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Cost-Benefit Analysis of Maintenance Measures for Power Transformers

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Submission date: June 2017
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Problem Description

A power transformer is one of the most important components in the power grid and is essential to maintain a steady and reliable power supply. It is also a very expensive component, making it extremely important to preserve the condition at a high level. This is done through different maintenance measures to avoid huge reinvestment costs. Maintenance measures vary in costs and how effective they are towards improving the condition, and for an asset manager it can be difficult to decide what measure that would provide the best cost-benefit for the company in different cases.

To make this decision-making process easier, different maintenance measures carried out on power transformers in Norway the last decades are going to be studied in this thesis. The objective is to expose what maintenance actions the companies normally have preferred, but also try to estimate the improvements that could be expected for each of the oil and gas parameters from different maintenance measures.

These results could be used as input to study the cost-benefit of different measures for the transformer in the proposed model from “Trafotiltak”.

The main tasks going to be performed in this master thesis are:

- Identify the most common maintenance measures used to improve the condition on power transformers in Norway, with focus on improving the transformer oil.
- Study the different oil and gas parameters from transformers service data that can be used to evaluate the condition of each transformer.
- Collect service data from power transformers that have experienced maintenance measures in the Norwegian market. From these documents sort out the useful data and use this to calculate the condition before and after the measures are conducted, using the health indexing model described in “Trafotiltak”.
- Use the historic condition improvements to estimate improvements for each measure that could be used to calculate the cost-benefit of different measures.
- Test the performance of the cost-benefit model from “Trafotiltak” through case studies on real transformers in the need of an upgrade in their condition.

Preface

This thesis is the result after the final semester of the master's degree in Electrical Power Engineering at the Norwegian University of Science and Technology (NTNU). The thesis was written in cooperation with SINTEF Energy Research and has been supervised by Eivind Solvang. The work for the thesis was conducted during the spring semester of 2017.

The thesis was conducted as a part of an ongoing science-project at SINTEF, called "Trafotiltak". The project has the aim to create a user-friendly decision-making tool for transformers, that can be used to support asset-management decisions when selecting maintenance measures.

I would like to use this opportunity to thank my co-supervisors, Jørn Foros and Maren Istad at SINTEF Energy, in addition to Eivind Solvang at NTNU and SINTEF Energy, for help and support during the last months of work. I am grateful to them for letting me be part of the project team and letting me write this interesting master thesis.

I would further like to thank the power companies in the project for contributing with service data from hundreds of their power transformers, making it possible to do a comprehensive analysis in this thesis. At last a thank you to Beate Rønneberg for proofreading the thesis.

Trondheim 08.06.2017

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Abstract

The work described in this thesis was conducted in cooperation with SINTEF Energy Research and their collaborating partners in the research project "Trafotiltak". The objective of the project is to develop a decision-making tool, based on both economic and technical data, to support asset management maintenance decisions on Norwegian power transformers.

Deciding when to perform reinvestments and finding the right type of maintenance action that creates the most benefit is challenging. Therefore, this thesis explores the different maintenance measures available for improving the condition of mineral oil within the transformer. To analyse the performance of different measures, service data from power transformers owned by Norwegian companies, collaborating in the project, were collected. The condition of each transformer was calculated by using a health index score, shorted HI-score. This score allows the asset manager to quickly compare power transformers against each other and find the transformers with the greatest need of improvements. This data acquisition of the condition improvements from previous cases helps create a statistical overview on benefits gained from different measures, and could be used as the input in a cost-benefit analysis between different maintenance measures.

The thesis has determined the estimated improvements for a standard reclamation of oil through the data acquisition, where also some of the other measures described in this thesis are included in the process. Due to lack of data from stand-alone measures e.g. recondition, oil change and drying of oil/paper it was not possible to make a corresponding statistical summary of expected improvements for other measures than reclamation of oil.

To test the performance of the proposed "Trafotiltak" model and especially the cost-benefit model included in "Trafotiltak", it was applied to two real power transformers in the need of condition improvements. By doing this it could calculate when maintenance was most beneficial and if reclamation of oil was a better alternative than to reinvest in a new transformer. The estimated improvements from reclamation found in this thesis are used as the benefit for the reclamation process in the model. The results from the case studies show that the model could give reasonable suggestions on which measure to choose and when measures should be performed. Even though the cost estimates and HI-scores that have been used are a little rough, they are still reliable and an indication that the model could be used in the industry to examine different maintenance alternatives.

Sammendrag

Arbeidet som er beskrevet i denne masteroppgaven er utført i samarbeid med SINTEF Energi og deres samarbeidspartnere i forskningsprosjektet" Trafotiltak". Målet i dette prosjektet er å utvikle et beslutningsverktøy, basert på både økonomiske og tekniske data, for å bistå og støtte opp om beslutninger angående ressursbruken til bedrifter som forvalter norske krafttransformatorer.

Å bestemme når en skal gjennomføre reinvesteringer og hvilken type vedlikeholdstiltak som vil være best for transformatoren kan være en vanskelig jobb. Derfor vil denne rapporten studere de ulike vedlikeholdstiltakene for å forbedre tilstanden til mineraloljen inni transformatoren. For å sjekke forbedringen av ulike tiltak ble det i denne oppgaven samlet inn oljedata fra transformatorer samlet inn fra de deltagende bedriftene i "Trafotiltak"-prosjektet. Tilstanden for hver trafo er beregnet med å bruke en helseindeks karakter, forkortet HI-karakter. Dette gjør det mulig for bedriften å raskt sammenligne trafoene sine mot hverandre og finne de enhetene som har størst behov for en forbedring. Denne datainnsamlingen av tilstandsforbedring fra tidligere tiltak hjelper til å danne et godt statistisk grunnlag av forbedringspotensial for ulike tiltak, som kan bli brukt til å regne på kost-nytte verdier av ulike tiltaksalternativer.

I oppgaven har en igjennom datainnsamlingen funnet estimerte forbedringer for en standard regenerering av olje, hvor også andre tiltak som er beskrevet i oppgaven er inkludert i prosessen. På grunn av manglende data i underlag fra deltagende bedrifter for andre enkeltstående tiltak som avgassing, oljeskift og tørking av enten olje/papir så var det ikke mulig å lage en tilsvarende oversikt av forbedring for disse tiltakene.

For å prøve ut den foreslåtte "Trafotiltak" modellen, og spesielt kost-nytte modellen inkludert i "Trafotiltak", så ble to ulike transformatorer med reelle gass- og oljemålinger testet. Ved å gjøre dette vil en kunne sjekke når vedlikehold var mest gunstig og om regenerering er et bedre alternativ enn å investere i en ny krafttransformator. De estimerte forbedringene fra regenerering som ble funnet i denne oppgaven ble brukt i analysen som nytte-bidraget for regenereringen. Resultatet fra casestudiene viser at modellen kan gi fornuftige råd angående valg av tiltak og når dette bør gjennomføres. Selv om estimat av kostnader og HI-karakter som er brukt her er litt grove, så er de likevel pålitelige og gir en indikasjon på at modellen kan bli brukt i industrien for å vurdere effekten av ulike vedlikeholdstiltak.

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Abbreviations

BDV	Breakdown Voltage
CBA	Cost-Benefit Analysis
CDF	Cumulative Distribution Function
CENS	Cost of Energy Not Supplied
CIGRE	International Council on Large Electric Systems
DDF	Dielectric Dissipation Factor
DGA	Dissolved Gas Analysis
DP	Degree of Polymerization
HI	Health Index
HV	High Voltage
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers.
IFT	Interfacial Tension
O&M	Operation and Maintenance
PDF	Probability Density Function

Definitions and Explanations

Aldehydes	“Dehydrogenate alcohol”. Chemical compounds containing the functional group –CHO. They are created as an intermediate product during oxidation of alcohols.
Bleaching Earth	Also called Fullers Earth. An aluminium-oxide found naturally in the nature, and later treated industrially to get the wanted qualities.
Hydrocarbons	Compounds only consisting of hydrogen and carbon.
Inhibitor	Additive in oil reducing and slowing down oxidations processes.
Kerosene	Also known as paraffin, is a colourless liquid. It is extracted from hydrocarbons from crude oil.
Ketones	Organically compound containing the functional group R-CO-R´. Here R and R´ are remnants from hydrocarbons. Oxidation product from secondary alcohols.
NPV	Net Present Value. NPV are used when analysing the profitability of different maintenance and reinvestment projects.
Passivator	Additive in oil reducing the development of corrosive reactions between the oil and metals.
Reactivating	The process that cleans the filter during reclaiming when the filter is no longer able to absorb more residual products and particles.
Reclaiming	Oil treatment used as a maintenance measure and consists of a chemical and physical process removing particles, ageing products, sludge, acid compounds and degassing/dehumidify the oil.
Recondition	Oil treatment used as a maintenance measure to degas and dry the oil.

1 Introduction

This thesis will study different measures used to improve the condition of the insulation materials in a power transformer. The purpose is to identify different practices on when measures are conducted, what parameters are improved by the different measures and the improvements on the transformer condition gained from each measure. The results provided in this thesis could be used in a reinvestment analysis or when planning different maintenance strategies on power transformers in a cost-benefit tool.

The work conducted in this paper was prepared and worked out in cooperation with SINTEF Energy and their on-going research project “Trafotiltak”. The main objective with “Trafotiltak” is to create a user-friendly decision tool that combines statistical data with condition data from oil samples and ageing of paper, and uses this data to carry out an extensive analysis of the overall condition of the power transformer. By combining both economic and technical data “Trafotiltak” believes the best overall decision can be taken every time and avoid that asset managers will only see either the economical or the technical side of the situation. The model has the intention to help transformer owners to do the right decisions regarding operation and maintenance management in a more effective way than before, without the need of unlimited amounts of service data. The result from the model can support the asset managers and backup their decisions by showing they have taken a weighted evaluation based on several data inputs [1].

1.1 Background

The Norwegian transformer fleet is slowly getting older, and the average age of the power transformers are approaching their anticipated lifetime of around 30-40 years, decided by manufacturers of the different transformers during production. From a survey conducted by Statnett on 2800 different power transformers in 2012 [2] it was shown that the average age was around 30 years, as seen in Figure 1.1. 50% of the transformers were above the average age, while 27% were over 40 years old. Since power transformers are vital to maintain a secure and reliable power supply for the grid it is important to make sure they stay in this good condition and not experiencing any breakdowns. When a high share of the transformers has reached their “expected lifetime” the right measures and decisions needs be taken to try to extend the lifetime and postpone some of the reinvestments costs in the Norwegian power grid.

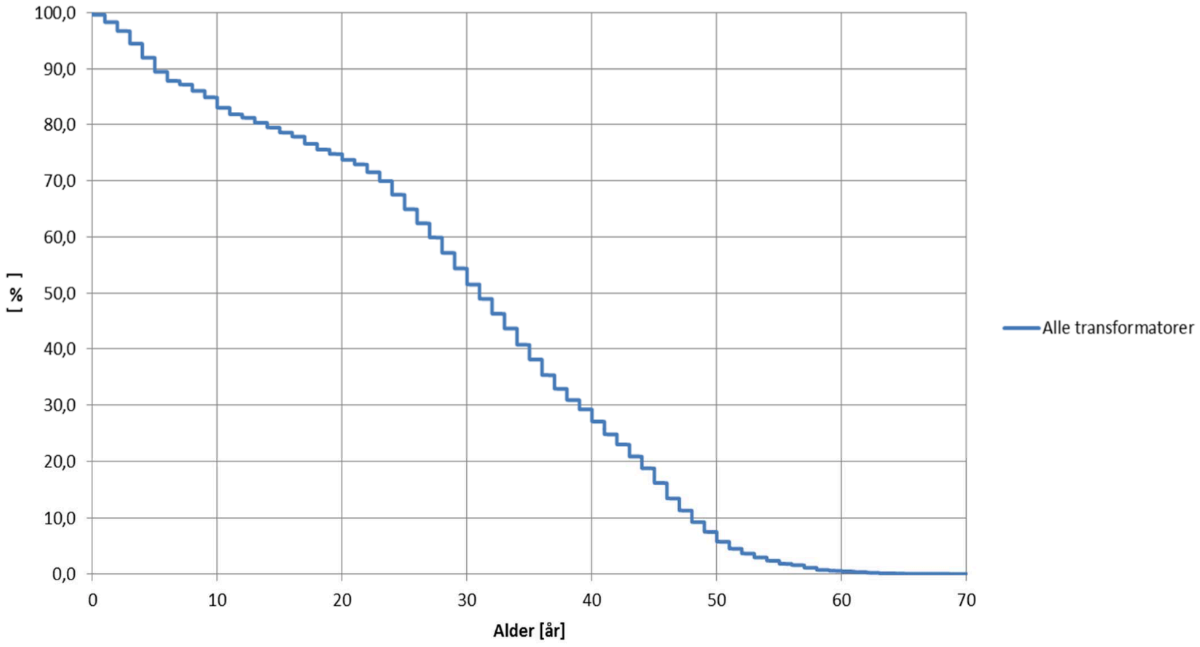

Figure 1.1: *Age distribution of Norwegian power transformers according to [2].*

New power transformers provide a considerable expense as they are the most expensive component in the power system. A potential defect on a power transformer could turn out to be a costly affair, and with expected delivery time of several months for a new transformer, it could result in enormous expenses for the owners. In addition to high reinvestment cost for power transformers, maintenance measures are generally also very expensive. A power transformer is a closed box where many of the most vulnerable components with the highest need of maintenance, are difficult to gain access to. This does not only make maintenance on power transformer a problematic task, but deciding on when maintenance and reinvestment are necessary are also difficult to predict. To help the asset managers, health indices could be created to calculate the condition of the transformers based on service data. Models like this should be useable for Norwegian transformers, and should not require a lot of input data and be very complicated. Also, many of the proposed models on the market requires data that are in some cases not measured for power transformers in Norway on a general basis. This makes the models a little deceptive regarding maintenance decisions and could turn out to not be usable for all the transformers in the power grid.

The ageing transformer population in addition to the lack of a maintenance decision tool directed towards available service data from Norwegian power transformers lead to inquiries to make this tool. Hence, SINTEF Energy created the project “Trafotiltak” in cooperation with several of the big power companies in the Norwegian power grid. The main objective with the project was to collect all available information about the power transformers and their operation, and from this create a tool that could compare the condition of different transformers and give the best advice on what to do regarding maintenance.

One of the objectives in the “Trafotiltak”-project was to evaluate the benefit of different maintenance measures, and this was the reason behind creating this thesis. In this thesis, the most common maintenance measures available for improving the condition of a power transformers are studied more closely. The objective is to analyse the maintenance measures that have been conducted to improve the condition of transformers the last 20-30 years in Norway. This could reveal the benefit that each measure provides for the transformer, and makes it possible to map what parameters are getting improved by each different measure. The result from this statistical analysis could be used as an estimation for the benefit part in the cost-benefit model created in “Trafotiltak”. By the basis for the benefit means that the results from the analysis cannot be used directly in the model, but this thesis illustrates how the improvements can be used to calculate the cost-benefit in the model. This is illustrated by case studies later in this thesis. The proposed model in the “Trafotiltak” project is described in detail in chapter 3.

1.2 Working Method

To try and answer some of the questions in this thesis a systematic literature study was first conducted to get an extensive overview of the different alternatives when planning to improve the condition of a transformer. Here relevant maintenance measures and transformer components were studied, together with the oil and gas parameters that gets measured during standard oil sampling to decide the condition of the transformer. Both Norwegian and international sources were reviewed to get as much information as possible about potential solutions, but at the same time ensure that the interest of studying Norwegian conditions was kept as the main priority. Theory from the topics mentioned above was compiled and processed into a summary in this thesis based on several different sources. In addition to the literature study the proposed model from “Trafotiltak” had to be analysed to better understand the different modules and calculation methods being used in the model.

While the literature study was conducted, there were a continuous gathering of transformer service data from the cooperating companies in the project. This data mainly consisted of different oil and gas samples obtained from the last 20-30 years of maintenance on the power transformers. The population data were then analysed to study the effects from different maintenance measures on the different oil and gas parameters. The idea was that the improvements would create a good statistical basis for estimating the condition of a transformer after different types of maintenance measures. Communication with the transformer experts in some of these companies were also established to answer specific questions about the service data during the analysis.

The results from the population study were then used to estimate the effect of different maintenance measure with the proposed cost-benefit model from “Trafotiltak”. This analysis consisted of two different case studies, where different maintenance alternatives were suggested for the two different transformers.

During the process of creating this thesis several meetings with the supervisors have been held to discuss issues and further progress. This also included a meeting with all the cooperating companies in the project held on the 15th of May in Trondheim.

1.2.1 References

The theory in this thesis are mainly based on the “Power Transformer Handbook” [3,4,5] made by members of “Brukergruppen for kraft- og industritransformatorer” and recognized standards from CIGRE, IEC and IEEE. The theory from all these different sources were modified and compressed together in this report to give the best possible summary on the topic. The result of the literature study is mainly presented in chapter 2 and 3, where chapter 2 explains the different measures to improve the condition of the oil. Chapter 2 also looks at the different oil and gas parameters used to estimate the condition of each transformer. In chapter 3 the different parts of the proposed model from “Trafotiltak” are studied.

The theory and equations from the cost-benefit model, and the HI-score module are presented in [1] from SINTEF. Since the decision-tool, based on the “Trafotiltak” model, had not been built yet when this thesis was written, the HI-score module was implemented manually in Excel based on the equations. The cost-benefit model was also made manually in Excel, based on formulas in [1], and benefits gained from the HI-scores of the measures.

Through contact with some of the transformer experts and the companies, economic data were collected and used in the CBA-model tested in chapter 5. The data not available were either estimated or fixed at a reasonable level after consultation with the companies.

1.2.2 The Structure of the Thesis

The thesis is mainly based around chapter 4 and 5, where all the maintenance data collected from the companies are analysed. In chapter 4 the improvements of the different maintenance measures are studied. From these statistics, improvements of the different oil and gas parameter for reclamation are estimated. Chapter 5 uses the estimated improvements found in the population study to test the proposed cost-benefit model from “Trafotiltak”. Chapter 4 and 5 also discusses the results found from the analysis in each separate chapter. Chapter 2 is the theoretically basis for the maintenance measures. Chapter 3 explains the structure of the “Trafotiltak” model and explains the different module models used in the model. Chapter 6 and 7 concludes with some of the main findings from the analysis and describes further work in the project and for this thesis. The structure of the thesis can be seen in Figure 1.2 below.

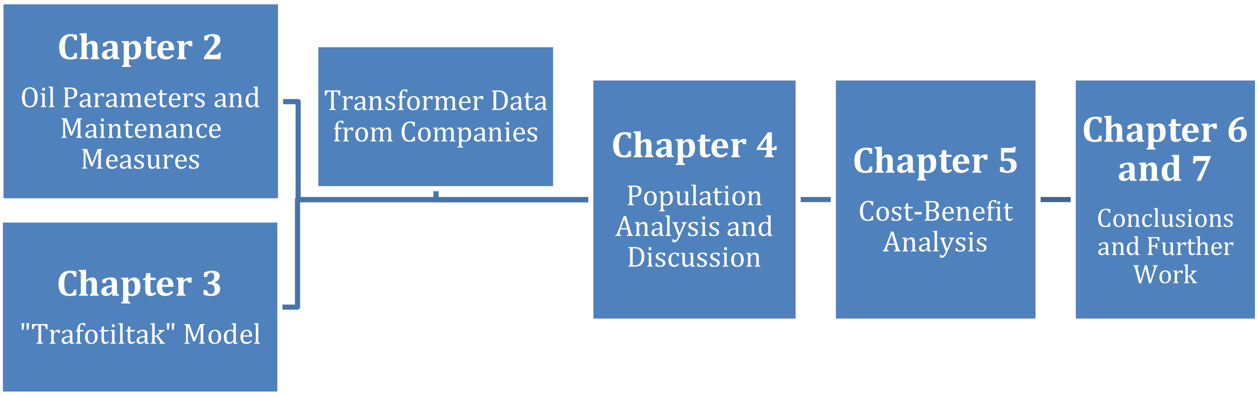

Figure 1.2: *The structure of the thesis.*

2 Oil Parameters and Maintenance Measures

In this section, chapter 2.1 will describe some of the usual oil and gas parameters measured from oil samples, and what each of these parameters could reveal about the condition of the transformer. Chapter 2.2 will primarily describe the different maintenance actions available for treating poor oil in a power transformer

This chapter is based on acknowledged theory and will be a summary of the literature review conducted in [6], which is loosely based on the relevant parts of the “Power Transformer Handbook” made by the members of “Brukergruppen for kraft- og industritransformatorer” [3,4,5].

2.1 Technical Condition

Studying the technical condition of power transformers could be a difficult task, because of the transformers unique construction and the fact that some of the components would be hard to gain access to while the transformer is energized. For these components, relying on examining service data and indirectly find the condition of the “inner” components are essential. The “inner components” are defined as the winding, core and oil. There are several methods that could be used to study these “inner” components, and some of the most common techniques are going to be described in this section.

2.1.1 Oil Analysis

When trying to find the condition of the oil, there are several oil parameters that should be measured and from this oil sample the condition could be analysed. These parameters are examined to find the overall condition and reveal any deviations from standard values that might occur inside the transformer, which are impossible to spot from just visual inspections. The most common parameters examined in the oil are listed in the section below.

2.1.1.1 Acidity

The acidity, or the neutralization value, specifies how much contaminations and acid particles the oil is containing. In new oil the acidity is negligible, but as time passes the ageing of the component will create formation of residual products due to oxidation. As the acidity increases it will start to affect the mechanical properties of the oil and accelerate the degradation speed of the cellulose paper surrounding the windings [5].

The acidity is estimated by adding a solution of different indicators and alcoholic potassium hydroxide (KOH) to an oil sample. The value of the acidity is measured in milligram KOH used per gram of sample oil [5] [7].

2.1.1.2 Water Content in Oil

Water content in the oil is one of the most important indicators to discover the true state of the transformer condition. This content also has a big impact on the operating conditions and lifetime expectation of the transformer. The water content affects several other oil parameters depending on the operating temperature and the amount of water present. The most important parameters affected by the water content are the dielectric strength (BDV), the state of the solid paper insulation and the acceleration speed of degradation of cellulose paper and the liquid insulation [8]. Water in oil usually appears due to ordinary ageing and oxidation processes, but the water content could also be due to poor maintenance leading to condensation and diffusion through poor sealing or through the air-drying silica gel filters [5]. The water content in oil is measured in milligram water per kilogram oil, or [mg_{H2O}/kg_{oil}]. Water in oil can also appear in several forms within the transformer [5, 6, 9]:

- *Absorbed or dissolved water* is the most common presence of water in oil. This happens when water molecules separate from the oil and lies side by side with the oil molecules. This type of water is easily detected through standard analysis of oil samples in the lab.

- *Condensed water* is water absorbed and kept in the oil. If temperatures vary too much and drops below the oils dew point, water will condense to liquid. The water separates from the oil and sinks to the bottom of the transformer tank as it is heavier than oil. Saturation level of water increases when the transformer age.

- *Chemical binding water* is only noticeable in aged oil or poor refined oil.

The way the water content is measured is by using a colorimetric method in the laboratory described in [9]. The method is both quick and reliable, and could detect even smaller amounts of water [5].

Some of the methods used to remove water in the transformer are described in chapter 2.2, but the most common method for removing water in oil is by vacuum treatment, which is a very time demanding process. At normal conditions 99% of all the water in the transformer is absorbed in the paper insulation, but with increasing temperature the water content in oil would increase [5]. The relationship between oil temperature and water content in oil versus paper can be seen in Figure 2.1.

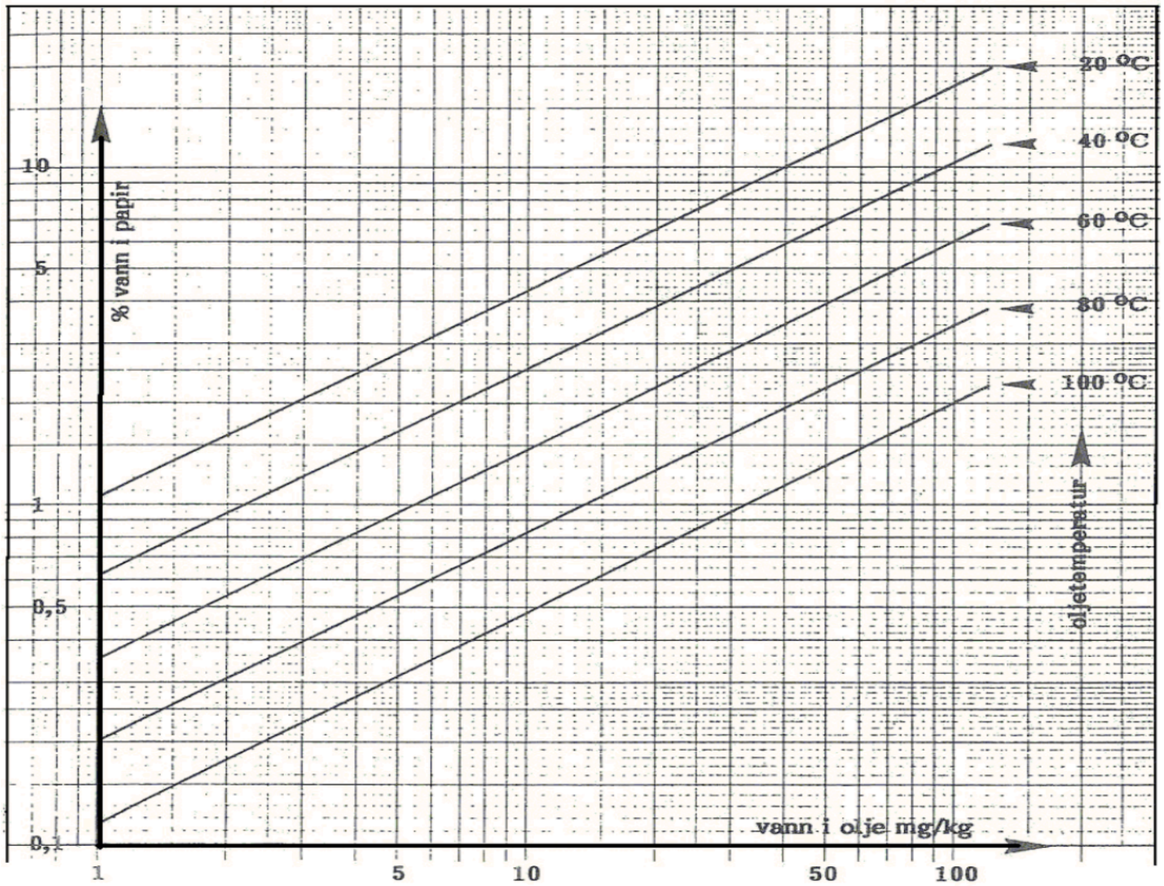

Figure 2.1: *Equilibrium curves for water content in paper and oil. The curves are based on new oil that still have not experienced ageing [5]. Oil temperature is showed on the right side of the figure, % water in paper on the y-axis and the water content in oil mg/kg is showed on the x-axis.*

2.1.1.3 Colour and appearance

The oil in a transformer should have a light colour and be clear, making visual inspections of the components inside the transformer tank possible. If the colour has changed it is a clear sign of contaminations in the oil [10]. One example is oil exposed to carbon contaminations would become darker as time goes by [11].

The oils colour number is decided by transmitting light and comparing the results to a colour standard [12]. According to NEK 240-1:2008 the colour number is between 0-8, where 0 resemblance a clear oil and 8 a dark oil. The standard explains that new oil should be given the colour number 0,5 and the critical value should be at 3,5 [13].

Although the colour is not a critical parameter by itself, it can reveal a lot about how the overall condition of the transformer might be. A high colour number is a strong indication that oil has a lot of contaminations and that degradation of oil or insulation paper already have started [5, 8].

2.1.1.4 Breakdown Voltage (BDV)

The breakdown voltage is a good indicator for oils ability to be used as an electrical insulation material. New oil has a high BDV and the electrical strength is naturally also very high. Presence of contaminations as water and oxidation products will reduce the BDV considerably. Hence, a lower BDV value could be an indicator that the oil is polluted in some way. It should be noted that a high BDV value does not necessarily mean that oil have completely absence of contaminations. It could just mean that oil contains other substances that does not affect the BDV [5, 14]. Measurements of BDV are also very temperature sensitive, as described for the measuring of water content, and oil should be sampled at operating temperature for the transformer [14]. This practice is not always followed and oil samples taken at different temperatures could mean frequently varying BDV values, which is a common sight in the transformer service data.

The method used to measure the BDV is described closely in [15], but summarized here. An increasing AC-voltage is applied to the oil sample until a breakdown happens. The test is conducted 6 times and the final BDV value is the average of these 6 measurements and is measured in [kV].

2.1.1.5 Dielectric Dissipation Factor (DDF or tanδ)

This parameter has many names, but will be called dielectric dissipation factor or just shorted DDF in this thesis. This indicator gives information on how much power that are lost when an electrical insulating material, as e.g. mineral oil, is exposed to an AC field. The losses are given as heat. A high DDF indicates high losses in the transformer [10]. The DDF is also used to detect water, oxidation and ageing products in the oil, since the parameter is very sensitive to pollutions in the oil [11].

The dissipation factor is also a good way to check the quality of a new transformer oil. The oil is tested to see if it contains other types of oil, like diesel or lubricating oil, instead of mineral oil which is the most common oil type used in a transformer. The other types of oil have a much higher dielectric dissipation factor than mineral oil and will easily be detected by performing a simple inspection [5]. The method for measuring the dielectric dissipation factor is described closely in IEC 60247 standard [16].

2.1.1.6 Inhibitor Content

The practises of adding inhibitor will be discussed more in chapter 2.2.1, but a short summary will be given here. Adding an inhibitor to the mineral oil under production of the power transformers has been common practice for a long time. The inhibitor is added to reduce oxidation and consequently reduce the ageing rate of the transformer. The inhibitor content is consumed as time goes by and if the inhibitor is still present in the oil, the qualitative characteristics will remain almost the same during this period. Therefore, it is important to monitor the remaining content of inhibitor. Another incentive to observe the inhibitor content is oil that previously has had an inhibitor added will age faster than uninhibited oil once the inhibitor is consumed. Refilling of the inhibitor are often done after a reclamation of the oil, and if reclamation is done before the inhibitor levels are too low the oil should nearly be as good as new [5]. For both new and newly reclaimed oil the inhibitor content should be between 0,3-0,4% of the total oil volume [5].

2.1.1.7 Interfacial Tension (IFT)

The IFT measures the attracting powers between oil and water molecules on the surface of the oil. This parameter is a good indicator when trying to detect oxidation products or polar contaminants in the oil [5]. The value of the IFT changes rapidly in the early stages of the ageing process, but slows down as the ageing process continues. This is opposite of what was described for the acidity, and together they could be used as indicators to observe the ageing process, e.g. by using the oxidation index described by equation (2.1) in chapter 2.2.8.
The way to estimate the IFT is by measuring the force needed to separate a planar ring of platinum from a bordering layer of oil and water [17]. The IFT is measured in [mN/m], and it is usually a strong indicator when a reclamation of the oil is required [5].

2.1.1.8 Passivator Content

Adding passivator to the oil will be described as a measure in chapter 2.2.2, but a short summary will be given here. Passivator, also called metal deactivator, is added to the oil to prevent corrosion. When the passivator reacts with the metal surfaces or the dissolved metals in the oil, such as copper and silver, it reduces the metals components reaction speed with other compounds in the transformer. The most common reaction is the oxidation reaction between organic materials and corrosive sulphur.

Unlike many of the other parameters the use of passivator is relatively new in the electrical industry, even though it has been used for several decades in the petroleum industry [18]. For this reason, many transformers do not have a passivator added to the oil, and consequently this indicator is not typically found in older service data.

2.1.2 Gas Analysis (DGA)

DGA is a diagnostic method very commonly used for checking the overall condition within the transformer. DGA is shorted for dissolved gas analysis and measures the content of different gases emerging within the transformer during operation [5]. The gases usually measured during a DGA are Hydrogen (H_2), Oxygen (O_2), Nitrogen (N_2), Carbon monoxide (CO), Carbon dioxide (CO_2), Methane (CH_4), Ethene (C_2H_4), Ethane (C_2H_6) and Ethyne/Acetylene (C_2H_2). DGA is a good way to check the quality of the insulation properties of the oil-filled equipment. The DGA cannot say anything about the oil quality directly, but the results can be used to analyse and find irregularities within the transformer [5].

During normal operation of the transformer great amounts of heat will be produced. This heat will then partly be removed by the ambient insulation consisting of mineral oil and oil-impregnated paper. When a failure happens within the transformer more heat will be created. The extra heat will weaken the insulation properties and start the formation of different gases, depending on the failure location, will emerge. By studying the amount of different gases appearing in the DGA sample the location of the failure could be determined. Experience from several years of studying transformer incidents and breakdowns have resulted in the creation of Table 2.1 below. The table describes failures that have happened and failures that could happen if measures are not taken seriously. Normal ageing also contributes to the formation of gases, but not at the same rate as actual failures. By looking at the evolution of each gas and ratios compared to other gases it can be determined if the gas content is due to normal ageing mechanisms or if there is an underlying failure, either electrical or thermal, causing the gas to increase. Therefore many contractors are, in addition to measuring the content of each gas, also quantifying the evolution of gas by ml/day. A transformer with a previously experienced failure might still have a high concentration for some gases. If the amount of gases are stable, and not rising considerably, it is not critical [5] [19].

Probable fault	**Gas Ratios**		
	C_2H_2/C_2H_4	**CH_4/H_2**	**C_2H_4/C_2H_6**
Partial Discharges (PD)	*	<0,1	<0,2
Low Energy Discharges (D1)	>1	0,1-0,5	>1
High Energy Discharges (D2)	0,6-2,5	0,1-1,0	>2
Thermal Fault T1	*	>1	<1
Thermal Fault T2	<0,1	>1	1-4
Thermal Fault T3	<0,2	>1	>4

Table 2.1: *IEC gas ratio limits related to typical electrical and thermal faults [20].*

Description of the different failures in Table 2.1 are explained in [19] as:

Partial Discharges (PDs): discharges in gas filled cavities that results in high-humidity and impregnation in the insulation paper.

Low energy Discharges (D1): Sparking or arching between poor contacts with different potential. Discharges happens between bushings, tank and clamping parts. Breakdown of oil could happen.

High Energy Discharges (D2): Flashover or arching of high local energy. Short circuits between ground and low voltage, windings, bushings, tank, windings/core or connectors can appear.

Thermal Fault (T1): Temperatures lower than 300^0C. Commonly happens when overloading the transformer during emergency situations, or if oil has restricted flow due to blocked items in the cooling system. Stray flux in the damping beams in the yokes could appear.

Thermal Fault (T2): Temperatures from 300^0C to 700^0C. Contacts between the bolted connections could be defective. Circulating currents between yokes clamps and bolts or between clamps and laminators.

Thermal Fault (T3): Temperatures over 700^0C. Large circulating currents in the tank and core could arise. Small currents in tank walls due to the high-uncompensated magnetic field.

As described earlier many of the faults gases are mainly formed due to discharges and overheated areas called hot-spots. Formation of hydrocarbons mainly appears from heated oil, while hydrogen and acetylene are formed by electrical faults. The degradation of cellulose paper is usually the source for the formation of CO and CO_2 [21]. In Table 2.1 IEC has only considered the ratios between hydrocarbons, but there are some other ratios that should be mentioned here. The ratios between CO_2/CO and O_2/N_2 are two widely used ratios in the industry and could reveal failures within the transformer. The critical limits here are not as fixed as for the hydrocarbons, but $CO_2/CO < 3$ is considered as a sign that degradation of paper is involved in the fault. Ratio of $O_2/N_2 < 0{,}3$ indicates oxygen is being consumed in some part of the transformer, either in the paper or the oil [21].

When calculating the gas ratios, it is important to use the most recent gas samples. By using this as a standard rule, it can prevent fault gases from being concealed by the content of gas the transformer had prior to the fault [20]. Some transformers could still have high values of certain gases after a renovation, and could still work like a transformer with low gas concentrations. Considering this fact, it is smart to check the maintenance history and check if the high gas concentrations could be due to any previous faults. The same is also applicable for acetylene (C_2H_2). If the concentration is high it could be smart to check the maintenance history and the technical specifications of the transformers. Diffusion of acetylene from tap changers operations could appear in the gas samples and give a wrong picture of the transformers real condition.

