Investigating the environmental benefits of oil reclamation - A case study

ABSTRACT

This paper contributes to increasing transparency on the impact of transformer service activities on avoiding GHG emissions in the electricity system by presenting a case study and quantifying the life cycle carbon impacts and benefits of mineral oil reclaiming services when compared to replacement with new virgin oil. Virgin oil is a non-renewable and highly prized commodity and should be reused as much as possible.

KEYWORDS:

Oil Reclamation, CO_{2e} emissions, sustainability, Life Cycle Assessment, Oil Excange, Case study

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1. Introduction

Ambitious pathways to reach net-zero carbon emissions require a concurrent transition to clean energy. Electrification will play a key role in electricity consumption, accounting for almost 50% of total energy consumption in 2050. This will require investment in infrastructure with the deployment of clean and efficient energy technologies, such as renewables, energy storage, and new solutions like hydrogen [1].

Generation, Transmission & Distribution network infrastructure comprises substantial amounts of materials that consume energy and emit GHG emissions during their manufacturing, transportation, installation and end-of-life treatment. Network infrastructure also consumes energy and creates additional GHG throughout their operational lifetimes through transmission losses as well as routine maintenance and refurbishments. Finally, there are energy and carbon implications when decommissioning infrastructure at the end of its useful life. As an example, one of the world's largest power grid infrastructure systems has consumed massive volumes of greenhouse gas (GHG) intensive products such as steel, copper, and aluminium. A quantitative analysis of the carbon implications of expanding the power grid sheds light on the trade-offs among three connected dimensions of sustainable development, namely, climate change mitigation, energy access and infrastructure development. It was reported that cumulative embodied CO_{2e} emissions have dramatically increased by more than 7.3 times from 1990-2017 [2]. For substations, transformers were reported to be the biggest contributors towards embodied CO_{2e} emissions. Hence, it is paramount that as we transition towards a low carbon power grid, we discuss measures for the mitigation of CO_{2e} emissions from power transmission infrastructure such that low-carbon transitions can be supported.

As electricity becomes the backbone of the entire energy system, transformer technologies will contribute to the journey, supporting the sustainability efforts of the industry. The main purpose of transformers is to enable efficient and safe generation, transmission, distribution, and consumption of electrical energy by adapting voltage levels. With increasing grid complexity, they are also being used for improving power quality and network management. With millions of transformers installed worldwide, there is a transformer nearby supplying you with electrical energy no matter where you are.

2. Sustainability in Transformers

At Hitachi Energy, our aim is to advance sustainability in transformers across the

