France

In France, a tax is levied on the sales of new oils that generate waste. The collection of waste oils is free of charge and the money that comes from the tax subsidises the payment to the collectors. The organisation in France that handles waste oil related issues is called ADEME which is the country’s environmental agency. France has only two re-refiners and five oil recyclers in 2010. Both the collectors and oil recyclers must be authorised before handling the waste oil. France exports has exported significant amounts of its waste oil to its neighbouring countries such as Germany, Belgium, Italy and Poland. [42] [43].

Business model

Our model is based on the idea of expanding a current refinery with a re-refining facility. Nynas has two refineries, one in Nynäshamn and one in Harburg. The refinery in Harburg, Germany was chosen for three reasons; the access of hydrogen, its location in Europe and its capacity for expansion. The information for the business model was partly from secondary information in the form of documents and primary in the form of interviews with Nynas employees and other companies.

For the economic analysis, the costs have been categorised as CAPEX, OPEX and financial costs. CAPEX shows the investment costs and OPEX shows the costs for running the facility.

Re-refining facility description

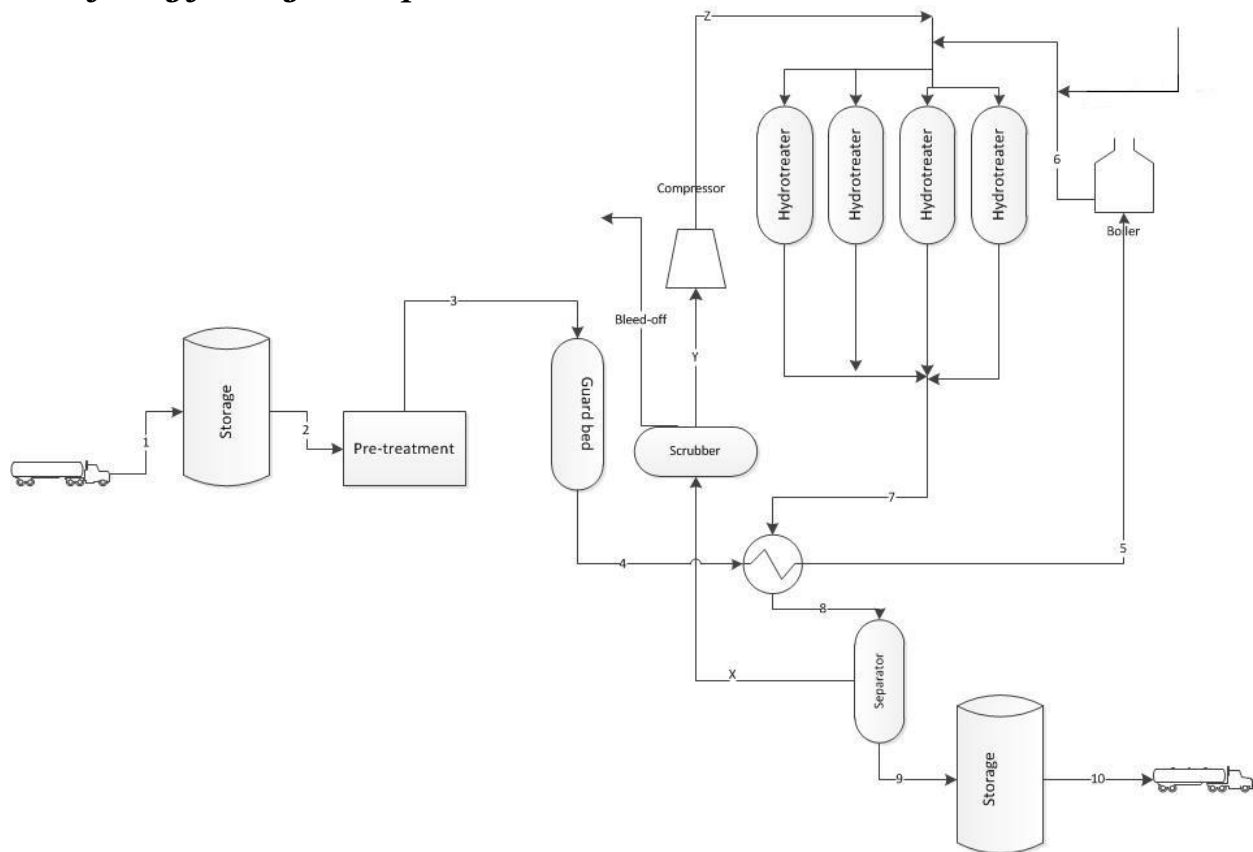


Figure 20 - Design of re-refining facility

The UTO arrives at the facility and is stored in a storage tank **1** and is then transferred to the pre-treatment **2**. The pre-treatment, which essentially is a filter, will remove the larger particles in the UTO and the filtered UTO will then pass through to the guard bed **3**. The guard bed is there as a measure to protect the catalyst in the hydrotreater from fouling. Once the UTO has passed through the guard bed **4**, it will continue to the boiler **5**. The boiler will raise the temperature to a suitable level. After heating **6**, the recirculating hydrogen stream **Z** will combine with the oil and enter the hydrotreater. In this facility, we assume a bleed-off and use make-up hydrogen **W** with the pressure needed in the facility. In the hydrotreater,

