Anniina Puska

Evaluating life cycle environmental impacts of power transformers with different dielectric liquids

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Author:	Anniina Puska
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ABSTRACT:

The aim of this thesis is to investigate the differences between the life cycle environmental impacts of different dielectric insulating liquids. The dielectric insulating liquids assessed are namely mineral oil, natural ester, synthetic ester, gas-to-liquid, bio-based hydrocarbons and recycled mineral oil. The dielectric insulating liquids were chosen from four suppliers, Nynas, Starke & Sohn, Shell and Cargill.

The thesis was done as a literature review using scientific publications and books. In addition to this, the knowledge of experts was a valuable source of information.

The thesis deals with multiple aspects of the environmental impacts. First the properties and supplier claims of the dielectric insulating liquids chosen for assessment were discussed. The operational lifetime of the transformer and what can be done to lengthen was the next step. Different failure modes and service and maintenance activities were explored. Moisture ingress of transformer and oxidation of transformer dielectric insulating liquid were also discussed as well as reclaiming mineral oil. Then the focus moved to the impacts of growing the crops for bio-based oils. The main take away here was that the crop and area affect the consequences, it can either be an advantage or disadvantage. Next step was to investigate leakages and toxicity, what happens when the dielectric insulating liquid is accidentally released to the environment. Biodegradable and non-toxic dielectric insulating liquids can have serious effects in nature, so all need to be cleaned fast and effectively. Lastly the different end-of-life scenarios were explored. This includes re-refining waste transformer oil, reusing it as lubrication oil, diesel and through pyrolysis, and incineration for energy production.

As a result from this thesis, advantages and disadvantages of the different dielectric insulating liquids were presented. No simple best dielectric insulating liquid for all transformers was found, as the projects differ widely. The results can be used in the future when choosing the best possible dielectric insulating liquid for future projects.

KEYWORDS: power transformer, dielectric insulating liquid, life cycle impacts, leakage, reclaiming

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TIIVISTELMÄ:

Tämän diplomityön tavoitteena on selvittää erilaisten muuntajien eristysnesteiden elinkaarivaikutusten välisiä eroja. Arviointiin valittiin mineraaliöljy, luonnonesteri, synteettinen esteri, gas-to-liquid, biopohjaiset hiilivedyt sekä kierrätetty mineraaliöljy. Eristysnesteet valittiin neljältä eri toimittajalta, jotka ovat Nynas, Starke & Sohn, Shell ja Cargill.

Diplomityö tehtiin kirjallisuuskatsauksena käyttäen tieteellisiä julkaisuja ja kirjoja. Tämän lisäksi asiantuntijoiden asiantuntemus oli arvokas tiedonlähde.

Diplomityö käsittelee useita ympäristövaikutusten näkökohtia. Ensin käytiin läpi valittujen eristysnesteiden ominaisuuksia sekä tuottajien lupauksia. Seuraava askel oli muuntajan käyttöikä ja toimet sen pidentämiseksi. Eri vikoja sekä huoltotoimenpiteitä käytiin läpi. Myös kosteuden pääsyä muuntajaan ja eristysnesteiden hapettumista sekä eristysnesteen puhdistamista tutkittiin. Tämän jälkeen painopiste siirtyi biopohjaisten öljyjen valmistamisessa käytettävien kasvien viljelyn vaikutuksiin. Todettiin, että kasvin ja kasvatuspaikan valinta vaikuttaa siihen, ovatko seuraukset positiivisia vai negatiivisia. Seuraavaksi tutkittiin vuotoja, mitä tapahtuu, kun eristysneste on ympäristössä. Myös biohajoavat ja myrkyttömät eristysnesteet ovat haitallisia luonnossa, ja puhdistus tulee suorittaa nopeasti ja huolellisesti. Lopuksi käytiin läpi erilaisia skenaarioita eristysnesteen käyttöiän päättyessä. Tämä kattaa muuntajien jäteöljyn uudelleen jalostuksen muuntajan eristysnesteeksi, uudelleen käytön voiteluöljynä, dieselinä tai pyrolyysin kautta sekä polton energian tuottamiseksi.

Tämän diplomityön tuloksena löydettiin eri eristysnesteiden etuja ja haittoja. Yksinkertaista parasta eristysnestettä kaikille muuntajille ei löytynyt, koska projektien tarpeet vaihtelevat suuresti. Tuloksia voidaan hyödyntää jatkossa valittaessa parasta mahdollista eristenestettä tuleviin projekteihin.

AVAINSANAT: power transformer, dielectric insulating liquid, life cycle impacts, leakage, reclaiming

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Abbreviations

BCH	bio-based hydrocarbon
CCRP	customer complaint resolution process report
GTL	gas-to-liquid
MO	mineral oil
Mha	million hectares
Mt	million tons
NE	natural ester
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
RMO	recycled mineral oil
SE	synthetic ester
WTO	waste transformer oil

1 Introduction

This thesis focuses on analysing the commercially available dielectric insulating liquids used in power transformers, namely mineral oil (MO), natural ester (NE), synthetic ester (SE), gas-to-liquid (GTL), bio-based hydrocarbons (BHC) and recycled mineral oil (RMO). The aim is to find the differences in the life cycle impacts of these transformer dielectric insulating liquids. This is done by a literature review of different aspects of the life cycle.

1.1 Construction of a power transformer

Harlow (2012, pp. 2-1–2-20) explains the construction of a power transformer. Power transformers are used at all points where the voltage levels change in the power system. They are selected individually for each application and usually custom designs. Because of this, the construction will differ between transformers, but the basic arrangement will be nearly the same in all. There is a core made of laminations, thin steel strips. It creates the magnetic circuit. The windings are wound around the core. They are made from insulated, supported and cooled conductors, usually copper or aluminium. They carry the current. Tap changers are used to change the turns ratio to compensate for voltage variations. There are many accessories, some standard and some custom. These include temperature indicators, surge protectors, liquid level indicators, pressure relays and dehydrating breathers. There is a liquid preservation system to isolate the internal environment from the outside. Insulation consists of solid insulation made from porous cellulose and liquid insulation, which is the dielectric insulating liquid. Cooling depends largely on the size, application and location of the transformer. Some type of cooling, internal or external, liquid or natural convection is always present.

1.2 Structure of the thesis

The thesis is divided into eight chapters, first of which is the introduction. The second chapter introduces the dielectric insulating liquids that were selected for assessment and their properties and supplier claims are explained. The third chapter focuses on the operational lifetime of a transformer. This includes the description of failure types, testing for failure, service and maintenance and oxidation of dielectric insulating liquids. The reclaiming potential of dielectric insulating liquids is explained here too. The fourth chapter is about the environmental impacts of growing the crops that are used to produce bio-based oils. The focus is on biodiversity loss, where they are grown, effects on local food crops and water when the production moves towards industrial needs, and deforestation. The fifth chapter explores environmental and safety priorities. It includes leakages, biodegradability of the dielectric insulating liquid, and fire hazards. The sixth chapter is about the different end-of-life scenarios for the dielectric insulating liquids. The focus is on circular potential, transportation regulation, different reusing options and incineration. Finally, there are two chapters for conclusions and summary.

1.3 The objective of the thesis

The objective of this thesis is to find the differences between the different dielectric insulating liquids considering the operational lifetime of a transformer and the environmental aspects. This information can then be used when selecting what liquid to use in projects in the future. One best dielectric insulating liquid for all projects cannot be chosen. The specifics of each project determine which will be best there.

2 Transformer dielectric insulating liquids selected for assessment

2.1 Properties

An excerpt of some relevant properties of these different transformer dielectric insulating liquid options can be seen in Table 1. Biodegradability and recyclability are important from the sustainability point of view. These affect the end of life of the dielectric insulating liquid. If it is not biodegradable or recyclable, burning it for energy is really the only option. Burning will release harmful gases, so it should be the last option. Flash point tells the temperature at which the vapours from the oil will flash when exposed to an open flame. Breakdown voltage and acidity affect the components. Breakdown voltage is the minimum voltage at which a dielectric liquid can safely be used in a transformer. If the voltage is higher than the breakdown voltage, there can be sparking which can lead to component failure. High acidity can lead to metals dissolving into the dielectric liquid. This harms the solid insulation. Toxicity is important in case of a leakage. Toxic oil is harmful to the flora and fauna if the oil gets to the environment. No dielectric liquid is safe in case of a leak, but non-toxic liquids have one less danger aspect. The information for the slots marked “not available” on Table 1 was not available from the producer.