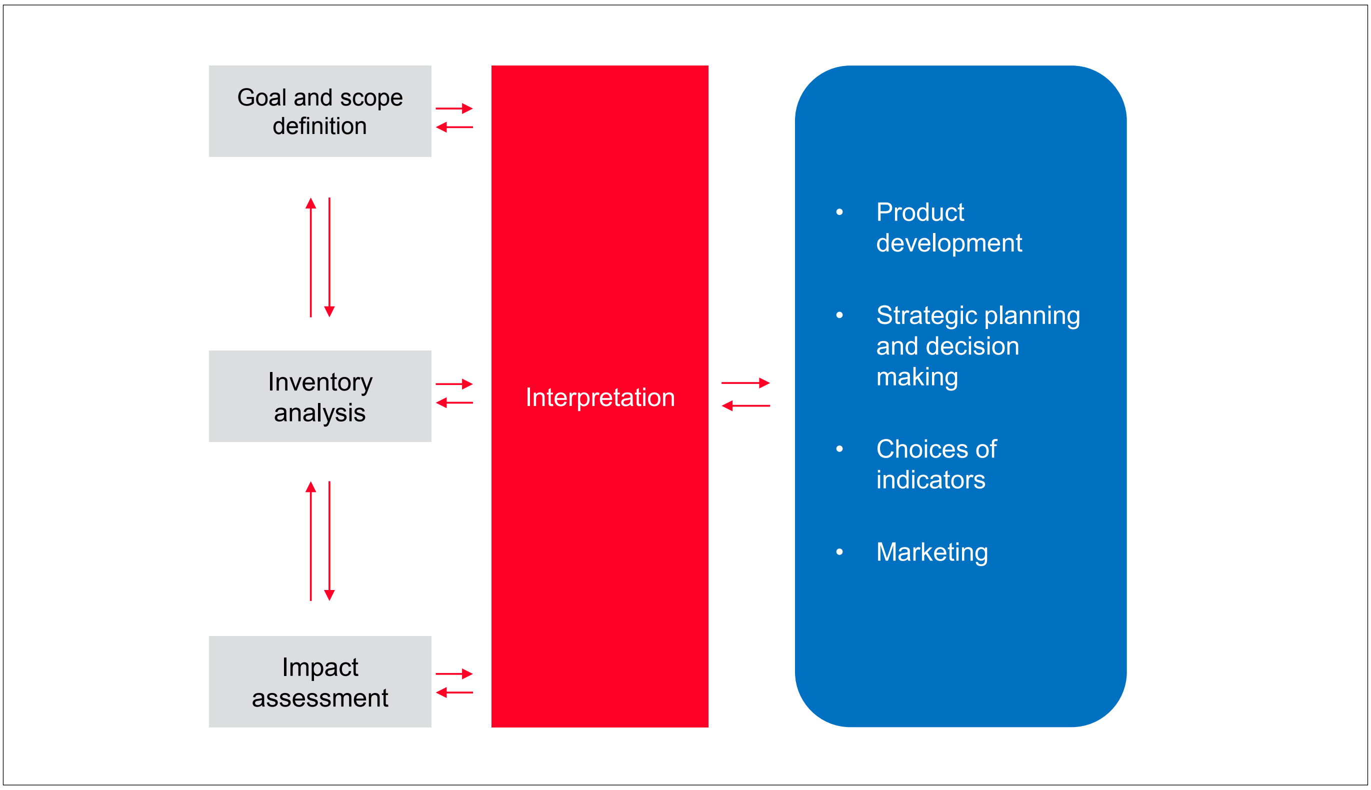

Figure 1. Illustration of the LCA Methodology

LCA is a holistic and science-based methodology that investigates and quantifies the environmental impact of a product, service, or system from cradle to grave throughout its life cycle

entire value chain, going beyond conventional financial and technical considerations to enhance environmental and economic benefits for all stakeholders [3]. When dealing with complex challenges, the first step in finding solutions is to objectively understand all associated aspects and related impacts and scientifically measure them. This gives perspective on the scale of the varied impacts and their criticality, what is known in the sustainability world as 'materiality.' This is crucial for investing the right resources to efficiently resolve the most important issues associated with sustainability and to avoid 'greenwashing.' Another important consideration is setting the 'topic boundary' or 'sphere of influence' of the transformer manufacturer.

Sustainability is a multidimensional field with several co-dependent variables that each add complexity. The Life Cycle Assessment (LCA) methodology, based on International Organization for Standardization (ISO) standards [4][5], is today considered the most scientific and credible system for measuring and communicating its environmental impacts, coming as close to reality as available methodologies today allow.

2.1 What is LCA?

LCA is a holistic and science-based methodology that investigates and quantifies the environmental impact of a product, service, or system from cradle to grave throughout its life cycle. This includes evaluating energy and resource consumption as well as emissions from all life cycle stages, including material production, manufacturing, use and maintenance and end of life.

An LCA is divided into four phases. In accordance with the current ISO terminology, the phases are called goal and scope definition, inventory analysis, impact assessment, and interpretation. These can be used in many ways, depending on how the goal and scope are defined, i.e., product or service development, decision making, indicator identification and marketing as examples of areas where the information retrieved from an LCA may be useful (Fig 1).

At Hitachi Energy, we promote sustainability in our transformers on the foundation of providing transparency obtained from LCA studies, for which we have developed a cradle to grave LCA model for transformers (Fig 2).

The LCA model has been built considering different environmental impact categories and involves creating an inventory of flows from and to nature for a product system as defined by relevant international environmental impact assessment standards such as the EN 50693:2019 and the EN 15804:2012+A2:2019/AC:2021. It is the process of quantifying raw material and energy requirements, atmospheric emissions, land emissions, water emissions, resource uses, and other releases over the life cycle of a product or process.

The main objective of enhancing the sustainable performance of transformers is to minimize any adverse social and environmental impacts across their life cycle, encompassing associated activities in the business value stream.

2.2 Sustainable Transformer Services

Fig. 3 below introduces the 5Rs Circularity multidimensional framework for achieving a more circular economic model and its applicability for the case of transformers.