2.2 Maintenance Measures to Improve the Condition of Transformer Oil

As time passes the different components in a power transformer would be exposed to great amounts of stress. Combined with ageing this would affect the power transformers ability to execute its designated tasks in a satisfying way. If ageing has been going on for a while and the stresses gets too high, it can result in a breakdown of the power transformer. To avoid this, it is important to apply condition monitoring to the power transformers. In Norway, the most common way to observe the condition is to take periodical oil and gas samples every other year. New transformers have numerous supplementary equipment that can oversee and conduct constant condition monitoring, e.g. temperature, humidity or gas monitoring of dissolved gases [4]. Since the average age of Norwegian transformers is high, these new monitoring techniques are not available for most transformers, and thus oil samples collected from each transformer are the best available source to monitor the transformers condition.

If an oil parameter has reached its critical limit, this will make the condition tend to worsen faster than normal and increase the likelihood of a breakdown. For a case like this maintenance measures needs to be completed to prevent this from happening. The measures could either be preventive or damage minimizing measures.

When reviewing relevant measures for the transformer, only methods to improve the "inner components" are studied in this thesis. The inner components are defined as the core, mineral oil and windings together with its paper insulation. As mentioned in the Power Transformer Handbook from "Brukergruppen for kraft- og industritransformatorer" it is hard to distinguish measures for oil and windings. The oil works as both a cooling medium and a liquid insulation for the windings. Maintenance measures on one of these components would usually also affect the condition of the other component as well [4].

Measures with the intention to decelerate ageing and extend the lifetime of a power transformer are usually called rehabilitating measures. Rehabilitating measures are usually very expensive, and therefore it is important to justify the measure costs. This is done by comparing the present value of a postponed investment against the lifetime extension that the measure gives. These comparisons will be closer explained in chapter 4 and presented as a case study in chapter 5.

2.2.1 Adding Oxidation Inhibitor to the Mineral Oil

Standard procedure in Norway is to add an inhibitor in the mineral oil before the transformer is energized and starts operating in the grid. The inhibitors primary objective is to retard the oxidation processes, naturally emerging in the oil, as it ages. The oils qualitative factors will remain on a satisfying level for a longer period if the inhibitor content stays above an acceptable limit. As time passes the inhibitor will slowly be consumed due to chemical reactions happening in the oil. Therefore, condition monitoring is important to make sure it always is a sufficient level of inhibitor mixed in the oil. Oil that previously had inhibitor added, will age faster once the inhibitor is fully consumed compared to oil that never had inhibitor added. Based on these facts the transformer owners should have the inhibitor levels under close surveillance [4].

A normal way to check the inhibitor content is through oil samples conducted every other year. If the level of inhibitor is found to be too low the oil will slowly start to get more acidic and measures needs to be taken to conserve the oil from getting inferior. One measure that tends to be very effective together with refilling inhibitor is reclamation of oil. In this process acids and residual products such as ketone, aldehydes and organic acids are removed so the oil can return to a normal state. The reclaiming process of oil will be described in chapter 2.2.5.

The typical warning level for refilling the inhibitor should be around 30% of the original value added, or easier explained, the value it had when energized the first time. The inhibitor concentration of a new transformer is usually between 0,3-0,4% of the total oil volume. This means the inhibitor should be refilled when it reaches 0,09-0,12% compared to the total oil volume. If the concentration gets below this threshold, refilling should be done as soon as possible or the condition of the transformer will rapidly get worse. Refilling normally happens with exhaust-equipment connected to the transformer so the inhibitor could be evenly refilled in the oil. Usually it takes some time after the measure is conducted until the inhibitor is evenly spread out, and samples may show a lower inhibitor content than what is the reality straight after a reclamation process.

REN published a document in 2014 containing guidelines for Norwegian companies in the electric power sector performing maintenance on the regional grid [22]. The document includes guidelines explaining when refilling of inhibitor should be considered:

- Remaining inhibitor content: $\leq 0{,}15\ \%$
- Acidity $\leq 0{,}06\ \mathrm{mg_{KOH}/g_{oil}}$
- IFT $\geq 30\ \mathrm{mN/m}$

An operator would usually need less than 1-2 days to refill the inhibitor, and the power transformer needs to be disconnected from the grid for the measure to be possible. If the refilling is not done all the oil qualities would continue to age, and reclaiming the oil should be considered [23]. The cooperating companies in the project were asked to estimate the cost associated to refilling inhibitor for a standard transformer here in Norway. Companies in the "Trafotiltak"-project estimated that the process would include around 15-30kNOK for the contractors' operator costs, 5kNOK for connection costs and 2kNOK per ton of oil in the transformer for the oxidation inhibitor solution.

REN has in addition to the other guidelines also set some requirements to the end-results when performing measures to improve the condition of transformers. When refilling the oxidation inhibitor, the requirements describes which parameters the contractor should take into consideration when calculating the amount of inhibitor that needs to be added [22]:

- The amount of oil in the transformer, the oil weight.
- Remaining oxidation inhibitor in the oil.
- The amount of inhibitor when process is finished should be minimum 0,30% and maximum 0,40% of the total oil in the transformer.

When the process is finished all the above requirements should be checked and verified by the contractor.

2.2.2 Adding Passivator Against Copper Corrosion

Corrosion is a chemical reaction happening between the metal surfaces and the liquid in the power transformer under certain chemical circumstances. In this case corrosion happens between cobber in the tank and the insulating oil of the transformer, and consequently the name given is cobber corrosion. Corrosion could also happen on the metal surface and weaken the metals physical qualities.

When adding a passivator in the oil, metal within the transformer will be protected against sulphur components, and this will prevent the beginning of a corrosion process. The passivator will in this case create a protective layer on the cobber making it difficult for corrosion processes to start. IEC has conducted several tests where oil with and without passivator added are compared and figured out that oil with passivator do not develop any corrosive components. Passivator are added to oil the same way as the inhibitor content.

Even though there has been showed a clear coherence between the use of passivator and corrosive components in the transformer, there are still some uncertainty around the practise of the passivator. The first, and most important uncertainty, is the long-term effects of passivator and how long it would protect against corrosion. Another doubt is how effective the passivator will be when a copper surface already has started corroding within the transformer. Previous tests have showed that in this case it has little or none effect.

A measure like the passivator is categorized as a temporary measure, and in a long-term perspective reclamation, oil change or drying of the oil should be considered. An operator will normally use the same amount of time adding passivator as for inhibitor, about one to two working days. Like the inhibitor, the transformer needs to be taken out of service while the passivator is added to the oil [23].

2.2.3 Recondition of Oil

Recondition is a measure intended to remove physical contaminations by degassing, drying and filtering the oil. Degassing is sometimes referred to as dehydration in a more technical language because it is effective against removing high water concentrations in oil. The measure reduces the gas pressure in the oil, which reduces the risk of bubble formation, but also removes particles leading to improvements of the electrical strength in the oil. This is a measure that could be conducted on-site, but the transformer would usually need to be disconnected from the grid. The recondition removes most of the solid particles with the filter, but since the oil-flow is rather low some particles will attach themselves to the transformer walls and the effect of the measure will be poor. The filters are ideal to remove solid particles, but are normally only able to remove smaller amounts of free-water in oil. If the transformer has a high quantity of water in the oil, most of it should be removed before the filtration starts [8].

Recondition of the oil is typically conducted while the oil is still in a good condition, but values for water content in oil and BDV have reached their critical limit, according to IEC 60422 [8] which is displayed in Table A.3 in Appendix A [5].

2.2.4 Continuous Drying of Oil

There are several constructions that makes continuous drying of the oil possible. Even though the methods are different, the main target for all of them is to reduce the oxidation of the cellulose paper insulation around the windings. By drying the oil the oxygen content could be reduced considerably, but the result of the reduction depends on if the transformer has an open or closed conservator. An open conservator could easily have an oxygen content of around 35000 ppm, and a measure like drying usually brings this concentration down to 8000-10000 ppm. Even though continuous drying of oil sounds like it contributes to reducing the water content in the cellulose, the reality is it has a very small effect [4].

2.2.5 Reclamation of Oil

Reclamation of oil is a process that contains many sub-processes that have the intention to improve the different oil qualities, and try to bring them back to a level that almost corresponds to new oil. Reclaiming consist of degassing/drying the oil, filtering of particles and removing waste products and sludge from the oil.

The process where waste products and sludge are removed from the oil is a chemical process where active filters containing bleaching earth (Fullers earth) removes the contaminations in oil. Bleaching earth is the most common active filter, but there are also other filters that are used as absorbent material, e.g. aluminium oxide and other mass changing ions [4][5].

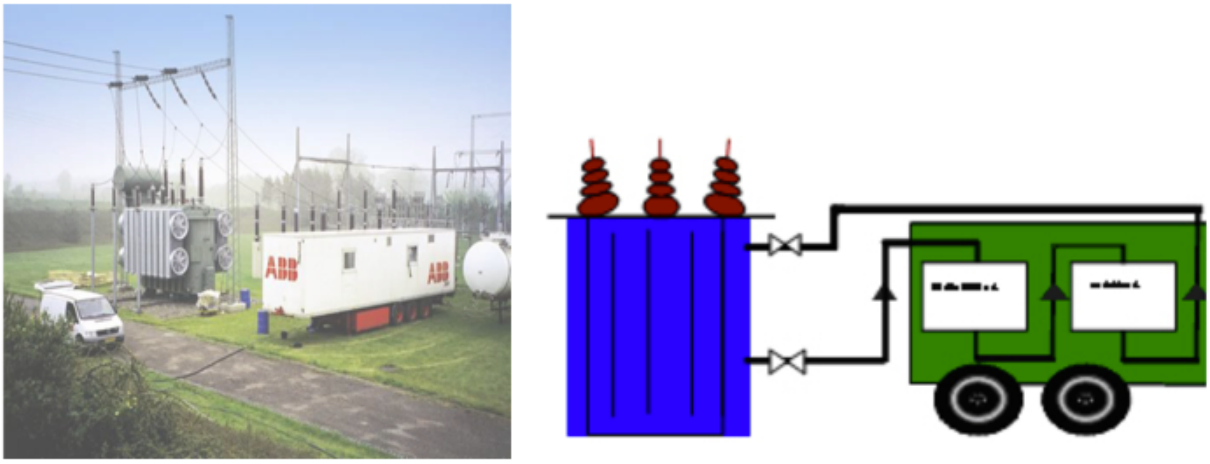

Figure 2.2: *A picture showing the portable reclamation laboratory used by ABB to reclaim the oil on-site. On the right is a sketch showing the portable unit receiving oil from the power transformer and sending it back once its treated. The two white boxes represent the filter and the drying/degassing processes [24].*

When should reclamation of oil be considered? There are different limits depending on different sources [22] [25], but the most common ones are:

- Inhibitor ≤0,10-0,12%.
- Acidity > 0,02mg KOH/kg.
- IFT < 30mN/m.
- Water content in paper insulation too high.
- Oxidation index < 300.

However, transformers older than 45 years old where service data indicates reclamation of oil should not be reclaimed, but rather have its inhibitor refilled if the transformer is planned to still be in service according to REN [22].

Reclamation of oil is done while the transformer is connected to the grid. The only time it should be taken out of service are during connection and disconnection of the reclaiming equipment, but only if the safety distance is too small from high-voltage components to safely do it while it is still connected. As described above, the oil will be refined by going through an active bleaching earth filter. During the process the filter will eventually get saturated, resulting in poor absorption of particles. This requires the filter to be purified. This engages the second main process for reclaiming oil, which is called reactivation of filter. During the reactivation, the waste-products and sludge absorbed in the filter, are burned away with a high temperature. While the filter is purified, common practice is to let the oil circulate in a system so it can be degassed and dried and make the whole purification-process run more efficiently [26].

It is important for the operator to take continuous samples during the reclaiming process to check if the oil has reached the desired quality stated before the process started. In Figure 2.3 below, a typical development of the most important oil parameters during the reclaiming process are displayed. From the figure, interfacial tension (IFT) and colour number are the parameters that takes the longest time to get within a satisfying level, and therefore these two parameters decides when the reclamation is finished.

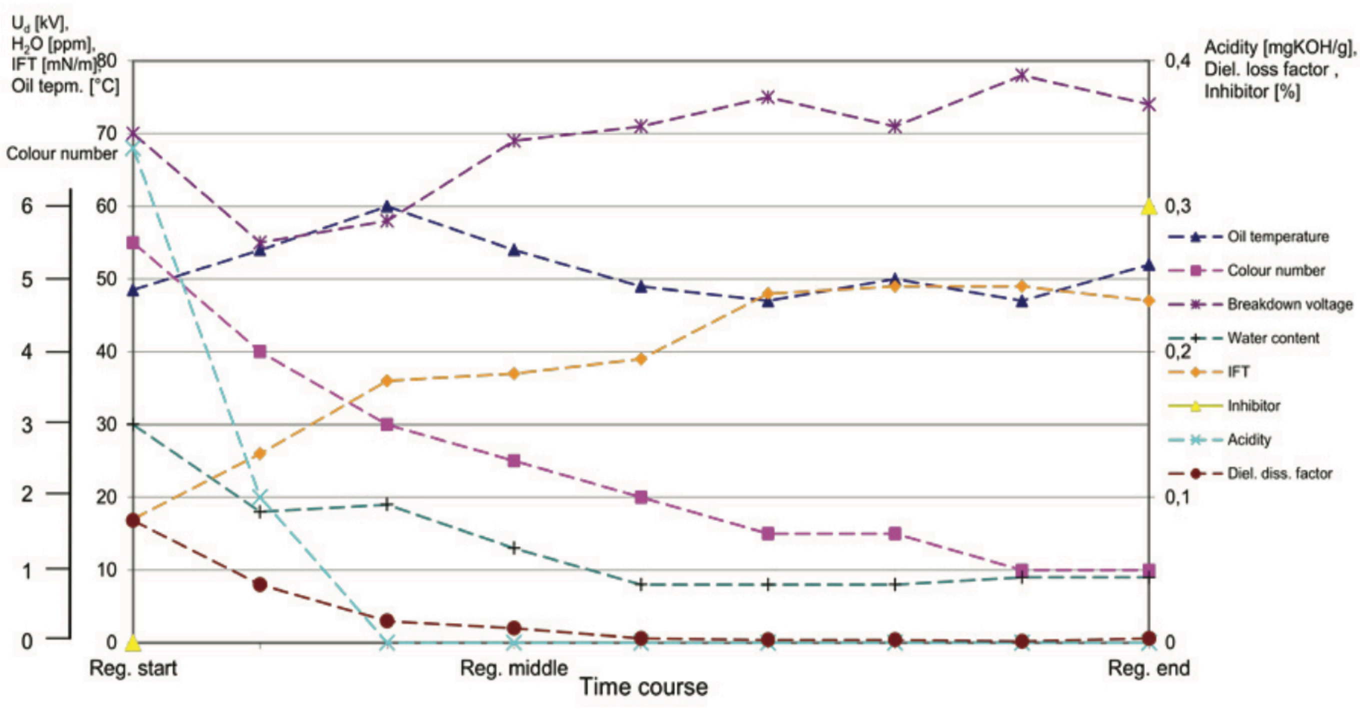

Figure 2.3: *The gradual improvements of oil parameters during a reclamation process [26].*

A reclamation process normally takes around one week to conduct, but in some cases, it can take several weeks depending on factors like oil volume and the state of the oil pre-reclamation [23]. The process has proved to give a prolonged positive effect on several of the most important oil parameters. It is also considered to be an eco-friendly measure, which is also regarded as one of the main incentives for conducting this measure. It should however be mentioned that reclamation will not directly improve the condition of the solid cellulose insulation which are protecting the windings. On the other hand, the reclaiming process removes particles and other substances that makes the ageing process of paper to slow down. Reclamation will therefore have an indirect impact on ageing of solid insulation. Seeing this fact, it is important that the reclamation of oil happens before the degradation of paper has gone too far [26]. After the reclaiming process is finished inhibitor are added to reduce the oxidation-rate, since the remaining inhibitor in oil pre-reclamation are removed during the process.

From [26] it is stated that the price of reclamation varies depending on several factors as transport of equipment, condition of the oil etc., but that a normal price-range is between 12-18 kNOK per ton of oil. Cost estimates from several of the members of the “Trafotiltak”-project claimed the CENS-costs during connection and disconnection of the reclamation equipment were so small that they usually were negligible.

As mentioned in chapter 2.1.1, REN have provided some requirements and guidelines when performing different measures on the transformer oil. For reclamation of oil the requirements for the end-result are [22]:

- Inhibitor content should be at a minimum of 0,30% and maximum 0,40% of the total oil volume.
- The interfacial tension (IFT) should be better than 35mN/m.
- The acidity should be 0,01 or lower.

2.2.6 Drying of the Cellulose Paper Insulation

Drying of the solid cellulose paper that surrounds the windings is an extensive process that can be done on-site with transportable drying equipment. Alternatively, the power transformer could be transported to a factory where the drying happens with a technique called “vapour-phase” [4]. In Norway, this measure usually takes place at ABBs transformer factory, which is located in Drammen. In addition to water removal in cellulose paper, organic acids evaporate easily and could be partly removed with this technique. The dryings main task is however to reduce the thermal ageing of the cellulose, which further extends the life of the transformer.

Of the two alternatives discussed above, drying in a factory with the “vapour-phase” technique is the most preferred and most effective alternative. “Vapour-phase” technique is also considered as the standard drying process used when transformers are produced, and a good result could be expected as this is a respected method [27]. The “vapour-phase” technique uses warm kerosene vapour which condenses on cold surfaces when added on the windings. This results in a heated surface and the water in the cellulose will slowly start evaporating. This vapour is then pulled out to where it is vacuum, and here the vapour could be removed from the transformer.

Drying of the cellulose insulation should be considered as a measure when the power transformer has high levels of water, and the ageing of the insulation still is at a reasonable level. When considering this measure, it is usually taken a weighted decision after a cost-benefit principle, according to Figure 2.4 below.

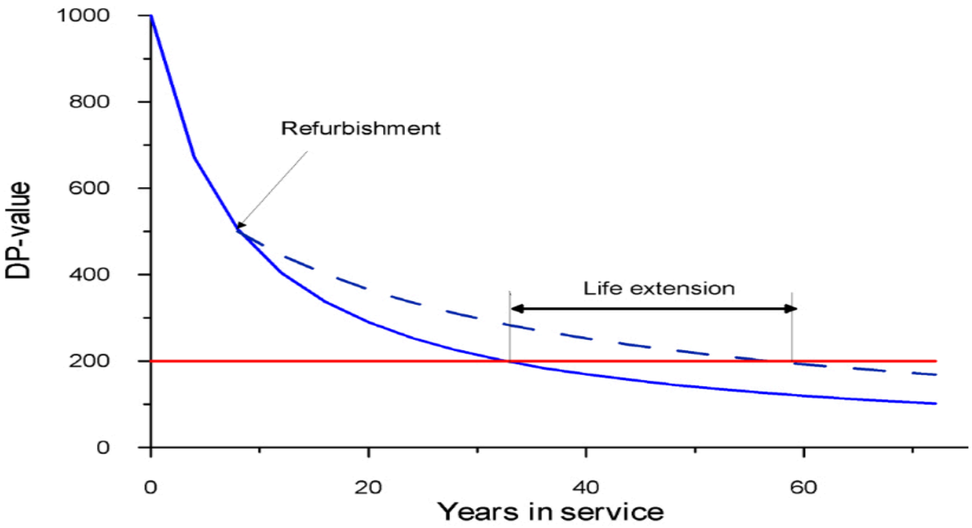

Figure 2.4: *Life extension when considering improving the quality of the cellulose insulation. The red line shows the critical DP-value in cellulose paper of 200. By performing a refurbishment measure before the paper quality reaches a too low level the life extension could be extended by several years as seen by the figure [4].*

For all the techniques of drying that happens in a factory the oil needs to be moved to another tank so the windings could be exposed. In this case, it is normal to conduct a reclamation process of the oil simultaneously as the paper dries. A drying process will be most effective when the water content is high, since the water concentration in the atmosphere around the windings also is high at this point. The life extension gained with drying of the cellulose is proportional with the amount of humidity removed. This reflects in the cost-benefit analysis, where naturally the measure provides most benefit in the start when the humidity is at its peak.

2.2.7 Removal of Halogens

This is not a widespread problem in Norway, but are an important maintenance measure used internationally. Halogens are environmental toxins, and could be introduced in a healthy transformer by using contaminated oil treatment equipment. Good routines should therefore be implemented to check that treatment gear are halogen free [4].

2.2.8 Replacement of Oil

Oil change is one of the most extensive measures that could be conducted to improve the condition of the oil. This maintenance measure is usually done when the oil no longer can perform its purpose as an insulation material for the transformer.

When deciding on which measure to choose, the oxidation index could be used. The oxidation index is showed in equation (2.1), and is the ratio between the two oil parameters interfacial tension (IFT) and the acidity. If this index scores between 30-300 reclamation of the oil should be considered, which is closer described in chapter 2.2.5. If the index is below 30 the oil should be changed [5].

$$Oxidation\ Index = \frac{IFT}{Acidity}\ \frac{[\frac{mN}{m}]}{[\frac{mg\ KOH}{g\ oil}]}\ . \tag{2.1}$$

In addition to changing the oil, the windings need to be washed and dried before new oil is poured in. The reasoning behind this procedure is to get rid of old oil stuck on the windings. If just a small amount of the old oil is mixed together with the new oil it is enough to pollute the new oil entirely, and could cause the oil to age faster than under normal ageing conditions. If this was the case then the measure could have been conducted for no reason, and it would prove to be a poor cost-benefit alternative overall.

Changing the oil will take two operators 5-10 days, depending on the size of the power transformer and its oil volume. The transformer also needs to be disconnected during the whole process. In Norway changing the oil in a transformer usually happens in ABBs factory in Drammen, which means big transportation costs, but on the other hand better drying and a faster oil change. Oil change could also be performed on-site for smaller transformers [23].

3 “Trafotiltak” Model

Trying to choose the right maintenance measure for the power transformer can be difficult and hence the benefit of each measure needs to be checked against the costs for all alternatives to achieve the optimal solution. The “Trafotiltak”-project has suggested a model to perform this calculation, and this model will be used later in this thesis to look at different possible measures and scenarios. The full method is more thorough described in the “Trafotiltak” report [1], but will be summed up here in this chapter, as the report is not published yet.

As Figure 3.1 shows, the model consists of a winding degradation model looking at the insulation papers quality and a HI-model analysing the oils quality. Together these two models calculate the apparent age of the transformer based on service data. The winding degradation model will not be described more in this thesis as paper is almost impossible to improve by maintenance actions once it is degraded. Together with apparent age a stochastic model calculates the risk of a breakdown for the transformer. The risk and remaining lifetime estimation decides what measure that should be taken in the last section of Figure 3.1 through a cost-benefit analysis [1].

Figure 3.1: *Flow chart of the model presented in "Trafotiltak" [1].*

3.1 Health Index Model

In the industry today, there is an increasing demand for optimal resource distribution and asset managers constantly needs to take choices regarding maintenance and reinvestments decisions in the electrical power grid. As the power transformer is one of the most crucial and expensive components of the power grid, a wrong maintenance decision for transformers could lead to tremendous costs for the power company and the society.

Considering this fact, the assets managers have an important job, making sure that the right decisions are taken at an optimal time to ensure that breakdowns do not happen, and that resources like time and money are spent in the best way possible.

A health index (HI) is a tool designed to help asset managers take better and more well informed decisions for different investment assessments aimed at power transformers. The health index use the available material about the transformer, and based on this data it makes an evaluation about the overall condition. By applying the health index for the whole transformer fleet the individual needs of each transformers, in terms of maintenance and repairs could be discovered, but the asset manager would also get a ranked list of the transformers based on their current condition.

The ranking of the transformers is usually based on the ranking of several smaller systems, or different components, eventually creating one final HI-score by merging the score from all the smaller subsystems. The final HI-score can tell the asset manager how the overall condition for each transformer scores, and this could also be used to estimate remaining lifetime as seen later in this chapter. By postponing maintenance to when its necessary, and not just by doing time-based maintenance, could be a trade-off by using the health index.

The main objective for the health index is to be a user-friendly tool and easy for users to understand. The model should not need endless amount of input data to reveal the condition, but at the same time enough information to make the obtained HI-score credible. The amount of information needed for each transformer to compute a result are therefore variable between different health indices. It is also important that a health index is based on service data measured frequently for all transformers. This is to ensure that the model rates the transformers on the same premises and that data are obtainable for all power transformers, even though certain transformers have less data available than others. If a health index model requires data that the user do not have available, they will not be using it [21].

All health indices are based on the same principles, but can differ in some degree on how the HI-scores are calculated. The most common method is to have a starting HI-score of 100% to symbolise the perfect score or the perfect transformer, and then give deductions as deviations from standard values are detected in the condition data. A different way to calculate the score is to start at 0% and add points to the score from each subsystem based on the condition, and the final score for the whole transformer is the total score from all these subsystems [6].

3.1.1 “Trafotiltak” Health Index Model

3.1.1.1 Description pf Model

This is the proposed health index model made by SINTEF Energy Research in the ongoing project “Trafotiltak” and the model used in this thesis for finding the condition and potential improvements of each maintenance measure. This model focus heavily on available condition data from Norwegian power transformers. This is mainly oil and gas data found from analysing oil samples in a laboratory. The model is still under development, but the main theory of the model is finished. This makes it possible to test transformers based on oil samples and comparing them by their achieved health index scores by calculate each score by hand [6].

3.1.1.2 Input Data

The model consists of 6 different components/subsystems that are being assessed on their own, and then merged as a final health index score in the end of the analysis. The 6 different subsystems included in the model are:

- Core/Windings
- Oil
- Oil Tank
- Bushings
- Tap Changer
- Cooling System/Auxiliary equipment

As explained earlier the model is not finished and the only subsystems currently available for analysing the HI-score are the Core/Windings and the Oil, also called “the inner components”. These components are usually the parts indicating internal faults in a transformer and therefore considered as the most important components in this model. Core/Windings is analysed by studying the dissolved gas analysis (DGA) and Oil is analysed by looking at various oil quality parameters found during oil sampling [6].

3.1.1.3 Assessment Method

The assessment method used in the model is quite simple, which is intentional since it should be easy for both the user and interested outsiders to understand how the results were found. The oil and gas values found from service data of the transformer are checked against different standards [8] [14] and then given deduction on the HI-score if the data deviates from recommended values, according to equation (3.1) below.

$$HI_i = HI_{i,0} - \sum_{j=1}^{n_i} R_j\left(\theta_j\right). \tag{3.1}$$

A power transformer that has no fault is in this model considered as "new" and given a score of 100%, and represented in the equation above as $HI_{i,0} = 1\ (100\%)$. $R_j\left(\theta_j\right)$ is the reduction of the health index due to condition data j, and θ_j is the grade on the condition data j. The index *i* describes the component analysed from the list in chapter 3.1.1.2. A list of all the different parameters of condition data are listed in Table 3.1 and 3.2. The reduction function $R_j\left(\theta_j\right)$ is defined as

$$R_j\left(\theta_j\right) = R_{j,max}\frac{\theta_j^x - 1}{\theta_{j,max}^x - 1}, \tag{3.2}$$

where $R_{j,max}$ is the maximum reduction on the health index due to the condition data j, $\theta_{j,max}$ is the worst condition and the highest possible grade for condition data j. *x* is an exponential that makes the reduction non-linear. The reason for using *x* is that high concentrations of gas should have bigger deductions, since the possibility for faults increase when the concentration of gas is high. It should also be pointed out that total score of the different $R_j\left(\theta_j\right)$ could become greater than 1, but the HI-score should always be between 0 and 1 (0-100%), as described by the constraint in (3.3),

$$0 \leq HI_i \leq 1. \tag{3.3}$$

Dissolved Gas Analysis (DGA)

As described in chapter 3.1.1.2, the DGA method is used to score the subsystem "Core/Windings". For Norwegian power transformers gas analysis is one of the few maintenance techniques available for most transformers, and older gas samples are recorded to easily spot a drastically change in formation of gases. This makes DGA a perfect candidate for checking condition in transformers.

The gas analysis used in this model are based on normal DGA sampling techniques, as described in chapter 2.1.2 where quantities of H_2 (hydrogen), CO (carbon monoxide), CO_2 (carbon dioxide), CH_4 (methane), C_2H_4(ethene) and C_2H_6(ethane) are taken into equation.

One important thing to mention for this model is that C_2H_2(Ethyne/Acetylene) is not included in the DGA as for many other HI models. Acetylene could appear in the DGA sample due to absorption from tap-changer operations. If the tap-changer shares the same volume as the oil, absorption of acetylene is a common phenomenon and since limits for normal concentrations of acetylene in oil are low, this would mean big deduction in the HI-score. In some cases, it is difficult to find technical information if the transformer has a separated volume for the oil and tap-changer, and since we want the transformers to be analysed on the same premises in this thesis the acetylene deduction has been removed from the grading of the HI-score.

The model considers two different types of gas deductions. The first one checks the amount of each gas against the CIGRÉ 443 standard [14], while the second checks the rate of change since last measurement. The reason why they have chosen this solution, is that a gas still can be under the critical limit for a specific gas, but a fast increase could mean that something is wrong on the inside of the power transformer.

Based on the standards [14] the gas concentration and the rate of change of one gas can be scored in 6 different categories, based on the condition, all with different size of deductions to the HI-score. The different parameters used to calculate the HI-score for the windings/core can be seen in Table 3.1.

Condition data j	**HI-reduction $R_j(\theta_j)$**
Gas concentration and gas concentration increase: H_2, CH_4, CO, CO_2, C_2H_4, C_2H_6	$R_{max} = 0.5$, $x = 2$, $\theta_{max} = 6$, $\theta = 1,2,3,4,5,6$

Table 3.1: *Scoring categories for gas concentrations and gas-rate increase based on DGA and standards in [14].*

θ represents the different scoring categories according to the standard [14] as:

- < Typical is represented by $\theta = 1$.
- < Level 2 is represented by $\theta = 2$.
- < Level 3 is represented by $\theta = 3$.
- < Level 4 is represented by $\theta = 4$.
- < Pre-Failure is represented by $\theta = 5$.
- > Pre-Failure is represented by $\theta = 6$.

If both the concentration and rate of the change for one gas exceeds the standards and receives deductions, the model is made to only include the biggest deduction for that gas. The equation (3.4) describes this case,

$$\theta_j = \max(\theta_{j,c,}\theta_{j,ci}) \qquad (3.4)$$

where $\theta_{j,c,}$ is gas concentration and $\theta_{j,ci}$ is rate of change in concentration for a gas.

The scoring tables for both gas concentration and gas change rate for each of the gases mentioned above can be seen in the Appendix A, in Table A.1 and A.2 respectively.

Oil Analysis

This analysis is conducted to decide the HI-score for the subsystem Oil in “Trafotiltak”. Here different oil parameters rate the oils ability to work as an insulation material and they are checked against the standard IEC 60422 [8] and given the right deductions. The different parameters could land in 3 different scoring categories: good, fair and poor, which are represented with $\theta = 1, 2$ and 3 respectively. The deductions for each category can be seen in Table 3.2 below. It should be mentioned that colour can only receive either the grade good or poor and therefore $\theta = 1$ or 3 for this parameter.

Condition data j	**HI-reduction $R_j(\theta_j)$**
Oil parameters: Breakdown Voltage, Water Content in Oil, Acidity, Dielectric Dissipation Factor, Interfacial Tension	$R_{max} = 0.25$, $x = 1$, $\theta_{max} = 3$, $\theta = 1,2,3$
Oil parameter: Colour	$R_{max} = 0.125$, $x = 1$, $\theta_{max} = 3$, $\theta = 1,3$

Table 3.2: *Scoring categories used for oil analysis based on the standard [8].*

In “Trafotiltak” there are a total of 6 different parameters being scored according to the standards. The different indicators are more thorough explained in chapter 2.1.1. The indicators are listed below:

- Breakdown voltage (BDV)
- Water content in oil
- Acidity/Neutralization factor
- Interfacial tension (IFT)
- Dielectric dissipation factor (DDF or tanδ)
- Colour

The reason the indicator “Colour” only has a potential deduction of 12,5%, while the other parameters have a potential deduction of 25%, is that colour is a good indicator of the overall condition of the transformer. If the other parameters are poor, the colour number usually is poor as well, and should not be deducted more than necessary. The colour is not a critical parameter by itself and therefore the deduction of this parameter should be smaller. Some health indices also use the inhibitor content, and in rare cases also the passivator content, as parameters for scoring the oil. As explained for acetylene and the DGA method all transformers should be analysed on the same premises and sometimes it is hard to find information that could confirm if the oil is inhibited or passivated. For this reason, these two indicators are not included in this calculation of the HI-score.

Each of the 6 parameters have an individual range according to [8], where deductions are based on which category each indicator scores in. This standard also deviates a little bit from the DGA standard, since it also categorizes the transformers based on the voltage level they operate on. The categorization based on the voltage size can be seen in Table 3.3 below [8].

Category	**Type of equipment**
Category O	Power transformers/reactors with a nominal system voltage of 400kV and above.
Category A	Power transformers/reactors with a nominal system voltage above 170kV and below 400kV.
Category B	Power transformers/reactors with a nominal system voltage above 72,5kV and up to including 170kV.
Category C	Power transformer/reactors for MV/LV application e.g. nominal system voltages up to and including 72,5kV

Table 3.3: *Categories for transformer equipment used to score oil parameters based on voltage levels [8].*

The deduction limits for the 6 oil parameters, in addition to limits for inhibitor and passivator, can be seen in Appendix A in Table A.3.

3.1.1.4 Output

The final HI-score will be given as a percentage (%), where 100% represents a brand-new transformer, with a perfect condition without any defects. During the assessment of the different subsystems, deviations are found and deductions are done according to the standards. Each of the 6 subsystems will be assigned their own HI-score based on the state of each component. The final HI-score for the whole power transformer will equal the score of the lowest scoring subsystem. If the subsystem "Oil" only scores 30% and this is the lowest score out of all the 6 components this will be the final HI-score for the whole transformer [6].

3.1.2 Apparent Age in the Health Index

When the HI-score has been calculated with the method described above, the score can be converted to a value describing the transformers "apparent age *t'* "based on the formula (3.5),

$$t' = \frac{1-HI}{0{,}0083}. \tag{3.5}$$

This formula is created from a reference population of several transformers where the correlation between HI and actual age are described by the trend line in (3.6)

$$HI_{ref} = 1 - 0{,}0083t \tag{3.6}$$

and seen in Figure 3.2 below. The reference population is also representative for the transformer studied later in this thesis. The basis of this population is a little small, but SINTEF is working on increasing the size of the population now. The population could create some uncertainty in the results, because of its current size. It should be mentioned that all the transformers in the reference population are transformers containing Kraft-paper as the solid insulation. To this date there is not enough data available to create the same correlation between thermally-upgraded papers HI and actual age. This means this figure is used for both types of paper for now, making the results a bit conservative [1].

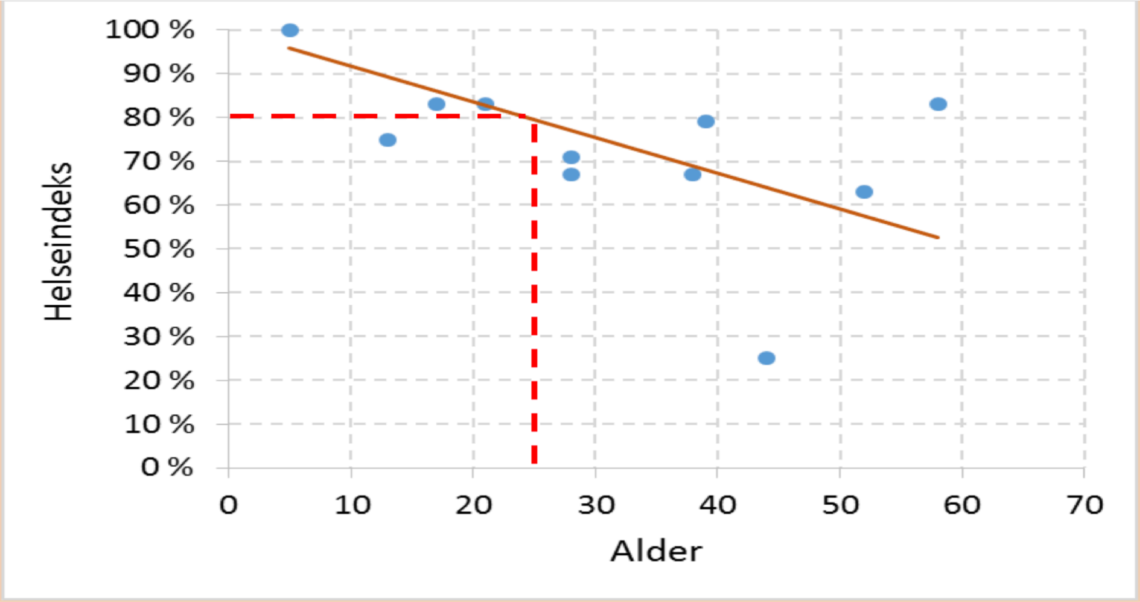

Figure 3.2: *The reference transformers with age on x-axis and corresponding HI-score on the y-axis. The red unbroken line is the coherence between age and HI-score described with equation (3.6) above [1].*

3.2 Stochastic Model and Risk Model

From the flow-chart in figure 3.1, "Trafotiltak" model consists of both a stochastic and a risk model. The models will not be thorough explained here, but a short description of both are given so the reader gets an understands how some values and formulas used in the cost-benefit analysis are found.