Table 1. Properties of the dielectric insulating liquids chosen for assessment.

Name	**Nytro 10X**	**Nytro bio 300X**	**Nytro RR 900X**	**Starke & Sohn recycled oil**	**Midel 7131**	**Shell Diala S4 ZX-I**	**Cargill FR3**
Type	Mineral oil	Bio based hydrocarbon	Recycled oil	Recycled oil	Synthetic ester	Gas to liquid	Natural ester
Material	Crude oil	Not available	Recycled oil	Recycled oil	Synthetic ester	Natural gas	Vegetable oil
Biodegradable	No	Yes	No	No	Yes	No	Yes
Flash point (°C)	142	145	not available	not available	260	191	260
Breakdown voltage (kV)	40-60	40-60	not available	not available	30	70	47
Breakdown voltage after treatment (kV)	>70	>70	not available	not available	not available	78	not available
Acidity (mg KOH/g)	0.05	0.01	not available	not available	0.03	0.002	0.1
Recyclable	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Toxic	not available	not available	not available	not available	No	No	No

2.2 Supplier claims

Oil suppliers state claims on the properties of their products. For example, fire safety and environmental claims can make a customer choose a certain oil over others. These claims affect what oil the customer chooses to go with, so it is important to know what the claims are.

2.2.1 Nynas

Nynas states (Nytro 10XN (IEC 60296, Ed. 5) - Super grade, n.d. -a) that Nytro 10X MO has extremely good heat transfer because of low viscosity and viscosity index. This lengthens the lifetime of core and windings. Transformer life is longer, and maintenance needs are minimized because of outstanding oxidation stability. It works well in low temperatures and dielectric strength is high.

Nynas claims (NYTRO BIO 300X (IEC 60296, ED.5) – SUPER GRADE, n.d. -b) that Nytro BIO 300X is bio-based and readily biodegradable as well as fully recyclable. The ultra-low viscosity offers exceptionally good cooling, even 10 degrees more than with MO.

Nynas states (NYTRO RR 900X (IEC 60296 ED. 5 TYPE A), n.d. -c) that the recycled oil reduces at least 70 % of lifetime greenhouse gas emissions. It can also be re-refined again at the end of life. It has the same performance as virgin oil. The dielectric behaviour is like traditional naphthenic fluids.

2.2.2 Starke and Sohn

Starke & Sohn state (Information on Starke & Sohn GmbH transformer oil, n.d. -a) that their recycled oil has the highest performance level according to IEC 60296. It can be used in higher temperatures and has a higher life expectancy, but it is not stated what the baseline is. It does not increase the degradation of inhibitors or have metal contamination. It is sustainable, environmentally friendly, and saves resources. Unfortunately, there is no explanation for any of these claims available, nor is the higher temperature mentioned. This means that the customer cannot know what the properties are compared to, so it is very hard to compare it to anything.

2.2.3 Shell

Midel is a part of the Shell Group. Midel state (MIDEL 7131 - premium performance since the 1970s, n.d.) that Midel 7131 SE is readily biodegradable and offers environmental safety. It has a high fire point, which means that it is safer and needs no fire deluge system. They state that the high moisture tolerance extends cellulose insulation lifetime. This is important because the degrading of the cellulose insulation shortens the lifetime of the transformer and the oil. The cradle to gate emissions are nearly three times higher than for mineral oil but are expected to reduce as the vegetable oil's suppliers lower their emissions. It can be recycled after use.

Shell state (Shell Diesel powered by GTL, n.d.) that Shell Diala S4 ZX-I GTL has outstanding oxidation performance and extended oil life. It can stand high voltage transient because of higher lightning impulse breakdown voltage than inhibited oil. It is non-corrosive towards copper without additives, because of zero sulphur base oil. It has good temperature properties even in low starting points. Specific heat and thermal capacity are higher than in conventional transformer oils, so it has better cooling benefits.

2.2.4 Cargill

Cargill states (FR3® fluid technical details, n.d) that FR3 is the most proven NE dielectric fluid. It is refined 100 % from vegetable oil. It has an increased fire safety with a fire point of 360 °C. It has smaller environmental impact by being biodegradable, non-toxic and carbon neutral. It extends transformer life by offering longer paper insulation life.

3 Operational lifetime of a transformer

Transformers have a long operational lifetime, averaging about 40 years. Service and maintenance plans assure continued performance. Transformers will always have moisture in them, and during the lifetime they can accumulate more moisture from the environment, if there is damage to the tank or cover. The moisture is not good for the electrical properties of the transformer and should be removed as best possible. Moisture can cause partial discharges, breakdown of insulation, corrosion, rust, and protection maloperation. Heat, vacuum and adsorbents are the main dehydrating methods. If there is a leak in the transformer, there will be oxidation, which will also tamper with the properties of the dielectric liquid. The changed properties include colour, acidic values, viscosity, and stability. Oxidation can also lead to sludge formation and metals dissolving into the liquid. MO can be reclaimed, and other dielectric insulating liquids replaced. Ward (2003, p. 5-1) states that adsorption should be used to remove oxidation products, ion exchange to scavenge for oxides and vacuum to remove oxygen. Then the antioxidants should be replenished. It is important to monitor the function of the transformer continuously, so the problems can be fixed as they rise.

3.1 Testing

The condition of a transformer should be continuously monitored so there will not be bigger problems, when they can be solved fast. There are many ways to evaluate the condition of a transformer. One way is by using the health index (HI) methodology. Murugan and Ramasamy (2019, pp. 281–284) introduce the HI method as one preventive condition assessment method for determining the status of the transformer. It measures the long-time degradation of the whole transformer, not for individual components. This method can be used to identify which transformers are close to their end-of-life or have higher failure probability. First, condition tests are run on the transformer to get an input for HI. The tests are operation observations, field tests and laboratory tests. Short-circuiting is tested with turn ratio testing in winding and tap changer and bushing short-circuit with a power factor test. Winding resistance test is also run for winding shortcircuits. Core grounding is tested with a core resistance test. Sweep frequency response analysis tests tilting, bending and movement of windings as well as winding lead and core deformation. Deformations are also tested with short-circuit impedance tests. Dissolved gas analysis tests for thermal problems and arcing, low-energy sparking, and partial discharge. CO_2/CO test analyses the aging or cellulose degrading. Breakdown voltage test indicates breakdown voltage of the aging oil and content of conducting particles in the oil. Interfacial tension test measures the degradation of oil. Frequency domain spectroscopy indicates failures in oil-paper insulation systems. These tests are scored and weighted based on international standards and importance of the component on the condition of the transformer. The final score will be calculated linearly to get a percentage. A percentage of 0-40 % indicates good condition and the transformer only needs inspection. The value 40-80 % indicates fair condition and need for repair and refurbishment. A percentage of 80-100 % indicates poor condition and the transformer should be replaced. Then actions can be taken based on the score. Murugan and Ramasamy (2019) note it is important, so that the actions will be taken as soon as possible to minimize the harm.

After the score is calculated the needed action should be taken. Murugan and Ramasamy (2019, pp. 286–287) tell that the three maintenance steps used depending on HI value are inspections, repair or refurbish, and replacements. For transformers in good condition, only routine inspection is needed. The inspection consists of visual inspection and condition testing. If these tests reveal problems, they are fixed. For transformers in fair condition repair or refurbishment is recommended. This includes repairing components that are repairable and re-winding or drying insulation systems. For transformers in poor condition replacement is recommended. Depending on the condition of the transformer the replacement is done for individual components or the whole transformer. With this method all problems should be noticed and dealt with before more serious issues rise.