The main objective of enhancing the sustainable performance of transformers is to minimize any adverse social and environmental impacts across their life cycle

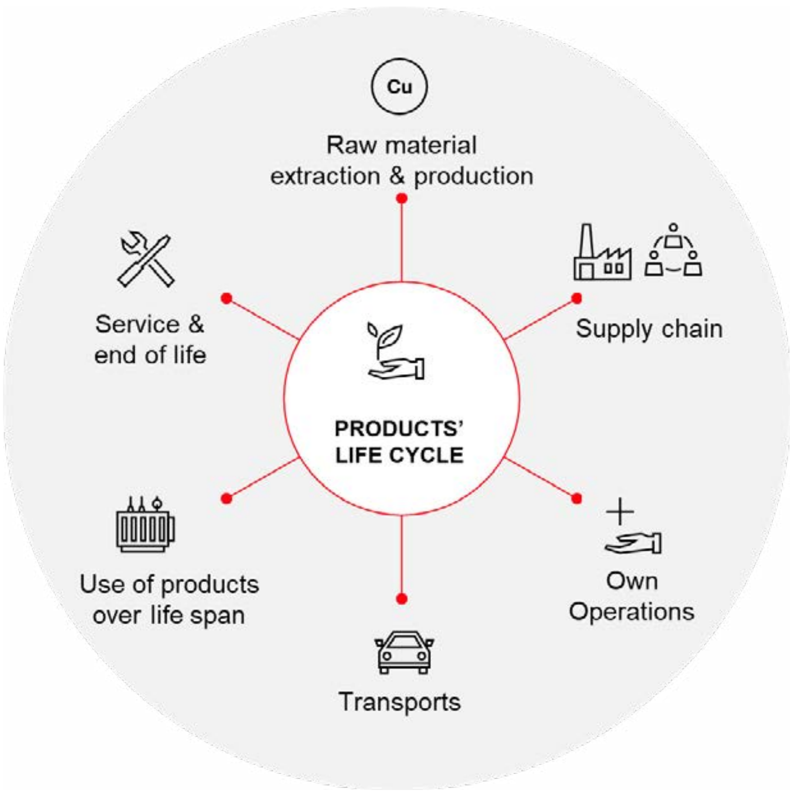

Figure 2. Cradle to Grave LCA across the whole transformers value chain

The sustainable transformer services concept encompasses the Repairing, Recycling and Rethinking paradigms

The model consists of 5 main strategies and levers as consumerism-altering concepts – Reducing, Reusing, Repairing, Recycling and Rethinking.

2.2.1 Reducing

The first concept in the 5Rs Circularity framework is Reducing, and its main aim is to reduce the reliance on virgin resources and to reduce waste generated throughout our value chain.

The "Reducing" concept could be achieved by superior transformer designs, lowering total material use while meeting operational energy efficiency specifications through compact designs.

2.2.2 Reusing

The second concept in the 5Rs Circularity framework is Reusing, and its main aim is to reuse the transformer after the end of life.

The "Reusing" concept could be achieved by utilizing midlife extension techniques. Typical life expectancy is 30-40 years, but planned transformer life extension actions and replacing key components such as bushings can allow the "reuse" of a transformer (instead of replacement) to an age of 60-75 years.

2.2.3 Repairing

The third concept in the 5Rs Circularity framework is Repairing, and its main aim is to repair the transformer and its parts to extend the valuable lifetime for as long as possible.

The "Repairing" concept could be fulfilled due to the availability of a complete suite of services, including life cycle extensions, asset management and digitalization technologies.