3.2.1 Stochastic Model

The same reference population of transformers used for the HI-model is also used here. The model is based on data for elapsed time for the transformer, the time interval from installation to taken out of service. A transformer is usually taken out of service before it has reached its technical lifetime as a safety precaution and avoiding an unexpected breakdown. The data collected from the time interval between installation and discard age are used to extrapolate an estimate on how much longer the transformer would have satisfied operating conditions before reaching "technical death". Technical death is considered to be when the insulation paper has reached a DP-value of 200, and is visualized in Figure 2.4.

When using this method on the reference population the result shown below in Figure 3.3 was achieved. The figure also shows the transformers normal distribution function with a mean of 62 years and a standard deviation of 23 years [1]. The distribution from the reference population could be used as an estimation for the probability distribution for technical lifetime L_t for an individual transformer. The standard deviation and mean of this reference population are also used to calculate probabilities in the cost-benefit model in chapter 5. The probability P for end of life for the transformer between installation ($t = 0$) and t are given as (3.7)

$$P(L_t \leq t) = \int_0^t f(u)du = F(t), \tag{3.7}$$

where $F(t)$ is the cumulative distribution function found from Figure 3.3 and $f(t)$ is the belonging probability density function to the normal distribution. It is assumed that the transformers are non-repairable.

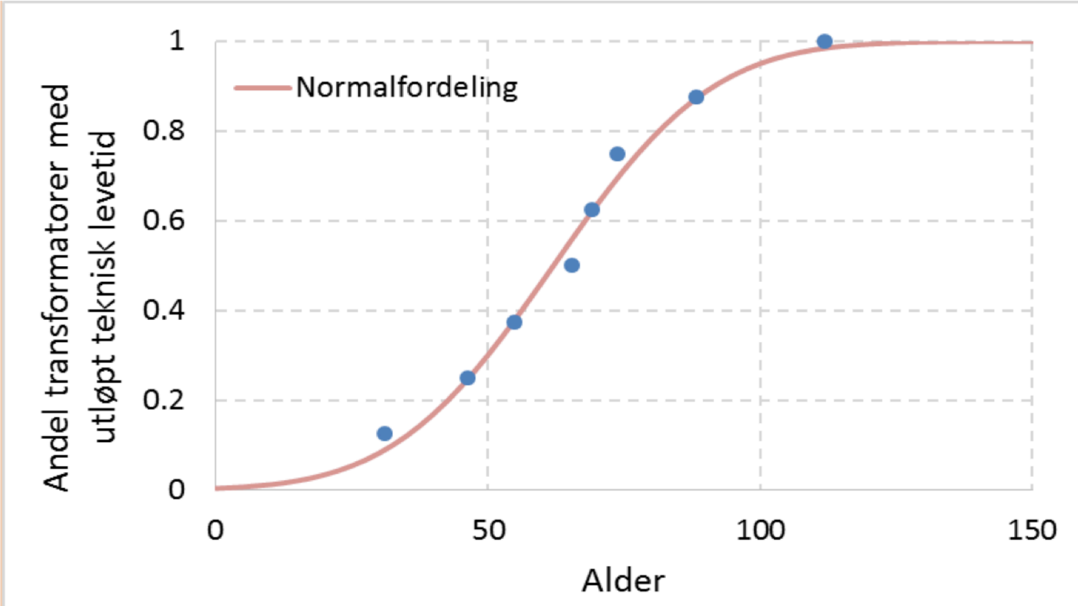

Figure 3.3: *Technical lifetime of the reference population and the cumulative normal distribution made from the transformer data [1]. The red line shows the normal distribution, the x-axis the age, while the y-axis show the share of transformers that have reached their technical lifetime.*

3.2.2 Risk Model

The probability distribution function for the technical lifetime L_t provided through the stochastic model could be assumed to be an approximation of probability distribution function for total breakdown for the transformer. Total breakdown is here defined as a complete failure where it is more beneficial to replace the power transformer than to repair it. The only occurrence included in the model is total breakdown since the main goal for the model is to find the best time to replace the transformer to avoid a potential breakdown. It is also important to point out that “Trafotiltak” only considers failure mechanisms associated with the inner components (core, oil and windings) when looking at events leading to a breakdown.

The probability for a breakdown is assumed to be decided by the "apparent age" t', found from equation 3.5, rather than the real age. The probability P for breakdown between *t* and $t + \Delta t$ for a transformer with real age *t* and apparent age *t'* is described in (3.8) as

$$P(t < L_h \leq t + \Delta t \mid L_h > t) = \frac{P(t<L_h \leq t+\Delta t)}{P(L_h>t)} = \frac{F(t'+\Delta t)-F(t')}{1-F(t')}. \tag{3.8}$$

Here L_h are the time from installation to breakdown, *F(t)* are the cumulative normal distribution function found from Figure 3.3 and the apparent age *t'* are found from the health index model [1].

3.3. The Cost-Benefit Model

Cost-benefit analysis (CBA) is a way to organise and estimate all costs together with all the profits and benefits gained from different investment proposals. By comparing benefits and cost, the investments with the best projections could be chosen among all the different solutions. When calculating CBA, the costs and benefits are usually valuated within a certain period called the "analysis period" *A*, typically around 20-30 years. All costs and benefits in this period are calculated with their present value. Present value is the value the current investment cost would be worth at the end of the analysis period if it would be invested in another project, with a discount rate normally around 4-6% [28].

In this section, the proposed cost-benefit model included in the "Trafotiltak" model is going to be explained more closely. As described in chapter 2.2 there are several possible measures available for the power transformers to improve the condition. The benefit from each measure are improvements in condition or delaying the ageing process. The benefit of a measure is given by (3.9)

$$\Delta t'_T = t' - t'_T = t' - \frac{1-HI_T}{0,0083} \tag{3.9}$$

where t' is the apparent age before the measure, while t'_T and HI_T are the apparent age and the HI-score after the measure. The lifetime of each measure is also important to define in the analysis. The lifetime of a measure is given as the time from a measure was initiated until the HI-score is back to the same as it was before the measure. For this reason, the duration of a measure L_T can be defined as (3.10).

$$L_T = \Delta t'_T. \tag{3.10}$$

The costs included in this analysis are operation and maintenance costs (O&M), costs of the measure and costs of a possible breakdown. The present value of the total costs K_A is defined as all costs over an analysis period of A years, with a measure T that is implemented in year s and are described with words in equation (3.11), while equation (3.12) gives the mathematically explanation of each term in this equation.

$$\begin{aligned} &K_A\left(s, \Delta t'_T, K_T, K_{T,u}\right) \\ &= \sum_{m=1}^{A} O\&M\ costs + \sum_{m=1}^{s-1} (Potential\ breakdown\ costs\ before\ the\ measure\ is\ conducted) \\ &+ \sum_{m=s}^{A} (Potential\ breakdown\ costs\ after\ the\ measure\ is\ conducted\ ) \\ &+ Cost\ of\ the\ measure \end{aligned} \tag{3.11}$$

$$\begin{aligned} &K_A\left(s, \Delta t'_T, K_T, K_{T,u}\right) \\ &\qquad = \sum_{m=1}^{A} \frac{K_{d,m}}{(1+r)^m} + \sum_{m=1}^{s-1} P(t+m-1 < L_h \le t+m \mid L_h > t) \frac{K_u + K_{new}\varepsilon_{r,L_t}}{(1+r)^m} \\ &\qquad + \sum_{m=s}^{A} P(L_h > t+s-1 \mid L_h > t) \\ &\qquad \cdot P(t+m-1 < L_h \le t+m \mid L_h > t+s-1) \frac{K_u + K_{new}\varepsilon_{r,L_t}}{(1+r)^m} \\ &\qquad + P(L_h > t+s-1 \mid L_h > t) \frac{\left(K_T + K_{T,u}\right)\varepsilon_{r,L_T}\lambda_{r,A-s}}{(1+r)^{s-1}}. \end{aligned} \tag{3.12}$$

Here the first term represents the operation and maintenance costs, the second and third term are costs in case of a breakdown occurs and the fourth term represents costs connected to the measure the owners choose to take. In both the second, third and fourth term the costs are adjusted to the probability of breakdown, while all the terms are adjusted to net present values. The O&M costs are summed over the whole analysis period, from year 1 to year A. The sum of the potential breakdown costs before a measure are the costs from year 1 to the year before the measure is conducted. The sum of the potential breakdown costs after the measure are the costs from the year the measure is conducted to the end of the analysis period A.

The other parameters included in the equation above:

- r is the discount rate (the required rate of return from the transformer owner or the socioeconomic discount rate).
- $K_{d,\,m}$ is the annually O&M costs for year m. The annually costs usually varies depending on if the measure has been conducted or not, but for the simplicity of this analysis these costs are fixed and do not to vary depending on this factor.
- K_u is the costs connected to unavailability after a breakdown. If this is a power transformer this is the interruption costs due to non-planned disconnections (CENS), while for generator transformers this cost is the costs of lost production.
- K_{new} is the cost of a new transformer and all the cost associated with this (installation, purchasing, removal of old transformer).
- K_T is the cost of the measure T.
- $K_{T,\,u}$ is the cost of a potential interruption of operation while the measure is conducted.
- L_T is the life of each measure.
- s is defined as the year the measure is implemented from the start of the analysing period A. If a measure is conducted at the start of the analysing period then $s = 1$ since the measure is done in the start of the first analysing year. The model is also created in a way that so that postponing measures should not be more than 10 years to get the most accurate results ($s \leq 11$) [1]. The reason is that the apparent age t' increases with one year when s is postponed one year in the model. This would not be very accurate if the measure is postponed more than 10 years.
- $\lambda_{r,A-s}$ is the capitalization factor and sums up all the annually costs for the measure over the analysing period A. The reason this parameter is included is that the measure could have a remaining economic value after the analysing period A is over. The capitalization factor could be calculated from equation (3.13).

$$\lambda_{r,A-s} = \frac{1-(1+r)^{-(A-s)}}{r}. \qquad (3.13)$$

- ε_{r,L_t} is the annuity factor and makes sure that the costs of a new transformer are distributed equally during the transformers technical lifetime L_t. The annuity factor can be calculated from equation (3.14).

$$\varepsilon_{r,L_t} = \frac{r}{1-(1+r)^{-L_t}}. \qquad (3.14)$$

- $P(t+m-1 < L_h \leq t+m \mid L_h > t)$ is the probability for a breakdown each year, given a real age *t* and an apparent age *t'* in the start of the analysis period *A* and is given ***before*** the measure starts ($m \leq s-1$) as equation (3.15),

$$P(t+m-1 < L_h \leq t+m \mid L_h > t) = \frac{F(t'+m)-F(t'+m-1)}{1-F(t')} \qquad (3.15)$$

and ***after*** measure ($m \geq s$) as equation (3.16),

$$P(t+m-1 < L_h \leq t+m \mid L_h > t) = \frac{F(t'-\Delta t'_T+m)-F(t'-\Delta t'_T+m-1)}{1-F(t'+s-1)}. \qquad (3.16)$$

- $P(L_h > t+s-1 \mid L_h > t)$ is the probability that a breakdown would not happen before the measure is conducted in year *s*, given by equation (3.17)

$$P(L_h > t+s-1 \mid L_h > t) = \frac{1-F(t'+s-1)}{1-F(t')}. \qquad (3.17)$$

The final cost-benefit formula uses the results from equation (3.12) to analyse the benefit from a measure *T* conducted in year *s* against a reference alternative (no measure at all, or in some cases by reinvestment in a new transformer). The cost-benefit or the net present value $NPV_{T,s}$ is the difference between the cost of a measure and the reference measure given by equation (3.18).

$$NPV_{T,s} = K_A\left(s, \Delta t'_T = K_T = K_{T,u} = 0\right) - K_A\left(s, \Delta t'_T, K_T, K_{T,u}\right). \qquad (3.18)$$

4 Analysis of Condition Data Before and After Maintenance Measures

4.1 Population Data

For analysis purposes in this thesis service data from hundreds of transformers were collected from companies taking part in the “Trafotiltak”-project. From the collected data, the transformers that had experienced maintenance actions needed to be located and this required several weeks of work and it went a lot of effort into filtering out these transformers from the rest. After finding all these transformers the next job was to sort out the values needed to calculate the HI-Score before and after the measure manually.

The data proved to be more lacking than expected, and for many measures it was not enough data to make conclusions and compare it to effects gained from other maintenance measures. From the data, it was clear that some measures were preferred compared to others. Reclamation of oil and refilling of the inhibitor were the most popular measures with around 150 and 60 incidents respectively from the available data in the period 1996-2017. From this data, around 137 of the transformers with reclaimed oil had sufficient and good enough data to be analysed in the “Trafotiltak”-model. Several of the older transformers had very few measurements taken and no information of the condition before the reclamation process. The same were the case for reclamation cases planned or conducted in 2017, where the measurements after the reclamation were not performed yet. Since inhibitor is added in oil to preserve the condition and stop formations of acid waste-products, and not necessarily to improve the condition immediately it was not further analysed in this thesis for use in the cost-benefit model. The focus in this thesis will consequently be on the effects from the reclamation process.

The 137 transformers with available data for the reclamation measure were of different sizes, voltage levels and age. Some of the different information about the population are described below:

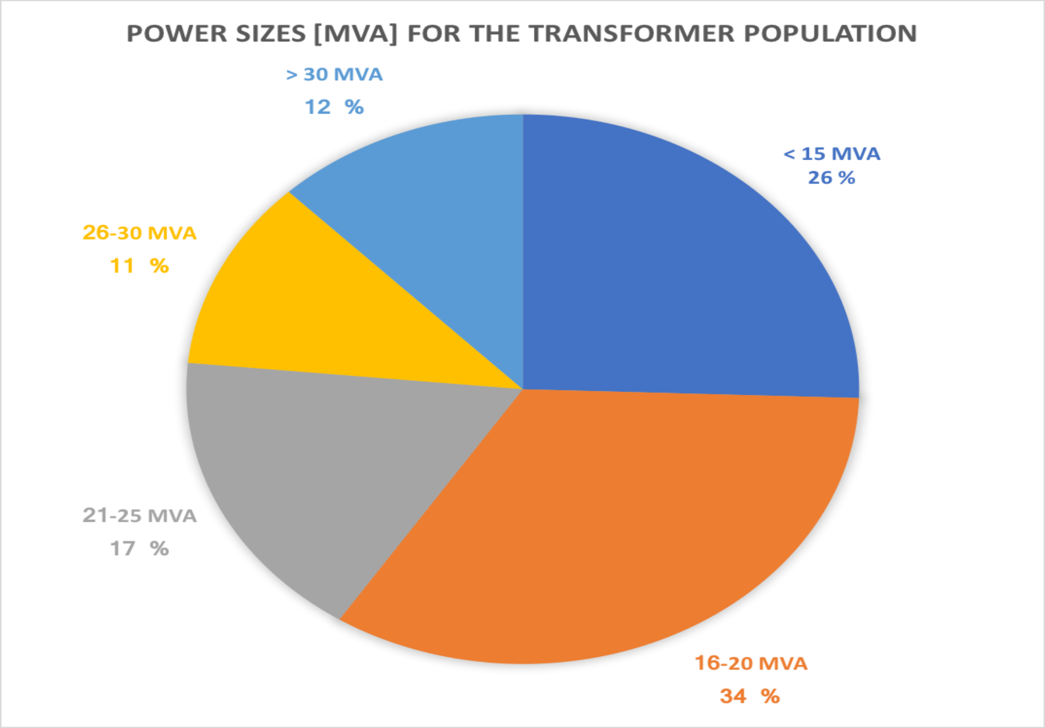

Figure 4.1: *Power size distribution of the transformer population given in [MVA].*

As seen in Figure 4.1 most transformers studied in this thesis are smaller transformers and are usually 25MVA and below. This can also be seen from Figure 4.2 where the voltage distribution of the transformer population is displayed. From these figures, it can be concluded that around 75% of the transformers can be categorized as small power transformers with a power range of ≤25 MVA and with a voltage size of ≤72,5 kV [29]. This would put almost all the transformers in the lowest category "C" according to Table 3.3. The other 25% are categorized as medium power transformers according to [29] and would be categorized as "B" in the "Trafotiltak"-project, referring to Table 3.3.

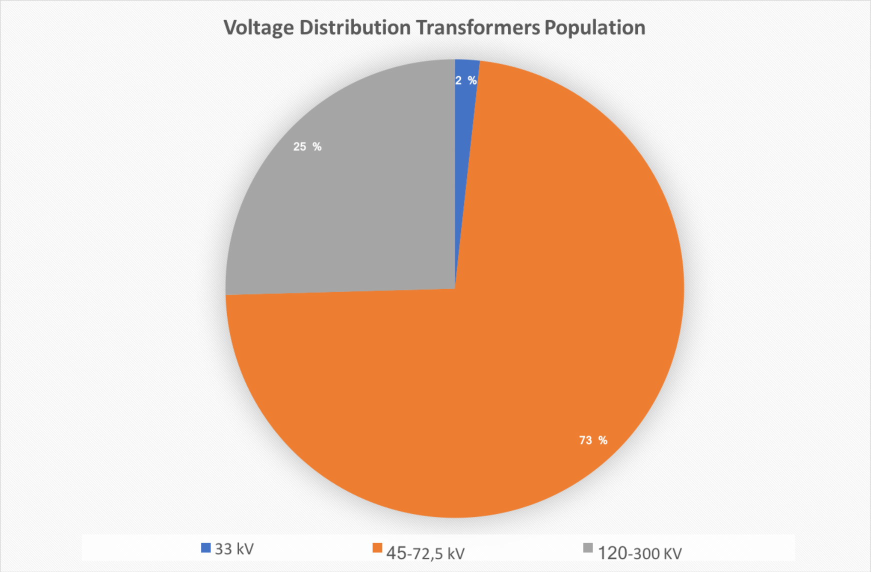

Figure 4.2: *Voltage distribution in the power transformer population.*

Figure 4.3 shows when the different transformers were energized and started operating in the grid. It is important to note that in many cases the companies only have information on when the transformers were produced and delivered, but in most cases this year is the same as it started operating. One assumption made for the data is that the delivery year is the same as the year the transformer started operating, since some of the necessary data are not available.

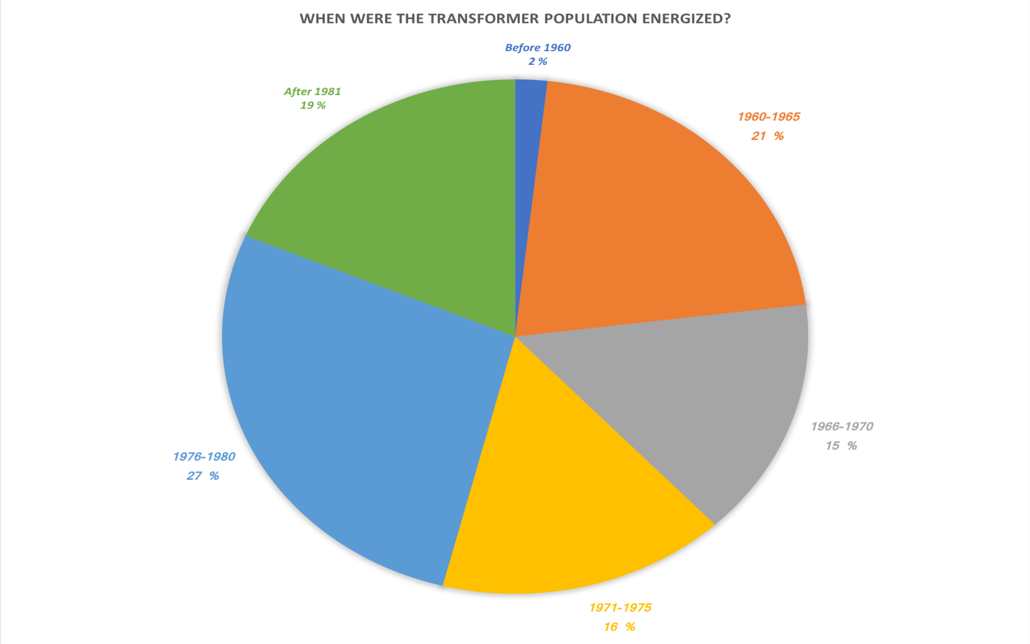

Figure 4.3: *This figure shows when the transformer in the population were energized in the grid.*

From Figure 4.3 there are very few transformers energized before the 60s that still are in operation and performed reclamation on in the period from 1996-2017. The other time periods have an almost equal share of transformers which are natural. There are almost none transformers reclaimed in the 90s. The youngest transformers having a reclamation process were 3 transformers energized in 1991. These transformers were at the time of the reclamation 10, 16 and 16 years old. They were also bigger transformers with a voltage ratio of 132/11 kV. The company owning them could confirm that these transformers are located close to a city-centre, and that they are of great importance to secure the power supply and that is why the oil was reclaimed this early.

So how long are the transformers usually in service before getting a reclamation process performed on their oil? The period from energization to the reclamation process started is an interesting difference and described by Figure 4.4 and Figure 4.5 below. Here Figure 4.4 shows the more general overview, while Figure 4.5 goes more in detail.

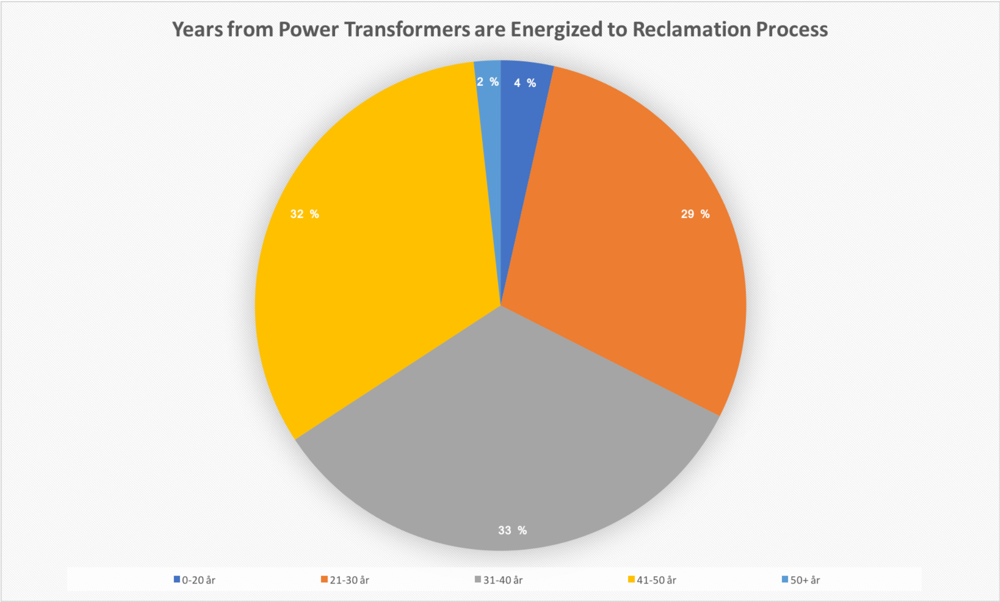

Figure 4.4: *This diagram shows how long the transformers in the population are operated before needing a reclamation on their oil is conducted.*

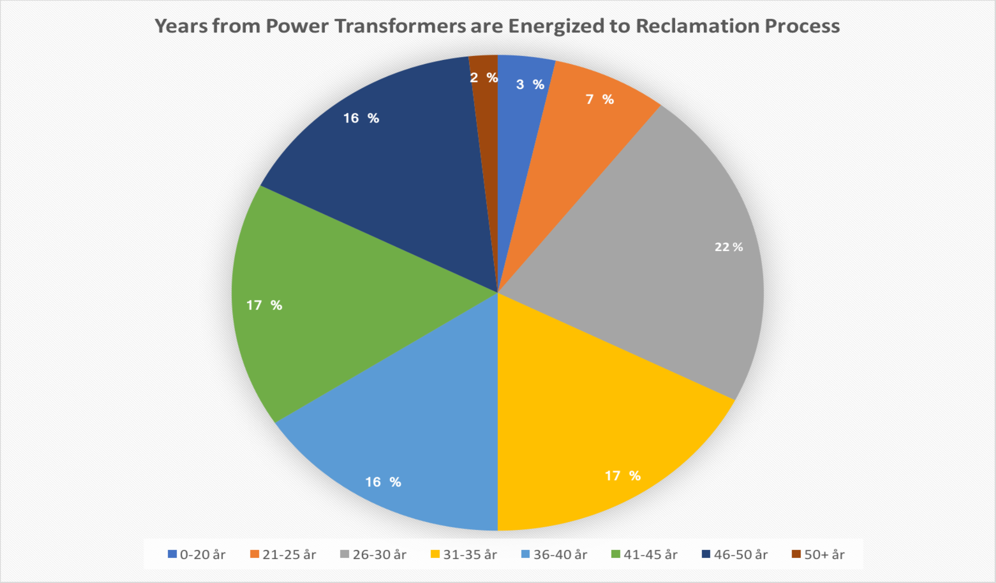

Figure 4.5: *This diagram is a more detailed version of the diagram in Figure 4.4.*

From the two diagrams above it is possible to spot that most of the transformer oils are reclaimed evenly in the 5-year periods after reaching 25 years in service. Very few transformers are reclaimed after 50 years in service, and in those cases, it is only done as a life-saving measure to extend the lifetime a little bit before reinvesting in a new transformer [22]. Another scenario is that these transformers could have been energized, but later kept as reserves, without this being mentioned in the data. Therefore, another assumption for the population should be that all the transformers have been energized since their operation start until the reclamation measure is conducted.

Figure 4.6 shows what year most transformers had the reclamation of the oil. From the figure, in the period (2012-2016), it has been conducted relatively few reclamation processes. This is also the case for the oldest data available, in the period 1996-1999. The two peak years for reclamation of oil were in 2007 and 2009 with respectively 33 and 26 reclamations each of these two years.

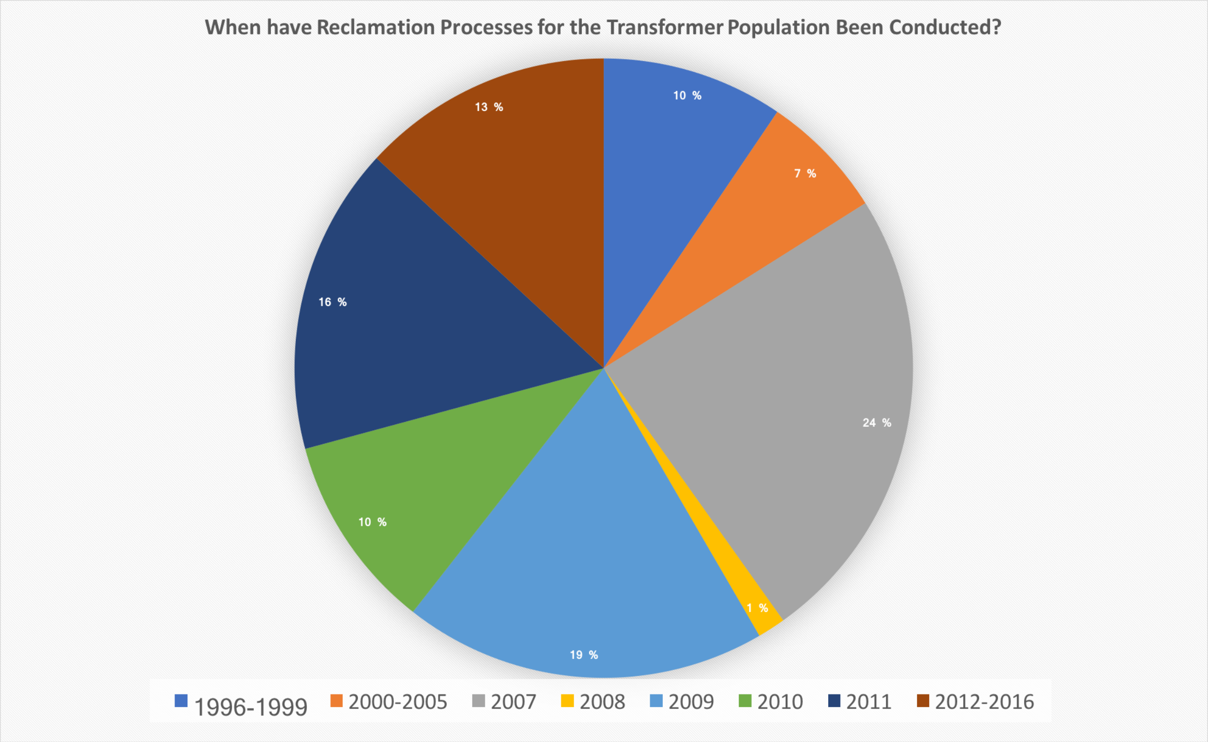

Figure 4.6: *The diagram shows what year the reclamation processes were performed.*

4.1.1 Restrictions and Assumptions in the Transformer Data

When working with big sets of transformer data some assumptions needs to be done in cases where some information and other parameters are lacking. The assumptions made during the analysis are listed below:

- No Difference in Quality of the Reclamation Processes

When companies decide they want to have a reclamation on the oil, it is assumed that all the different reclamation contractors provide the same quality in terms of results. The suppliers of the reclamation process, probably have different prices depending on the quality they provide. Since in most cases the contractor of the reclamation is not given, it is assumed they provide the same quality for the oil.

The length of each reclamation could show difference in the results achieved for the oil. Since this information is not available in most cases it is assumed that the oil has been circulated equally to a satisfying limit when the reclamation process was conducted.

- The Year the Transformer was Produced is Equal to the Year it was Energized

In very few cases the year for both the production and energizing year of the transformer are given in the data. In most cases, they are also the same. In consultation with some of cooperating companies in the "Trafotiltak"-project, they could confirm most transformers were energized straight away after production. Therefore, it is assumed that the production year equals the year the transformer was energized for all the transformers in this thesis.

- Other Measures Included in the Reclamation Process

The standard reclamation in Norway currently includes degassing and drying of oil while the filter is reactivated during the reclamation process. After the reclamation, inhibitor is also added to prevent oxidation products to return.

Usually the service data only includes information about what measure that was conducted, and not any details if some of the additional measures included in the standard process were skipped. For some older reclamation processes the standard process was a little different, but since there is no information on what measures that were included and not, it is assumed that all the transformers have been treated with the same standard process as being used today.

- Lack of Some Oil and Gas Parameter Data When Calculating HI-Scores

In some cases, there are some oil or gas parameters not measured in either the last oil or DGA sample before the reclamation process or in the first samples after the process is finished. In cases like this, the following principles have been followed:

1. In the case of a missing measurements of values in the first oil or gas sample after the reclamation process, the next available oil sample has been used. If the next available measure of the parameter is more than 2,5 years after the reclamation was conducted or not available at all, the parameter should not be included when calculating the HI-score before or after the measure.
2. In the case of a missing measurements of values in the last oil or gas sample before the reclamation process, the previous oil sample should be used. If the previous measurement of the parameter is more than 2,5 years older than the sample looked at for the other parameters the parameter should not be included when calculating HI-score before or after the measure.
3. If no measurement of an oil or gas parameter is available in the first sample after the reclamation process, and at the same time unavailable for the same parameter in the first sample before the reclamation process, the parameter is not included in calculating the HI-score.

- Old Oil and Gas Samples Before and After Reclamation

Optimally the oil and gas parameters should be measured right before and after the reclamation process by the contractor in addition to the check-up measurements taken some months after the process is finished. The problem in many cases is that this data is not stored together with the transformers owners own oil data which been received in many cases. This complicates the HI-scoring as the quantities in many are 1-2 years before or after the measure, which could lead to a different improvement than the actual result from a sample straight after the reclamation was conducted. When calculating the HI-score from the different reclamations it is assumed that the samples are taken straight before and straight after the measure.

4.2 Main Results from the Population Analysis on the Reclamation Measure

The transformer population described in chapter 4.1 will here be tested with the suggested “Trafotiltak”-model. The main results and analysis conducted in this thesis are based on the population data received from the companies. Most of these results can be found in the appendices. The HI-score before and after the measure of the 137 transformers experiencing a reclamation can be seen in Appendix B. The values for the different oil and gas parameters before and after a reclamation in addition to improvements for each parameter can be seen in Appendix C. The results of this analysis are mainly discussed in 4.3-4.5.

The estimated improvements are decided to be the median value of the improvement for each parameter. The median is defined as the value in the middle if you sort the values from smallest to biggest. This value can also be found when looking at the grey values in the graphs in Appendix C and finding the x-value where 50% of the population sees an improvement.

From Table 4.1 and 4.2 the main results of the extensive analysis on reclamation processes are presented. Table 4.1 shows the estimated improvements for the oil parameters, while Table 4.2 shows the estimated improvements for the different gas parameters. When deciding to do a reclamation in the CBA-model, the first column in these two tables show how much each parameter could be improved based on the analysed transformer population. The two other columns are also added to give the reader some more information about how well the reclamation process works on improving each individual parameter, and setting the expected improvements in context. The prolonged effects for each parameter will not be discussed here, but rather discussed in chapter 4.4.

Parameter	**The Estimated Improvements for the Population**	**% of Population with a Positive Effect from Reclamation of Oil**	**Prolonged Effect on this Parameter?**
BDV	5 kV	62,5%	No
Water Content in Oil	3,7 mg/kg	82,0%	No
Acidity	0,055 mgKOH/g Oil	95,5%	Yes
DDF	0,0363	100%	Yes
Colour	1,5	94,7%	Yes
IFT	20 mN/m	100%	Yes
Inhibitor	0,25%	99%	Yes

Table 4.1: *The estimated improvements after a reclamation for oil parameters, found from Figures C.1-C.7 in Appendix C.*

Parameter	**The Estimated Improvements for the Population**	**% of Population with a Positive Effect from Reclamation of Oil**	**Prolonged Effect on this Parameter?**
Hydrogen H_2	3,6 ppm	75,4%	No/Yes
Oxygen O_2	1000 ppm	53,5%	No/Yes
Nitrogen N_2	11245 ppm	78,4%	No/Yes
Methane CH_4	1,8 ppm	75,5%	No/Yes
Carbon Monoxide CO	150 ppm	87%	No/Yes
Carbon Dioxide CO_2	1616 ppm	94%	No/Yes
Ethene C_2H_4	19,2 ppm	81,2%	No/Yes
Ethane C_2H_6	2,6 ppm	73,0%	No/Yes

Table 4.2: *The estimated improvements after a reclamation for gas parameters, found from Figure C.8-C.15 in Appendix C.*

The results gained from the analysis of previous reclamation procedures are going to be used to test the CBA-model in two different case studies reviewing two different aspects of maintenance. This analysis will be illustrated in chapter 5.

4.3 HI-Outputs After Reclamation

In this part of the thesis different aspects mentioned in earlier chapters should be studied more closely, in addition to some of the results from the analysis. Some of the topics that will be highlighted are the HI outputs and improvements of the different parameters after a reclamation process.

As mentioned in chapter 4.1 the service data were somewhat lacking for most measures made at the contributing companies. The only measure worth analysing from all the service data, from the hundreds of transformers, was the measure reclamation of oil with a total of 137 occurrences. The HI-scores before and after from all these reclamation processes can be seen in Appendix B. Here the blue columns indicate the HI-score of the transformers before the measure, and the orange columns indicate the HI-Score when the reclamation processes are finished. Some of the results from Appendix B are interesting and needs to be addressed more closely. Especially the 3 possible HI outputs scenarios are going to be discussed in detail: An improvement in condition, a decrease in the condition and no change in the HI-score.

4.3.1 Achieving a HI-score of 100% After Reclamation

As seen from the results in Appendix B most transformers reach a HI-score of 100% after the reclamation of the oil. Only 20 out of 137 transformers, or 14,6% of the population, are not reaching a full HI-score after the reclamation. The remaining 117 transformers reaches a "perfect score" according to the health index. From a maintenance aspect, this is good indicator that the reclamation process of oil is a very solid and reliable action for improving the condition of the oil in a transformer.