the oil will react with the hydrogen with help of a catalyst. This process breaks down aromatics and other compounds such as PCB.

The hydrotreated oil and the excess hydrogen will first pass through the heat exchanger **7**, allowing for energy savings in the facility and then continue to the gas/liquid separator **8**. The re-refined TRO will be separated from the excess hydrogen **9** and then stored in another storage tank **10** while the hydrogen stream will be recirculated in the facility **X** with the help of a scrubber where the bleed-off will occur and a compressor to re-pressurise after the hydrotreatment.

List of assumptions

- Discount rate for NPV
- Inflation rate
- Interest rate
- Amortisation rate
- Quantity of UTO
- Price of UTO
- Exchange rate between US\$ and SEK
- Exchange rate between EUR and SEK
- Facility lifetime
- Operating time
- Hydrogen price

Capital cost

| Equipment | % of total cost |
|-------------------|-----------------|
| Hydrotreaters | 53 |
| Storage tanks | 10 |
| Compressor | 16 |
| Scrubber | 3 |
| Guard Bed | 2 |
| Pretreatment | 2 |
| Separator | 4 |
| Construction cost | 10 |
| Total Investment | 100 |

Table 6 - Capital cost of re-refining facility

The price for the hydrotreaters is based on available information from Hydrodec and the costs for the remaining equipment have been calculated together with Nynas personnel.

Operation cost

| Operation | % of total cost |
|---------------------------|-----------------|
| Hydrogen consumption | 0.4 |
| Personnel | 0.82 |
| Replacement cost catalyst | 0.53 |
| Energy cost | 0.12 |
| Maintenance | 1 |
| Storage | 1 |
| Feed Stock | 59 |
| Transportation | 37 |
| Total Operation Costs | 100 |

Table 7 – Operation costs for the re-refining facility

The operation costs were calculated with the help from Nynas engineers and the energy cost for heating were calculated with the following expression:

$$Q = \dot{m} \cdot C_p \cdot \Delta T \quad (1)$$

$$Q_{\text{hydrogen consumption}} = \dot{m}_{\text{hydrogen}} \cdot C_{p,\text{hydrogen}} \cdot \Delta T_{\text{hydrogen}}$$

$$Q_{\text{hydrogen consumption}} = 1,86 \frac{\text{kJ}}{\text{kg} \cdot \text{K}}$$