3.2 Transformer failures

Different transformer types have different main failure types. Jagers and Tenbohlen (2009) found that for general step-up transformers, most of the failures appear in insulation, with windings and winding connections after that. They found that in transmission transformers failures in protection devices are the biggest contributor to failures, and the next biggest contributors were tap changers and bushings. For distribution transformers most of the classified failures were found in windings and bushings. Most of these failures result from faults causing loosening or displacement in the windings. Insulation deteriorating can also cause flashovers in windings. A cause for insulation deteriorating is moisture and other impurities in the transformer dielectric liquid. After 25 years, wear out of components becomes a major cause of failure. Some components can be replaced, lengthening the life of the transformer. Accelerated aging with environmental factors and inherited deficiencies can lead to dielectric mode failures such as flashovers between windings near the exit leads and core to ground insulation. Inherent deficiencies, for example inadequate design, cause most of the failures in general step-up transformers. In transmission transformers inherited deficiencies, such as improper assembly were found to be the largest cause of failures. Knowing the common failures is important in preventing them.

3.2.1 Moisture ingress in dielectric insulating liquids

There is always moisture present in a transformer, for example in the solid insulation. If the transformer is damaged because of an outside factor, for example an earthquake, the tank or cover can break, and more moisture can get in. Murugan and Ramasamy (2019, p. 279) found that pressure rising due to overloading causing temperature increase or gas formation in the tank can cause the tank to rupture. Leakages were found to happen because of corrosion, cracks, and tank gasket seal degradation. This moisture ingress can lead to problems with dielectric insulating liquid, solid insulation, and other components. To minimize the problems caused by moisture and prevent accidents and breakages, it is important to remove the moisture from the transformer. The main ways to dehydrate transformer dielectric liquid are heat, vacuum, and adsorbents.

Moisture in the transformer is in the dielectric insulating liquid and the solid insulation and will move between them with changes in temperature. The migration causes the solid insulation to break down. Villarroel et al. (2021) explain that due to the temperature changes in transformers, moisture will travel between the dielectric insulating liquid and insulation paper. When the temperature increases, the water adsorption capacity of the cellulose decreases, and the water solubility of the dielectric insulating liquid rises. The changes caused by the temperature differ between different dielectric liquids. They found that NE has a high absorption capacity compared to MO. This means that the moisture is more in the dielectric insulating liquid than in the paper. The moisture migration rate when temperature drops is higher in the NE than in MO, meaning that the moisture moves faster between the oil and paper. The moisture migration leads to formation of partial discharges and breakdown of the insulation due to hydrolysis regardless of what dielectric liquid is in use. Villarroel et al. (2021) also note that IEEE standard C57.91-2011 states that over 4 % moisture content of insulation materials is too wet for safe operation, for all dielectric insulating liquids. Because of cellulose degradation, and leaks from the conservator or tank the moisture level always increases in the transformer in use. Jagers and Tenbohlen (2009) point out that the biggest reason for minor failures in protection circuitry is due to moisture ingress. Moisture leads to corrosion, rust, and protection mal operation.

Even a small amount of moisture in a transformer can cause big effects for the lifetime. Jadav et al. (2014, p. 369) explain that it has been found that a 2 % moisture increase in the solid insulation in 90 °C will reduce the lifetime of the insulation from 40 years to 5 years. Booser (1994, p. 274) says that the hydrolysis yields acid esters from both NE and SE that can be corrosive, dissolving metals into the oil. The metals then can catalyse the reaction further. Raof et al. (2019, pp. 2–7) point out that the dissolved copper deteriorates the insulation performance by migrating and depositing on the paper. The amounts of dissolved copper for SEs vary between 0.1 ppm for a palm-based synthetic ester and 763 ppm for trimethylolpropane trilaurate, while for mineral oil it is 13 ppm. With esters the metals will form soluble metal salts, leading to less wear for the components than with mineral oil. Because of this it is important to dry the transformer if needed.

For the above-mentioned reasons, it is important to remove moisture from the transformer. Moisture detection is the first step in the process. It is an ongoing process, done either offline or online. It is important to do this continuously so that the moisture will be detected as early as possible before there are more serious effects. Kondalkar et al. (2019, p. 377) describe chromatography methods and coulometer as the primary ways to detect moisture in transformer dielectric insulating liquids. These are both offline methods, so samples are collected and sent for analysis regularly. The analysis takes time and moisture content of the dielectric insulating liquid can change in storage. For this reason, Kondalkar et al. (2019, p. 377) support online monitoring for real time results. The online sensors measure air humidity via for example capacitance, resistance, electrochemical method, optical fibre, field-effect transistor, surface acoustic wave or quartz crystal microbalance. Online methods give real time results, with no waiting time for transportation and analysis as in offline methods. This means that the results will be received faster and can be more accurate than with an offline method.

If moisture is detected, the next step is dehydration. Fuller’s earth can be used to remove moisture from esters (Ghani et al., 2017, p. 658). Ward (2003, pp. 5-1–10-14) names heat, vacuum, and adsorbents as the main oil dehydration methods for MO. Heat and vacuum are expensive and meant for big amounts of oil. Adsorbents are smaller online options, but their capacity is limited by the adsorbent and the material must be changed regularly. The dehydration of oil dries the rest of the transformer as well, as the moisture from other components diffuses to the oil that is drying. The effect that the dielectric insulating liquid has on the solid insulation depends on the water solubility of the liquid, average temperature, and temperature changes. The water solubility determines how much of the water is in the dielectric insulating liquid as opposed to the solid insulation.

Moisture migrates depending on the temperature, which causes the discharges and breakdowns in the solid insulation. Ward (2003) notes that there is an equilibrium for all the liquids, where the moisture does not migrate, and this equilibrium is different for different liquids. As the MO can be reclaimed nearly infinitely with the right practices, the residual strength of the cellulose determines the lifetime of the transformer. Because of this, it is important to also clean the paper. This means that the degradation products should be removed from the transformer dielectric liquid as soon as they appear, not when it is not usable anymore. The dehydration should be done as soon as moisture is detected to avoid the problems moisture can cause.

3.2.2 Oxidation of transformer dielectric liquids

Leaks in the transformer can cause air to get in and lead to oxidation. Oxidation can cause changes in acidic values, viscosity and stability as well as cause metals to dissolve and sludge formation in the dielectric liquid. These can cause the transformer to not function properly. Safiddine et al. (2017, p. 2912) tell that the oxidation process starts when the transformer is energized. They found that the exposure to thermal and electrical stresses, oxygen, and coil core components begins the process. Raof et al. (2019, p. 2) say that oxidation of esters is a three-step process. First in the initiation stage free radicals are first formed by removal of a hydrogen atom. Then comes propagation stage where peroxy radicals are formed and they will form hydroperoxides with lipid molecules. Termination stage ends the reaction when radicals combine with other radicals to end the chain reaction. Hydroperoxides propagate and branch, decomposing to peroxide, polymeric compounds, and other secondary oxidation products. Main products are water, alcohols, and carboxylic acids. These can then cause problems in the transformer, for example by causing corrosion and leaking of metals into the dielectric insulating liquid leading to degradation of the solid insulation.

The changing of the properties varies between different oils. Raof et al. (2019, pp. 5–8) oxidated different SEs and mineral oil and tested their properties afterwards. They found that the colour change is the most obvious indication of oxidation for most. They point to the research of Urness et al. who suggest that the colour change happens because of formation of carbonyl groups and conjugated double bonds. The most and least changed dielectric liquids can be seen in Table 2. The acidic values of all the oils increased during oxidation. The reason for this is the production of carboxylic acids, as well as alkane, aldehyde, methyl esters, symmetric ketone, partial esters, and other impurities, according to the study of Urness et al. Sludge formation was bigger in the mineral oil than the SEs. It is suggested that the polarity is the reason for the little or no sludge formation in ester oils. As the oxidation products are polar, they dissolve in the ester oil, but not in the non-polar mineral oil. The viscosity rose in all the samples, but palm fatty acid ester (PFAE). The increase happens because of formation of high molecular weight oxidation products. The decomposition of the ester chain could be the reason for the lower viscosity. Mineral oil and polyol monoester 2EHE C18 showed highest amounts of oil-soluble iron compounds. The other oils do not corrode iron as much because of little or no catalytic effect. Sulphur content was found to be highest in mineral oil. Copper content was highest in trimethylolpropane tricaprylate/tricaprate (TMPE C8/C10) and trimethylolpropane trilaurate (TMPE C12) esters, with most of the other ester also being higher than mineral oil, except for methylpropane trioleate (TMPE C18) and PFAE. TMPE C18 is found to be the most stable and mineral oil the least stable. All the SEs are found to be stable at least up to 367 °C, mineral oil to 297 °C, PFAE to 340 °C and TMPE C18 to 435 °C. For mineral oil the changes caused by the oxidation process can be reversed through the reclaiming process. For SEs replacing the oil is the only method if the conditions get too bad.