On the other hand, it is important to mention that if a transformer reaches a HI-score of 100% after the reclamation measure it does not mean that it can be compared to a new transformer in all incidents. The values could be satisfying the limits sat in the standards by IEC or CIGRE, but still be high compared to other transformers with a HI-score of 100%. This can easily be seen when looking at Figure 2.3 in chapter 2.2.5, where the improvements of the oil indicators are showed during a standard reclamation process. The oil gradually gets better depending on how many times it is circulated through the filters and degassed. This proves that the oil could almost have all its oil parameters back as brand new if this is wanted, just by running the process for a longer period of time and a higher cost. For some reclamations found in service data, the oil parameter values were only brought back to fair values, while most reclamation processes were running until all the oil values were back in a good condition. There could be many reasons why they choose to only bring the oil back to fair values, but the most natural explanation is that the transformers only were going to be operated for a few more years before being replaced. The reclamation process will in this occasion just bring the oil values back to a level where the transformer could operate for these few more years before a new transformer is replacing it.

4.3.2 Achieving a HI-score Lower than 100% After Reclamation

As mentioned above there are a total of 20 transformers not reaching a HI-score of 100% after a reclamation. How these 20 transformers scored can be seen in the diagram in Figure 4.7.

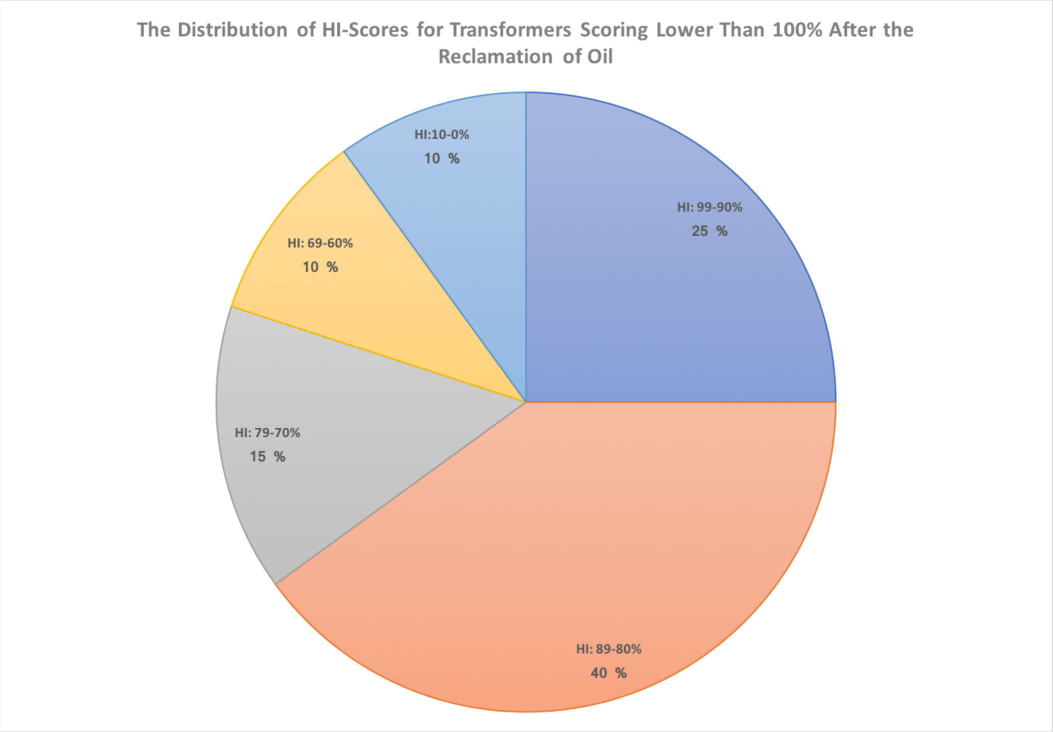

Figure 4.7: *The figure shows how the 20 transformers not reaching a HI-score of 100% after reclamation are distributed on the HI scale. As expected most of the transformers are close to a HI-Score of 100%, in the two groups 99-90% and 89-80%.*

Most of these transformers still scores close to 100%, but there are 7 transformers scoring lower than 80%. There is also a clear tendency on why these transformers score lower than 100%. 15 of the 20 transformers had their reclamation in 2001 or before, making them some of the oldest transformers in this analysis. There could be several explanations why the older reclamation processes scores bad, but the most natural one is that the process has become more efficient than it was back in the late 90s and early 00s. This was also confirmed by several of the companies attending in the "Trafotiltak" project.

In Figure 4.8 below it can be seen another explanation why some transformers are not able to reach a score of 100% after the reclamation. A lot of the transformers receives deductions because of their high gas concentration after reclamation. 68% of all deductions made after reclamations are due to too high gas concentrations. By combining this finding with the previous one, with old reclamations, it could be assumed that degassing during reclamation processes was not as effective before as it is today. It could also be the case that degassing was not included in the standard reclamation process like seen on the Norwegian market today.

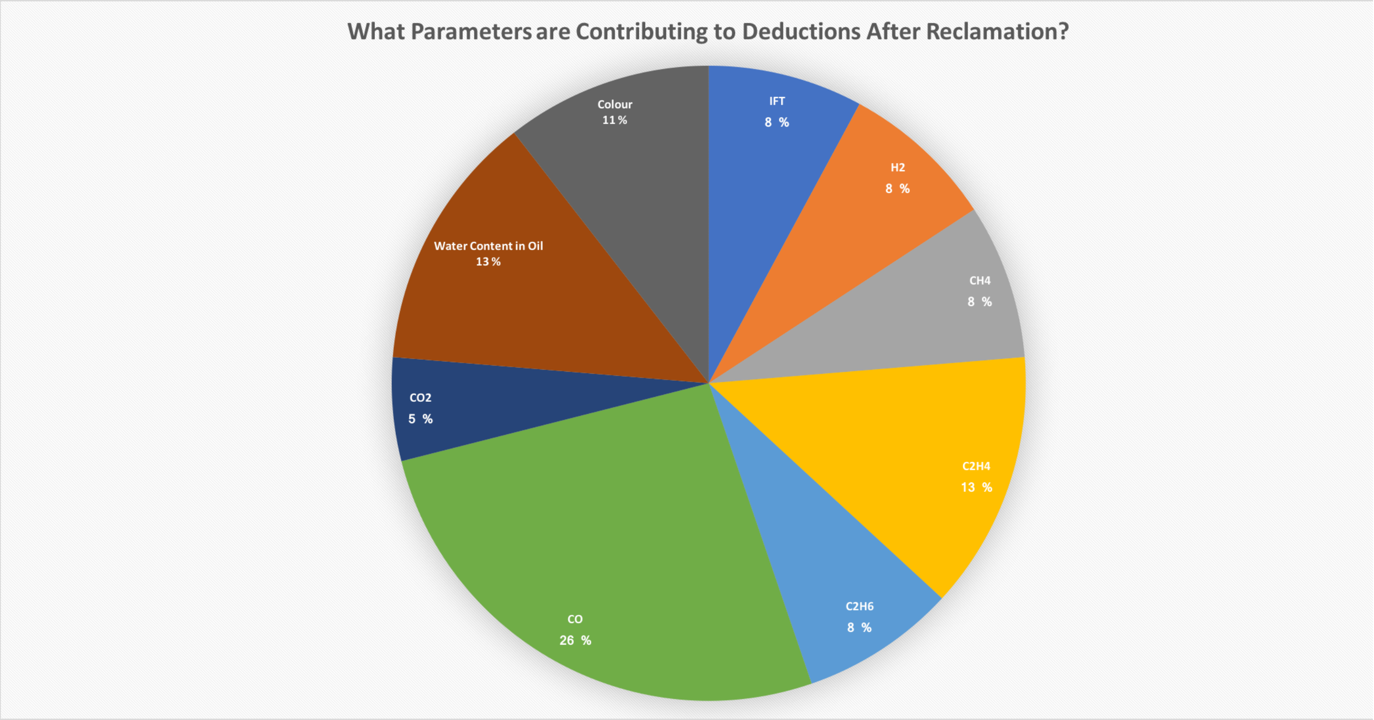

Figure 4.8: *Deductions after reclamation on transformers not achieving a HI-Score of 100% after the reclamation.*

From CIGRÉs report from 2002 [30] a research team from several countries working for ABB studied transformers in Northern Europe experiencing on-site oil reclamations. The study looked at several aspects of the reclamation process, including the long-term stability of the different parameters in the oil. Acidity and colour only saw small changes the first years after the reclamation measure, while water content in oil started to increase immediately after the process was finished. Within 3 years several transformers had the same water content as before the reclamation started, which was the same tendency as seen in this thesis. Transformers with a high concentration of water before reclamation would shortly after a reclamation process start to increase towards the same levels as before. This might be the reason why some transformers receive deductions for water content after the reclamation, if the first oil sample after the reclamation process is taken 1-2 years after the process. All the 5 transformers receiving deductions of water in oil after reclamation had too high water concentration before the measure. All the 5 transformers, also had the first oil sample taken 1,5-2 years after the reclamation was finished, indicating that in this short time-period the water content in the oil has returned to the previous value. From [30] there are two separate populations treated with reclamation of the oil. In the first population, the water content had already returned to its previous value after 3,5 years, or it did not get removed properly in the first place. The other population had its water content reduced to 25% of the original value but already 4,5 months after the reclamation process the water was back to 50% of what the concentration was before the measure. The observations made in this thesis together with [30] might indicate that the standard reclamation process should not be recommended as a long-term solution to improve the water content in oil of a transformer. Since water content is closely related to BDV reclamation is not recommended for improving this parameter either.

4.3.3 No Improvements in the HI-score After Reclamation

When deciding to improve the condition of the oil the last thing an asset manager wants to see are no changes, or even worse, negative changes. For the population in this thesis a total of 17 transformers that does not see any improvements in the HI-score after the reclamation. The transformers in this group can easily be divided into two different types of sets: the transformers having a perfect score of 100% before reclamation and transformers with a lower score than 100%. Of these 17 transformers, there are 10 transformers receiving a score of 100% before and after reclamation, while the last 7 transformers are receiving the same score below 100% as before the reclamation.

4.3.3.1 Seeing No Improvement with a HI-score below 100%

Figure 4.9 shows how these 7 transformers score.

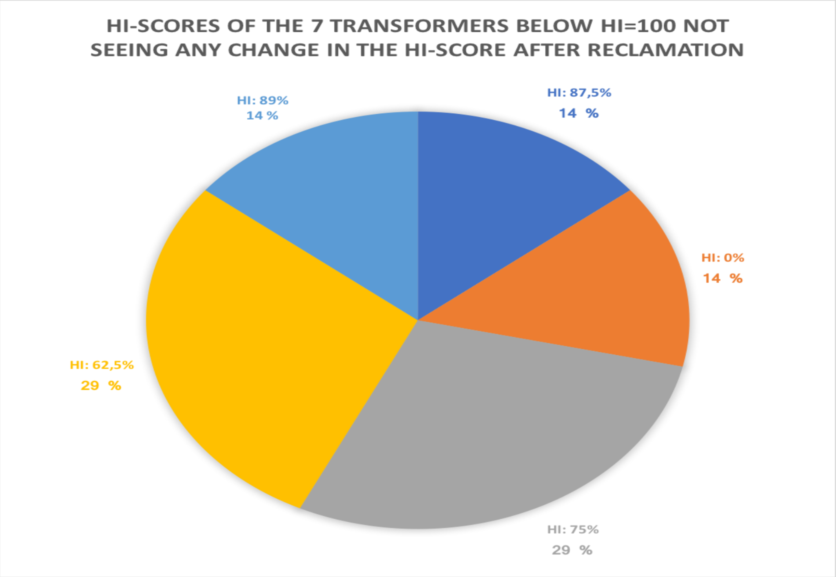

Figure 4.9: *HI-score distribution of the 7 transformers not seeing any change in HI-score before and after the reclamation measure.*

The 7 transformers were discussed in chapter 4.3.2 as being some of the transformers not reaching 100% after the reclamation, but here it is taken a closer look on what might have caused them not to have any improvements. There is only 1 out of 7, that was treated with reclamation of oil after the millennium in 2000. This was as late as in 2009, and the transformer received a deduction for IFT both before and after the reclamation. Even though the IFT had improved a little bit, as shown in Table 4.3, it is still a bit below the deduction limit sat by IEC for this oil parameter [8]. Except from the IFT and the inhibitor content all the limits are very good prior to the reclamation and all parameters show a slight improvement after. From chapter 2.2.5 and Figure 2.3 it could be seen that during the reclamation process the IFT and colour number were the two parameters taking the longest time to improve and often these two parameters decides when the process should end. Their main objective with the reclamation for this transformer was probably to refill the inhibitor, lower the gas concentrations and improve the IFT. When all the other parameters were improved without seeing that much improvement in the IFT, they probably made a calculated decision that the costs would be greater than the benefit by continuing the reclamation. After discussions with the company owning the transformer they agreed that this was probably decided in this specific case.

For the other 6 transformers in this category, the reclamation process was performed before the year 2000. These transformers are seeing big improvements for some of the parameters while other parameters stay high and keep the deductions at the same level leading to the same HI-score as before.

Transformer No.	Year Reclamation Measure	HI-Score Before and After	BDV [kV] (Before/after)	Water Content [mg/kg oil]	Acidity [mgKOH/gOil]	Dissipation Factor [%]	Colour	IFT [mN/m]	Inhibitor Content [% of Total Oil Volume]
T86	2009	87,5	84/83	4,2/4,3	0,05/0,01	0,0079/0,0029	1,5/1,0	23/25	0,08/0,42
T125	1998	0,0	-/-	80/18	0,14/0,06	-/-	3,0/2,5	-/-	0,04/0,4
T127	1999	62,5	30/60	40/43	0,01/0,12	-/-	7,5/6,0	-/-	0,07/0,26
T128	1999	75	84/70	75/78	0,07/0,02	-/-	2,5/2,0	-/-	0,04/0,32
T129	1997	75	-/-	50/70	0,09/0,05	-/-	2,5/2,5	-/-	0,03/0,28
T133	1999	89	86/79	16/14	0,02/0,05	-/-	3,0/3,0	-/-	0,04/0,36
T135	1999	62,5	67/70	70/55	0,09/0,02	-/-	4,0/3,5	-/-	0,03/0,31

Table 4.3: *Oil parameters before and after reclamation for the 7 transformers not seeing change and scores below 100% in the HI-score after a reclamation. Red values show deductions for parameters.*

Transformer No.	Year Reclamation Measure	HI-Score Before and After	Hydrogen H_2 [ppm] (Before/After)	Methane CH_4 [ppm]	Carbon Monoxide CO [ppm]	Carbon Dioxide CO_2 [ppm]	Ethene C_2H_4 [ppm]	Ethane C_2H_6 [ppm]
T86	2009	87,5	42/9	8/2	425/70	2656/913	32/1,4	10/1
T125	1998	0,0	177/153	271/354	741/651	15161/7415	1416/1277	238/166
T127	1999	62,5	26/21	30/10	1109/1143	11128/7698	16/115	10/5
T128	1999	75	17/7	6/4	267/172	2852/2043	35/61	2/1
T129	1997	75	5/78	1/10	517/578	3294/8469	4/21	8/3
T133	1999	89	14/31	24/37	798/798	3418/3402	52/108	10/9
T135	1999	62,5	46/43	33/17	485/559	-/3698	69/294	42/6

Table 4.4: *Gas parameters before and after reclamation for the 7 transformers not seeing change and scores below 100% in HI-score after a reclamation. Red values show deductions for parameters.*

Table 4.3 and 4.4 shows all the oil and gas parameters for the 7 transformers. As discussed in chapter 4.3.2 there are a lot of high gas concentrations both before and after for the oldest reclamation processes. This can strengthen the argument that degassing either was not part of the process for older reclamations or it was much less effective than today. Also, many of the oil parameters seem to shrink less on these older transformers compared to more modern processes, which could indicate that the process also has become much more efficient for this part of the process. This can especially be seen on the colour parameter, which for more modern reclamation processes reaches colour numbers of 1,0 or 1,5 while in this case they are only able to improve them a little bit from its original value.

4.3.3.2 Reclamation of Oil Before Deductions are Made?

As mentioned 10 transformers are having a HI-score of 100% both before and after a reclamation. Why would the companies want to use a lot of assets on a transformer that, based on its oil and gas data, are in a pretty good condition? The companies answered that they have several reasons for doing this:

- The IEC standards are just a recommended limit for executing deductions, and if the company feel that the limits are too high for what they are comfortable with, they make an overall decision based on the oil data and then decide. Gas and oil values could still be bad and have several values close to the deduction limits without receiving any deductions. If they wait some years before performing a measure many of the parameters could have dropped below the deduction limit and it will receive a HI-score much lower than 100%. All the 10 transformers have the inhibitor content in the poor category recommended by the IEC. This could also be an incentive for doing the reclamation process as a part of the job due to refilling inhibitor to stop further oxidation in oil. In all the 10 cases the IFT is close to the first deduction limit.
- In some cases, several transformers are located at the same place. If a transformer at a location already needs to improve the oil by having its oil reclaimed it could be beneficial to perform reclamation on all the transformers here considering transportation and operator costs of the equipment.
- By performing a reclamation process early, it could prevent the insulation paper from being damaged. While oil could be restored to almost new conditions through a reclamation process, insulation paper is almost impossible to improve once its damaged. In many cases if the paper is degraded too much it is easier and more

beneficial to just change the whole transformer than to change the paper. By doing the reclamation early and before the oils condition can affect the paper, it reduces the chance of paper damage considerably.

- In some cases, the power transformers have such an important location in the power grid, that it is essential to keep them in a good state all the time. This is often the case for power transformers located near the city centres. These transformers are often located in groups, with backup transformers if the main transformer should experience a breakdown. When one of these need maintenance measures like reclamation it is normal to also perform it on the other transformers to make sure they always have good transformers in backup.

4.3.4 Negative Results After Reclamation

This is the worst-case scenario for an asset manager while trying to conduct maintenance on the transformers. When doing any sort of maintenance, the condition is minimum expected to improve, or at least stay at the same level and extend any further degradation. Of the 137 transformers receiving reclamation of the oil there is only one transformer receiving a lower HI-score after the process is finished than it had before.

This transformer is T121 according to the tables in Appendix B. Before the reclamation process the transformer received a HI-score of 50%, where it got big detections of both water content in oil (-25%) and IFT (-25%). It also receives big detections for gases, but only -46% in total for 4 different gases (-4% CH_4, -4% CO_2, -34% C_2H_4 and -4% C_2H_6). This makes the oil parameters the deciding factor on the HI-score and the final score is 50%. But after the reclamation, all the oil parameters are within very good levels, not receiving any deductions, while some gas parameters have increased a lot making a total deduction of gas to be -100% (-34% CH_4, -50% C_2H_4 and -21% C_2H_6). This makes the HI-score 0% after the reclamation process, which is a little strange.

The most natural explanation of these high values is that an electrical or thermal fault has happened within the transformer, causing it to have high gas values both before and after reclamation. The company has also commented in the service data that they are unsure what really happened here, but indicate that most likely a thermal fault has occurred. According to Table 2.1, with the ratios between gases and faults, the ratio of this transformer could indicate a thermal T3 fault has happened. The ratio between the two hydrocarbons C_2H_4/C_2H_6 for the transformer is 6,77 and all ratios above 4 is a sign of a T3-fault according to Table 2.1.

As described in IEC 60599 [20] a transformer that had experienced a thermal fault could have its gas values lowered with a degassing measure or a reclamation with degassing combined in the process. But the high gas values would soon return due to the previous fault in some cases, as described in chapter 2.1.2. The newest gas sample prior to the reclamation was 2 years old. And the newest gas sample after the reclamation process was two years after. This could conceal that the thermal gas values are returning to the concentrations they had just before the reclamation. Gas values before reclamation could have been close to -100% in deductions, but the numbers are not recorded. It is commented in the service data after the first gas measurement that the gas values are stable and the gas are increasing, but not that drastically even though they are high. When a transformer has experienced a thermal fault, it is not unusual that gas values return to its previous values, but if the amount is stable and not increasing too much, it is not critical. This shows how important new supplementary equipment like constant DGA sampling could be to avoid uncertainty around high gas concentrations. The constant DGA sampling gives easy access to gas data and faults, either thermal or electrical, could be detected much faster than taking samples manually every 1-2 year.

4.4 Estimated Improvements from Reclamation of Oil

In this chapter, the results and improvements of the previous reclamation processes conducted on Norwegian power transformers are studied and discussed. All the transformers studied are owned by the cooperating companies in the “Trafotiltak”. A possible pattern in the parameters for the reclamation process could be found, e.g. how much each parameter is estimated to improve. The oil and gas parameters not seeing any big improvements are also going to be located here.

All the available measurements, both before and after the reclamation process, of the 137 transformers are put in an individual graph. This is to better visualize improvements of each parameter during this maintenance measure. The method used is a cumulative presentation based on the theory from distribution function (CDF), which adds up the amount of the total population having a specific value or below this value. The method is described more detailed in Appendix E. The results and improvements of each oil and gas parameter are showed in Appendix C, in Figure C.1-C.15.

4.4.1 Estimated Improvements Oil Parameters

In this section, the different oil parameters are studied closer to see the affect that the reclamation process has on each individual parameter. The results can be seen in Appendix C, in Figure C.1-C.7.

4.4.1.1 Breakdown Voltage, BDV

This is a very unpredictable parameter which needs to have the right conditions during measuring or the results will vary from time to time. Results can be seen in Figure C.1 where as much as 37,5% of the transformers have no improvements or a decrease in the BDV value after the reclamation. The next 35% only have an increase between 1-10 [kV] after the improvement, which is not a good result. From these results, it can be concluded that the BDV is a parameter not improving much after a reclamation from the data available in this thesis. This also corresponds well to CIGRÉs analysis in [30] where both the BDV and water content did not see any big improvements after reclamation. These two parameters also have a close relationship, and if one of them have a poor value, usually the other parameter is poor as well.

Table D.1 in Appendix D show the recommended values on what should be the min./max. values of different oil parameters for oil added to new transformer equipment. The minimum value for BDV in new equipment should be 55-60 [kV] depending on the transformer voltage categories described in Table 3.3. This show that only 2,5% of the transformers are at this limit or below after the reclamation. It should be emphasized that 55-60 kV is the minimum, and that values in oil added to new equipment should be much higher than this. Still the oil after a reclamation would be considered good enough to be added in new transformer equipment in most cases for this parameter.

4.4.1.2 Water Content in Oil

This is also a very unpredictable parameter like the BDV. Figure C.2 show that 18% of the transformers see no improvement or a negative change after the reclamation. 87,5% have a concentration of 5 ppm or below after the reclamation process, which is good, but the last 12,5% are very evenly spread out. By studying the values the first years after the reclamation the transformers with high concentration of water tend to return to their previous values 2-3 years after the reclamation process. For some of the older transformers the first measurement of the oil parameters is 1-2 years after the treatment, and then the water content has already returned to its previous concentration. This can explain why in some cases the water content are extremely high. From [30] they also studied several transformers and found that water content could be decreased to satisfying levels, but would soon return to old levels as found in this thesis. Table D.1 shows that the level of maximum water concentration of oil in new transformers are between 10-20 ppm depending on the voltage level. Studies of the transformer population in this thesis, show that 85-95% of the transformer satisfies this limit and scores below this maximum after the reclamation.

4.4.1.3 Acidity

Acidity is one of the most important parameters to improve due to its impact on the insulation paper when getting too high. Figure C.3 shows that 95,5% of the transformers experience a positive impact from the reclamation process. From [22] it is decided that the acidity should be 0,01 or lower after the reclamation process. About 81% of the transformers are 0,01 or lower after a reclamation according to the data set. Some of the measurements above this limit have been recorded sometime after the reclamation process was finished and not straight after, making room for some error. Table D.1 allows the acidity to be maximum 0,03 mg_{KOH}/kg_{oil} when adding oil to a new transformer. Figure C.3 show that 92% of the transformers have this value or below after a reclamation.

4.4.1.4 Dielectric Dissipation Factor (DDF)

The dielectric dissipation factor is an easy parameter to improve with a reclamation process. From Figure C.4 all the transformers are improved by the process and that almost all the transformers have the exact same value after the reclamation process. As many as 99% of the transformers also score below the maximum limit set for oil in new transformers of 0,015 from Table D.1, proving that the reclamation process is decent when trying to improve the DDF values.

4.4.1.5 Colour Number

The colour number should improve a lot from a reclamation process since waste products and sludge are removed from the oil through purification filters. From Figure C.5 it can be observed that no transformer experiences a negative effect in the colour number from the reclamation process even though 7 transformers (5,3%) sees no improvement in the colour number. According to the standards for oil in new electrical power equipment made by IEC [8], showed in Table D.1, the colour number should be maximum 2,0 at energization of new equipment. From Figure C.5 it can be spotted that around 90,2% of the transformers have 2 or lower for the colour number after reclamation. Before reclamation only 16,5% of the transformers had a colour number of 2 or lower showing a good improvement of this parameter overall.

4.4.1.6 Interfacial Tension (IFT)

This is maybe one of the few oil parameters which solely sees improvements after the reclamation process. When looking at Figure C.6 the improvement curve almost overlaps the values from before reclamation, meaning that IFT almost doubles from what it was before the reclamation. The IFT after reclamation is recommended to be at minimum 35mN/m according to [22], which means only 4,4% of the transformers are too low after the reclamation. This is also the minimum limit for oil in new transformer decided by IEC in Table D.1. This is a good improvement considering IFT is the parameter that takes the longest time to improve with a reclamation process. Before the reclamation process all the transformers scores below 35mN/m, which proves that the reclamation process really helps for this parameter.

4.4.1.7 Inhibitor Content

This is not the most exciting parameter since it is not included as a deduction parameter in the HI-module of the "Trafotiltak" model. But the interesting thing about this parameter is the level the companies let this parameter drop to before refilling it and how much they refill it with after the reclamation. According to REN [22], described in chapter 2.2.1, the amount of inhibitor should be between 0,3% and 0,4% of the total oil volume. From Figure C.7 in Appendix C around 30% of transformers are below 0,3% inhibitor content after reclamation. Some of these transformers could have been refilled to 0,3% and then the next recorded measurement is taken 1-2 years after, but then the content should not have been reduced much. Inhibitor content of 0,26% or below should take consideration for some late measurements and means that all transformers at this value or below are not refilled to a satisfactory level. This means 6,2% of the transformers are refilled with inhibitor content that is too low according to the standards. On the opposite side, there are around 8,5 % of the transformers having an inhibitor content that is too high, above 0,4%, after reclamation. This means that about 14,7% of all transformers ends up outside the recommended limits after a reclamation process.

Around 50% of the transformers have an inhibitor content of 0,06% or lower when the reclamation process is engaged. This is well below the lowest scoring category decided by the IEC standard [8], which has the poor category at 0,14% and lower. When as much as 50% of the transformers are well below this limit, oxidation processes have started a long time ago as seen by the acidity content in most of these transformers before reclamation. According to chapter 2.2.1, oil which have used up most of its inhibitor will age faster than oil that never had inhibitor added. This means that it is important to not let the inhibitor content sink as low as it have in many of these incidents. A low inhibitor content could also lead to degradation of the insulation paper and lead to breakdown of the transformer.

4.4.2 Estimated Improvements of Gas Parameters

In this section, the improvements of the reclamation process for different gas parameters included in a normal DGA sampling are going to be studied. In addition to the gases included in the "Trafotiltak" model, oxygen and nitrogen are also studied here due to their importance of detecting thermal and electrical faults in the industry. The cumulative distribution plots of the different gases can be seen in Appendix C, Figure C.8-C.15.

4.4.2.1 Hydrogen (H_2)

Hydrogen is a common gas in a transformer, but not in great amounts. From Figure C.8 the concentration of hydrogen both before and after tends to be below 50 ppm, apart from some extreme values. After reclamation as many as 75% of the transformers are below a concentration of 15 ppm, which is good compared to the first critical limit for hydrogen being at 100 ppm [14]. From the graph, it is also clear that transformers are not reaching the critical limit of 100 ppm very often. Only 7 transformers breach the 100 ppm limit before the reclamation process, while only 3 transformers after the process breach this limit. All the 3 transformers over 100 ppm after reclamation are transformers with older reclamation processes from 1998, 2000, and 2001. Like discussed in chapter 4.3.2 the older reclamation processes have a bigger gas concentration after the reclamation process, and this may be due to the lack of degassing during reclamation.

When studying the grey line in Figure C.8 the number of transformers improved by the reclamation can be found. In general, the number of transformers having a higher gas concentrations after the measure than before are higher for gases than for the oil parameters. This is due to the poor degassing of many of the earlier reclamations, but also that many of the companies do not have a record of the gas values straight after the reclamation process, as performed for the oil parameters, but sometimes measures it 1-2 years later. For hydrogen, the proportion of transformers seeing no change or a negative trend after the measure are around 25%.

4.4.2.2 Oxygen (O_2)

As mentioned in the intro of this section, the improvements of oxygen are mainly going to be used for finding thermal and electrical faults in the industry. The problem with oxygen is that the concentration within the transformer is normally very high. A poor gasket or poor ceiling during maintenance could lead to a considerable increase in oxygen. Also, if the transformer has an open conservator the oxygen concentration could be very high. For this reason, the number of transformers having an increase in concentration after the reclamation process are higher than for other gases. From Figure C.9 the grey line shows that around 45% of the transformers sees no improvement, or has a negative trend when the oxygen levels are considered.

4.4.2.3 Nitrogen (N_2)

Like oxygen the improvements of nitrogen are mainly analysed here so the results could be used to find thermal or electrical faults through ratios between gases. As for oxygen, nitrogen concentrations are high during normal operations, but could increase drastically. From Figure C.10 the grey line shows that around 22% of the population have no improvement or an increase in the amount of nitrogen within the transformer.

4.4.2.4 Methane (CH_4)

Methane is one of the gases that can receive deductions in the "Trafotiltak" model, but deductions of this gas are very rare. Most transformers have a concentration way below the first critical limit of 80 ppm according to [14], as seen in Figure C.11. There are only in total 3 transformers over 80 ppm before reclamation and 3 transformers over this limit after reclamation. Two of the transformers have both deductions before and after reclamation for this gas. One out of these two is the transformer studied in chapter 4.3.4, that has deductions of gases due to a thermal fault. The other of these two transformers had the reclamation process in 1996 and the concentration may be due to poor or lack of degassing during the process. This is also the case for the last transformer having a high concentration of methane after the reclamation process, which had reclamation performed on the oil back in 1999. The last transformer with high methane concentration before the measure had reclamation of oil in 2009, but the reclamation process was successful in this case, and the transformer did not receive deduction after the reclamation. As described in Figure C.11 the transformers reaching the critical limit of 80 ppm are removed to better see the overall improvements.

From the figure, there are no big differences from before and after reclamation, with around 26% of the transformer seeing no improvement or a negative effect of the reclamation.

4.4.2.5 Carbon Monoxide (CO)

Carbon monoxide has a good response to the reclamation process overall. Several of the transformers have small deductions of this gas before reclamation measures are conducted. The first critical limit for CO is at 500 ppm. From Figure C.12 it is possible to spot that around 19% of the population gets deductions of the CO gas before the reclamation, while after only 7% get deductions. This is still a big amount of the population, and from Figure 4.8 carbon monoxide represents 26% of deductions given after a reclamation process. The reasons for high CO-concentrations could have many explanations:

- This gas could be the fastest gas to return to its previous state after a reclamation process, if the check-up DGA is taken later than it should.
- It is more difficult to remove CO-gas from the oil compared to the other gases.
- CO is not considered as the most threatening gas to the condition of the transformer, and maintenance workers do not focus on getting it as low as possible.
- The standard [14] have a too low limit for first deduction of this gas, and should be moved higher

All the above are valued points, but several of the companies included in the project could confirm that CO-concentrations were not their biggest priority when looking at the gas concentrations. This combined with late measurements after reclamation and a low first critical limit makes it a gas that often gets deductions. However as mentioned in chapter 2.1.2 high CO and CO_2-concentrations could be an early sign of paper degradation that should be taken seriously. From Figure C.12 the grey improvement line shows that around 13% of transformers have no improvement or a negative effect for its CO-concentration after the reclamation process.

4.4.2.6 Carbon Dioxide (CO_2)

Carbon dioxide has a better response to the reclamation than its close related name brother, carbon monoxide. The overall deductions, both before and after the reclamation, are fewer than for CO. Compared to CO, carbon dioxide usually have a much bigger concentration within the transformer. This can also be seen from Table A.1, where the first critical limit for CO_2 is at 8900 ppm. From Figure C.13 it can be spotted that in general very few transformers reaching this limit both before and after the reclamation. Before the measure around 16% of the transformers exceeds the limit of 8900 ppm, but after only 1,5% of the transformers have a concentration of 8900 ppm or more. From Figure C.13 around 6% of the transformers in the population are not seeing any improvements or experienced a negative effect in the CO-

concentration after the process. From Figure 4.8 it can also be seen that CO_2 are responsible for only 5% of deductions made after the reclamation process compared to 26% for the CO.

4.4.2.7 Ethene (C_2H_4)

Looking at Figure C.14 reclamation looks to have some impact on the ethene concentration in the transformer, but not much. The first critical limit for C_2H_4 is at 89 ppm, and before reclamation around 14% of the transformers gets a deduction for this gas. After the measure, around 8% of the population get a deduction. This is not the best reduction, and from Figure 4.8 C2H4 is the biggest reason for deduction after a reclamation except from carbon monoxide. Figure C.14 shows that around 19% of the transformer population sees a negative effect or have no improvement in the ethene concentration after the measure.

4.4.2.8 Ethane (C_2H_6)

Ethane concentration is like the ethene showing some improvement, but not too much. From Figure C.15 around 27% of the transformer population sees no improvement in the ethane concentration, or even worse sees a negative effect after the reclamation. According to Table A.1 [14] the first critical limit for ethane is at 47 ppm. From Figure C.15 it can be observed that 7% of the transformers are above this limit before the maintenance measure, and only 2% of the transformers exceeds this critical limit after the reclamation measure.

4.4.3 General Improvements and What to Expect When Performing Reclamation on Oil

In this section, some of the findings from the oil and gas parameters discussed in chapter 4.4.1 and 4.4.2 are listed in Table 4.5 and 4.6. The numbers in this table could be used to calculate the improvements of the condition in a cost-benefit model, where Table 4.1 and 4.2 are a summary of these tables as showed in chapter 4.2.

Parameter	The Estimated Improvements from Reclamation	% of Population with Positive Effect from Reclamation	REN's Recommended Limits and % of Population Reaching this Limit [22]	% of Population Reaching IEC Limits for New Transformers [8]	Prolonged Effect on the Parameter?	Is the Reclamation Process Improving this Parameter?
BDV	5 kV	62,5 %	-	97,5%	No	No
Water Content in Oil	3,7 mg/kg	82,0%	-	85-95%	No*	Yes*
Acidity	0,055 mgKOH/g Oil	95,5%	0,01 (80,6%)	92%	Yes	Yes
DDF	0,0363	100%	-	99%	Yes	Yes
Colour	1,5	94,7%	-	90,2%	Yes	Yes
IFT	20 mN/m	100%	35 mN/m (95,4%)	95,5%	Yes	Yes
Inhibitor	0,25%	99%	0,30-0,40 % (78%)	-	Yes	Yes**

Table 4.5: *Listed improvements from the reclamation process for the typical oil parameters measured in an oil sample.*

Parameter	The Estimated Improvements from Reclamation	% of Population with Positive Effect from Reclamation of Oil	Prolonged Effect on the Parameter? ***	Is the Reclamation Process Improving this Parameter? ****
Hydrogen, H_2	3,6 ppm	75,4%	No/Yes	Yes
Oxygen, O_2	1000 ppm	53,5%	No/Yes	Yes
Nitrogen, N_2	11245 ppm	78,4 %	No/Yes	Yes
Methane, CH_4	1,8 ppm	75,5%	No/Yes	Yes
Carbon Monoxide, CO	150 ppm	87,0%	No/Yes	Yes
Carbon Dioxide, CO_2	1616 ppm	94,0%	No/Yes	Yes
Ethene, C_2H_4	19,2 ppm	81,2%	No/Yes	Yes
Ethane, C_2H_6	2,6 ppm	73,0%	No/Yes	Yes

Table 4.6: *Listed improvements for the reclamation process for the typical gas parameters measured in a DGA sample of the transformer oil.*

From Table 4.5 and 4.6 there are a few things that should be explained. The stars (*) shows where in the tables the discussions are centred:

The Prolonged Effect on Water Content in Oil (*):

From Table 4.5 it can clearly be seen that in many cases the water content does decrease, but not much with just below 4 ppm as the estimated improvement. So, for a short-term perspective the water content in oil could be improved, but in the long run the water content would soon return to its previous state. This can also be seen in the service data received from the companies in this thesis, but is also supported by CIGRÉs report [30]. This report indicates that for high water contents in oil, reclamation is not a long-term solution, but rather a short-term solution.

The Prolonged Effect on Inhibitor Content (**):

The reclamation process normally includes the addition of inhibitor after the process is finished. The reclamation does not improve the parameter directly, but because of the purification process, the inhibitor is refilled and indirectly the reclamation improves this parameter.