$$\Delta T = \text{Temperature difference between feed and product}$$

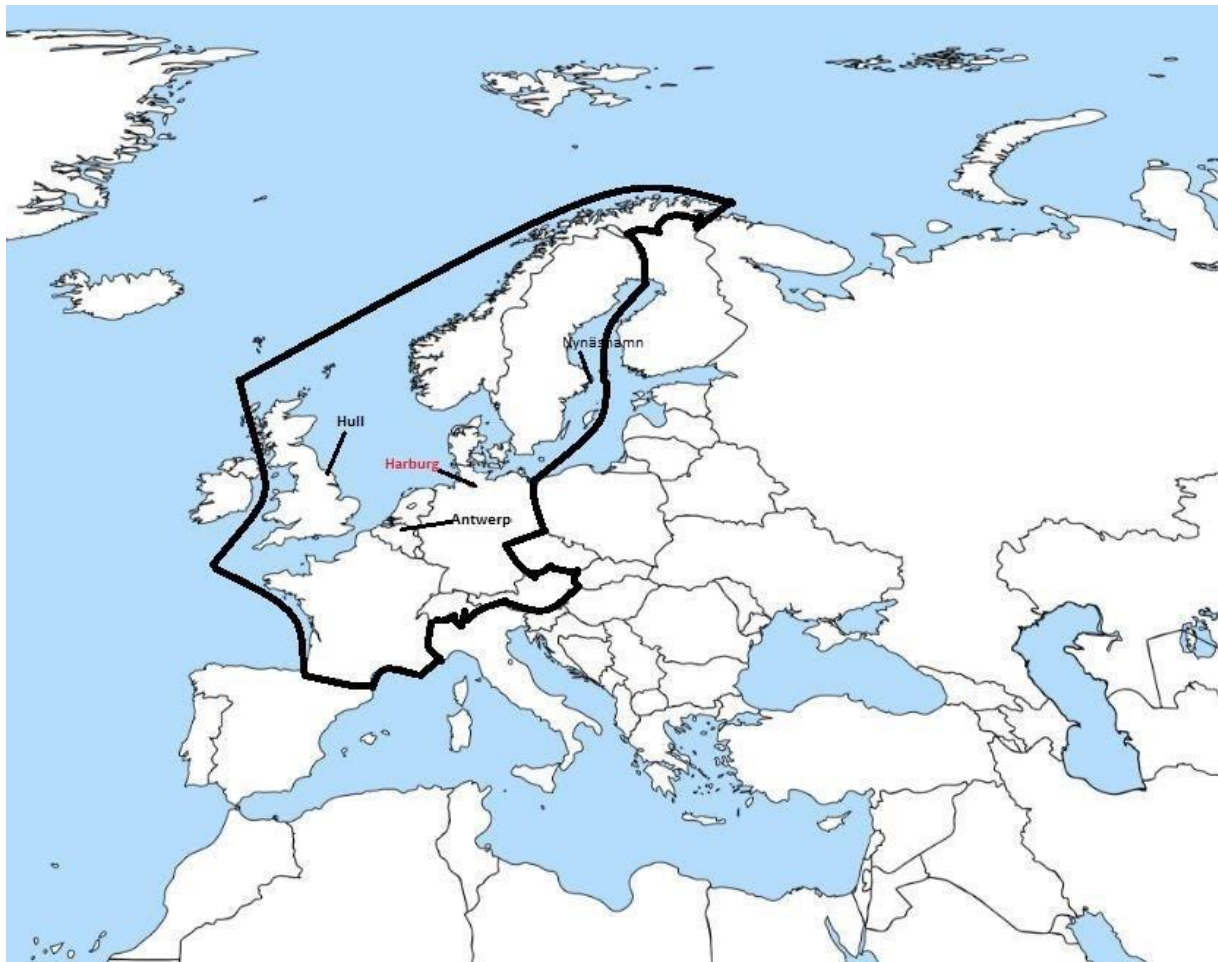


Figure 21 - Area of UTO feedstock

In this report, a conservative estimation has been made regarding the amount of feedstock to the facility. The feedstock for the facility is assumed to come from the area marked in Figure 19. The reason for this limitation is because of the free-market system present in primarily Germany, Austria and Netherlands and the lack of adequate waste oil legislation in the UK. The business model is based on the assumption that Nynas will handle the collection of UTO, eliminating scrappers which probably decrease the collection cost.

Nynas has depots in Hull, Antwerp and Nynäshamn and a facility in Harburg.

In the business model, it is assumed that the UTO is collected and transported to the depots either by road transportation or shipping before taking the waste oil to the facility. The road transportation cost is calculated by estimating average distances to the depots from various sites in the marked area. Shipping costs is calculated by using data from Nynas shipping department.

The estimation of the amount of UTO were based on the amount of waste oil generated in countries near the depots.

Investment

To decide whether to proceed with a project or not, several approaches are used. NPV and payback period are the most common methods and the methods used in this report. NPV is used in capital budgeting to analyse the profitability of a projected investment or project [44].

$$NPV = \sum_{t=0}^n \frac{CF_t}{(1+r)^t} - CF_0$$

n = number of time periods

r = discount rate,

CF_0 = total initial investment costs,

CF_t = net cash inflow during period t

The discount rate is defined as the interest rate needed on an investment to receive a profit. The discount rate in this report is Nynas own WACC. The WACC is the interest rate that a company requires on its assets to generate profit [44].

$$WACC = \frac{E}{E+D} \cdot r_E + \frac{D}{E+D} \cdot r_D \cdot (1 - \tau_c)$$

r_E = Cost of equity

r_D = Cost of debt

E = Market value of the company's equity

D = Market value of the company's debt

$E+D$ = Total market value of the company's equity and debt

$E/(E+D)$ = Percentage equity of the total market value

$D/(E+D)$ = Percentage debt of the total market value

τ_c = Corporate tax rate

Results

The characterisation results give an indication to where the largest impact comes for each category and life cycle. For the categories Climate Change and Ozone depletion, the mineral oil has the highest environmental impact but not for the other categories. The normalisation gives a more meaningful way of comparing the oils. From the normalisation data, the mineral oil has the biggest impact in terms of kg CO₂-equivalents. This is because of the carbon sequestration of the vegetable oils. For the ozone depletion, there is no particular process that causes that the mineral oil is higher than the other oils but it is an accumulation of all of the underlying processes involved in the production for example the production of naphtha used in the process. For the other categories, the vegetable oils seem to have a larger environmental impact than the mineral oil. In the category “Freshwater Ecotoxicity” and “Freshwater eutrophication”, the environmental impact for the sunflower oil is several times higher than all of the other oils.