Table 2. Changes in the oils after oxidation (Raof et al., 2019, pp. 5–8).

Attribute	**Most changed**	**Least changed**
Acidic value	Trimethylolpropane trilaurate	Palm fatty acid ester
Sludge formation	MO	Trimethylolpropane tricaprylate/tricaprate
Viscosity	Trimethylolpropane trioleate	Palm fatty acid ester
Iron content	MO	Palm fatty acid ester
Sulphur content	MO	Palm fatty acid ester
Copper content	Trimethylolpropane trilaurate	Palm fatty acid ester
Stability	Trimethylolpropane trioleate and High oleic trimethylolpropane	MO

The oxidation products can be cleaned from the dielectric insulating liquid to some extent. Ward (2003, pp. 5-1) says that mechanical filters should be used to clean particulates, adsorption to clean acids and oil and paper oxidation products, ion exchange to clean ionic species and dissolved metals, scavenging for oxides, peroxides and free radicals and membrane and vacuum for oxygen and gases. Heat and vacuum can also be used for drying, but it is expensive and needs a large amount of oil to work properly. Vacuum can also help remove oxygen, but the method can form gas bubbles which are harmful. Nitrogen purging can also work. Slowing the oxidation process is important to minimize the cleaning needs.

Slowing the oxidation process is important, so the oil can be used for as long as possible. Even with mineral oil the slowing is important, because reclaiming is also a costly process. Oumert et al. (2018, p. 5895) note that antioxidants should be used in the oil to slow down the oxidation process. This is used as a preventive maintenance process.

Antioxidants trap free radicals and electrons, preventing the chain reaction that leads to production of free radicals, oxides, and peroxides. They can also function by metal chelation and synergism. Antioxidant performance varies with temperature. Antioxidants need to be replenished, as they are consumed in the process. It is important to monitor the amount of antioxidants present, so they can be replenished as needed and oxidation is prevented. With this the lifetime of the transformer is longer and costs stay lower.

3.3 Service and maintenance

Maintenance is an important part of the lifetime of the transformer. If maintenance is done correctly, the unexpected service is minimized. This means that the costs stay down, and the transformer can be used for longer, lowering lifetime cost and emissions. Also, neglecting the maintenance can lead to failures. Koksal and Ozdemir (2016, p. 1976) state that transformers are an important part of the infrastructure, and a sudden outage can lead to economic losses, technical failures, service interruptions and customer dissatisfaction. On average, transformers have a 40-year lifetime. The maintenance becomes more important the longer the transformer is in use.

There are many ways to classify maintenance types. Costa et al. (2015, pp. 202–203) highlight corrective, preventive, predictive and proactive maintenance as the four main maintenance types. These are all used together, not just one type for a transformer. Corrective maintenance uses system restoration. Flaws are fixed unplanned without an intervention plan or planned as they are detected with a preventive or predictive maintenance model. The latter is better, as the costs and implementation time are lower. Preventive maintenance tries to avoid unplanned maintenance by correcting problems before they occur. This means that sometimes the parts are replaced earlier than needed. Parts may also break before maintenance, as it is done at set time intervals. Predictive maintenance focuses on failure prediction through monitoring parameters. The choice to replace parts is then done by analysing the parameters. Proactive maintenance focuses on dealing with the root issues for failures before problems arise. The maintenance type should be selected on case-by-case basis, depending on the type, use and location of the transformer.

Maintenance of a transformer can affect the lifetime costs. If it is not done in time, there can be more serious issues which can be more expensive to fix. Marchi et al. (2016, pp. 74–75) calculated the lifetime costs of transformers and found that annual maintenance costs consist of ordinary maintenance activities, out of service cost, and reliability penalty of the transformer. To keep costs lower, the maintenance should be done as scheduled. Replacing the transformer can lead to smaller lifetime costs, but that needs big capital investment. Installing smart equipment and defining maintenance policy also yield savings and can be more viable solution. With smart equipment the condition of the transformer can be regularly measured, so preventive measures can be used as soon as issues are detected.

The lifetime of transformer oil can be lengthened by reclaiming the oil. Reclaiming is a process where the oils original attributes are returned by cleaning. Reclaiming is done for a transformer using MO while the transformer is still in use. Recycling is done to waste transformer oil (WTO), the used oil is cleaned and treated to be reused as transformer oil or to produce other products. Recycling is done at the end of life to reuse the transformer dielectric insulating liquids as transformer dielectric insulating liquids. Reusing is also done at the end of life, but it is downcycling the oil to other products, such as lubricants and fuels. Reclaiming is the only option to use the dielectric insulating liquid in the same transformer for longer.

Most transformers need only one reclaiming in their lifetime, as the effects last 30 years. Reclaiming is currently only being done to transformers using MO and the time of the reclaiming is decided by the results of the oil monitoring. However, transformers operating with low temperatures have longer lifetimes and will need reclaiming done multiple times. The status of the oil is monitored, and based on that an early warning will be given when the properties are “fair” and a stricter warning when they are “poor”. Usually, the first sign for the condition decreasing is the interfacial tension changing or other contaminations, for example silicone or sulphur (L-A. Eriksson, personal conversation, 23.5.2024). This requires regular monitoring, so that the reclaiming can be timed right.

Reclaiming is a complicated process that lengthens the lifetime of both the dielectric insulating liquid and the solid insulation. According to Ghani et al. (2018, pp. 428-433) MOs can be reclaimed while in-service, lengthening the lifetime of the transformer without having to change the oil to new. They note that the reclaiming process also lowers the insulation paper and pressboard aging by removing decomposition products. In the reclaiming process the properties of the oil are regenerated to near the level of a new oil. The IEEE Std 637-1985 (R2007) and BS EN 60422:2013 standards give a guide for the procedure and test methods and the criteria the oil needs to fulfil so it can be used. Reclaiming can be done onsite and without downtime. Safiddine et al. (2017, pp. 2915–2918) found that the most cost-effective reclaiming process is to use both physical and chemical processing. The first step is to separate the water and solid parts by using centrifugal force. After this, the oil is dehydrated in a vacuum, reducing both gas and water content. Removing water raises the breakdown voltage and removing solid particles lowers the acidity. The next step is adsorptive treatment, where the soluble contaminants are adsorbed. The oil is heated and forced through the absorbent. The adsorbent is usually Fuller’s earth, but other adsorbents such as activated alumina, activated Fuller’s earth or activated carbon, or bentonite or membrane can also be used. Adsorption increases the dielectric properties, thermos-oxidative stability, and colour of the oil. Ward (2003, p. 1-2) mentions adding inhibitors to the reclaimed oil to slow down oxidation and other ageing processes. Inhibitors can also be replenished without the reclaiming process to slow down the degrading process. This will not clean the solid insulation, so reclaiming is needed at some point. After this process the properties are nearly the same as for a new oil.

Fuller’s earth is often mentioned as the sorbent used in the reclaiming process. Fuller’s earth is a name that covers a wide range of different sorbents. The name comes from historical context when alumina rich clay was used for reclaiming. The sorbents currently in use can be called diatomaceous clay. Different sorbents have different properties regarding which kind of contaminations they adsorb. Some of the clays can be regenerated, and because of economic and environmental reasons those are more widely used. The regeneration is done by combusting the adsorbed contaminations and some oil adhered to the pores of the clay (L-A. Eriksson, personal conversation, 23.5.2024).