Prolonged Effect on Gas Parameters (***) and Reclamation Process Improvement on Gas (****)

From the results, it can be observed that for most reclamation processes the gas content of different gases are improved by degassing the oil. The problem is how the gases have emerged in the oil. If the gases have emerged from normal ageing processes the degassing process included in the reclamation process is a perfect measure to make sure the content is lowered to recommended limits. If, however the gases in the oil are due to a thermal or electrical fault the values would very soon return to the high levels they were pre-reclamation. In this case, the reclamation process would only work as an antifebrile measure for the transformer and would not have any long-lasting effects. This would also ruin the diagnosis as the reclamation process removes most of the gas, and it can be difficult to trace the location of the fault.

For this reason, many transformer owners do not like the reclamation process and how the degassing procedure might trick them to believe the transformer is in a better state than what really is the reality. Therefore, the gases have both “No” and “Yes” as a prolonged effect depending on the cause of the gas.

4.5 Reclamation of Oil vs. Refilling Inhibitor as the Best Alternative

Even though reclamation has showed to be a great measure considering improvements on several parameters, it is still discussed by transformer owners if it is the best alternative in every case. As seen in chapter 4.3. not all transformers are having a bad HI-score before they are reclaimed. For some of these transformers the low inhibitor content could have been resolved by only refilling the inhibitor and not having a full standard reclamation process performed on the oil. The contractors of the oil samples will in many cases where a transformer has a low inhibitor content suggest that the transformer owners perform a reclamation of the oil. This is in their interest since most of these contractors also conduct the reclamation processes of the transformers. In many cases where there is a doubt the asset manager should look at the numbers himself and make a weighted decision based on both the recommendations from the contractor and the service data available.

From a study [31] conducted in Canada the difference in ageing/oxidation of oil, for different maintenance strategies were studied by accelerating the ageing in the lab. From Figure 4.10 and 4.11 some of the main results are presented. As the legend on the side of Figure 4.11 explains, the blue line represents an oil in a new transformer. This oil is being used as the reference in this experiment. The green line symbolizes a used oil that has been reclaimed by the standard reclamation procedure once the inhibitor content was consumed. The red line shows the same oil as the green line, only this sample did not have a reclamation, just had its inhibitor refilled once it was consumed. The last line, the orange line, shows the same oil as both the red and the green line only this sample was aged longer after the inhibitor was fully consumed, and then reclaimed and refilled with an inhibitor. The ageing after the inhibitor was consumed did more damage than for the others to the insulation materials. Based on the theory this would make this oil age faster once the measures are conducted, which also happens when looking at the figures below.

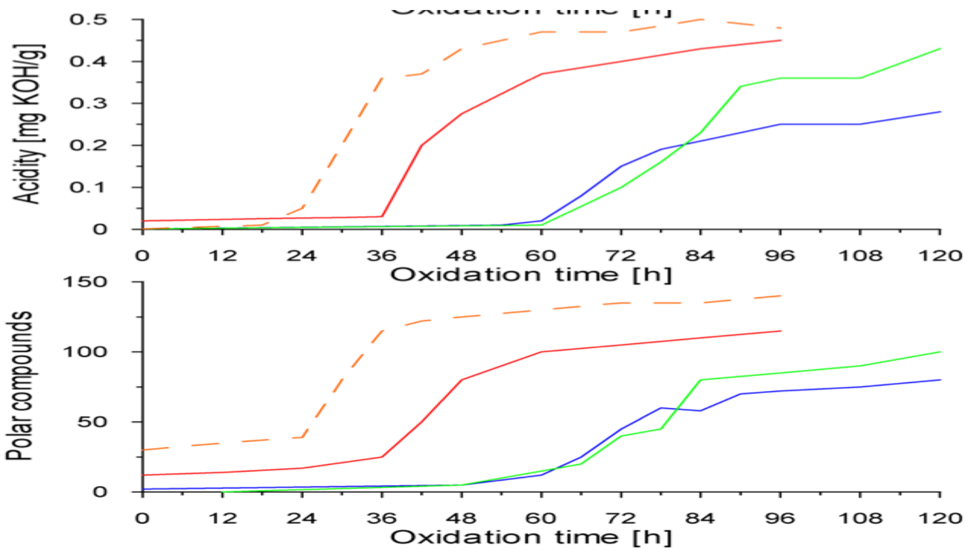

Figure 4.10: *The figure shows the evolution of acidity and polar compounds during ageing/oxidation of oil which have experienced different types of maintenance measures [31].*

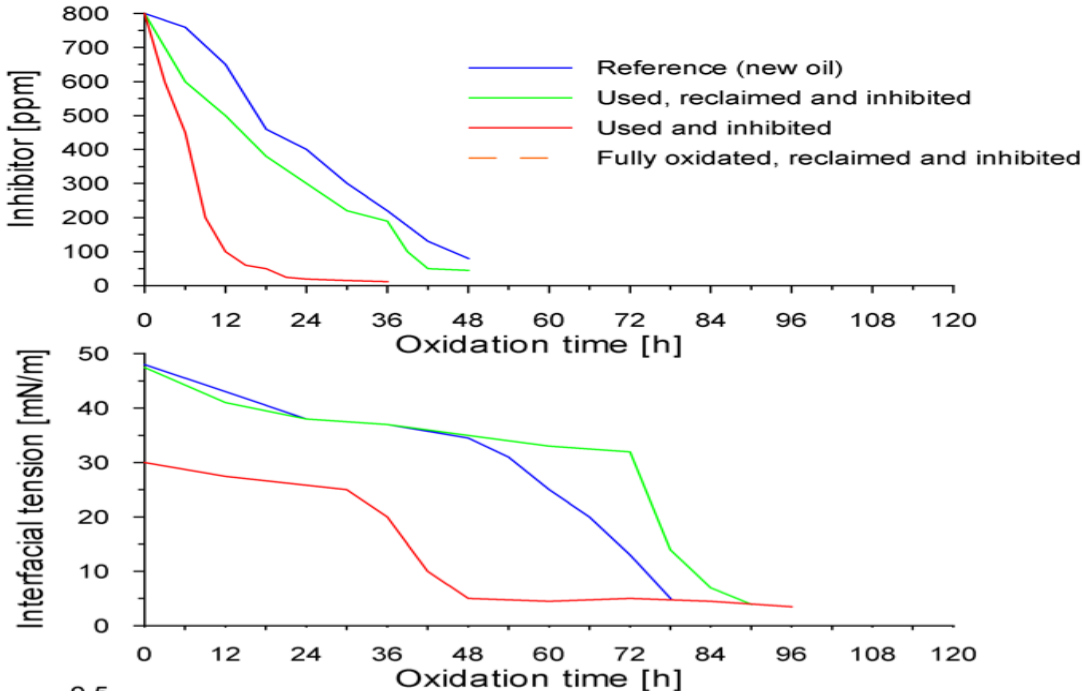

Figure 4.11: *This figure shows the evolution of inhibitor content and the interfacial tension (IFT) during ageing/oxidation of different types of oil [31].*

From the figures, there are a few things that should be commented on regarding choosing inhibitor or reclamation as the best measure for improving oil. First, it is important to remember that this was an experiment performed in a lab and not a real study performed on standard operating transformers. This allowed the oxidation and ageing processes to go faster than ageing processes for a normal transformer. In Figure 4.11 the inhibitor content for the different oils can be seen in the uppermost graph. As expected the inhibitor of the reference and reclaimed oils decrease slower than the oil with only the inhibitor refilled. This are due to the ageing products already appearing in the oil making the consumption of inhibitor faster than for the two others. By the 12 hour mark the inhibitor content for inhibited oil (red) is already very low. By this time, the oxidation processes start to develop and when the inhibitor have been fully consumed at around 36h, and the formation of acidity and polar compounds skyrockets for the red line, making the IFT decrease drastically.

For reclaimed oil and new oil, it can be observed that the ageing processes takes way longer to start since the inhibitor content is not being consumed as fast here. But once the inhibitor content is gone, the same processes happens as for oil only refilled with inhibitor. The test also reveals that reclaimed oil is almost as good as the reference oil. The inhibitor is consumed a little faster for the reclaimed oil than for the reference. For the IFT the reclaimed oil scores much better than the reference oil. However, the two graphs in Figure 4.10 shows that the reclaimed oil get more polar compounds and acidity within the oil compared to the reference oil as times passes. This reveals that even though the reclamation measure improves the oil to a level where it can be considered as new, the oil is still older than the new oil and this would affect the oil more once it passes a certain point in the ageing process.

The conclusion from this report was that if the inhibitor content did not get too low and allowed the formation of acidity within the oil, all the oils would have a similar ageing process. This could mean that for transformers with used oil and a low inhibitor content, a better solution than a reclamation measure could be just refilling the inhibitor. This only implies when the formation of acidity, copper content and polar compounds still are at a low level [31]. The results from this case are interesting and are one of the reasons why it is so important for asset managers to keep the inhibitor content within satisfying levels. As explained in [31] the transformers should not be allowed to age after their inhibitor content is consumed as seen for the orange line. This makes the reclamation process not effective at all, and no real improvements are made for the condition.

4.5.1 Study on the Inhibitor Refill Solution vs. Reclamation of Oil

As described in [31] and statements from the transformers owners, some transformers may have been reclaimed too early and instead an inhibitor refill could have been a more suiting solution. To examine this, the 10 transformers getting a reclamation before receiving a deduction in the HI-score, and seemingly having a perfect condition, are studied closer here.

The oil parameters for the 10 transformers not receiving deductions had the following measurements taken before the reclamation process:

Transformer No.	Inhibitor Content [% of Oil Volume]	Acidity [mgKOH/g Oil]	Interfacial Tension (IFT) [mN/m]	Water Content [ppm]	Oxidation Index [IFT/Acidity]	Years Old at Reclamation Point	Satisfying Requirements for Refilling Inhibitor?	Satisfying Requirements for Reclamation?
1	0,04	0,06	29,5	5,3	492	42	Yes/No	Yes
2	0,10	0,04	30	4,4	750	30	Yes	No
3	0,11	0,03	32	7,6	1067	36	Yes	No
4	0,08	0,03	-	4,9	-	29	Yes/No	No
5	0,04	0,13	29	10,2	223	32	No	Yes
6	0,14	0,04	29	5,4	725	44	Yes	No
7	0,05	0,07	29	10,8	414	41	Yes/No	Yes
8	0,12	0,02	32	1,8	1600	45	Yes	No
9	0,12	0,06	29	3,1	483	38	Yes/No	Yes
10	0,09	0,03	29	6,2	967	33	Yes	No

Table 4.7: *The oil parameters for the 10 transformers which have had its oil reclaimed before receiving deductions.*

Comparing the numbers in Table 4.7 against the recommended limits for refilling the inhibitor or reclaiming the oil, explained in chapter 2.2.1 and 2.2.5, there are a few things that should be mentioned.

- Transformer 8 should have had its oil refilled with inhibitor instead of having a reclamation. First of all it had the lowest acidity of all the 10 transformers. It also had the joint highest IFT measurement of the transformers. From RENs recommendations in [22] it is also recommended that transformers that are 45 years and older should be refilled with inhibitor even though service data might suggest that the transformer need a reclamation. As seen in Table 4.7, transformer 8 is the only transformer that has passed this age. So, if the oil parameters would have been worse, refilling of the inhibitor should still have been selected as the right measure according to REN anyway.

- From [25] it is suggested that the oxidation index, the relationship between the IFT and the acidity, should decide when it is time for a reclamation. If the oxidation index is equal to 300 or below then reclamation should be considered. From Table 4.7 the only transformer that is within this limit is transformer 5. Considering the low age and the high acidity levels in this transformer reclamation was probably the right decision here.

- For the remaining transformers number 2, 3, 6 and 10 should have been refilled with inhibitor together with transformer 8 based on their low acidity, relatively high inhibitor content and IFT. 6 and 10 have an IFT value just below the recommended limit for inhibitor refill, but the other parameters are much better than the recommendations.

- Transformer 1, 4, 7 and 9 are more difficult to decide what measure that should have been taken in each case. These are the transformers with the lowest oxidation index, excluding number 5, but they are still above the limit for reclamation. The age should probably be an important factor here, together with the remaining inhibitor content that could tell if the ageing has gone too far. More information should be considered by the asset managers when deciding on the maintenance measure for these 4 transformers.

5 Cost-Benefit Analysis

The results gained from the population analysis of previous reclamation procedures are going to be used to test the CBA-model included in the “Trafotiltak” model with two different case studies reviewing two different aspects of maintenance.

- Case 1 will look at a transformer that is due to have its oil reclaimed later in 2017. Here reclamation of oil is already decided to be the optimal maintenance measure, but the model will show if this really was the right choice.

- Case 2 will study a transformer with degraded oil chosen randomly from the received service data. The CBA-model could decide when reclamation of the oil would be most beneficial or if the condition suggest the transformer to be replaced.

The methods for calculating the HI-scores according to the “Trafotiltak” model and how much the parameters are estimated to improve will be explained in detail for case 1, but for case 2 the results from the analysis will be the focus since the calculation here is the same as for case 1.

5.1 Cost-Benefit Analysis Case 1

In this case, a transformer from the received population is going to be studied more closely. For this specific transformer, the owners already decided that reclamation was the best alternative and a reclamation of the oil is going to be performed later in 2017. The aim of the analysis is to see if the CBA-model could decide if this was the right choice or not for this transformer. If it turns out to be the right decision it would also be interesting to see if postponing the measure to a later date could be beneficial. To see how much, they would save by choosing reclamation compared to reinvesting in a new transformer would also be interesting.

5.1.1 Component Data and Technical Condition of the Transformer

The available data for the transformer are listed in Table 5.1. The gas and oil data from the latest oil sample are listed in Table 5.2 and 5.3.

Voltage Ratio [kV]	Size [MVA]	Year Energized	Years in Service	Oil Volume [kg]
132/11	25	1976	41	22900

Table 5.1: *Component data for the transformer studied in case 1.*

BDV [kV]	Water Content in Oil [mg/kg]	Acidity [mgKOH/g_{oil}]	DDF	Colour	IFT [mN/m]	Inhibitor Content [%]
26	25	0,02	0,0187	2,5	28	0,12

Table 5.2: *Latest oil measurements taken from the transformer in case 1.*

Hydrogen H_2 [ppm]	Oxygen O_2 [ppm]	Nitrogen N_2 [ppm]	Methane CH_4 [ppm]	Carbon Monoxide CO [ppm]	Carbon Dioxide CO_2 [ppm]	Ethene C_2H_4 [ppm]	Ethane C_2H_6 [ppm]
5	24950	67250	2,1	75	2300	20,3	0,8

Table 5.3: *Latest gas measurements taken from the transformer in case 1.*

The current technical condition of the transformer is going to be calculated based on the most recent oil and gas samples. The values are put into the HI-model of the “Trafotiltak” model to calculate current state of the transformer. From data in Table 5.1 it can be seen that this transformer has a bigger voltage ratio than most of the other transformer studied earlier, by having 132kV on its HV-side. This means the transformer is categorised in category B according to Table 3.3. When calculating the current condition before the measures are taken, oil deductions needs to be given according to category B in Table A.3.

5.1.2 Calculation of Current Condition with the HI-module

The following parameters from Table 5.2 receives a deduction in the model:

- BDV has a value of 26 kV, making it score in the poor category→ -25%.
- Water content in oil has a value of 25 ppm, making it score in the fair category→ -12,5%.
- IFT has a value of 28 mN/m, making it score in the fair category→ -12,5%.

This makes the total deductions for the oil parameters to be 50%. For the gas parameters, no gases are close to the deduction limits, making the total gas deductions 0%. Since the biggest deduction is made for the oil parameters, the oil will decide the final HI-score. This makes the final HI-score for the transformer 50% before the reclamation of the oil, according to equation (3.1) and (3.4), showed in Table 5.4.

HI-Deductions from Oil Parameters	HI-Deductions from Gas Parameters	Total HI-score (equation 3.1)	Apparent Age t' (equation 3.5)	Actual Age
-50%	0	100%-50% =50%	60,3	41

Table 5.4: *Calculation of the transformers HI-score and apparent age before reclamation.*

From the analysis based on previous reclamation processes, showed in Table 4.1 and 4.2, it is possible to estimate how much each parameter can expect to be improved by a reclamation on this transformer. From these numbers the estimation of the HI-score the transformer will receive after the reclamation is finished can be conducted.

5.1.3 Estimating the HI-score After Reclamation

The 137 different reclamation processes studied in this thesis resulted in the graphs in Appendix C. From these graphs the individual improvements for each oil and gas parameter were studied, with the results showing in Table 4.5 and 4.6.

When analysing the condition of the transformer after a reclamation, the estimated improvements for each parameter is done a bit cautious by choosing the median of all the improvements for the transformers in the population. The estimated improvement for all the parameters are located by finding the corresponding x-axis value to 0,5 or 50% on the y-axis for the grey values in Figure C.1-C.15. This is the improvement that at least 50 % of the transformers achieves from the reclamation, and the median of the population studied in chapter 4. For faster calculations, the estimated improvements for each oil and gas parameter are also listed in Table 4.1 and 4.2. The improvements of the condition are taken on a 2-year assumption basis and it is probably a little optimistic that the values would stay this good for 15 years before being back at the same values as before the reclamation. But this is one of the assumptions for the model.

Table 5.5 shows the estimated improvements of each parameter and what the value of each parameter are anticipated to be after the reclamation measure. As explained in chapter 2 some oil parameters are improved by getting their value increased like BDV, IFT and inhibitor. The rest should be lowered as much as possible. For the gas parameters, it is only desirable to lower the concentrations.

Oil Parameters	BDV [kV]	Water Content in Oil [mg/kg]	Acidity [mgKOH/g_{oil}]	DDF [%]	Colour	IFT [mN/m]	Inhibitor Content [%]
Improvement (Table 4.1)	5	3,7	0,055	0,0363	1,5	20	0,25
Value After Reclamation	31	21,3	0,01	0,0001	1,0	48	0,30

Gas Parameters	Hydrogen H_2	Oxygen O_2	Nitrogen N_2	Methane CH_4	Carbon Monoxide CO	Carbon Dioxide CO_2	Ethene C_2H_4	Ethane C_2H_6
Improvement (Table 4.2)	3,6	1000	11245	1,8	150	1616	19,2	2,6
Value After Reclamation	1,4	23950	56005	0,3	1	684	1,1	0,1

Table 5.5: *Estimated value of the different oil and gas parameters after the reclamation process.*

From Table 5.5 the values that received deductions before the reclamation process are the most interesting ones to evaluate after the measure is finished. The IFT has improved very much, while the BDV and water content in oil did not improve much. The reason for this are the poor values these two parameters had prior to the reclamation started, and that estimated improvements for these two parameters are low for the reclamation measure. The new condition of the transformer after the reclamation together with the new apparent age *t'* are listed in Table 5.6 below.

HI-Deductions from Oil Parameters	HI-Deductions from Gas Parameters	Total HI-Score (equation 3.1)	New Apparent Age t' (equation 3.5)	Actual Age
-37,5%	0	100%-37,5% =62,5%	45,2	41

Table 5.6: *Calculation of the transformers HI-score and apparent age after the reclamation.*

5.1.4 Cost Estimates for the Transformer and Reclamation of Oil

To be able to use the CBA-model made by “Trafotiltak” cost estimates for the reclamation of oil and cost for a new transformer needs to be created. The estimation of these costs has been done by the companies in the project. The different costs are explained in Table 5.7.

Estimated Costs for a 25 MVA Power Transformer, 132/11 kV, 22900 kg Oil	
Description of the cost	Cost Estimation, given in per 1000NOK [kNOK]
New transformer	5000
Cost breakdown (between 1-10MNOK) (cost of a breakdown excluding a new transformer)	5000
Oil and gas tests with documentation before a reclamation	11
Transportation + Connection/disconnection of equipment reclamation	20
Labour costs reclamation	50
Cost oil reclamation, 8kNOK/ton oil	183,2
Total cost for reclamation of oil for this transformer	264,2

Table 5.7: *Estimated costs for the transformer in case 1.*

For the estimation concerning breakdown costs it is assumed that the power is possible to redirect automatically, making the CENS-costs very low. If this was not possible the costs here would have been significantly higher. The remaining costs here are also difficult to estimate since different types of breakdowns would create different consequences. Estimation of the costs here would be between 1-10MNOK. In the analysis, the breakdown costs are fixed at 5000kNOK. O&M costs are neglected in the analysis.

5.1.5 Analysis Alternatives for Case 1

In this case, there are two possible measures being studied and that creates the different alternatives of this case. The two measures are as mentioned in the start of this case reclamation of oil and replacement of the transformer by reinvesting. The costs of the two measures are listed in Table 5.7, while the different alternatives for the case can be seen in

Figure 5.1. Each alternative is represented by a number, A0-A6, where A0 represents the reference alternative of doing nothing. Reclamation of oil is displayed as a blue triangle, while reinvestment of a new transformer is represented by a red triangle. The scale goes from year 1 to year 20, which represent the analysis period *A*. A measure is always conducted at the start of a year, and in this case only performed in periods of 5-years from the start. The economic life of a reclamation process is estimated to be around 15 years based on experience from transformer owners, while the economic life for a transformer is sat equal to the mean of the reference population, in Figure 3.2 and 3.3, at 62 years.

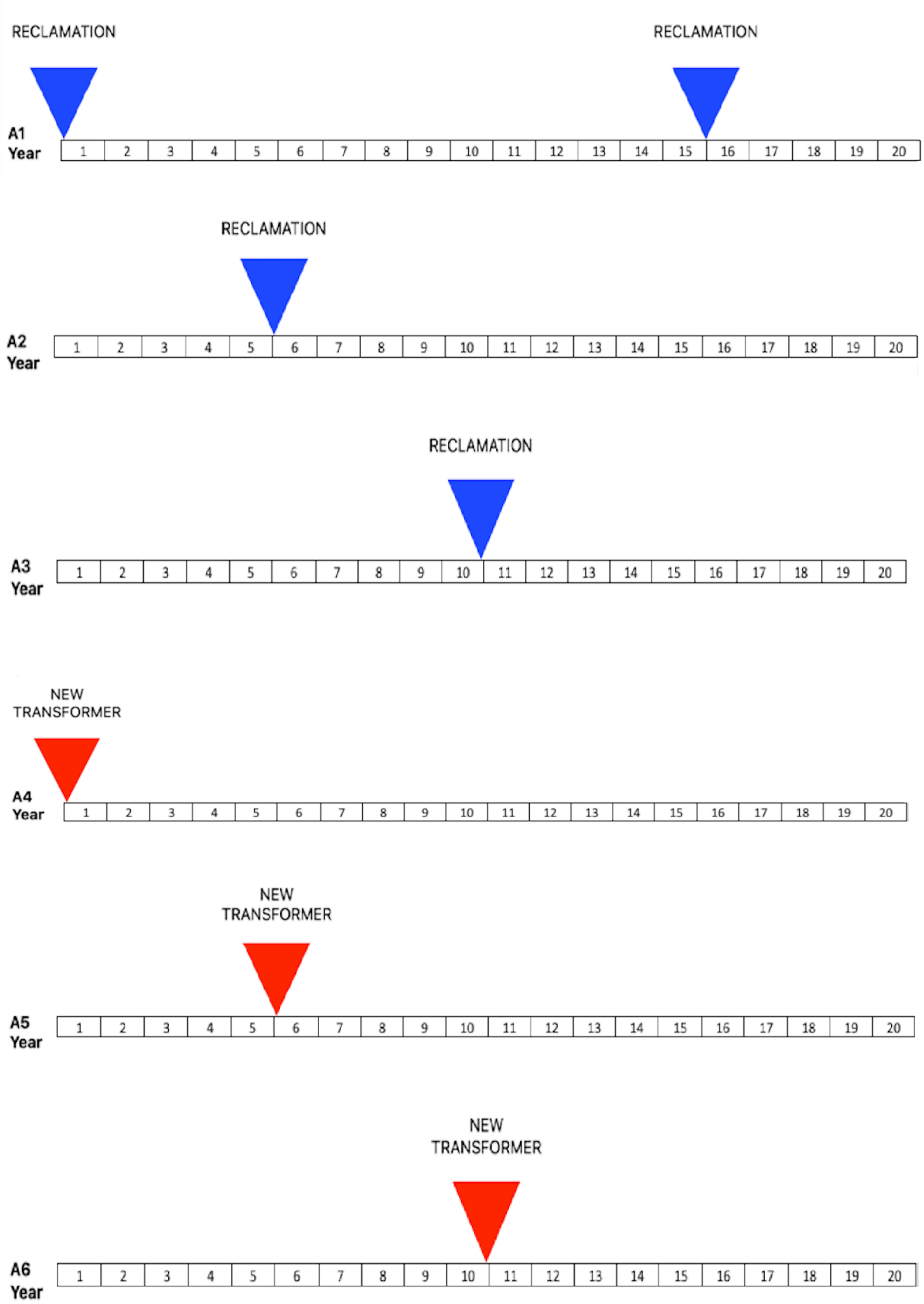

Figure 5.1: *The different measure alternatives studied in case 1.*

The model is created to repeat a measure if the economic life of the measure ends before the analysis period is finished. This is what happens in A1, where the effects of the first reclamation end after 15 years, and a new reclamation is conducted in the start of year 16.

5.1.6 Results

In case 1 the analysis period *A* is sat at 20 years and discount rate *r* at 5,0%.

The reference alternative A0 is to not do any measure at all and just make the transformer operate as before. All the other alternatives are compared to A0, according to equation (3.18), and if the result is positive then the measure should be conducted. The results of the different alternatives are displayed in Table 5.8 below.

Case Nr.	Measure	Breakdown cost before measure	Breakdown cost after measure	Cost of measure	Total Costs	NPV
A0	No measure	0	2003	0	2003	-
A1	Reclamation year 1	0	1349,6	307,6	1657,2	345,8
A2	Reclamation year 6	743,6	855,4	165,2	1764,2	238,8
A3	Reclamation year 11	1308,6	470,5	75,4	1854,5	148,5
A4	New transformer year 1	0	86,0	3175,5	3261,5	-1258,5
A5	New transformer year 6	743,3	60,4	1705,6	2509,3	-506,3
A6	New transformer year 11	1308,6	36,5	778,2	2123,3	-120,3

Table 5.8: *Cost of the different alternatives and the cost-benefit results comparing them to the reference alternative A0. All the numbers are given in kNOK.*

The results above show that performing the reclamation of oil in year 1 (A1) is the overall best alternative. Alternative A2 and A3 also gives a positive cost-benefit, while the other alternatives give a negative result. For alternative A3 the probability of a breakdown almost gets to big before the measure is conducted and makes the alternative just beneficial. This means that only alternative A1, A2 or A3 should be conducted or the company would lose money. Another thing to remark is the high measure cost in A1. The reason the measure cost is bigger than the reclamation cost in A1, are due to the measure getting repeated in year 16, since the economic life of the reclamation ends and it needs to be repeated according to the model. The measure is consequently conducted two times for this alternative.

The high costs of a new transformer in A4-A6 make these alternatives not cost-beneficial. Considering the breakdown costs they clearly have the lowest cost. This is also expected, since a new transformer reduces the probability of a breakdown considerably. If these alternatives should be cost-beneficial the breakdown costs must be higher than 5MNOK. Alternative A6 is just not cost-beneficial as it is close to 0.

With the given estimations and assumption in this analysis it can be concluded that the company probably did the right thing by choosing reclamation in year 1, as this is the best cost-benefit alternative for this transformer.

5.2 Cost-Benefit Analysis Case 2

In this case, a random transformer from the received transformer population is chosen. The transformer has a better condition than the transformer in case 1. The aim of this case is to see if the CBA-model can distinguish between a bad condition and a better condition for this transformer and suggest a later reclamation than it did in case 1.

5.2.1 Component Data and Technical Condition Before and After Reclamation

The available data for the transformer are listed in Table 5.9, while the gas and oil parameters before reclamation and the estimated values they will have after a reclamation are listed in Table 5.10 and 5.11 respectively. Expected values after reclamation are calculated from values in Table 4.1 and 4.2.

Voltage Ratio [kV]	Size [MVA]	Year Energized	Years in Service	Oil Volume [kg]
132/11	40	1994	23	17900

Table 5.9: *Component data for the transformer studied in case 2.*

	Hydrogen H_2 [ppm]	Oxygen O_2 [ppm]	Nitrogen N_2 [ppm]	Methane CH_4 [ppm]	Carbon Monoxide CO [ppm]	Carbon Dioxide CO_2 [ppm]	Ethene C_2H_4 [ppm]	Ethane C_2H_6 [ppm]
Value before reclamation	20	27487	56587	2	241	3687	60	1,5
Estimated values after reclamation	16,4	26487	45342	0,2	91	2071	40,8	0,1

Table 5.10: *Gas parameters before the reclamation process and estimated values after reclamation.*

	BDV [kV]	Water Content in Oil [mg/kg]	Acidity [mgKOH/g_{oil}]	DDF [%]	Colour	IFT [mN/m]	Inhibitor Content [%]
Value before reclamation	68	4,4	0,08	0,0398	3,5	29	0,12
Estimated values after reclamation	73	0,7	0,025	0,0035	2,0	49	0,37

Table 5.11: *Oil parameters before the reclamation and estimated values after reclamation.*

5.2.2 Calculation of Current Condition and Condition After Reclamation

The only oil parameter getting a deduction according to the IEC standard [8] prior to a reclamation is the colour [8]. In addition to the colour the IFT and inhibitor content are fairly low. The current condition and estimated condition after the reclamation are calculated in Table 5.12.

	HI-Deductions from Oil Parameters	HI-Deductions from Gas Parameters	Total HI-Score (equation 3.1)	Apparent Age t' (equation 3.5)	Actual Age
Before	-12,5%	0%	87,5%	15,06	23
After	0%	0%	100%	0,0	23

Table 5.12: *Current condition and estimated condition after the reclamation measure.*

5.2.3 Cost Estimates for Transformer and Reclamation of Oil

Estimated costs for this transformer are the same for this transformer as in case 1, as seen in Table 5.7. The only change from case 1 is the estimated cost for the reclamation process, since the oil volume is smaller for this transformer. Estimated costs for the reclamation in case 2 can be seen in Table 5.13 below.

Description of the cost	Cost Estimation, given in per 1000NOK [kNOK]
Other reclamation costs as in Case 1	81
Cost oil reclamation, 8kNOK/ton oil	143,2
Total cost for reclamation for this transformer	224,2

Table 5.13: *Estimated costs for transformer in case 2.*

5.2.4 Results

For case 2 the analysis period *A* is sat at 20 years and discount rate *r* at 5,0%, the same as in case 1. The different alternatives are also the same as for case 1, and can be seen in Figure 5.1. The cost-benefit from each alternative can be seen in Table 5.14.

Case Nr.	**Measure**	**Breakdown Cost Before Measure**	**Breakdown Cost After Measure**	**Cost of Measure**	**Total Costs**	**NPV**
A0	No measure	0	300,3	0	300,3	-
A1	Reclamation year 1	0	86,0	261,0	347,0	-46,7
A2	Reclamation year 6	62,2	71,2	165,2	298,7	1,6
A3	Reclamation year 11	134,7	51,9	91,0	277,6	22,8
A4	New transformer year 1	0	86,0	3175,5	3261,5	-2961,2
A5	New transformer year 6	62,2	71,2	2009,9	2143,3	-1843,0
A6	New transformer year 11	134,7	51,9	1107,4	1293,9	-993,6

Table 5.14: *Cost of the different alternatives and the cost-benefit results compared to the reference alternative A0. All the numbers are given in kNOK.*

From Table 5.14 the best alternative for this transformer is as expected to have a postponed reclamation process. The alternative of postponing the reclamation to year 6 (A2) is just cost-beneficial, while the alternative to have the reclamation in year 11 (A3) gives the most value. In this case, the company will lose money by performing a reclamation in year 1. This are also the case for A4-A6, where the company will lose a lot more money than by choosing these alternatives in case 1.

5.3 Discussion on Results from the Cost-Benefit Model

In this section, the results from testing the CBA-model in Chapter 5.1 and 5.2 are commented and analysed. First the proposed best alternatives from the analysis are discussed, before other alternatives are commented on. The second section here will have a closer look at the uncertainties in the model, "hidden costs" and some sensitivity analysis around some of the parameters used.

5.3.1 Different Alternatives in Case 1

As seen from the acquired results in this case study it could be observed that A1, reclamation at the start of year 1, was the overall best alternative available for the transformer given the assumptions in the model. Reclamation was already chosen by the maintenance department as the best alternative, showing that the model could do an overall good assessment of the alternatives and locate the best measure. The transformer also reduced its apparent age from 60,3 to 45,2 years old almost reaching its real age of 41 years old. This is a decent result as it is assumed in the analysis that the effects of a reclamation process should last 15 years before being back at the same condition as before the measure. As the apparent age is improved by 15,1 years this result is just a little better than the assumption.

5.3.1.1 Recondition as a Better Alternative?

For this case, the overall improvements are not good, as the HI-score only increases from 50 to 62,5%. While both the inhibitor and IFT are brought back to reasonable levels, the water content and BDV are still way to high. As explained earlier, reclamation of oil is not the best way to handle high water concentrations. This is also established through the extensive analysis on the improvements of reclamation from genuine transformers in the Norwegian power grid. These parameters often have a strong correlation and by reducing the water content can make the BDV increase.

Since the amount of different measures were lacking in the received data from the industry, it was only possible to make an overview of the estimated improvements for reclamation of oil. This resulted in having only two different maintenance alternatives in the analysis, reclamation or a new transformer. For this transformer, it would have been more interesting to see if the costs and effects of e.g. a recondition in addition to refilling the inhibitor could be a more optimal solution for the transformer. Based on the data available, this could unfortunately not be tested for the transformer.

5.3.1.2 When is Reinvestment the Best Alternative for Case 1?

Since the transformer is still in a pretty reasonable condition and the age is not too high, reinvestment for a new transformer would not be a beneficial measure in this case, as seen in Table 5.8. If the company however decide they want to run the current transformer for as long as possible without experiencing a breakdown and securing safe operations, the scenario changes. This can happen if the company decides to upgrade the grid and need more power capacity for the transformer. In this scenario, it is interesting to see when the cost of a potential breakdown outweighs the cost of a new transformer.

From Table 5.8, reinvestment in year 11 gave a cost-benefit of -120,3kNOK. The perfect time to change the transformer would be the year when the cost-benefit breaks even, or if the company dares, even longer. In Table 5.15 the cost-benefit of the next years are showed:

Years delay *s* of reinvestment	***s*=11**	***s*=12**	***s*=13**	***s*=14**	***s*=15**	***s*=16**
Cost-Benefit [kNOK]	-120,3	-75	-38	-9	13	30

Table 5.15: *The table shows what year it would be beneficial to reinvest in a new transformer according to the cost-benefit model.*

From this table, it seems that it would be smart to change the transformer between year 14 and 15 if they plan to replace it. This should give the transformer owners good enough time to plan and acquire a new more fitting transformer for the upgraded grid.

5.3.2 Uncertainty in the Model

As discussed earlier there are several costs estimates that are difficult to predict in addition to several factors that could vary in this analysis. This makes the model and the experiment a little vulnerable and changing one variable could change the optimal alternative for case 1 and 2.

5.3.2.1 “Hidden Costs” Not Included in the Model

As mentioned before there are a lot of uncertainty included in analysis like this, and assumptions must be taken for some of the variables. As for the costs, there are in addition to the already estimated breakdown costs a lot of “hidden costs” not included in the analysis. When analysing the cost of a breakdown only the physical costs of the transformer are included here. This includes cost of clean-up and removal of old transformer, installation of new transformer and possible repairs for the on-site area or building. One cost that should be included, but usually too hard to estimate are the “reputation costs”. For the power companies their main job is to secure a safe and steady power delivery within their grid, and a good reputation is important for companies like them. If breakdowns happen this will create dents in their good reputation, and possibly ruin potential support and deals in the future because of their lack of credibility in operation. This is a scenario all companies would want to avoid and therefore this cost is much higher than some of the other breakdown costs.

In addition to “reputation costs” there are also hidden costs included in redirecting power to a new transformer. Normal procedure for most power grids is to have at least one possible way to redirect the power in case a breakdown happens. Most transformers in Norway run on a much lower peak than they are designed for in case of emergencies like this. This also explains why so many of them gets past their expected lifetime since they are not operated at maximum load. By redirecting power from a transformer experiencing a breakdown to a transformer running at a low peak, could make a drastic change to the operating scheme for this transformer. Changes in operations could lead to extensive stresses for a transformer, and result in a more rapid ageing. If the condition of the transformer already is degraded then the apparent age would be increased and potential remaining operating years could be reduced severely. If this scenario happens a new transformer needs to be invested in earlier than planned and this is not costs considered in the model.