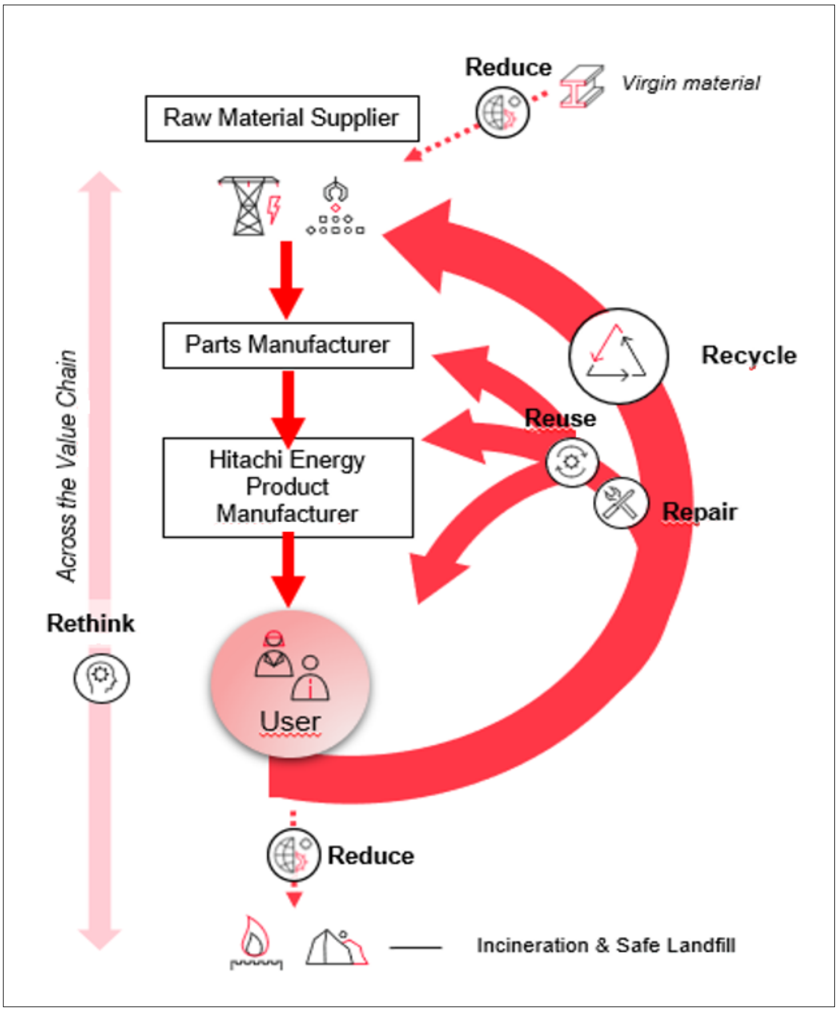

Figure 3. Circularity framework for transformer

2.2.4 Recycling

The fourth concept in the 5Rs Circularity framework is Recycling, and its main aim is to recycle materials from transformers that no longer can be reused or repaired. Strive for closed loop recycling where necessary, and use open loop recycling elsewhere. The "Recycling" concept could be achieved by increasing the share of recycled content in materials for new transformers and by offering guidance on how to disassemble units reaching their end of life to maximize the recoverability and recyclability of embedded materials. Oil reclamation is an example of closed loop recycling, which can be done either at site or offsite, and it can also be offline or online.

2.2.5 Rethinking

Rethinking, the fifth concept in the 5Rs Circularity framework, is about the way value is delivered to customers to design waste out of the equation. This concept is continuously applied across the value chain function to deliver the function with minimum waste. Digitalization is a prime example of rethinking where data is used to reduce waste. It can be in the design stage or even in the services stage, where we move from time-based maintenance to condition based maintenance.

The sustainable transformer services concept encompasses the Repairing, Recycling and Rethinking paradigms.

Under the recycling paradigm comes the concept of Oil Reclamation. Transformer oil represents 10-25% of the transformer's weight, theoretically, mineral oil can be 100% recycled and reused. According to the IEC oil maintenance guide, reclaiming is "a process which eliminates, by chemical and adsorbent means, the acidic and colloidal contaminants and products of oil deterioration from the oil, to obtain an oil with many characteristics similar to those of a new product" [6].

The essential elements of the oil reclamation technology are that relatively small amounts of sorbent are used and reactivated after each cycle. Usually, the process (as shown in Fig 4) is run in two alternating modes:

In this example, we investigate the outcome of carbon emission assessment (Oil Reclamation vs Oil Exchange) for a 300 MVA GSU, 20/420 kV transformer with 100,620 kg of mineral oil

A. The treatment mode, where the oil is:

1. drawn from the bottom of the tank,
2. heated,
3. pumped through the sorbent columns,
4. passes a filter and degasser,
5. and finally, is returned to the transformer through the expansion vessel.

B. Reactivation mode

In this stage, the sorbent columns are by-passed, and the oil is led directly to the filter-degasser. The sorbent is reactivated, e.g., by in situ incineration. Meanwhile it is possible to continue to circulate the oil to lower the water content even further, as well as the quantity of dissolved gases.