The contaminants in the dielectric insulation liquid can also enhance the degradation of the solid insulation. Ward (2003, pp. 1-1–2-2) explains that if oil is regularly reclaimed, the insulation paper will degrade slower. The treatment does not remove degradation products from the paper, because they are bound to the paper. Even after several days, there are notable amounts of degradation products left bound to the paper, because they migrate slowly back to the oil. However, if the maintenance is done continuously, the moisture, oxygen, acids, and other decomposition products will not accumulate in the oil to the levels where there will be irreversible damage to the paper. This could reduce the risk of dielectric breakdown, which is the cause of 75 % of extra high voltage transformer failures. Reclaiming will lengthen the lifetime of the transformer by removing the contaminants. It is also cheaper than replacing the oil.

4 Land use and biodiversity impacts

Bio-based oils are refined from oil crops, crops that have high oil content either in the plant or the seed. Nytro bio 300X and Cargill FR3 are both bio-based oils. Ahmad et al. (2022, p. 75) explain that growing the crops takes land area and work. The oil crops cannot be eaten if they are used for oil production. This means that growing them takes away land that could be used for food production for either humans or animals, or as a feeding ground for animals. This can lead to rising food prices or lack of food. Water will be needed for the oil crops as well, which can lead to droughts. This raises the need for more field area, which could mean deforestation. The oil crop fields are large monocultures, that lead to biodiversity loss which can bring problems to the insects and animals in the area. The monocultures are also more susceptible for diseases, because one disease can kill of the whole plantation. If there are multiple crops, the same disease might not be able to harm all of them. The oil crops can also be invasive species, harming the original biodiversity. Also, the oil crops take land that could be used for long-term carbon sequestering, for example by using it as forestland, which can even lead to largening the greenhouse emissions. Same can happen if the growing leads to large amounts of biomass burning. The customer needs to be aware of this so they can make mindful decisions when choosing an oil supplier. The customer needs to know what possible issues there are to look for an ethical and environmentally friendly option.

The research here focuses on the oil and biofuel crops more widely, since there is little research done about the crops used for transformer oils specifically. Biofuels and biobased transformer dielectric insulating liquids are not the same thing. They can be refined from some of the same plants, but the refining process and product are not the same, nor can they be used in a similar fashion.

Biofuels are used because when done right, they are carbon neutral. There is growing pressure from government policies to move to more environmentally friendly options than crude oil. The carbon released when burning is the same that the plant has stored in the biomass during photosynthesis. With oils, we can achieve carbon negativity, if the oils are reclaimed or recycled instead of burning when they cannot be used in the transformer anymore.

4.1 Biodiversity loss

There are many ways for a cropland to cause biodiversity loss. Loss of one animal or plant can cause a chain effect leading to loss of many. Verdade (2015, pp. 65–70) found that the spreading of the biofuel cropland leads to loss of habitat to wildlife. That leads to decrease of diversity or population. Using degraded land increases the use of chemicals leading to pollution of land and water, which can lead to decreases of diversity and population. The spreading can also result in use of suspended compounds, that might lead to for example neurotoxic, reprotoxic or carcinogenic effects in both people and wildlife. The biofuel crops can be invasive species to the area, bringing novel diseases to plants and animals. The invasive species can spread wider than the meant field, killing off the local flora. This could lead to altering of ecological communities, changing of the patterns of periodical events, and altering of ecosystem processes, which can lead to further extinctions. They can also have a positive impact. The crops can increase the amount of food for the animals and insects, increasing diversity and populations, if the crop suits the local wildlife. This is negative consequence for the producer, as if the crop is eaten, there is lower production. The plants can also offer cover for animals, thus largening the population. The larger number of rodents and insects then provides food for larger animals. The biofuel production also needs large amounts of water, which can lead to droughts that would be harmful for people and wildlife. These possible problems need to be taken into consideration when choosing what to grow and where.

4.2 Agriculture

The plant grown and where it is grown affects the effects it has. Different crops have different needs for example for pesticides and water. The amount of water to use for the crops before there are problems varies between places. According to Kazmi et al. (2011, pp. 24–31), in 2008 palm oil, soybean oil, rapeseed oil and sunflower oil were the most cultivated oils in the world. Nynas does not state what their biobased Nytro 300X is made of, other than that it is feedstock. Rapeseed, sunflower and palm oil are also used in transformers but not in the ones assessed here. In 2008 Europe was a major rapeseed oil producer and had soybean and sunflower oil production. There is potential for more production, but the growth is determined by prices compared to other crops on rotation, climatic adaptability of the crops, and policies. Rapeseed oil is the most cultivated, as it can be grown in colder climates and has many uses both as a food crop and as an industrial crop. Rapeseed is the most common crop for industry use in Europe, and soybean in the USA, Brazil, and Argentina. According to Kazmi et al. (2011, pp. 24–31), of the soybean production Europe had only 1 %, with North and South America, India and China being the largest producers. Europe had 21.9 % of the sunflower oil production in the world in 2008. Other large producers were Argentina, Russia, and the USA. Sunflower is also a good base for both food production and industrial applications. According to Ritchie (2021) the biggest palm oil producers are Indonesia, and Malaysia. Figure 1 shows the production amounts and land uses for palm, soybean, rapeseed, and sunflower oils in 2020. Climate change, and changing policies and prices as well as more emphasis on environmentally friendly growing can change where and what crops are grown in the future.

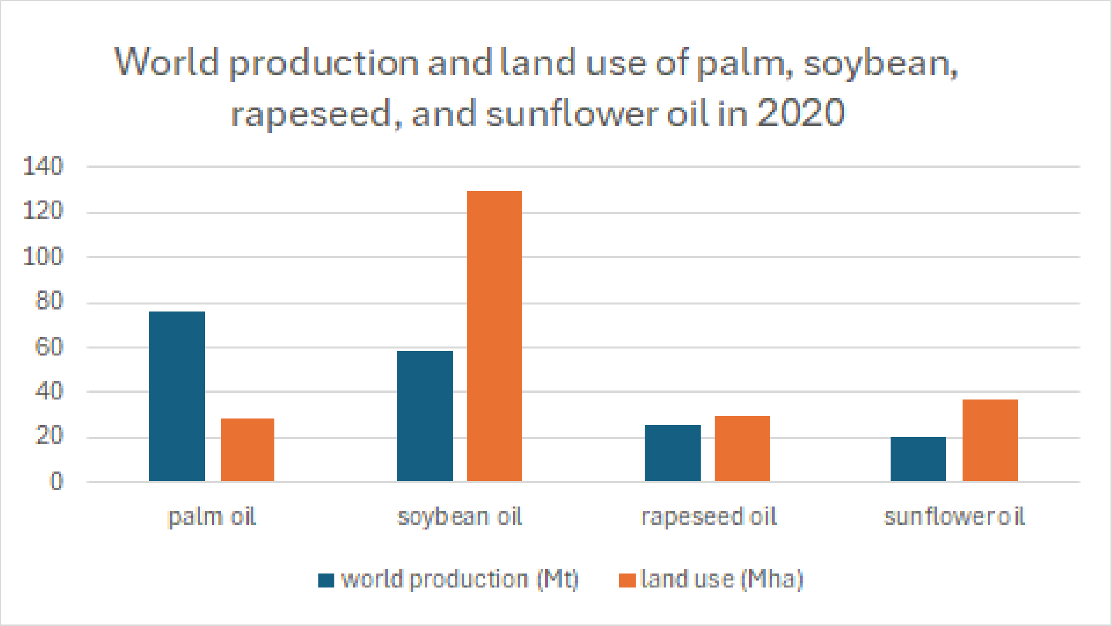

Figure 1. World production and land use of palm, soybean, rapeseed, and sunflower oil in 2020 (Ritchie, 2021).