The current wait for a new transformer is also significant nowadays, and this is also a factor not included in the model. The model assumes there is a cost for a new transformer, but not the cost of waiting on this new transformer. This creates increased wear on several other transformers managing the power supposed to be distributed through the transformer that has experienced a breakdown.

But hidden costs could also act the other way, as benefits not considered. If another transformer at the same location already needs reclamation of the oil the reclamation equipment already are on-site. The money saved on postponing the measure 5-10 years for the relevant transformer could be equal to the transportation cost of the reclamation equipment already there for the other transformer. If this is the case then the company should just do the reclamation on the relevant transformer too as this would save them time and potential money.

5.3.2.2 Sensitivity Analysis of the Estimated and Variable Parameters in the Model

When performing CBA on a proposed model like this it could sometimes be interesting to see how the model responds if assumptions or estimated costs varies. Could a small variation of a parameter make the most beneficial alternative in case 1 to change? Tests like this determines how well the model is constructed and how stable the results are. As there are several parameters estimated here, changing numerous of them at the same time would create an inaccurate and wrong sensitivity analysis for this case. Therefore, only one parameter is varied at the same time. Looking at case 1 in chapter 5.1, it is interesting to see what happens if the breakdown costs, K_u, is varied. As discussed, this parameter could potentially be very large, but is estimated to be between 1-10MNOK for the transformer in case 1 and 2. In the analysis, K_u was fixed at 5MNOK, but would the change in this variable change the outcome of the best alternative? Table 5.16 shows K_u varying between the estimated interval, 1-10MNOK for reclamation conducted in year 1 for case 1. Measure costs is the same for all alternatives with 307,6 kNOK as seen for reclamation year 1 in Table 5.8, and breakdown costs before the measure are 0, as the measure is conducted in year 1.

Alternative	Measure	K_u [kNOK]	Breakdown Cost After Measure [kNOK]	Reference Cost (No measure) [kNOK]	Total Cost (Breakdown + Measure) [kNOK]	Cost-Benefit [kNOK]
1	Reclamation Year 1	1000	323,8	480,6	631	-151
2	Reclamation Year 1	2000	580,3	861,2	888	-27
3	Reclamation Year 1	3000	836,7	1241,8	1144	97
4	Reclamation Year 1	4000	1093,1	1622,4	1401	222
5	Reclamation Year 1	5000	1349,6	2003	1657	346
6	Reclamation Year 1	10000	2631,74	3906	2939	967

Table 5.16: *Variation of the estimated breakdown costs K_u for reclamation in year 1.*

The cost-benefit from this sensitivity analysis shows the anticipated outcome. Once the risk, in this case the breakdown cost increases, the measure becomes more cost-beneficial to conduct in year 1. Already when breakdown costs are estimated at 3MNOK it is cost-beneficial to reclaim the oil in year 1. But what happens if K_u is varying for reclamation in year 6 compared to reinvestment in year 6? Table 5.17 and 5.18 respectively shows the results for these two alternatives.

$K_{,u}$ [kNOK]	Breakdown Cost Before Measure [kNOK]	Breakdown Cost After Measure [kNOK]	Measure Cost [kNOK]	Reference Cost (No measure) [kNOK]	Total Cost (Breakdown + Measure) [kNOK]	Cost-Benefit [kNOK]
1000	178,3	205,25	165,2	480,6	549	-68
2000	319,6	367,8	165,2	861,2	853	-9
3000	460,8	530,33	165,2	1241,8	1156	85
4000	602,0	692,86	165,2	1622,4	1460	162
5000	743,3	855,4	165,2	2003	1764	239
10000	1449,4	1668,1	165,2	3906	3283	623

Table 5.17: *Variation of the estimated costs connected to a breakdown K_u for reclamation in year 6.*

$K_{,u}$ [kNOK]	Breakdown Cost Before Measure [kNOK]	Breakdown Cost After Measure [kNOK]	Measure Cost [kNOK]	Reference Cost (No measure) [kNOK]	Total Cost (Breakdown + Measure) [kNOK]	Cost-Benefit [kNOK]
1000	178,3	14,5	1705,6	480,6	1898	-1417,4
2000	319,6	26,0	1705,6	861,2	2051	-1189,8
3000	460,8	37,5	1705,6	1241,8	2204	-962,2
4000	602,0	49,0	1705,6	1622,4	2357	-734,6
5000	743,3	60,44	1705,6	2003	2509	-506
10000	1449,4	117,9	1705,6	3906	3273	633

Table 5.18: *Variation of the estimated costs connected to a breakdown K_u for reinvestment in year 6.*

From the two measures conducted in year 6 there are two things from the results that should be mentioned:

- When K_u gets as big as 10MNOK in year 6 reinvestments for a new transformer gives a bigger cost-benefit than the reclamation measure, with 633 and 623 kNOK respectively.
- It is more beneficial to choose reclamation in year 6 when K_u are 1-2 MNOK, but once K_u gets bigger it is more beneficial to choose reclamation in year 1. It should be

mentioned that reclamation is not recommended for either alternative when K_u are 1-2MNOK as the cost-benefit is negative for both alternatives. But for reclamation in year 6 the company would lose less money than choosing reclamation in year 1 when the breakdown costs are so small in this case.

As seen from this short sensitivity analysis it is important to get as many of the costs and parameters as accurate as possible as just small changes could change the optimal alternative.

5.3.3 Apparent Age After Reclamation

In case 2 the apparent age after the reclamation is 0,0 years. The oil is considered as new since the oil values are respectable and could be compared to the values for new oil. However, the age of the paper is not considered here and would probably cause the apparent age to be higher. The apparent age of the paper is covered by the winding degradation model, but are not included in this thesis. This is a limitation in the model that the model just considers the condition of the oil in case 1 and 2. One solution could be to give the real age a weight for the apparent age, and this could be an area for potential further work for this thesis.

6 Conclusion

In this thesis, the most common maintenance techniques to improve condition of mineral oil in operating power transformers have been reviewed. In addition to these different measures, frequent oil and gas parameters exposing likely failures and preventing possible breakdowns have also been studied. This extensive literature study on the available theory for measures connected to improving the condition of oil in a transformer were important to get as much information as possible about alternatives that further could be used in the cost-benefit model.

After the literature study, it was important to do an extensive gathering of service data from operating transformers in Norway to survey what maintenance actions that have been performed on the transformers the past decades. From the collected data, transformers that had experienced maintenance measures were picked out and studied closer. The intention of this task was to map what measures the transformer owners typically preferred and from the different measures find what oil and gas parameters that usually was improved. From the data, it was clear that only the improvements for reclamation were possible to map as there were lack of other measures conducted. The values for all gas and oil parameters were mapped before and after reclamation to find the estimated improvements. From this the estimated improvements for each parameter, the median for the population, could be used as the benefit gained from reclamation in the CBA-model.

The proposed CBA-model made in the “Trafotiltak” project was tested on two real life transformers with different age, size and condition. The benefits gained from the population study for reclamation were used as benefit in the model and costs based on experience cost from companies in the project. The case study showed that the model could choose the alternative already decided as the optimal one by the company in case 1, just based on the oil and gas values for the transformer. In case 2 the model was also able to recognize the condition as fair for the transformer and suggesting the optimal solution would be to postpone the reclamation with 10 years.

Based on the literature and the population study it was clear that the reclamation struggled to improve the water content and BDV in many cases, with values returning soon after the measure was conducted. Reclamation would therefore not be suggested as a measure to improve these two parameters. The same could be said for gas values. Degassing in the reclamation process could help conceal thermal or electrical faults happening within the transformer, as it removes the gas, making it more difficult to track and locate the fault within the transformer.

Further analysis also revealed that refilling the inhibitor was very important to keep the condition of the transformer stable. If the inhibitor refill was conducted at the right time the measure could be as effective as the reclamation, but much cheaper overall.

7 Further Work

Due to the lack of different maintenance measures in the received data used for the analysis purposes, a natural field of further work would be to collect more data here if this data is available. This would allow the “Trafotiltak” model to consider more measures than just reinvesting and reclamation of oil, leading to a more optimal decision for the transformer. The “Trafotiltak” tool based on the models is still in the making and finishing it would also be a priority for further work in the project. A standard method on how to enter and register oil samples digitally in Excel for the companies taking part in the “Trafotiltak”-project is also in the making. This would make the tool able to read Excel-files, instead of typing every single value into the tool, and would save the company much time when analysing different transformers.

One interesting field of further work are to study the prolonged effects of reclamation of oil and refilling the inhibitor. Since much of the data received were from recently conducted measures there were not enough material in form of condition data after the measures to analyse this. This could result in a better estimate of the lifetime of each measure, especially reclamation of oil, which are estimated to different lengths depending on the sources. The apparent age of the transformer should also potentially take the real age as a weight when being calculated as the paper might be in a bad condition, even though oil values look good if the transformer is old.

Another interesting area for further work are development of national standard limits for gas and oil parameters in Norway, like the ones issued by IEC and CIGRE. As mentioned in IEC and CIGRE standards they are just guiding limits, and it should be considered making own national boundaries for both gas and oil parameters based on condition data from Norwegian power transformers.

One crucial part of the project is to continue collecting service data from Norwegian power transformers. This includes oil samples, load data, DP-values of the paper from transformer taken out service, reclamation data etc. If data could be collected during the whole lifetime of the power transformer, statistical analysis would be better and could answer more questions regarding the estimations on the transformer condition. This would be the “dream scenario” for statistical purposes and lifetime estimation for power transformers in the project. As this is the dream scenario it is explanatory that this would not be possible to do in near future, due to the cost and available resources.

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Appendix

A| Scoring Tables used in “Trafotiltak” Health Index

The two first tables contains the limits for both the concentration and the rate of change of each gas used to calculate the HI-score for the Core/Windings in “Trafotiltak”, and is based on [14].

Concentration [ppm]	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
Typical	100	80	170	55	3	500	8900
Level 2	180	129	270	126	13	766	14885
Level 3	254	170	352	205	32	983	20084
Level 4	403	248	505	393	102	1372	29980
Pre-Failure	725	400	800	900	450	2100	50000

Table A.1: *Oil sampling intervals for gas concentration set by CIGRÉ in [14] for power transformers in service, in µl/l.*

Rate [ppm]	H_2	CH_4	C_2H_4	C_2H_6	C_2H_2	CO	CO_2
Typical	83	65	89	47	2	660	5850
Level 2	179	175	218	176	7	1737	15382
Level 3	280	313	369	382	17	3054	27012
Level 4	509	679	745	1074	47	6491	57351
Pre-Failure	1095	1825	1825	4015	182	17000	150000

Table A.2: *Oil sampling intervals versus rates of gas increases set by CIGRÉ in [14] for power transformers in service, in µl/l/year.*

The following table show the limits given in the IEC standard [8] for scoring the 8 different oil parameters used to decide the HI-score for the subsystem Oil in "Trafotiltak". The different transformer categories can be seen in Table 3.3.

	O, A	**B**	**C**	**Scoring Category**
Breakdown Voltage (BDV) [kV]	> 60	> 50	> 40	Good
	50-60	40-50	30-40	Fair
	< 50	< 40	< 30	Poor
Water Content in oil (mg_{H2O}/kg_{Oil} at transformer operating temp.)	< 15	< 20	< 30	Good
	15-20	20-30	30-40	Fair
	> 20	> 30	> 40	Poor
Acidity (mg_{KOH}/g_{oil})	< 0,10	< 0,10	< 0,15	Good
	0,10-0,15	0,10-0,20	0,15-0,30	Fair
	> 0,15	> 0,20	> 0,30	Poor
Colour	Clear and Visible, < 3,5			Good
	Dark and turbid, ≥ 3,5			Poor
Inhibitor Content (Normal value 0,3%-0,4%)	> 60% of normal value (>0,21% of total oil volume)			Good
	40-60% of original value (0,14-0,21% of total oil volume)			Fair
	< 40% of original value (<0,14% of total oil volume)			Poor
Passivator Content (mg/kg)	> 70 and stable (rate of decrease < 10mg/kg/year)			Good
	50-70 mg/kg **or** < 70 mg/kg with a significant rate of decrease of >10mg/kg/year			Fair
	< 50 and decreasing at > 10mg/kg/year			Poor
Interfacial Tension (mN/m)	Inhibited: > 28 Unihibited: > 25			Good
	Inhibited: 22-28 Unihibited: 20-25			Fair
	Inhibited: < 22 Unihibited: < 20			Poor
Dielectric Dissipation Factor ($\tan\delta$) at 40- 60Hz at 90°C	< 0,10	< 0,10		Good
	0,10-0,20	0,10-0,50		Fair
	> 0,20	> 0,50		Poor

Table A.3: *Scoring limits for the different oil parameters made by IEC [8] and used in "Trafotiltak" HI-module.*

B| HI-scores Before and After Reclamation Measures

The service data acquired from the transformers that have had oil reclaimed were tested in the health index model from the “Trafotiltak”-project. The HI-scores before and after reclamation are presented in Figure B.1-B.8 below. The blue columns indicate the HI-score before reclamation, while the orange columns indicate HI-scores after the measure.

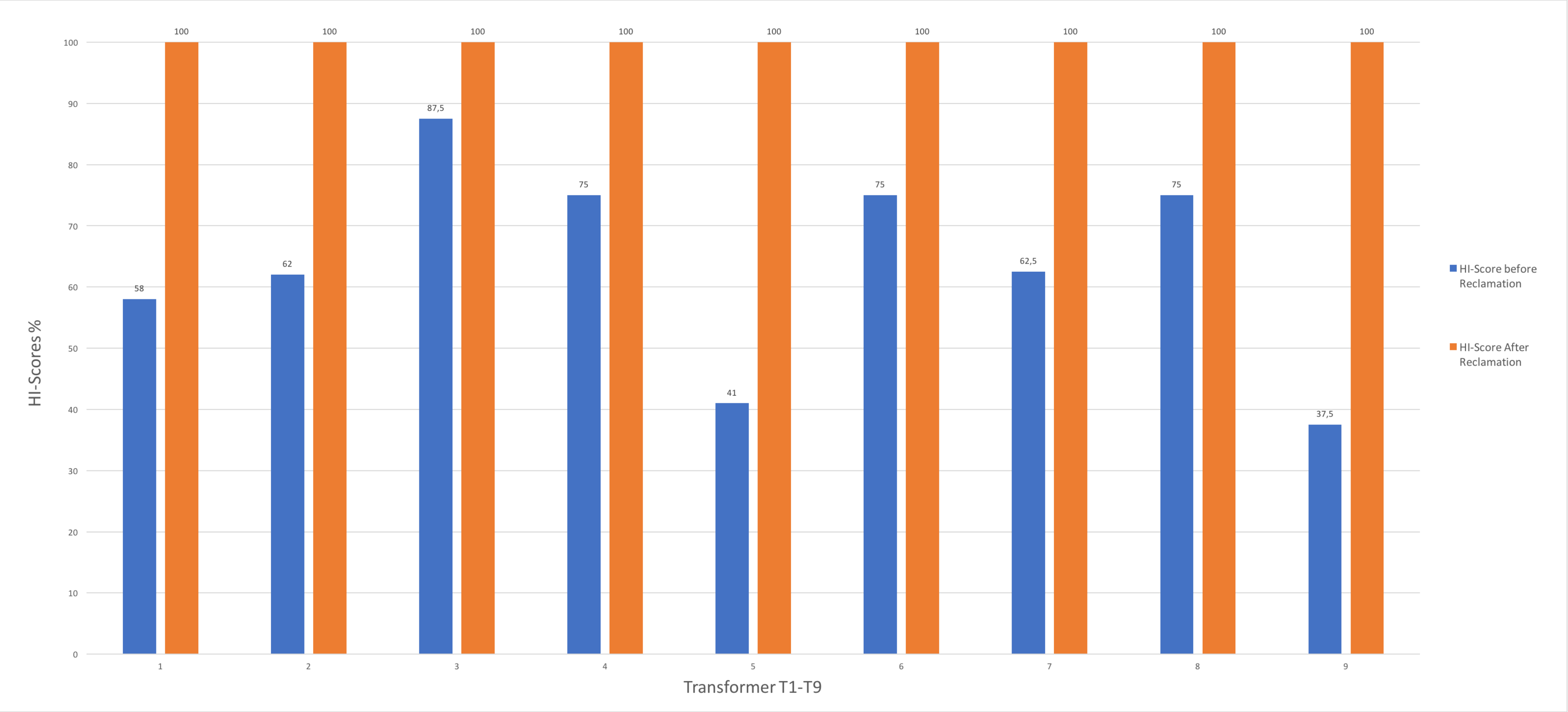

Figure B.1: *HI-Scores before and after reclamation of oil for transformers T1-T9*.

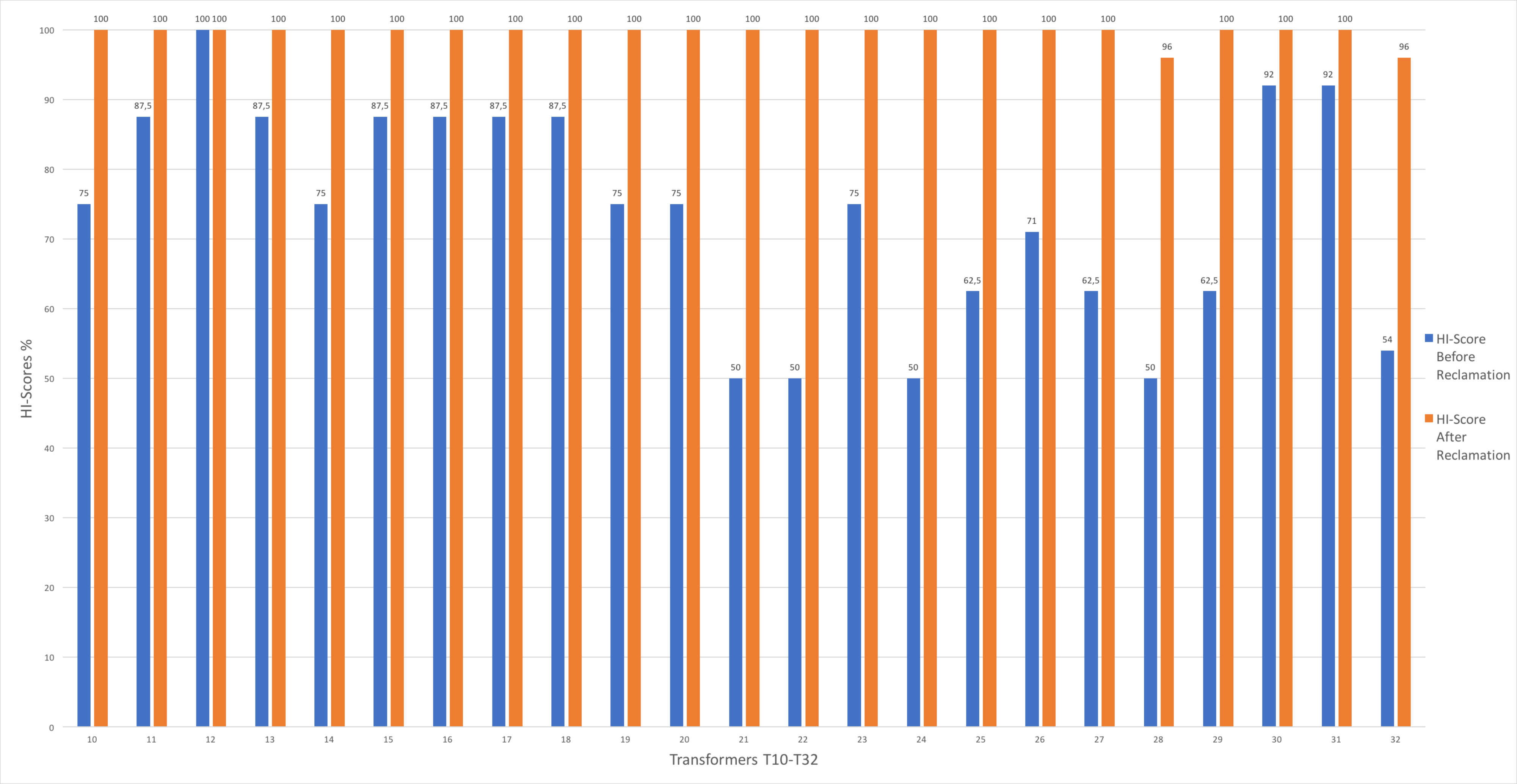

Figure B.2: *HI-Scores before and after reclamation of oil for transformers T10-T32.*

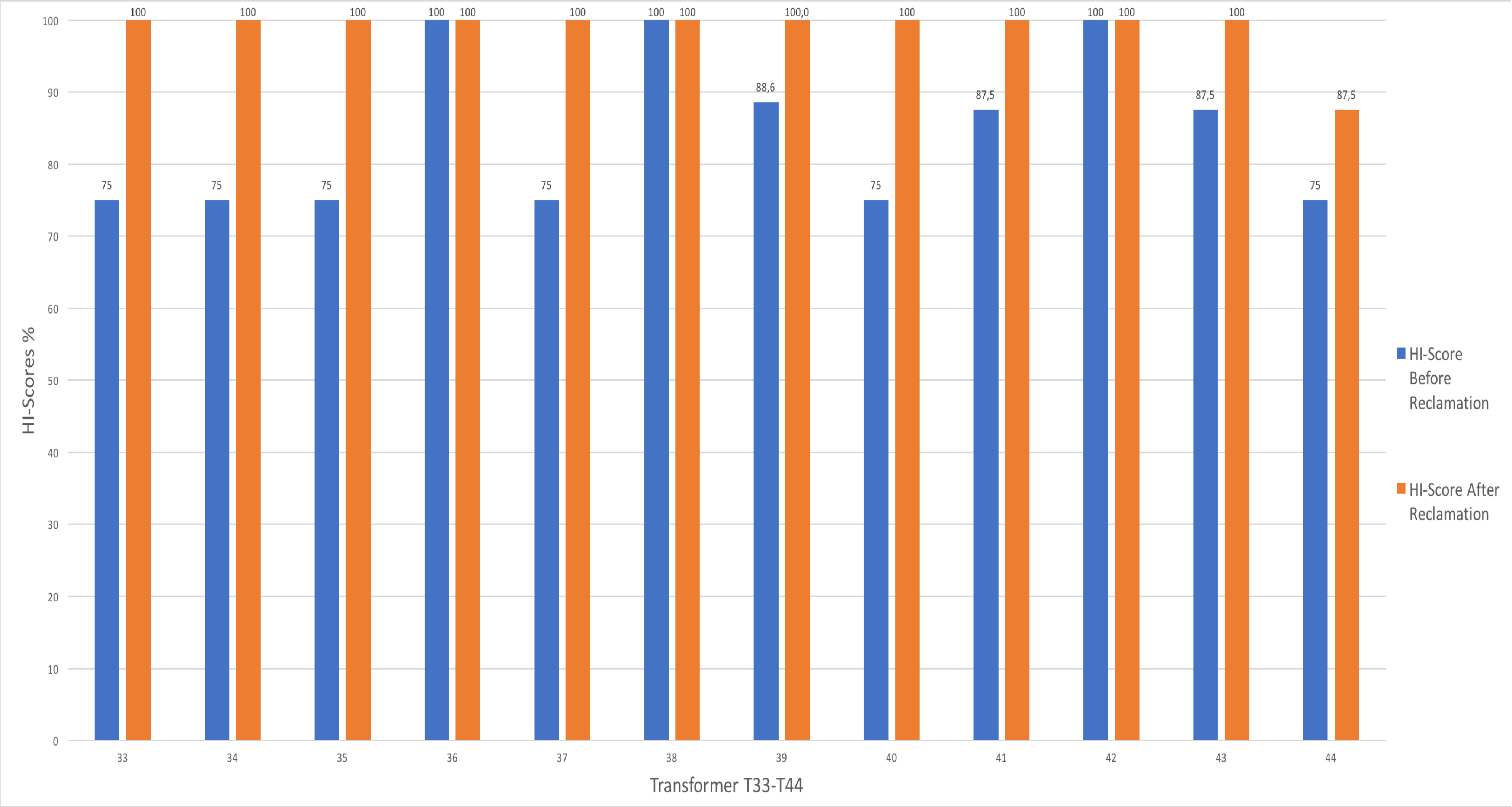

Figure B.3: *HI-Scores before and after reclamation of oil for transformer T33-T44.*

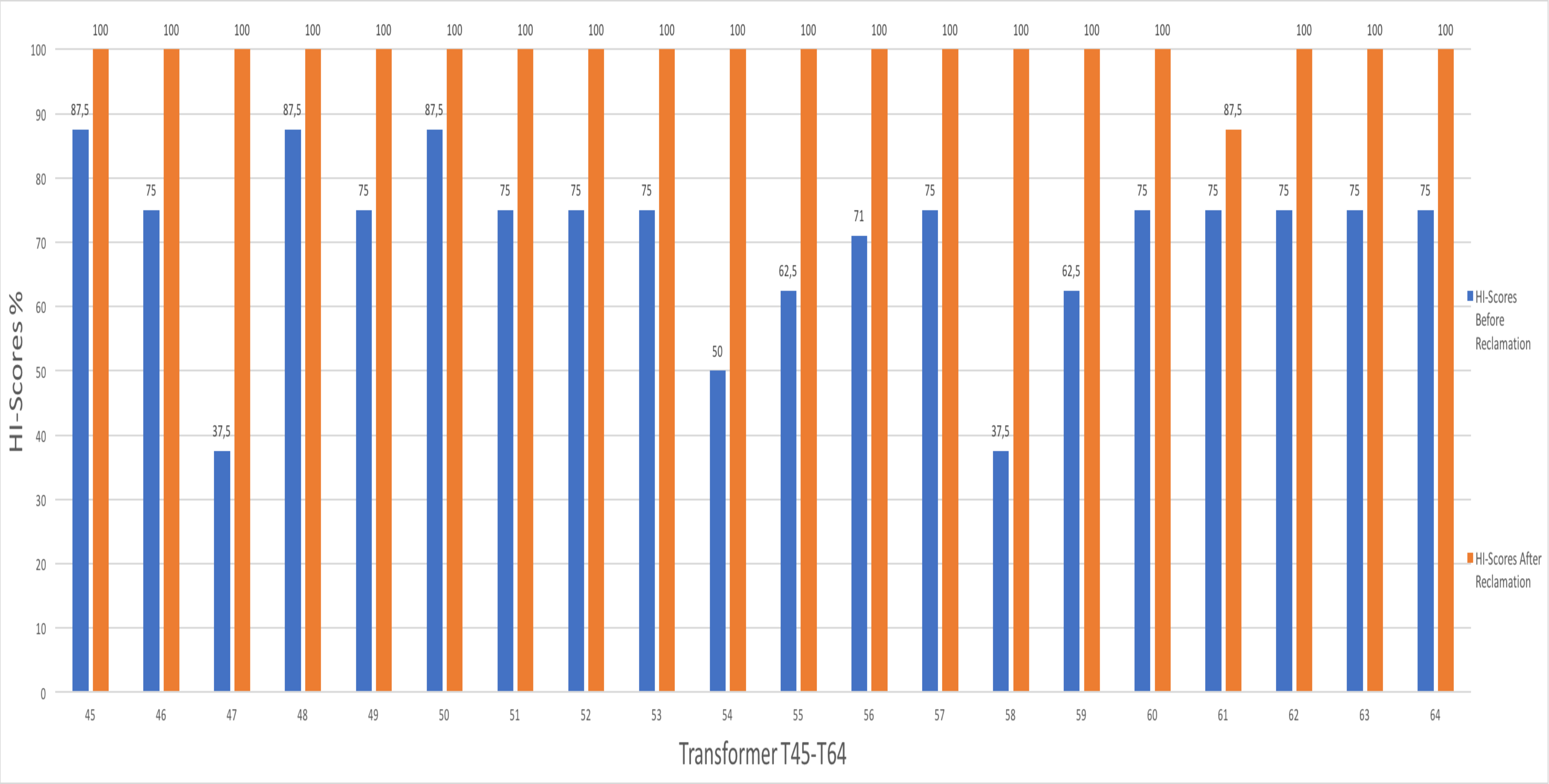

Figure B.4: *HI-Scores before and after reclamation of oil for transformer T45-T64.*

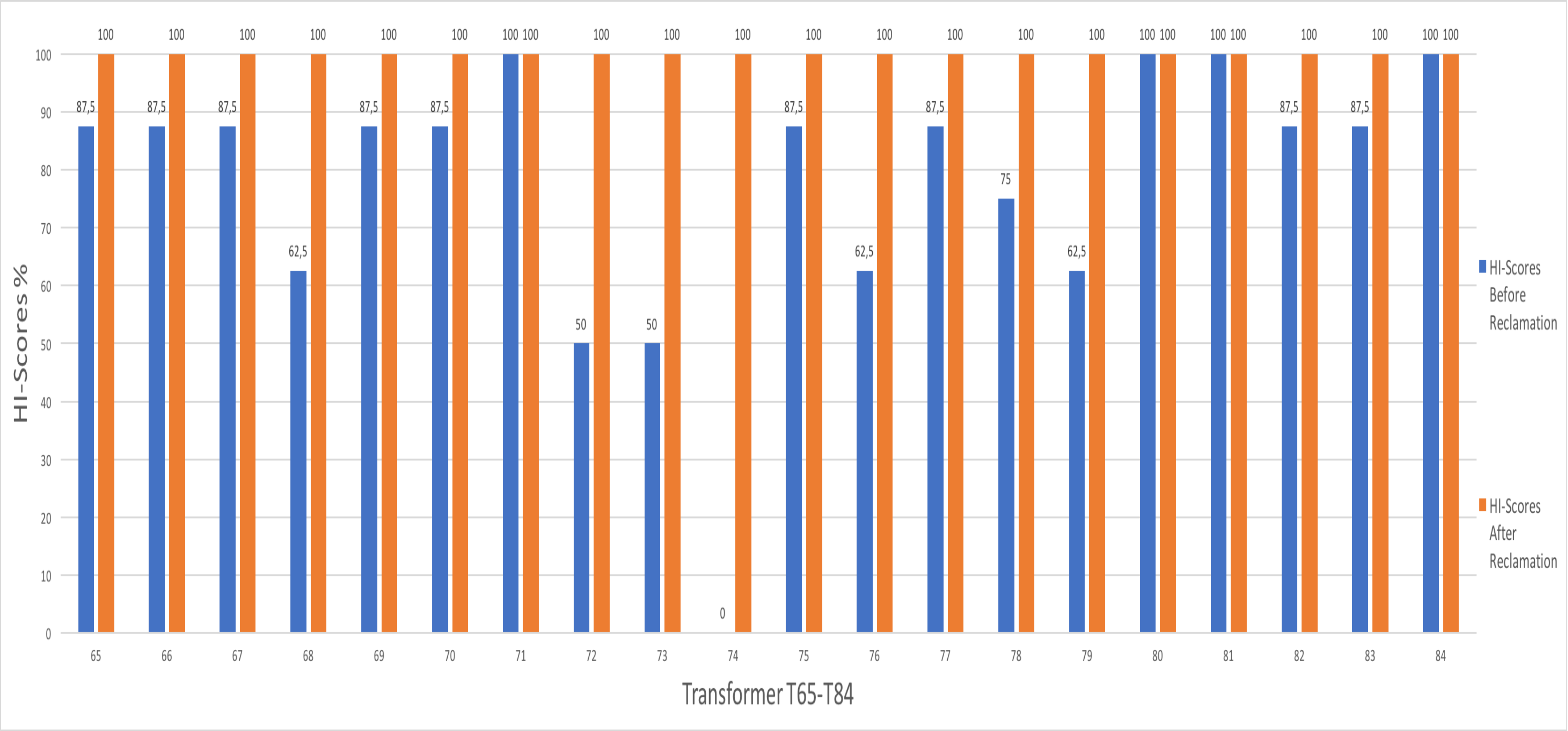

Figure B.5: *HI-Scores before and after reclamation of oil for transformer T65-T84.*

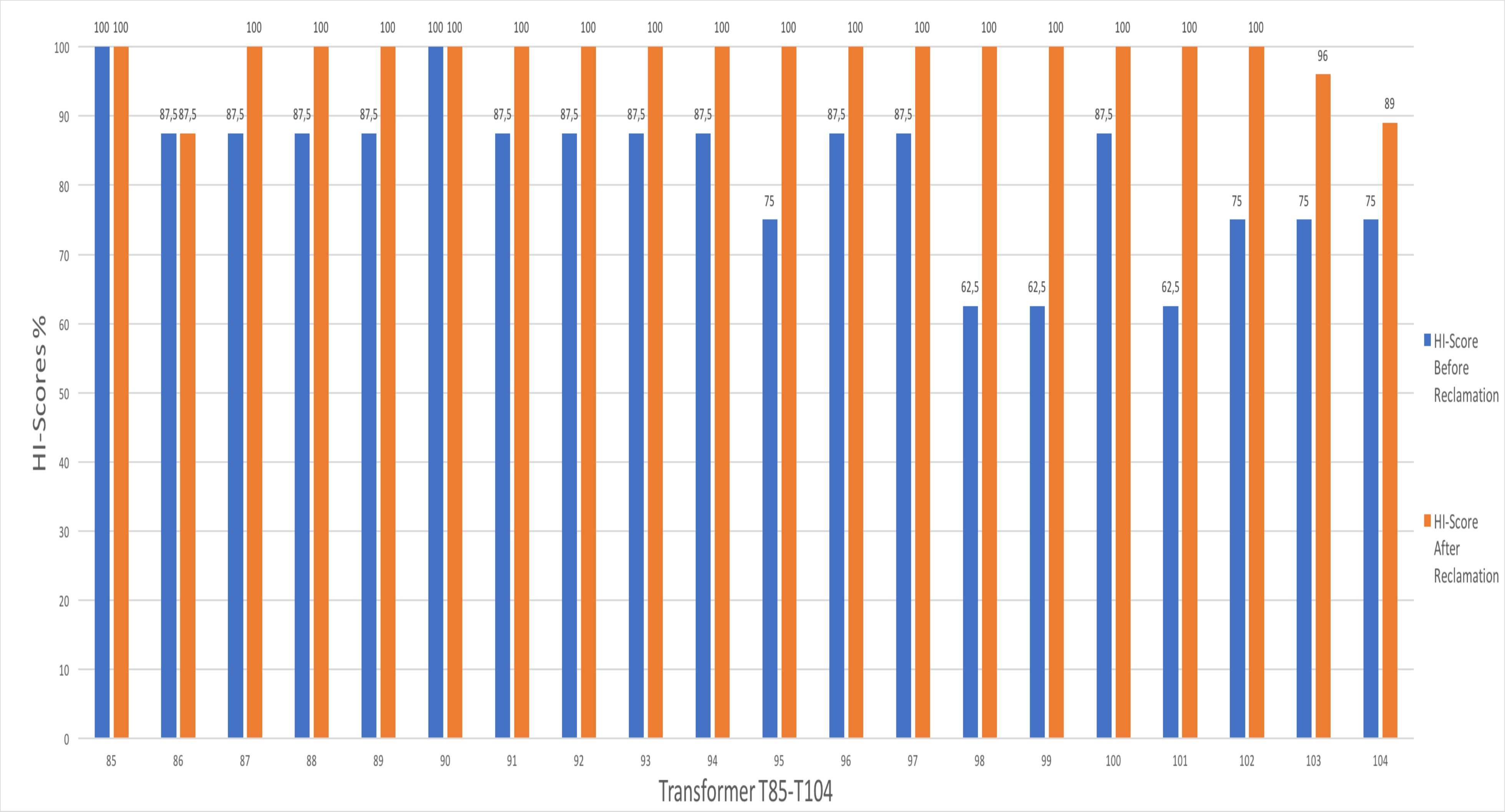

Figure B.6: *HI-Scores before and after reclamation of oil for transformer T85-T104.*