When examining these processes in more detail, this large impact is thought to come from the use of insecticides in the cultivation process, more specifically from a toxic substance called Chloropyrifos for the increase in ecotoxicity and the use of fertiliser, increasing the amount of phosphate and eutrophication. In the category “Land use”, the sunflower oil is still higher than the other oils and this is because the land use change for the cultivation of the sunflower crop is higher than for the other oils. For both categories of “Human toxicity”, zinc emitted to the soil and water is thought to be the reason for why the vegetable oils have a higher environmental impact than the mineral oil. Zinc is a heavy metal and has the potential to be highly toxic both for human and plant life.

When looking at the results of the re-refining, there is an overall smaller environmental impact for both ratios of re-refining despite the significant amount of incineration. The decrease is largest in the categories “Photochemical ozone formation”, “Acidification” and both categories of “Human toxicity”. This is because of the lower air emissions of nitrogen oxides and ammonia during the re-refining. The particulate matter has also been reduced during the re-refining.

The profitability of the financial results was calculated using the net present value for costs and revenues over 20 years, using the WACC rate as the discount rate. By keeping the same purchasing cost of the feedstock and calculating for three different sales prices for the re-refined transformer oil, the break-even was reached after 3rd, 5th, and 10th year.

Comparison with other studies

There are no current commercial studies done on transformer oils. There are several LCA studies on transformers and comparative studies between bio lubricants and mineral oil based lubricants and even some studies that examine the re-refining of base oils but the results cannot be extrapolated to account for transformer oils. The only available studies that compare different types of transformer oils against each other are from NIST with the BEES software.

Discussion

The results from the LCA study are surprising. One would expect that the refined vegetable oils have an overall lower impact since they are advertised to be a much more environmentally friendly option, especially when studying on a cradle-to-gate perspective. Although the results achieved in this report cannot be compared to the studies from NIST because the use of different impact assessment methods but generally the mineral oil has a lower environmental impact than refined vegetable oils that are used for transformer oils.

In this report, carbon sequestration has been accounted for the vegetable oils but carbon sequestration is usually accounted for products with lifespans over 100 years which is not the case for vegetable transformer oils. An issue is also the recyclability of the vegetable oils. It's known that mineral oils can be re-refined an indefinite amount and retain its performance but it is not clear how the outcome of recycling vegetable transformer oil will affect its performance.

For the operation costs in the business model, the feedstock and transportation are the factors that affect the OPEX significantly. The feedstock cost is extremely variable and highly dependent on supply and demand of the UTO and crude oil price. There is no correlation data between the crude oil price and UTO since there is no index for UTO. The price of the feedstock also varies from where it is purchased.

The transportation cost of UTO is higher than transportation of other oils. In the business model, the trucks are vacuum trucks which means that the transportation is between the depot and the sites. This means that the trucks arrive at the site empty and return full to the depots. This is not optimal from a financial perspective because for each empty transport, money is lost.

There is a lack of information regarding scrappers. In this report, we have been able to make a table of scrappers in several countries in Europe that takes care of transformers but information of the price that the scrappers are selling transformer oil to collectors and other actors is unknown. Vattenfall has recently signed a deal with Stena Recycling to handle their old transformers and there could be similar deals between scrappers and utilities in other countries.

Conclusion

Based on our results, mineral oil is a better choice than vegetable transformer oils and that re-refining lowers the total environmental impact of the mineral oil. The results have also shown that the investment of a re-refining facility is feasible assuming a reasonable feedstock price and capacity.

Recommendations

We would recommend looking at the recyclability of vegetable oils in order to establish whether its performance stays the same after recycling. The re-refining facility is currently designed for a certain capacity so to scale the capacity, a more detailed study is necessary. To add to the accuracy of the LCA, emission data for the re-refining of UTO is necessary, it is currently modelled based on a naphtha hydrotreater and finally, more data in Eastern European countries is necessary to establish a complete picture of the re-refining market in Europe.

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