How much crop can be grown per hectare is an important part when considering the effects. When less land is needed for larger harvest, the effects might be smaller in the end. Ritchie (2021) tells that in 2020 the four most produced oils have stayed the same as in 2010. The total production has grown. Palm oil production has increased the most, about 35 million tons (Mt), soybean 20 Mt, and sunflower and rapeseed about 5 Mt. The land use of soybean cultivation has increased the most with 30 million hectares (Mha), palm second with 10 Mha, and sunflower and rapeseed around 7 Mha. Palm oil takes only 8.6 % of the land used for vegetable oil production but produces 36 % of all the vegetable oil. Soybean takes 39 % of land and produces 25.5 % of oil. Rapeseed takes 12 % of land and produces 11.3 % of oil and sunflower takes 8.3 % and produces 9 %. This means that cultivating palm oil is less harmful from the deforestation point of view, as more oil is produced with less land.

The impact on people is also an important thing to note when considering bio-based oils. Coleman (2023, p. 9) found that the growing of biomass will have economic impacts. The impacts can be positive or negative depending on the level of governance. In a well governed area, agriculture can provide more income, employment, and energy security. If done poorly and not integrated into the existing agriculture, it can lead to loss of income and weaker food security when farmers lose productive farmland. This should be considered when choosing bio-based oil.

4.3 Effect on food crops and water

Growing pressure to produce bio-based oils can lead to crops used more for that and less for food. This can lead to weakening food security. Kazmi et al. (2011, p. 30) point to Carlsson's and Golbitz's works that state that soy is the most grown seed oil crop, 53 % of the production in the world. It has 50-60 % protein, making it an important food crop. In 1999, 95 % of all soybean oil produced in the USA was used for food. In 2009 85 % was used for food, and the rest for industrial applications. In Europe 55 % was used for food and the rest for industry. However, global production is expected to grow, so the production has just moved to other places, mainly South America, India, and China. Food security needs to be taken into consideration when producing more bio-based oils.

The crops will need watering, which can mean too little water for other uses. Coleman (2023, p. 9) found that oil crop production can affect water resources and quality both positively and negatively. The effect depends on local freshwater reserves, competition for water and the quality of water needed. Perennial oil crops can restore degraded lands to have better water retention and perspiration. The crops will also need fertilizers and pesticides, which both can have runoff that damages water quality. Growing one crop should not be done on the cost of causing drought in the area, so water is an important consideration.

4.4 Deforestation

Deforestation has different effects on global temperatures depending on where it is happening. Longobardi et al. (2016, pp. 3–23) modelled deforestation with the University of Victoria Earth System Climate Model. They found that the deforestation causes cooling of the surface air globally when deforestation happens in high or mid latitudes. The input of CO_2 causes some warming first, but albedo effects overcome that when deforestation happens in high or mid latitudes. If the deforestation happens in low latitudes, the albedo effect is not enough to get the temperatures negative and temperatures warm globally. Deforestation at higher latitudes caused more cooling, because of snow. Soil temperature lowers globally but increases in the deforested areas, for high and mid latitudes. Again, for low latitudes the deforestation leads to higher soil temperatures. The deforestation causes drying both locally and globally, but local drying is larger. In mid latitudes in areas of warming and cooling soil temperatures, conditions get wetter. In low latitudes some areas in Africa and Amazon get wetter. In all latitudes atmospheric CO_2 content increases with deforestation. In high latitudes as the deforestation rate increases, the CO_2 bonds into the soil. In mid latitudes the soil carbon increases as well, but less than in high latitudes. The warmer soil temperatures lead to losses of soil carbon leading to higher average CO_2 in the less deforested scenarios. In low latitudes the soil releases the CO_2 more than in mid latitudes, leading to increased average CO_2 levels in all scenarios. This means that the latitude of the field is very important when considering global warming.

The growth of production does not necessarily mean growing effects on the environment. Vijay et al. (2016, pp. 7–12) found that palm oil production led to deforestation in Asia, South America, Africa, and Central America. The increase of palm oil production did not however indicate the increase of deforestation. In Mesoamerica and Africa there was little to no deforestation, although the palm oil plantation areas grew. In Asia and South America, palm oil production and deforestation grew more together. There are wide differences between countries in the regions. Vijay et al. predict more deforestation in the future and note that monitoring needs to be increased.

5 Environmental and safety priorities

Environmental considerations are an important part of all technology nowadays. Transformers are no exception to this. Transformers are filled with dielectric insulating liquid, which is harmful to the environment if there is a leakage, no matter what it is made of. The liquids can be toxic if indigested or harmful to plants, they can contaminate water and soil, and they can be suffocating in aquatic environments. The oil also burns well, making it a fire hazard if the temperature gets too high because of internal malfunction or outside accidents. Because of these minimizing leakages is very important as is cleaning in case a leakage happens.

5.1 Leakages

Leakages can be dangerous to the environment and people because of toxicity and soil contamination. All oils must be cleaned after spillage, whether they are toxic or not. Módenes et al. (2018, pp. 312–313) point out that even non-toxic biodegradable oils can do much damage by smothering organisms and reducing oxygen exchange because of their smothering properties. This can even make them more dangerous than mineral oil in aquatic environments. Toxic oils pose a danger to the environment by killing flora and fauna. It is important to focus on minimising the number of leaks, and to use oils that are less harmful in case of a leak.

The cleaning process has many steps and varies depending on the liquid and where the spill happens. Adesola et al. (2016, p. 103) reviewed oil spill cleaning methods. The first action is to minimize the amount of oil spills. This does not mean that there are no spills. For the spills there needs to be an efficient clean-up protocol, so that the effects on the environment can be minimized. Cleaning is achieved by mechanically controlling the spreading of the oil by using booms, barriers and recovering it with skimmers and sorbent materials. Biological gelling and dispersing agents can also be used for this. Módenes et al. (2018, p. 316) explain that for biodegradable oils, after the mechanical clean up a biodegradation process can be used to speed up the cleaning process. It is also important to prevent animals getting to the oil as much as possible (Bucas & Saliot, 2002). The plan for the cleaning is done for a specific case when the spread, area and oil are known.

Of the oils chosen for assessment, the mineral oil and recycled oils are toxic meaning that ingesting them is harmful. The other oils are non-toxic. This does not mean that they are safe for the environment. If digested, MO can lead to skin issues, change in blood cell count, organ function and cancer in animals, and has also been shown to lead to cancer in humans (Otunga et al., 2019). The MO will also contaminate the soil and groundwater and other waters if it gets to them. NEs without additives were found not to be toxic to living organisms (Jacob et al., 2019, p. 3). The ionization potential additives used for enhancing lighting impulse breakdown potential are highly toxic to humans and the environment, so non-toxic alternatives should be formulated (Ghani et al., 2017, pp. 661–662). The toxicity information of the transformer dielectric insulating liquids chosen for assessment can be found in Table 3. Nynas and Starke & Sohn do not state the toxicity, so they have been left out of the table. The toxicity is an important property when choosing which dielectric insulating liquid to use.

Table 3. Toxicity of the transformer dielectric liquids.

Transformer dielectric insulating liquid	**Toxicity**
Midel 7131	Low oral, dermal and inhalation toxicity, does not irritate skin or eyes, is not an aspiration hazard and in case of fire produces non-toxic smoke (Safety Data Sheet, 2024)
Shell Diala S4 ZX-I	Not acutely toxic ingested, breathed or through skin contact (KÄYTTÖTURVALLISUUSTIEDOTE, 2021)
Cargill FR3	Non-toxic in soil, water and orally (Safer and better for the planet, 2024)

Soil contamination is one possibility in case of a leak. Tiwari et al. (2023, pp. 307-308) reviewed soil contamination by transformer oils. They state that mineral oil-based transformer oils contain hydrocarbons, such as polycyclic aromatic hydrocarbons (PAH) and polychlorinated biphenyls (PCB), heavy metals, and additives which can all contaminate soil and water. PCBs are banned, as they bioaccumulate, but they are still found in old transformers. PAHs were found to contaminate the soil and lower the soil pH and increase organic carbon levels thus affecting the microbiota in the soil. This then contaminates the flora, which can affect humans or animals eating the plants. The higher organic content of the contaminated soil also increases the amount of heavy metals by immobilizing them. The levels of metals were found to be above the limits, so they pollute the soil. This can then lead to plants and water being harmful after contamination. The oil needs to be cleaned from the polluted site as fast and well as possible to minimize these effects.