This process is repeated until the desired oil quality is achieved. Typically, the sorbent can be reactivated several hundred times. This means that the amount of waste per ton of oil treated is very small. Furthermore, this minute quantity of spent sorbent is problem-free from a disposal point of view since the last reactivation leaves it free from oil.

The final step is to restore the inhibitor content. The appropriate amount is dissolved in a portion of the newly treated oil. This stock solution is introduced in the main oil flow and then circulated until it is well blended. The concentration should be approximately 0.3%.

3. Case Study – Oil Reclamation

In this example, we investigate the outcome of carbon emission assessment (Oil Reclamation vs Oil Exchange) for a 300 MVA GSU, 20/420 kV transformer with 100,620 kg of mineral oil, which showed the following characteristics upon standard oil testing in Table 1.

[7] provides very extensive information on the Cu_2S failure mechanisms, its causes, practical failure and risk mitigation options. From the work of the CIGRE technical brochures, we now know that:

f) For insulation to be contaminated by Cu_2S, it is a precondition that the oil is corrosive as determined by IEC 62535 and/or DBDS >10 mg/kg in oil.
g) The risk is increased significantly where temperatures of the oil or hot spots are >80°C, oxygen concentration in oil is low, but >1000 ppm, (typical in transformers with sealed conservators), and dielectric stress level is high.
h) High voltage shunt reactors, generator step up transformers, HVDC trans-

Table 1: Oil Test Results for 300 MVA GSU

Oil Test	Results	Limits
Corrosive Sulphur as per IEC 62535	Corrosive	Non-corrosive
DBDS Content as per IEC 62697	37ppm	<5ppm