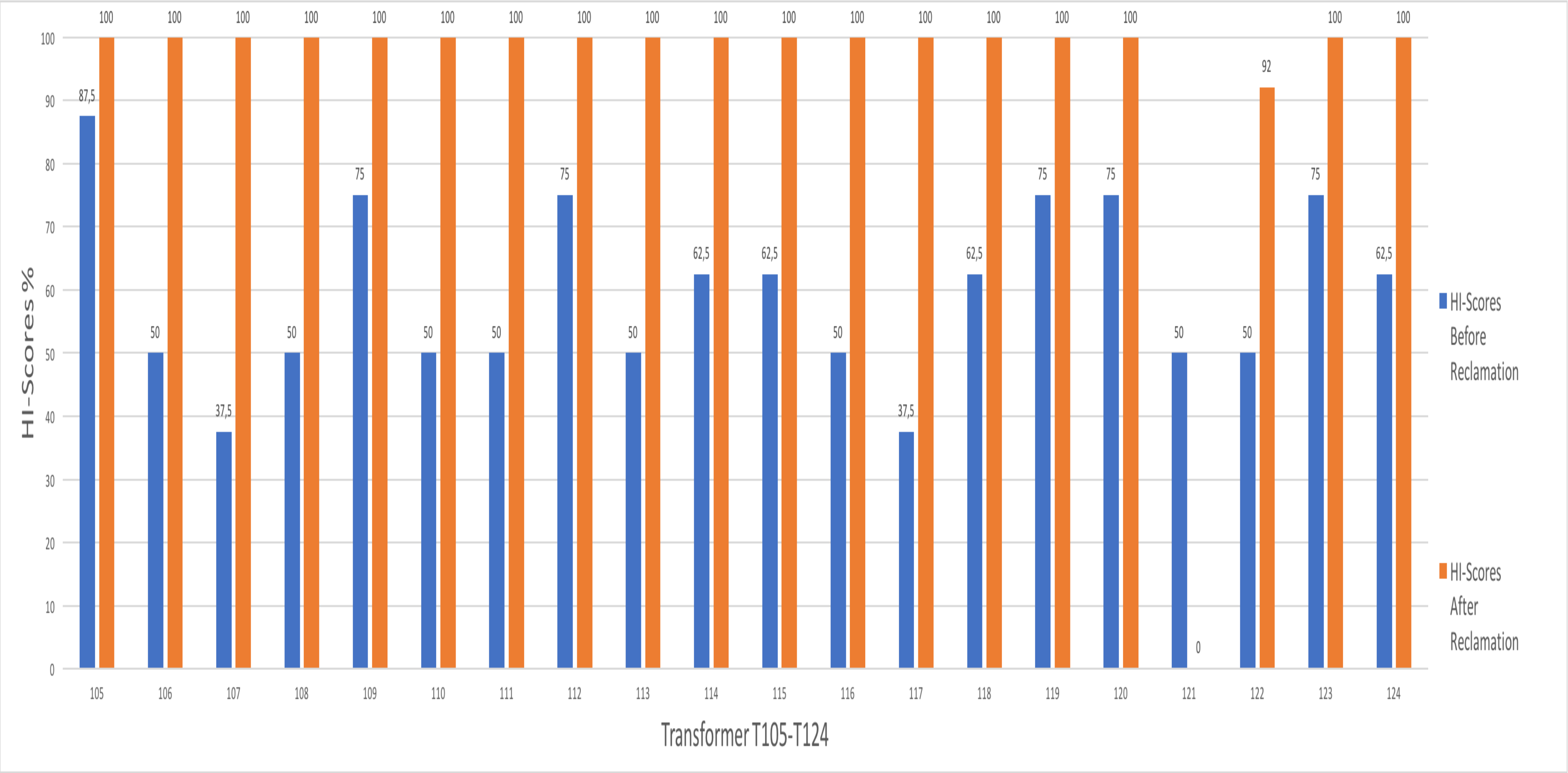

Figure B.7: *HI-Scores before and after reclamation of oil for transformer T105-T124.*

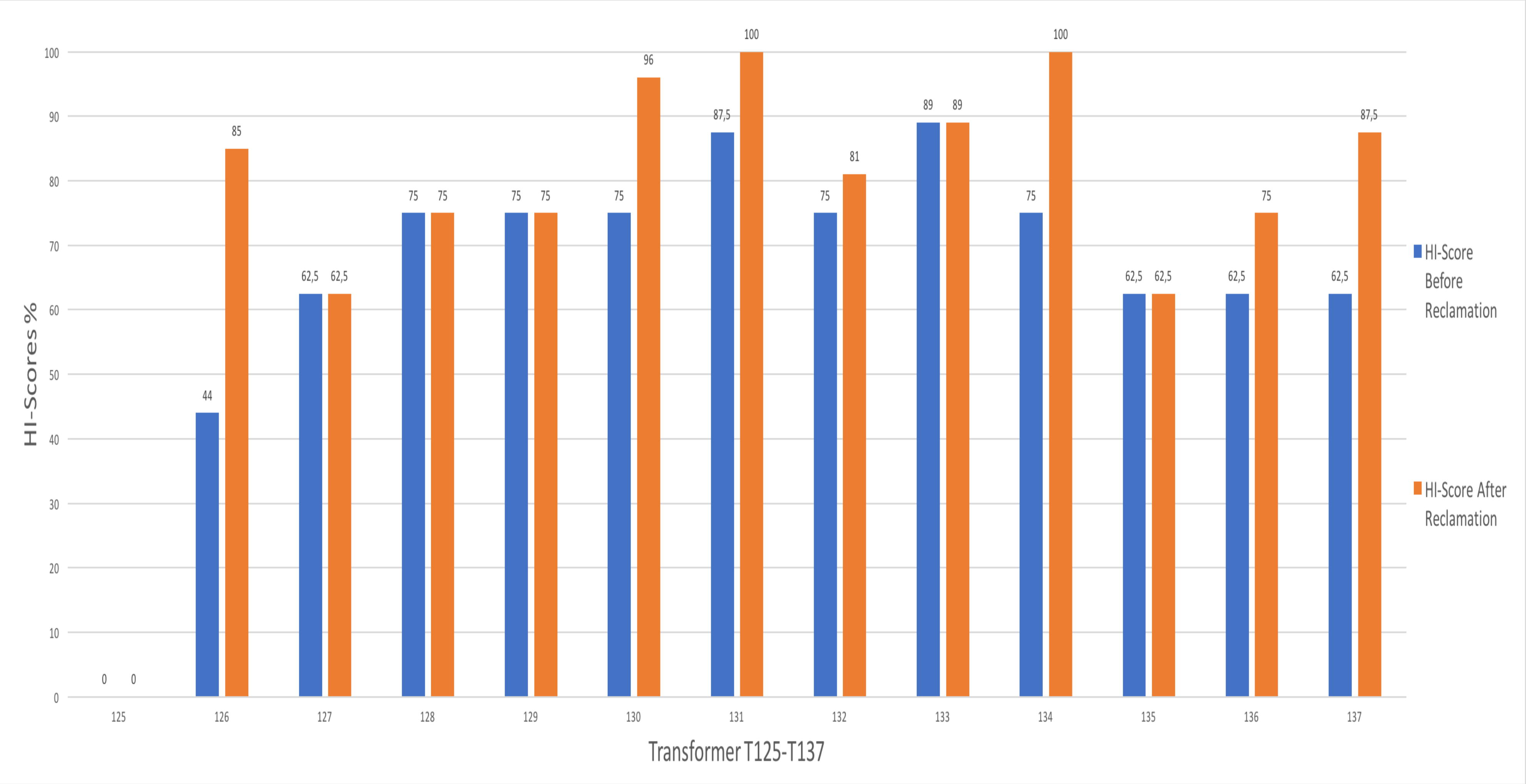

Figure B.8: *HI-Scores before and after reclamation of oil for transformer T125-T137.*

C| Cumulative Representation of Oil and Gas Parameters for Reclamation of Oil

The oil and gas parameters collected during maintenance before and after a reclamation measure are put into a cumulative representation to find a coherence in values and show the overall estimated improvement for each parameter from a reclamation process. The different parameters are showed in Figure C.1-C.15 below.

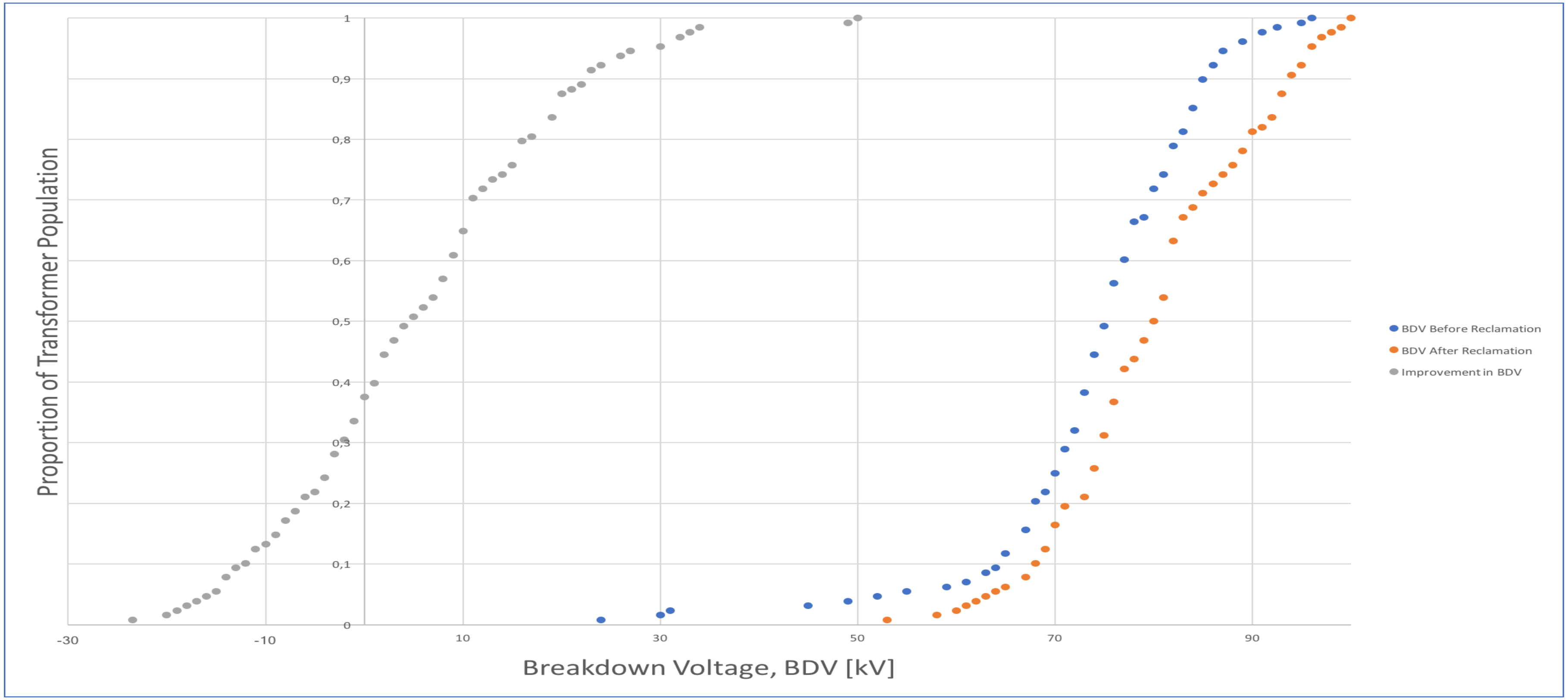

Figure C.1: *Cumulative representation of the oil parameter BDV. As showed in the plot the BDV is a very unpredictable value and are depending a lot on right temperatures during measuring to get an accurate result, as mentioned in chapter 2.1.1.4. BDV is also a parameter that increases when it gets better as seen comparing the blue and orange lines. Of the137 transformers in the population only 128 transformers had a BDV value available both before and after the reclamation process.*

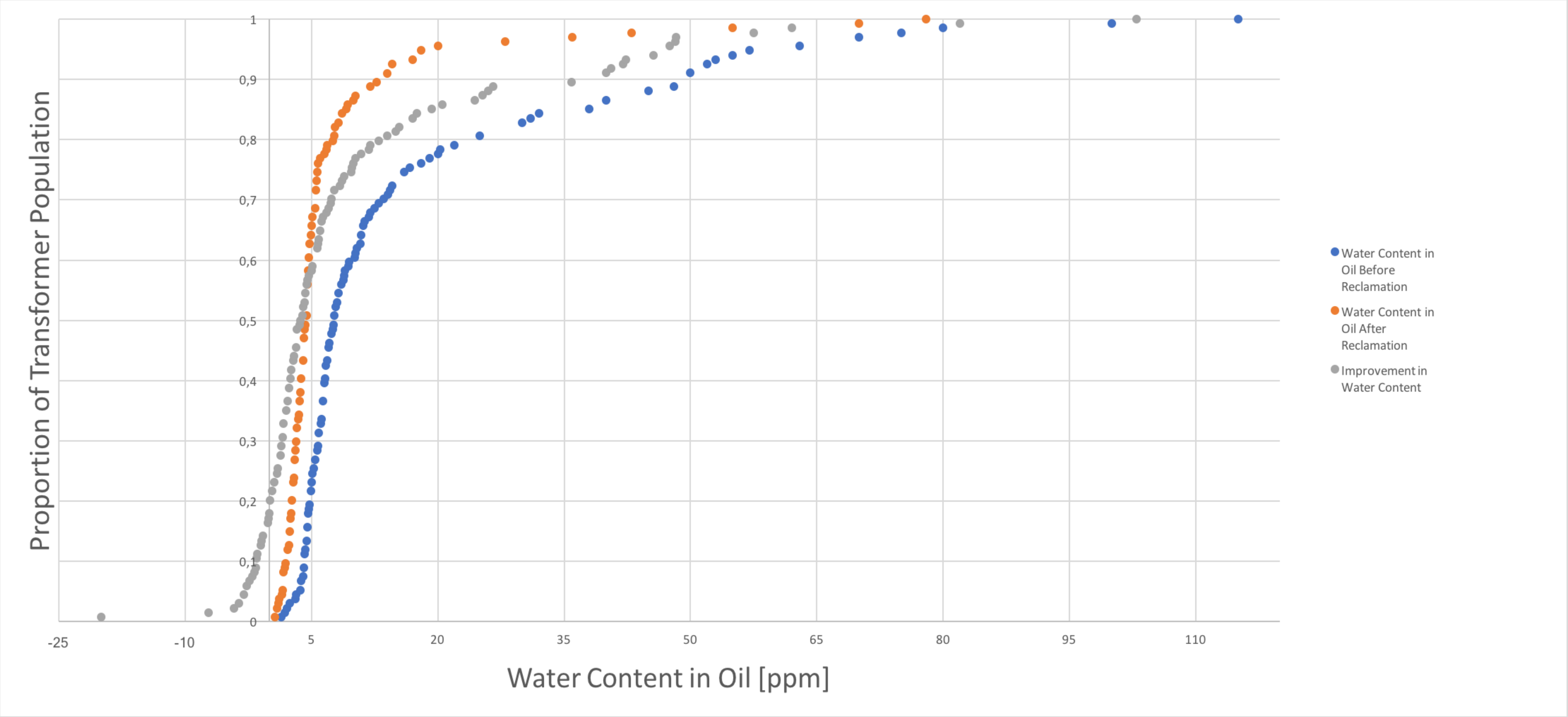

Figure C.2: *Cumulative representation of the water content in oil. From the plot, it can clearly be seen that the water content is reduced. By looking at the orange and blue lines we can see that water content in oil is a parameter that is decreasing when getting an improvement. Of the 137 transformers in the population 134 transformers had a measured value for the water content in oil recorded both before and after the reclamation process.*

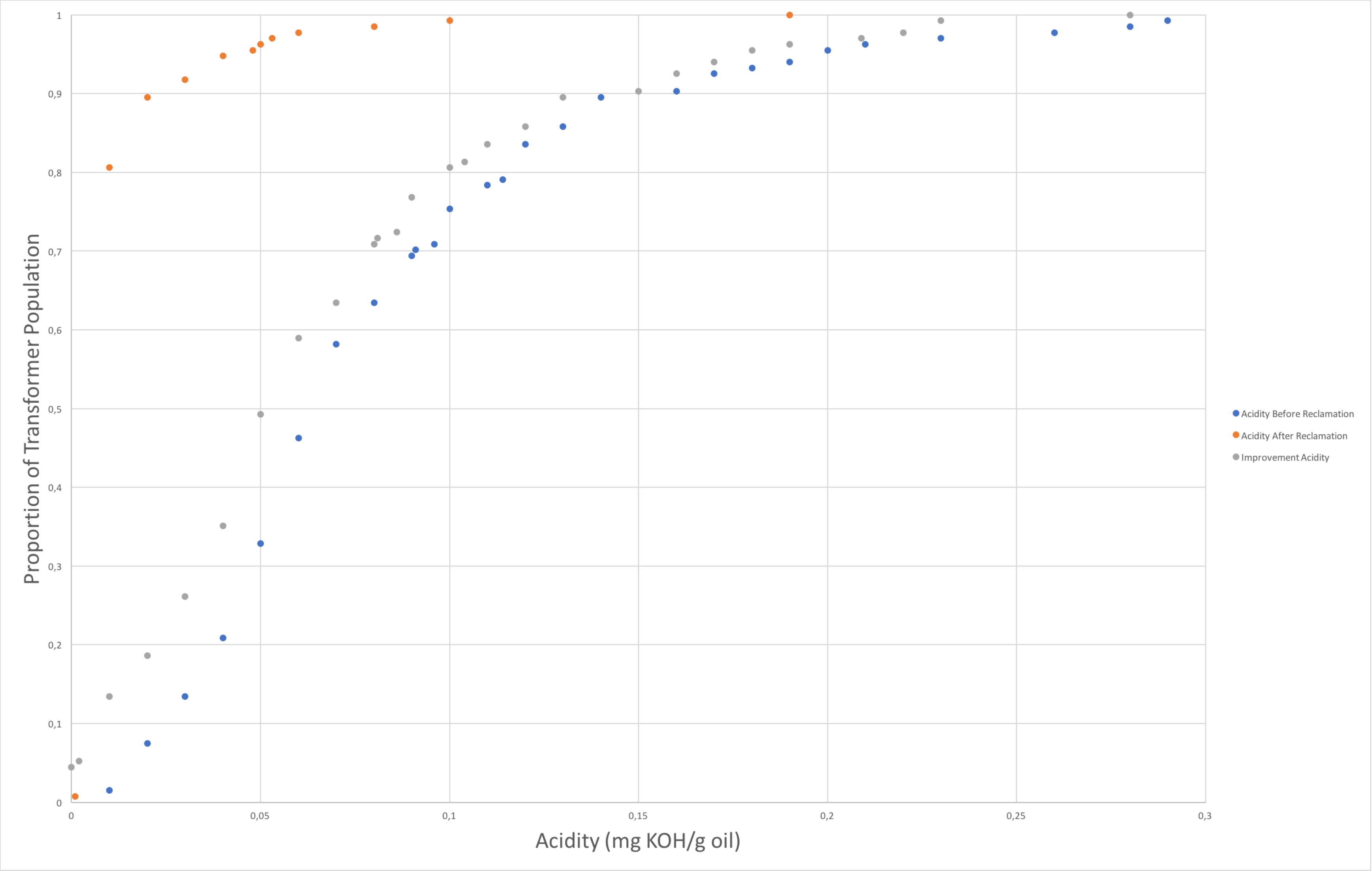

Figure C.3: *Cumulative representation of the Acidity/Neutralization Value. Removed an extreme value of 0,36 mgKOH/g oil to get the values within reasonable levels for the visual aspects for the figure. As seen from the orange and blue points in the plot the acidity decreases when the parameter is improved. Of the 137 transformers in the population 134 transformers had a measured value of acidity both before and after the reclamation process.*

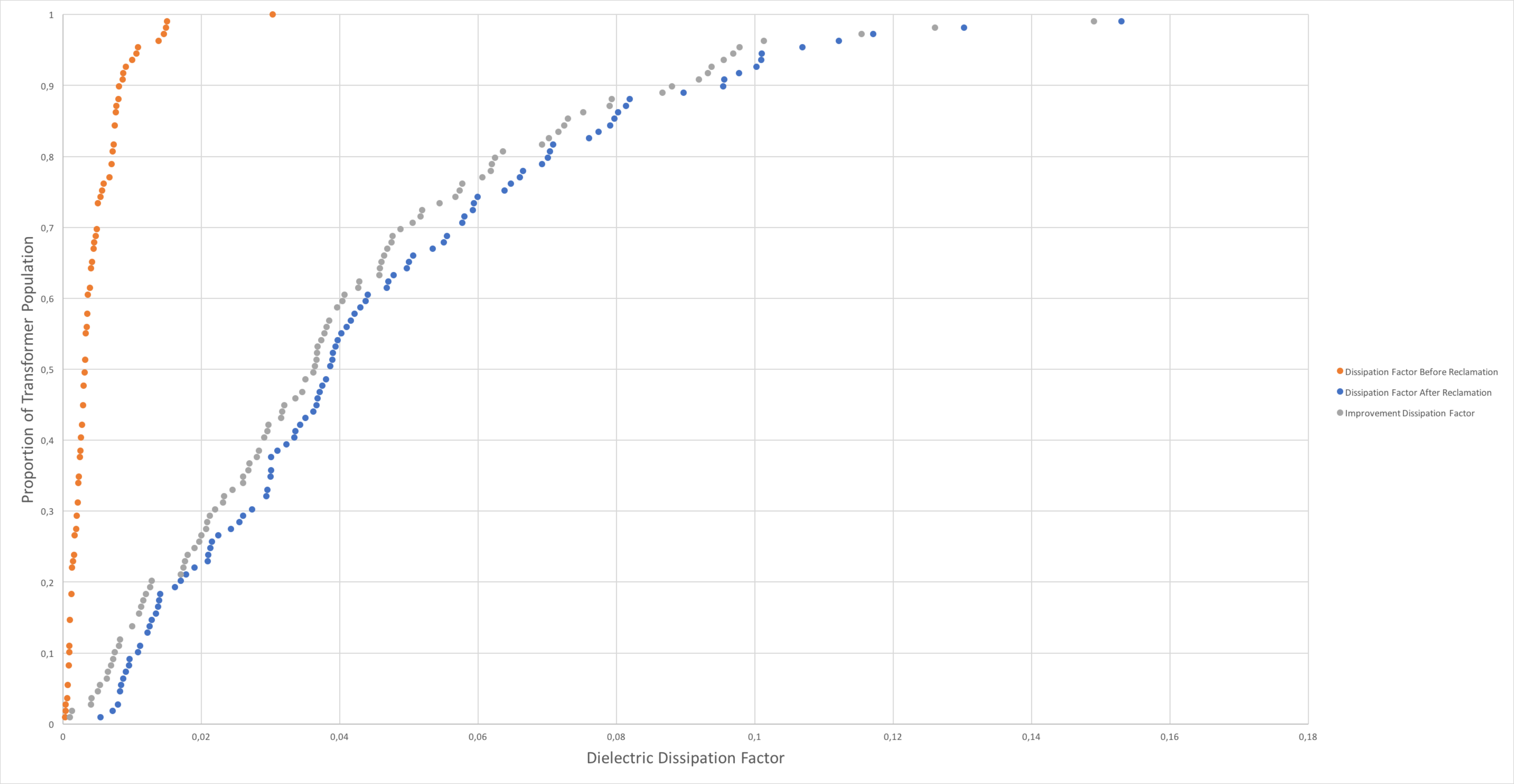

Figure C.4: *Cumulative representation of the dielectric dissipation factor (DDF). Removed an extreme value of 0,3938 to get a better show the improvements for the transformers. As for acidity, the dielectric dissipation factor is a parameter that decreases when improving, as seen comparing the blue and orange lines in the plot. Of the 137 transformers in the population only 109 transformers had a measured value of the DDF both before and after the reclamation process.*

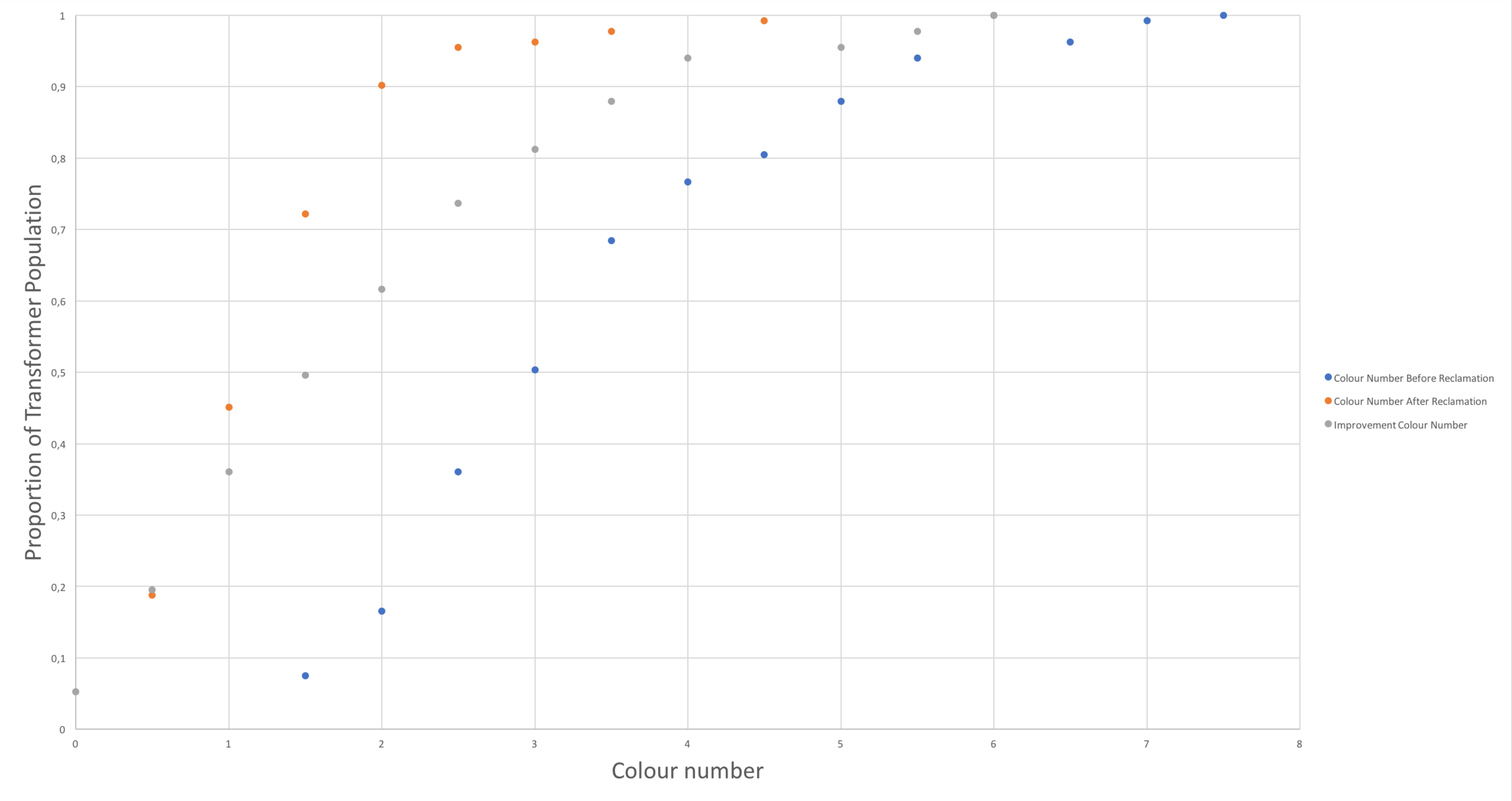

Figure C.5: *Cumulative representation of the Colour number. As seen from the orange and blue dots in the plot the colour number decreases when the transformer values are improved. Of the 137 transformers in the population 133 transformers had a measured value both before and after the reclamation process.*

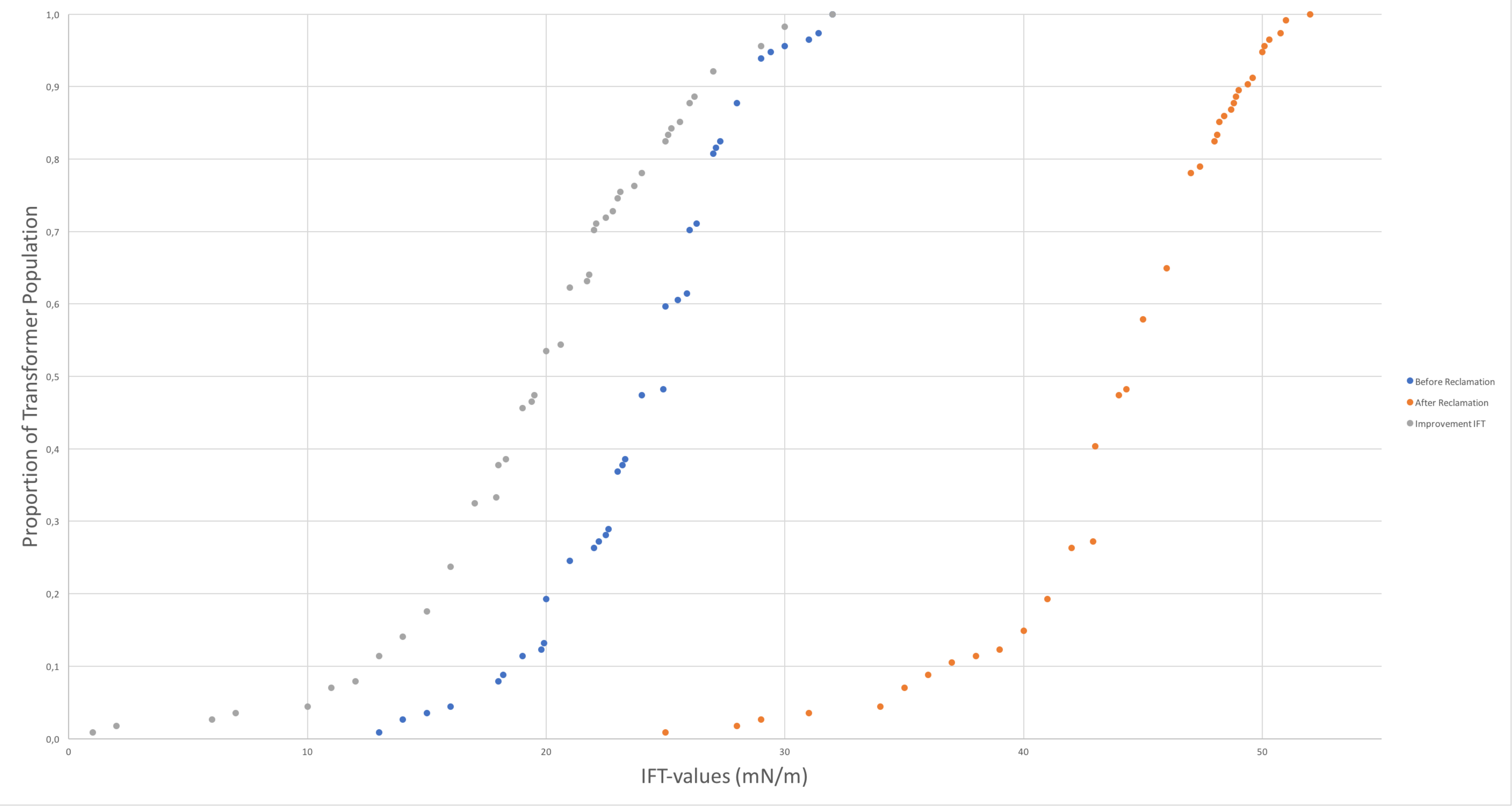

Figure C.6: *Cumulative representation of the Interfacial Tension (IFT). From the orange and blue dots in the plot it is easy to see that the IFT is a parameter that increases when experiencing a reclamation process. Of the 137 transformers in the population only 114 transformers had a measured value both before and after the reclamation process.*

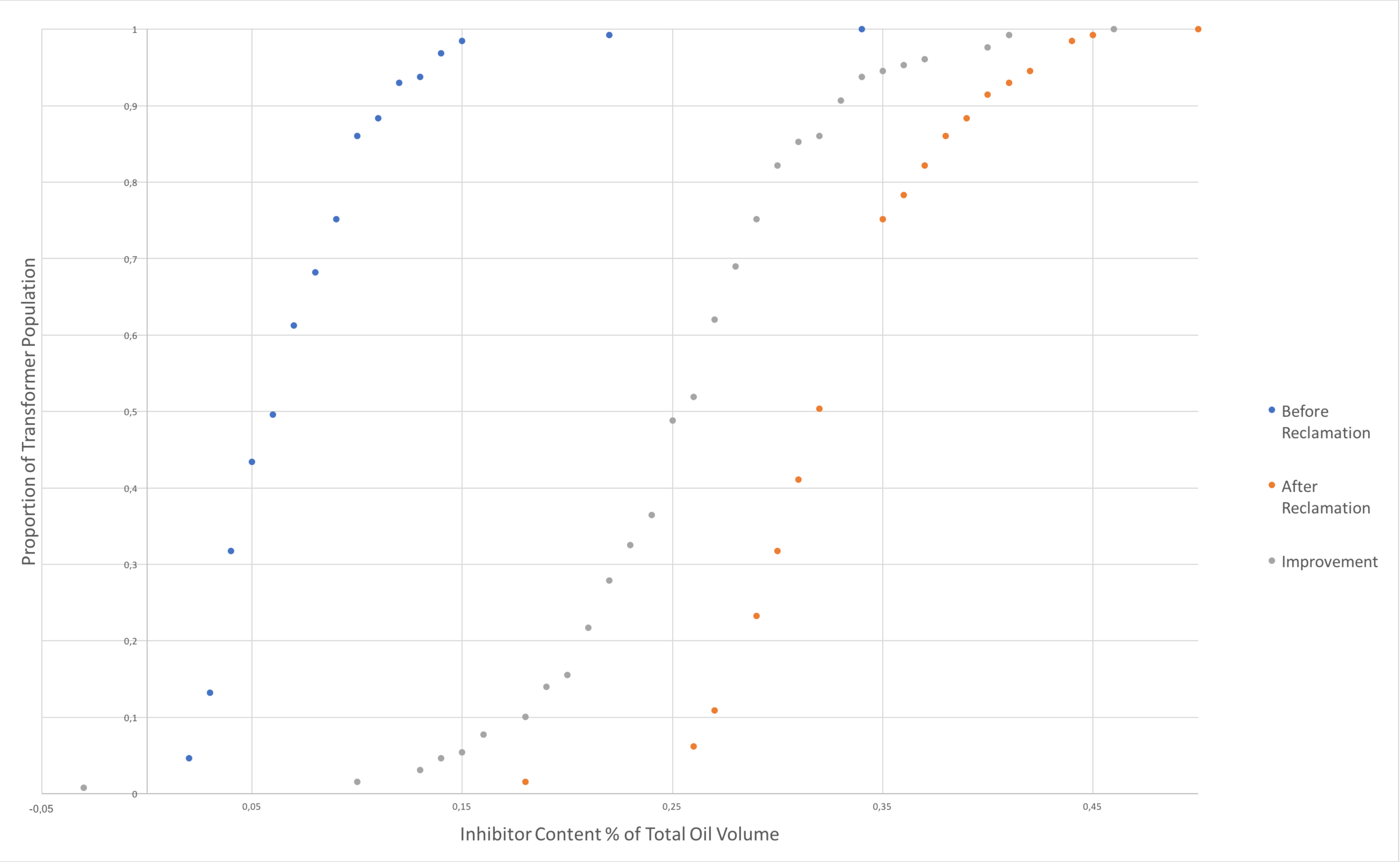

Figure C.7: *Cumulative representation of the Inhibitor content. As expected the inhibitor concentration increases after a reclamation process since it is refilled after the process is done. Of the 137 transformers in the population 129 transformers had a measured value both before and after the reclamation process.*