Vegetable oils are not necessarily safer in the environment than mineral oil. Módenes et al. (2018, p. 316) explain that vegetable oil has good coating properties. Because of this, it can be more dangerous to marine life than mineral oil. The oil can be on the surface or emulsified in the water, and cause suffocation or clogging of the digestive tract in fauna living near or on the surface. In addition, it can cause oxygen depletion and form non-degradable polymers. Bucas and Saliot (2002, pp. 1391–1392) state that the polymers can then lead to suffocation of bottom dwellers, by forming a cap over the surface. The spills can also be dangerous to birds, by affecting their feathers so they drown or freeze, forcing them to take time to clean and thus be vulnerable to predators. Spills can suffocate birds or lead to starvation. It is assumed that vegetable oil is more dangerous, because it is colourless and almost odourless, so it is harder for animals to notice. The biodegradability does prevent the oil from contaminating the soil and lessens the effects on water, as the oil will break down faster (Soni & Mehta, 2023). Biodegradable and bio-based oils need to also be cleaned from the environment as best possible.

5.2 Biodegradability potential during the life of the transformer

Biodegradability is defined by the European Environment agency to mean that a material is “capable of decomposing rapidly by microorganisms under natural conditions” (EEA, n.d.). The speed of the decomposition is the definitive point. Aluory and Ori-jesu (2009, p. 918) note that all materials start to degrade in the environment, but the biodegradable ones break down faster. They say that there are various methods for testing biodegradability depending on what parameters are chosen for assessment. The tests include for example measuring the amount of CO_2 or methane produced, the loss of organic carbon in water soluble oils, the loss of hydrocarbon infrared bands and uptake of oxygen.

Of the oils chosen for assessment Nytro bio 300X, Midel 7131, and Cargil FR3 are biodegradable. Aluyor and Ori-jesu (2009, p. 918) explain biodegradability. Biodegradation can be separated into two main types. In primary biodegradation, microorganisms make measurable changes to the substance, while the molecules stay unchanged. This can result in toxic products, so this is avoided as much as possible. Secondary biodegradation is mineralization, where the substance is changed completely by microorganisms, and carbon dioxide, methane, water, mineral salts, and new microbial cellular constituents are produced. The suppliers only mention the oils being biodegradable, so it is not known whether it is primary or secondary biodegradability.

5.3 Fire hazards and regulations

Flash point and fire point are important properties to know when considering fire safety. Flash point is the temperature at which the vapours from the oil will flash when exposed to an open flame. Fire point is the temperature where the oil will stay burning for at least five seconds after being exposed to an open flame. Srivastava et al. (2021, pp. 2853) state that both SE and NE have higher flash point and fire point than MO. Flash point is 250-270°C for SE and 315-328°C for NE, compared to 100-170°C for MO. Fire point is over 300°C for both SE and NE compared to 110-185°C for MO. Saikkonen states in Laakso’s (2022) article, that when ester is used as insulation oil, there is much less need for fire protections. No protective walls or fire extinguishing systems need to be implemented, and the shielding pool can be smaller. This is because ester oils are practically non-combustible because of the higher flash point. This comes from the FM Global standards (2023, pp. 20–26), where the protections are allowed to be smaller regardless the amount of oil in the transformer for an approved oil. In FM Approval 6933 (2020) it is stated that approved oil must have an average fire point of at least 300°C and the fire point must be higher than the boiling point. Insurance companies do still require the protections, so they often must be built even if the standard allows fewer measures.

In case of a fire, the conditions will affect the burning. Jun et al. (2022, pp. 4–10) experimented with transformer oil burning in different conditions. In open space, the oil thickness increased the flame height when moving from 0.5 cm to 1 cm, but not when moving from 1 cm to 2 cm. Jun et al. (2022, pp. 4–10) refer to research done by Suo-Anttila et al. and Vali et al., saying that when the oil thickness is beyond a critical value, it can be seen as infinitely deep because of an isothermal layer forming below the oil surface. Flame height increases when temperature increases. This is because the higher initial temperature enhances the combustion reaction. The fuel burns longer the deeper the layer is. Mass loss rate increases when thickness increases to 1 cm, but not beyond that. The mass loss rate for all thicknesses drops as the amount of oil drops until all the oil is burned. The initial temperature does not affect the mass loss rate much, higher temperatures have a bit higher rate. Fire plume temperature increases when oil thickness or temperature increases. The plume temperature decreases when the flame height rises from the oil surface. In confined space the flame increases rapidly after ignition, then stabilizes to a lower height. Temperature rises when the chamber diameter increases. The temperature lowers as the flame height rises. This needs to be considered when creating the fire protection.

There are different reasons that cause transformer fire. Pompili et al. (2019, pp. 21–22) state that the typical cause for a transformer fire is the internal temperature rising because of an electric arc or other external causes. There is no oxygen inside of the transformer, but temperature and pressure rise when an electric arc happens, meaning the tank can rupture or explode. This can result in an oil leak and fire. They state that in large transformers, the risk for a serious fire is 10^{-2} globally according to the International Council on Large Electric Systems (CIGRE) TB 537 Brochure, other companies have calculated it higher or lower.

6 End-of-life scenarios

It is important that there are ways to minimize the waste and to reuse what ends up as waste. In this chapter, some ways for those are explored. For many practises there is not research specifically for transformer oil, but the research focuses on all waste oils. This means that there are no specific numerical values for transformer oils. Recycling happens at the end of life when the product is recycled back to the original use. Reusing means downcycling the product at the end of life, for example to a lubricating oil. The focus should be on circular economy and recycling to minimize waste and environmental impacts.

6.1 Circular potential

We should move more towards a circular economy from a linear economy. Amsen (2022) explains the difference between linear and circular economy is how waste is handled. In a linear economy, we refine resources, use them and then they end up as waste that is discarded. In a circular economy, the waste is then re-refined back to a usable product, ideally to the same product that it was before. Recycling is a part of a circular economy. When recycling, the material always deteriorates and cannot be reused infinitely. Whereas in a circular economy the focus is to reuse the material without degrading it. Recycling methods should be improved so the material ideally would degrade minimally or not at all.

Reclaiming is also a part of a circular economy. Reclaiming is done while the transformer is still in use and can currently only be done to MO. The reclaiming process is complicated. Because of this, especially many smaller companies just change the oil to new when servicing the transformer. The WTO can at the end of life be recycled to other products or back to transformer oil. All the dielectric insulation liquids chosen for assessment here can be recycled. It is not mentioned what they are recycled to. Nytro RR 900X and Starke & Sohn recycled oil are recycled transformer oils. Nynas and Starke & Sohn are using circular economy, as old transformer oils are re-refined to be used again as transformer oil.

There are different ways to re-refine the WTO. Starke & Sohn (Rescue the molecules MSR-Technolgy: StaSo®, n.d. -b) use a Multiple-Selective-Refining (MSR) technology, in which the WTO is re-refined to base oil, spindle oil or transformer oil. The oil is first heated, and then solid particles are mechanically separated. After this water, gases and low boiling pollutants are removed in thermal vacuum separation. Then activated reagents and catalytic activated adsorbents are used to remove the rest of soluble contaminants. The oil is then ready for use as ground oil or spindle oil, additives and further blending can be used as needed. The oil can also be further processed to decolouring and chemical or physical sorption to be used as MSR base oil. Here it is again possible to add additives or blending if needed. For transformer oil there is still catalytic exhaust treatment, additives for inhibition and degassing before it is ready for use. Different companies use different procedures.

6.2 Regulation on transportation of used oils

The regulations on collection and transportation differ between countries. In Directive 2008/98/EC of the European parliament and of the council (2008, Article 21) it is stated that EU member states should collect waste oils, not mixing them with other waste or material and prioritize regenerating or otherwise recycling them to be reused. In addition to this, the member states have their own regulation on how the oil should be collected, stored, and handled.

Haavisto et al. (2018, pp. 17–27) notes that in Finland, waste oil is considered hazardous waste, meaning that transporting and collecting it needs permission from the Ministry of the Environment. Municipalities are required to organise a collection for small amounts of oil from households and companies are responsible for the waste they produce. The company needs to collect different oils separately and mark the containers accordingly. The company is responsible that the collector has the needed permissions for transporting the oil and that the needed paperwork, including information on the type, amount, origin, date, and driver. The oil will then be regenerated if possible or used as a fuel in energy production. Lassila & Tikanoja Oyj is responsible for organizing the recycling for the collectors, but the user can also deliver the oil to another party that has the needed permissions. There are regeneration and energy production plants in Finland.

6.3 Reusing potential

Recycling is an important part of lessening the environmental impact of transformer dielectric liquids. By recycling, the same oil will be used in one form or other multiple times, instead of just disposing it as hazardous waste or burning it. WTO, except for GTL can be recycled to be used again in a transformer, or for example as a fuel for diesel engines, as a base for lubricating oil, or to produce hydrogen fuel and carbon black.

WTO can be used in diesel engines, either just as it is or as a mixture with diesel. Belkhode et al. (2022) note that WTO has higher viscosity, even 5 times higher, than what diesel used in engines should have. The higher viscosity affects the fuel atomization and mixing with air, meaning that the fuel cannot be used as efficiently. Yadav and Saravanan (2015) explain that for this reason, the WTO can also be treated to lower the viscosity. The WTO is first filtered to get rid of sludge and other undesirable material, that has mixed into the oil during the lifetime of the transformer. Then it can be re-refined for example by distillation, transesterification, or catalytic cracking.

Transformer oil can be used as a base oil for creating lubricating oils. Japar et al. (2019) mention fumed silica grease as one option for reusing. Fumed silica grease is a lubrication grease where fumed silica is used as a thickener. Other thickeners than fumed silica can be used. The WTO must be pre-treated before use. First the water is removed from the WTO by use of gravity. The oil is left to settle, and the water sets to the bottom. After this, solid particles are removed by vacuum filtering. Leftover moisture and volatile components are removed through evaporation by heating the oil to 120 °C for 2 hours. The oil is then cooled for storing. The grease is formed by heating the oil to 80-90 °C and then adding the thickener and possible additives. It is then homogenized to disperse these. After cooling the grease is ready to use. The properties of the WTO based grease are according to the ASTM International standards for oil and grease.

One option for recycling is pyrolysis. Lam et al. (2016, pp. 744–750) explain that in pyrolysis the material is heated to high temperature in an oxygen depleted environment, where it decomposes. The usual way to do the pyrolysis is an electrical-heated pyrolysis. This means that the oil is heated with an external heater. The heater also heats all the other substances in the heating chamber and heat is distributed unevenly. This is not energy efficient and produces PAHs, bigger amounts of char and the oil has more heavy PAHs in it. This means that the products must be treated before using, to not be toxic. The products also vary as the uneven heating leads to different results. The pyrolysis can also be done using electric arc heating, where the oil is heated by a momentary electric discharge to 1300-1500 °C. Microwave heating is also an option. There the heat is generated in the oil with an electromagnetic wave. Therefore, the heat is more evenly distributed and more energy efficient than with the electrical heating. Microwave pyrolysis produces more energy than it uses with net energy output of 179,390 kJ/h. There is no consensus on what the main products are as they vary based on the conditions and methods. The products include hydrocarbon oils, gases, and char as well as energy. The products can then be used, for example the hydrogen gases to produce hydrogen fuel and char in place of carbon black.

6.4 Incineration

If the oil cannot be re-refined to be reused for example because of different oils being mixed, it can be used for energy production (Haavisto et al., 2018). Using specifically WTO in energy production has not been researched, so here the focus is on all waste oil from the industry. This includes for example lubrication oils, heat transfer fluids and cooking oils as well as WTO. (Lam et al., 2016).

In incineration the oil is burned, and the energy is retained. This is the last option, as only the calorific value can be retained, and the oil cannot be reused after this. Burning also forms CO_2 and other greenhouse gases as well as releases the toxic components the oil has (Lam & Chase, 2012). In transformer oils this includes heavy metals, PAHs, and PCBs (Tiwari et al., 2023). To prevent this, the flue gases need to be cleaned, which can be complex and expensive (Lam & Chase, 2012). According to the United States Environmental Protection Agency, (EPA, 1996) fuel oil boilers can be used to burn waste oil without modification. Fuel oil can be added to the waste oil for cleaner burning. The oil can also be treated before the burning to reduce the hazardous components and improve combustion efficiency. The treatment methods are the same as when recycling the oil. The pre-treatment increases the cost of the procedure, meaning that they are not used that widely, mostly only filtration is used. The method used depends on the local emission regulations.

7 Discussion

There are many advantages and disadvantages for all the dielectric insulating liquids. They and the different end-of-life scenarios available for each are collected to Table 4. For the bio-based hydrocarbon and natural ester, the way in which the crops are grown is also an important point to take into consideration when making a choice. That is not included in the table, as it is different for different producers and can either be an advantage or disadvantage.

Table 4. The advantages, disadvantages and end-of-life scenarios of the dielectric insulating liquids.

Dielectric insulating liquid	**Advantages**	**Disadvantages**	**End-of-life scenarios**
Mineral oil	-reclaimable -well researched -recyclable	-made from crude oil -not biodegradable	-recycling -downcycling -incineration
Bio based hydrocarbon	-biodegradable -recyclable	-not currently reclaimable	-recycling -downcycling -incineration
Recycled oil	-reclaimable if made from recycled mineral oil -made from recycled oil -recyclable	-not biodegradable	-recycling -downcycling -incineration
Synthetic ester	-biodegradable -not toxic -high flashpoint -recyclable	-not currently reclaimable	-recycling -downcycling -incineration

Dielectric insulating liquid	**Advantages**	**Disadvantages**	**End-of-life scenarios**
Gas to liquid	-low acidity -not toxic -noncorrosive	-not biodegradable -not currently reclaimable -not recyclable	-incineration
Natural ester	-biodegradable -not toxic -high flashpoint -recyclable	-not currently reclaimable	-recycling -downcycling -incineration

8 Conclusions

This thesis has shown that there are both advantages and disadvantages for all of the investigated dielectric insulating liquids, and none of them can be stated the best or worst for all applications. The uses vary and so does the best option for the specific project. The information collected here can be used to make the best choice for each case.

The end-of-life scenarios are mostly the same for all dielectric insulating liquids. Reuse and recycle rates are also not available. These are also aspects that should be considered when choosing what dielectric insulating liquid to use, so there needs to be to be more research.

9 Summary

The objective of the thesis was to find differences in the properties of the different dielectric insulating liquids. The information was collected based on a literature review. The aim was not to find a single best option, but to collect the differences.

For the operational lifetime the focus was first on the different failure modes of a transformer and moisture ingress in the dielectric insulating liquid. It was found that even 2 % moisture increase in the solid insulation will reduce the lifetime, so dehydrating the dielectric insulating liquid is important. Then the service and maintenance activities of the whole transformer and reclaiming potential of MO were explained. Reclaiming is usually done only once during the lifetime of a transformer and will lengthen the lifetime of MO as well as the solid insulation. Finally, oxidation of different SEs, and MO were compared. The sludge formation and iron and sulphur content were found to rise most in MO, acidic value, viscosity and copper content in the SEs.

The environmental impacts evaluation started with going through the impacts growing crops for bio-based oils has on land use and biodiversity. From this it should be noted that the effects vary based on what is grown, where and is the local agriculture taken into consideration. Then leakages and toxicity were explored. It was discovered that non-toxicity and biodegradability do not mean that the dielectric insulating liquid is safe in case it leaks to environment. Instead, there are different effects with different oils, but all should be cleaned as fast and effectively as possible. Last was reviewing the different end-of-life scenarios. Re-refining the WTO to transformer oil, different reusing options such as lubrication oil, fuel for diesel engines and pyrolysis were explored. Incineration was noted as the final solution.

The thesis concluded with a table showing the advantages and disadvantages of the different dielectric insulating liquids as well as the different end-of-life scenarios.

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