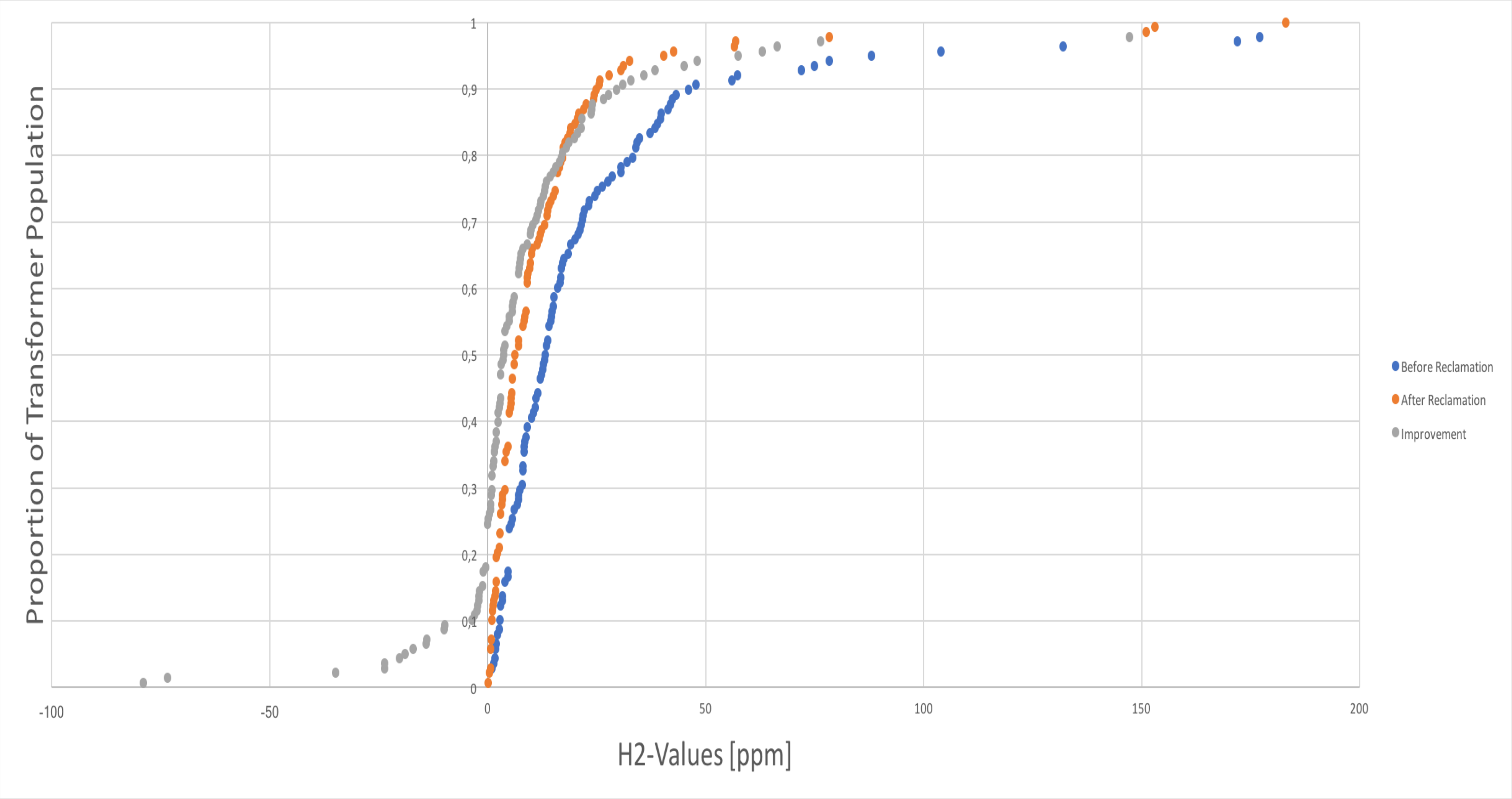

Figure C.8: *Cumulative representation of the H_2-content. Removed three extreme values (364, 308 and 223) and their improvements (338,304 and 190) to better show the normal improvements during a reclamation process. As expected gas values decrease when experiencing a reclamation of the oil. All the 137 transformers in the population had a measured value of hydrogen before and after the reclamation process.*

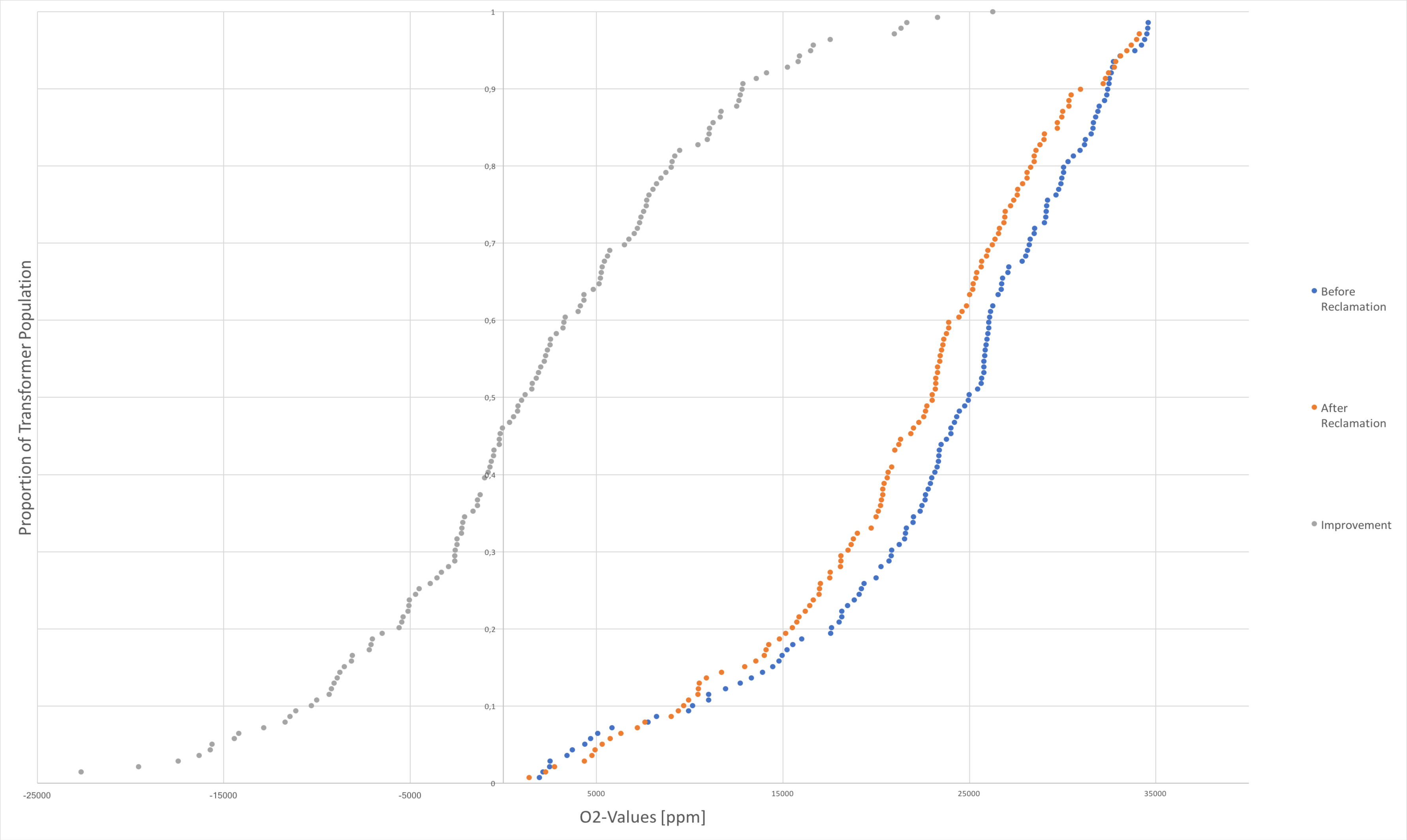

Figure C.9: *Cumulative representation of the O_2-Concentration. As expected the oxygen concentration in the transformer is decreasing for most transformers. All the 137 transformers in the population had a measured oxygen value before and after the reclamation process.*

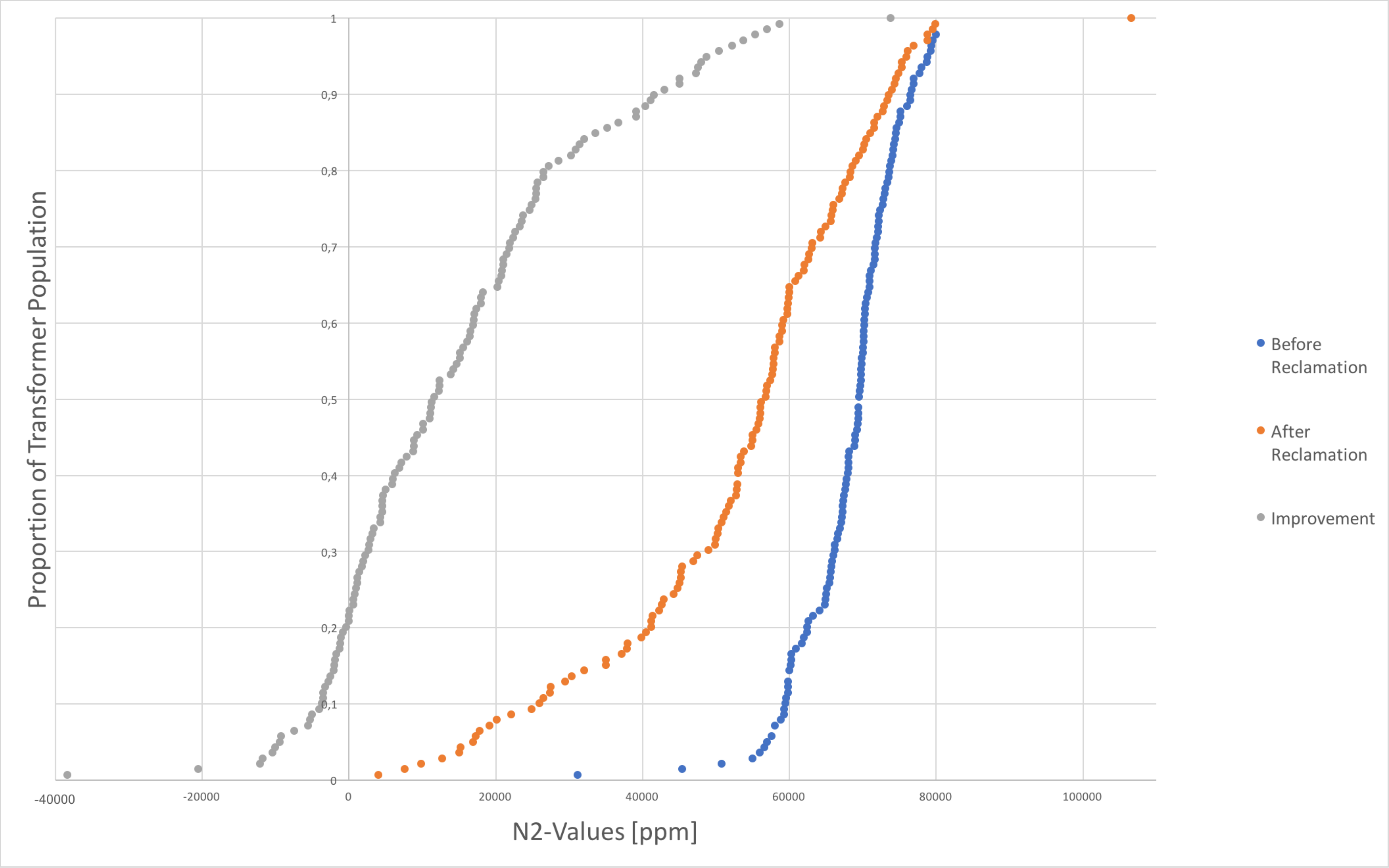

Figure C.10: *Cumulative representation of the N_2-Concentration. As expected the nitrogen concentration in the transformers decreases for most transformers. All the 137 transformers in the population had a measured nitrogen value before and after the reclamation process.*

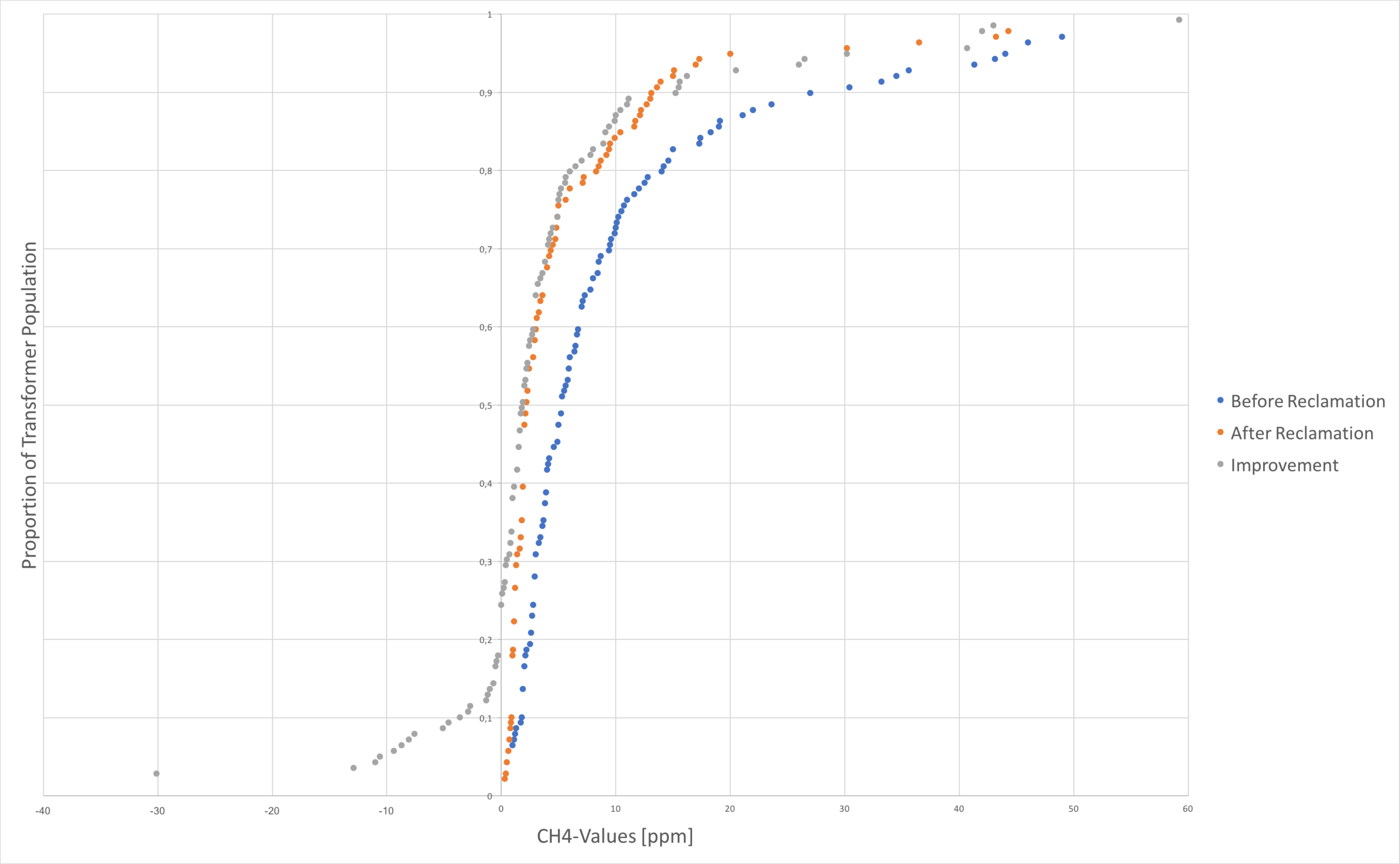

Figure C.11: *Cumulative representation of the CH_4-concentration. Here several extreme values are removed to show the general improvements and values. Removed values before reclamation (271, 170 and 84), after reclamation (357, 354 and 93) and improvement (-273, -92 and 157). As expected the methane concentration for most transformers decreases after a reclamation process. All the 137 transformers in the population had a methane value measured both before and after the reclamation process.*

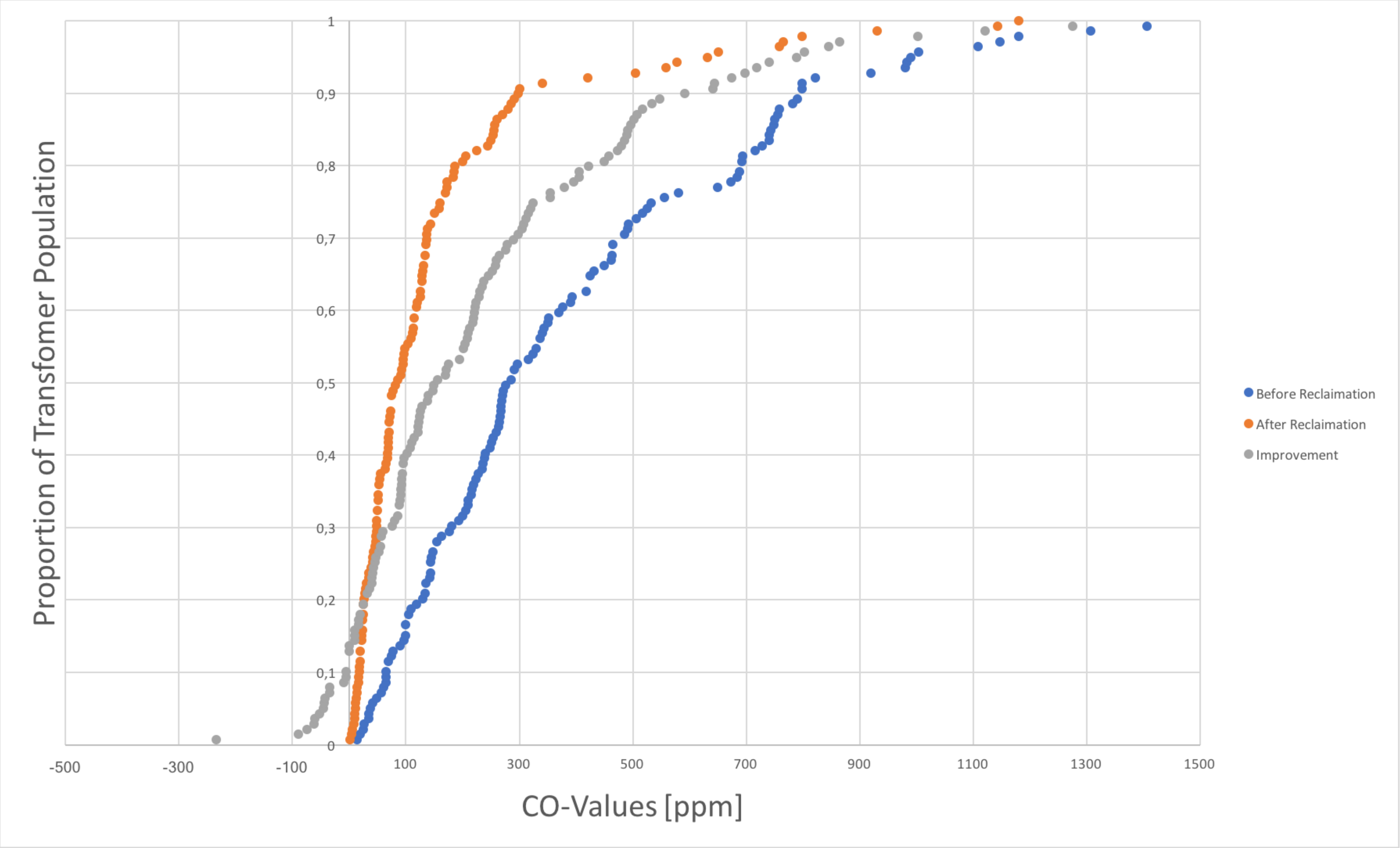

Figure C.12: *Cumulative representation of the CO-concentrations. In this plot one extreme value was removed to get a better visual of the normal values. The removed value was 5322 ppm before reclamation and the belonging improvement 5061ppm. As expected the carbon monoxide concentration decreases for most transformers. All the 137 transformers in the population had a measured carbon monoxide value both before and after the reclamation process.*

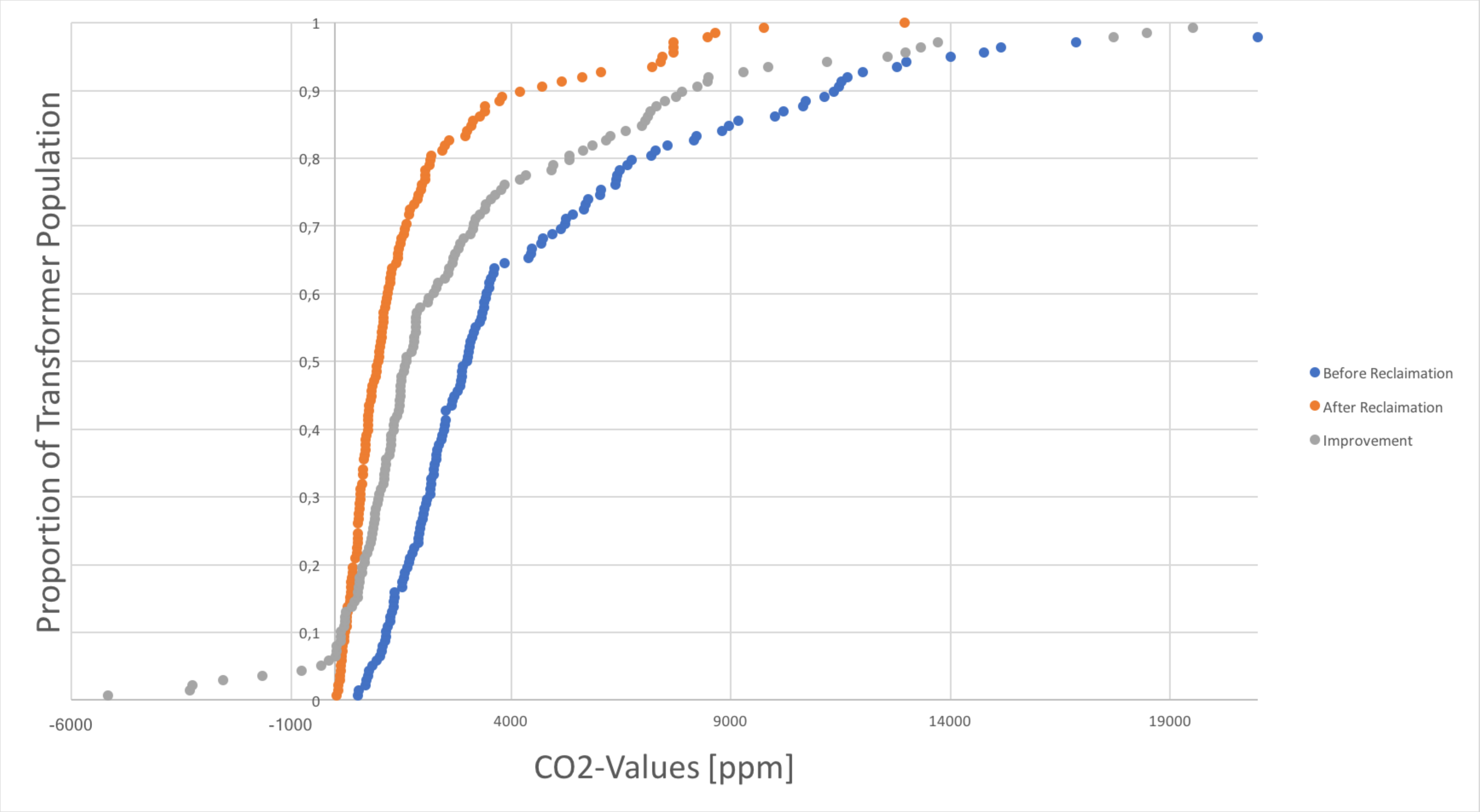

Figure C.13: *Cumulative representation of the CO_2-concentration. In this plot, some extreme values are removed to show the more general improvements. The extreme values removed are (31416, 30092 and 26978 ppm) and the improvement of 25893 ppm. As expected the carbon dioxide concentration decreases for most transformers with a reclamation process. All the 137 transformers in the population had a measured carbon dioxide value both before and after the reclamation process.*

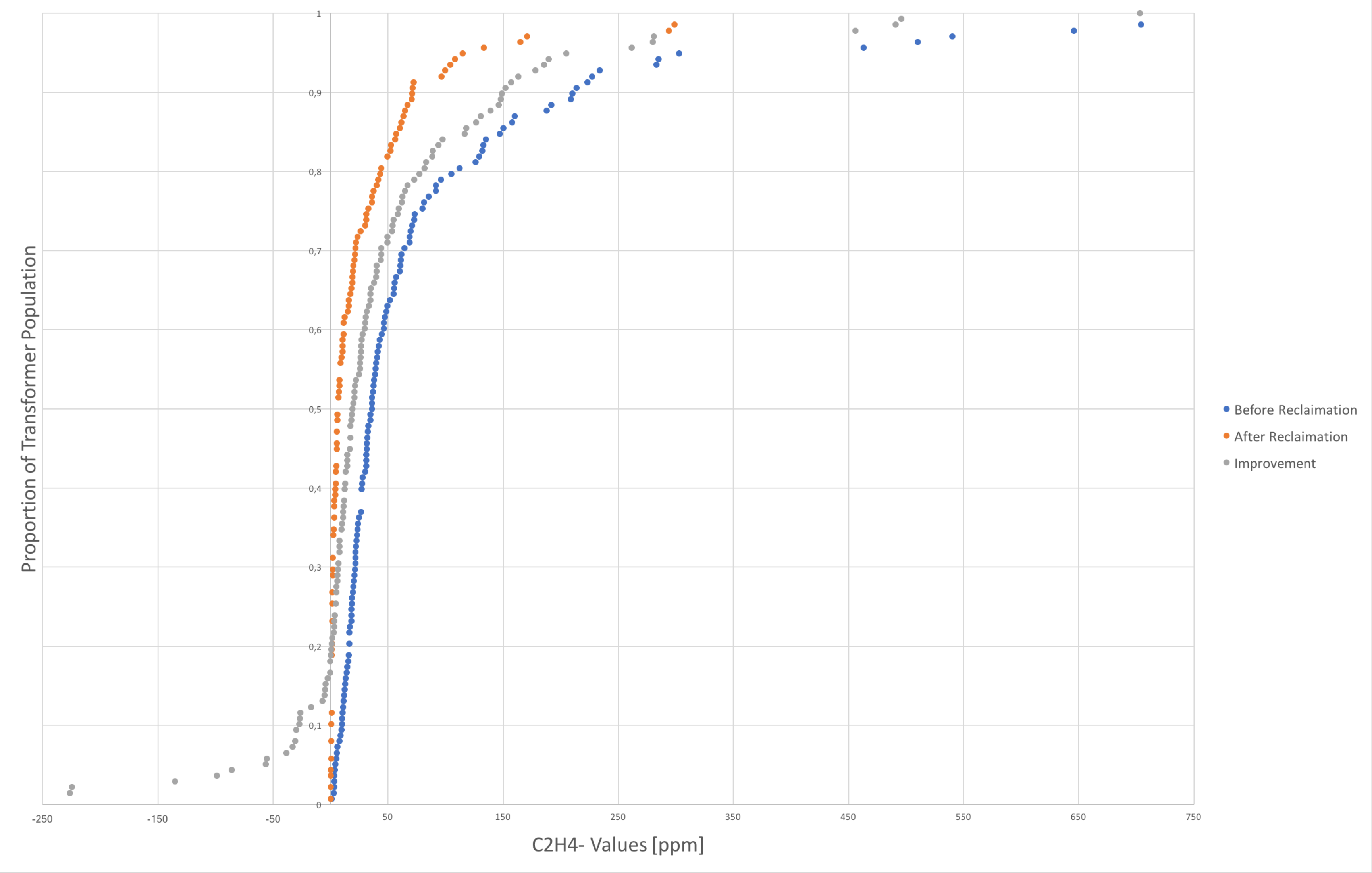

Figure C.14: *Cumulative representation of the C_2H_4 –concentration. In this plot, some of the extreme values have been removed to get a better look at the improvements from the reclamation. Before reclamation (1570, 1277 ppm) and after reclamation (1277 ppm) are removed in addition to the negative change of -924 ppm. As expected the ethylene concentration decreases after the reclamation process is finished for most transformers. All the 137 transformers in the population had a measured ethylene value both before and after the reclamation measure.*

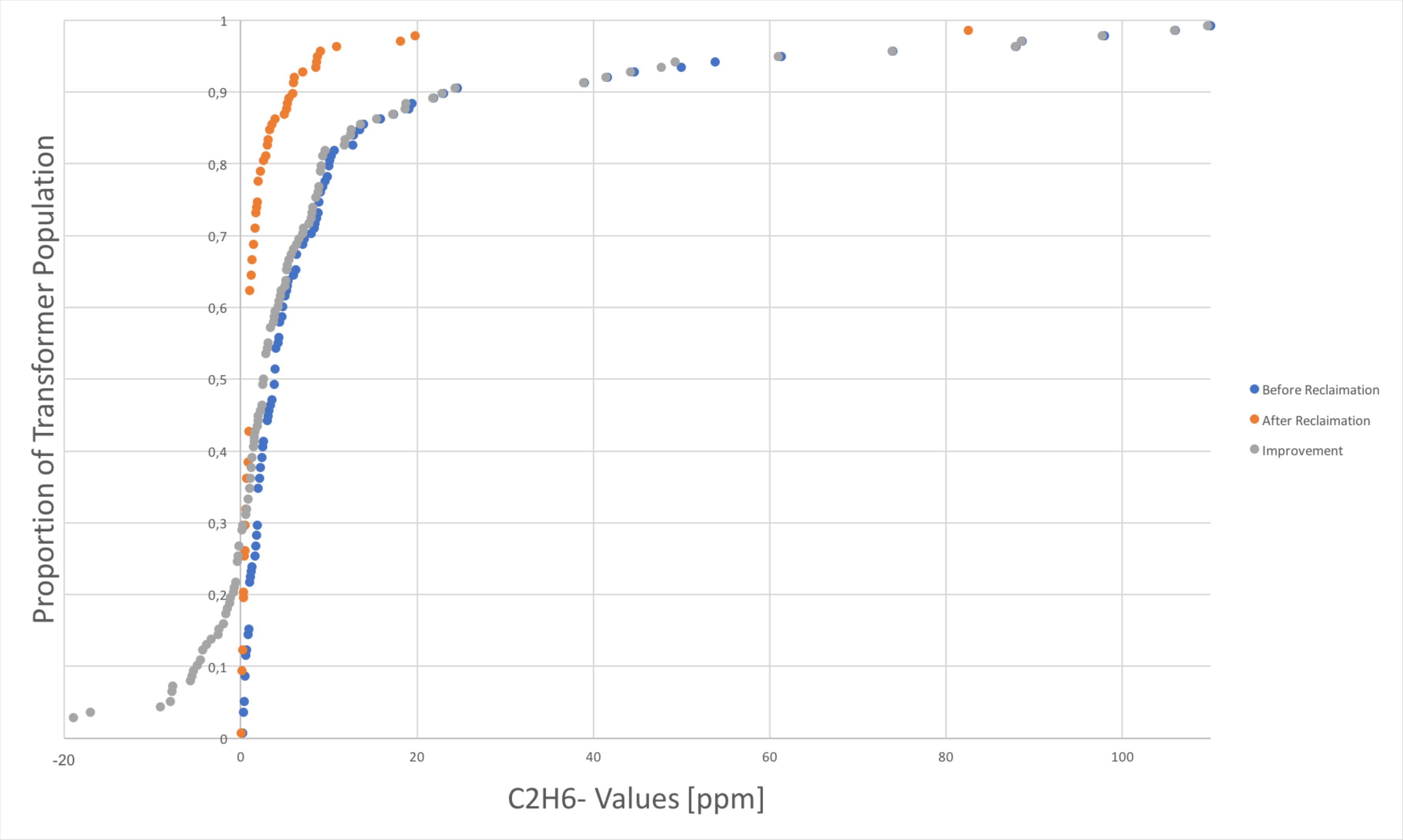

Figure C.15: *Cumulative representation of the C_2H_6-concentration. In this plot, some extreme values have been removed to better show the improvements achieved with reclamation. The removed values are 238 ppm (before measure), 232 and 166 ppm (after measure) and the negative change of -232 and -165 ppm. As expected the ethane concentration decreases for most transformers after the reclamation process. All the 137 transformers in the population had a measured ethane value both before and after the reclamation process.*

D| Recommended Limits for Mineral Oil in New Electrical Equipment

When studying the results achieved for different measures in this thesis it can be useful to compare these to what IEC have decided that new oil-filled equipment should have before they get energized. These values are just a guidance and an upper limit to what is recommended and the new oil in the transformer should be much lower than this. The limits can be seen in Table D.1 below [8].

Property	**Highest Voltage for Equipment**		
	<72,5	**72,5 to 170**	**>170**
Transformer Category	**C**	**B**	**A**
Colour	Max 2,0	Max 2,0	Max 2,0
Breakdown Voltage (kV)	>55	>60	>60
Water Content (mg/kg)	20	<10	<10
Acidity (mg KOH/g Oil)	Max 0,03	Max 0,03	Max 0,03
Dielectric dissipation Factor at 90^0 C and 40 Hz to 60 Hz	Max 0,015	Max 0,015	Max 0,010
Interfacial tension (mN/m)	Min. 35	Min. 35	Min. 35

Table D.1: *Recommended limits from IEC for mineral oils filled in new electrical equipment prior to energization.*

E| Statistical Theory

When working with big amounts of numbers and condition data it is sometimes easier to present the results as a function in a graph to prove a certain point. The cumulative distribution function, sometimes just called a CDF, is one easy way to do this. The theory of this distribution function and other relevant statistical theory are discussed in the sections below. The theory in this chapter is summarized from two educational [32] and [33], which are explaining statistical theory.

Probability Density Function (PDF)

Before describing the CDF, it is important to define the probability density function, or the PDF. The PDF is a representation, or a function *f(x)* of all the probabilities of for a continuous random variable *X*, defined over a set of real numbers. To be defined as a PDF the criteria in equation (E.1) needs to be satisfied [33]. A formula like this would need to be a function of the numerical value *x* and be written as *f(x)*.

1. $f(x) \geq 0,$ for all $x \in R$.
2. $\int_{-\infty}^{\infty} f(x)\,dx = 1.$ (E.1)
3. $P(a < X < b) = \int_{a}^{b} f(x)dx.$

Condition 1 explains that the probability cannot be lower than zero for any outcome, which is natural since probabilities are only positive numerical values and always above the x-axis in a plot. Condition 2 describes that the area under the probability density curve is equal to 1, or 100%. The last condition explains the probability that *X* is a value between the interval *a* to *b* equal to the to the area under the density function as seen in Figure E.1 [32].

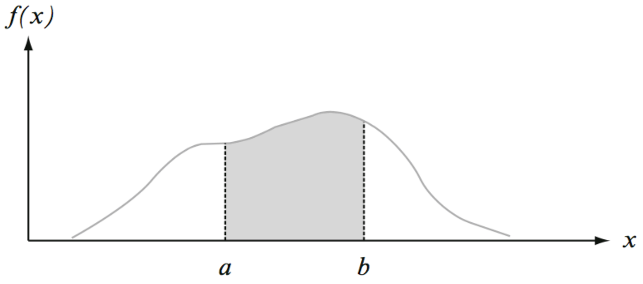

Figure E.1: *Condition 3 for a PDF as described above in (E.1).* $\boldsymbol{P(a < X < b)}$ *is equal to the area under the curve between a and b.*

Cumulative Distribution Function (CDF)

As described in the intro of this chapter the CDF is an easy function to prove certain points for a range of numbers. A normal purpose for a CDF that has a fixed value of *x,* is to compute what the probability of an observed value of *X* will be at most *x* [32].

The CDF *F(x)* of a discrete random variable *X*, with a PDF defined by *f(x),* can be described for every number *x* by equation (E.2) [33].

$$F(x) = P(X \leq x) = \sum_{t \leq x} f(t), \qquad \text{for } -\infty < x < \infty. \qquad \text{(E.2)}$$

For a continuous random variable *X* with the PDF *f(x)*, the CDF *F(X)* is almost the same as described above in (E.2), but with a little twist. The CDF for a continuous random variable *X* are described in (E.3) [33].

$$F(x) = P(X \leq x) = \int_{-\infty}^{x} f(t)\ dt, \qquad \text{for } -\infty < x < \infty. \qquad \text{(E.3)}$$

An example of a continuous CDF *F(x)* can be seen on the right in Figure E.2 [32], while the belonging PDF *f(x)* can be seen on the left. The relation between the PDF and the CDF are described by the lines in the plots.

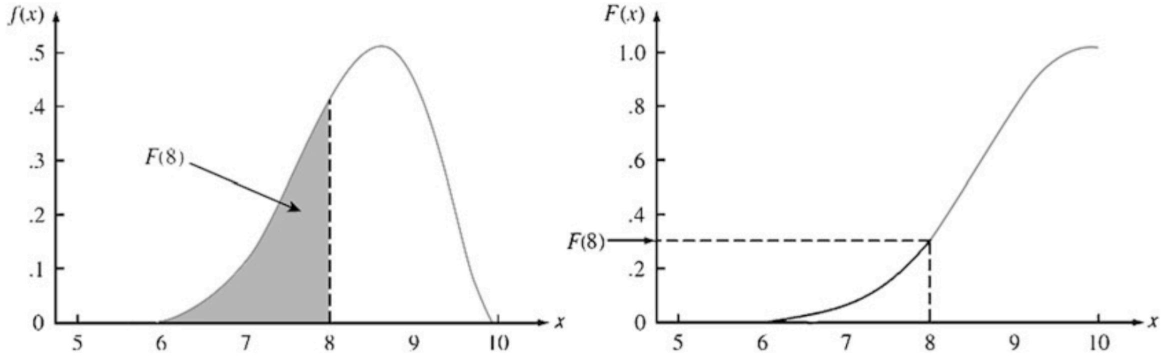

Figure E.2: *The correlation between the PDF on the left and the CDF on the right are described by the lines in the plots [32].*

From the plot, we can see that the correlation between a PDF and a CDF can be described by equation (E.4).

$$f(x) = \frac{dF(x)}{dx}. \qquad \text{(E.4)}$$