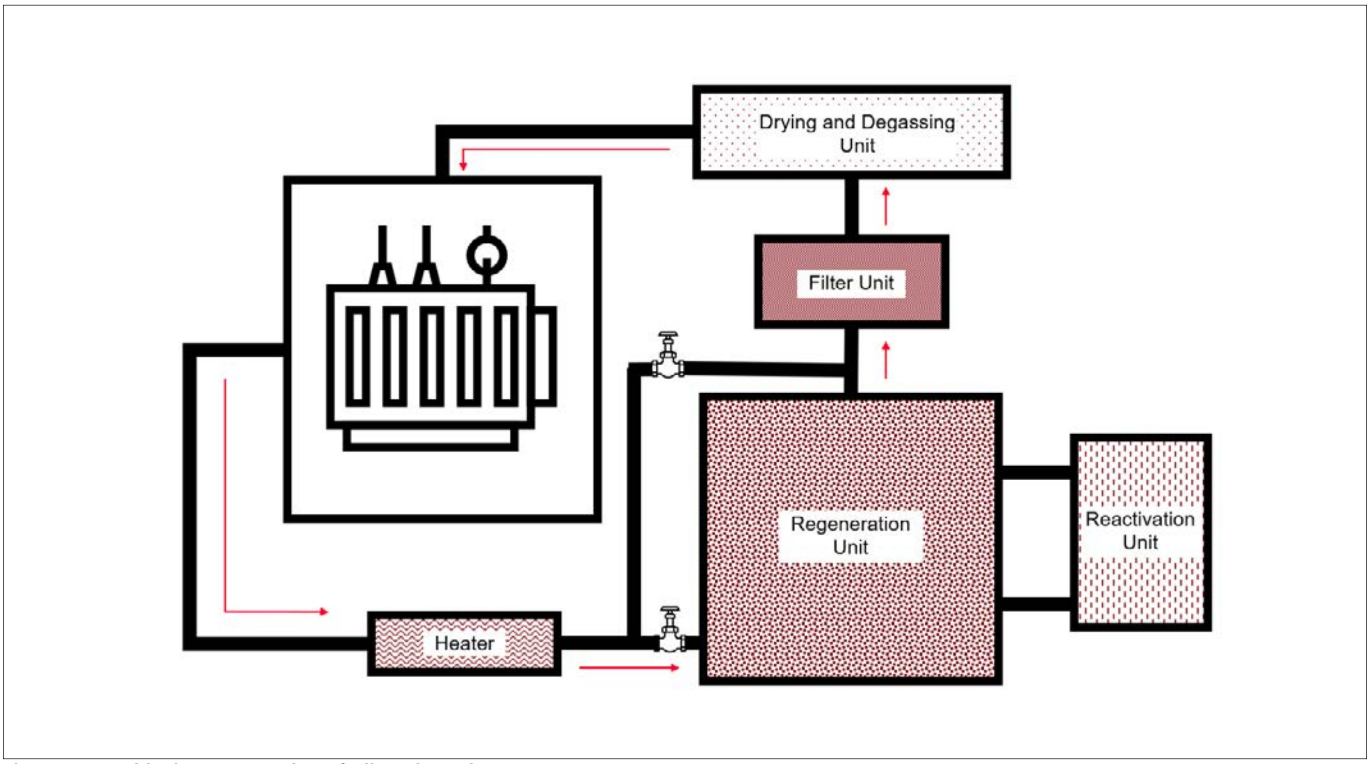

Figure 4. Graphical representation of Oil Reclamation

The risk of failure can be mitigated by exchanging corrosive oil with new oil (i.e., oil exchange) or by oil reclamation and, in the majority of cases, by oil passivation

formers, and rectifier transformers have the highest risk of failure, but other transformers are not immune to Cu_2S caused failures.

The risk of failure can be mitigated by exchanging corrosive oil with new oil (i.e., oil exchange) or by oil reclamation and, in the majority of cases, by oil passivation. A comparative table (Table 2) is listed here for the different techniques used for mitigating corrosive sulphur. Adding metal passivators is, up until now, the most widely used method as it is simple, reliable, and easy to implement. In some tough cases, the oil remains corrosive. In these cases, performing only passivation without reducing corrosive sulphur level to non-corrosive level and DBDS <5 ppm, the added additives (2,6-ditertiarybutyl para-cresol [DBPC] & Irgamet 39) will deplete faster due to residual polar oil contaminants, corrosive sulphur elements & DBDS mercaptans (organic components of hydrocarbons with Sulphur) present in the transformer oil. In these cases, the most beneficial solutions are to replace the oil or perform online reclamation. Hence, in this article, a comparison is carried out between Oil Reclamation or Oil Exchange.

Experiences from the field indicate that residual corrosiveness may appear because of incomplete rinsing of the active part [8]. The effects of residual corrosiveness are usually weak but may vary depending on the amount of residual oil and concentration of corrosive sulphur compounds in the original oil. The transformer design also plays a major role in the effectiveness of the action. For example, the amount of residual oil trapped in the tank can be relatively high if the oil drain valve is not located at the tank bottom.

When comparing oil exchange to oil reclamation, there are several attractive features of reclaiming, including environmental benefits. From a technical point of view, the repeated, or rather continuous, washing of the solid insulation represents a large advantage. In the case of oil exchange without proper cleaning of the active part (e.g., by "Vapour Phase" processing), these residual degradation products can cause a substantial shortening of the life of the new oil. The environmental benefits can be quantified by performing LCA quantifications.

The typical sources of CO_{2e} emissions during the oil reclamation process include the following (Fig 5):

a) CO_{2e} emissions due to transportation of reclaiming truck.
b) CO_{2e} emissions due to electricity consumed by the reclaiming truck.
c) CO_{2e} emissions due to waste oil at the end of the process and reactivation

The typical sources of CO_{2e} emissions during the oil exchange process include the following (Fig 5):

a) CO_{2e} emissions due to the production of new oil.
b) CO_{2e} emissions due to the transportation of new oil.
c) CO_{2e} emissions due to the incineration/landfill of in-service oil.
d) CO_{2e} emissions due to the electricity usage of the retro fill process.

3.1 Quantifying the carbon footprint of the oil reclamation service scenario:

3.1.1 CO_{2e} emissions due to transportation of reclaiming trucks.

- Weight of the reclaiming unit/truck – 15 ton

Table 2. Comparison of mitigation measures

Key Deciding Factors	Mitigation Methods			
Removal of DBDS	Adding Metal Passivators to existing oil	Oil Reclamation	Oil exchange with addition of metal passivators	Chemical process
Cost	Low	Medium	High	Medium
Complexity	Simple	Medium	Medium	Complex
Time	Low	High	Medium	High
On load?	Yes	Yes	No	Yes
Oil properties improved?	No	Yes	Yes	Yes
Stray gassing?	Yes	No	Yes	No
Acceptability?	Reliable, widely used, easy	Mixed response	Reliable, widely used	New Technique
Maintenance	Monitoring & Periodic replenishment	Monitoring	Monitoring & Periodic replenishment	Close monitoring

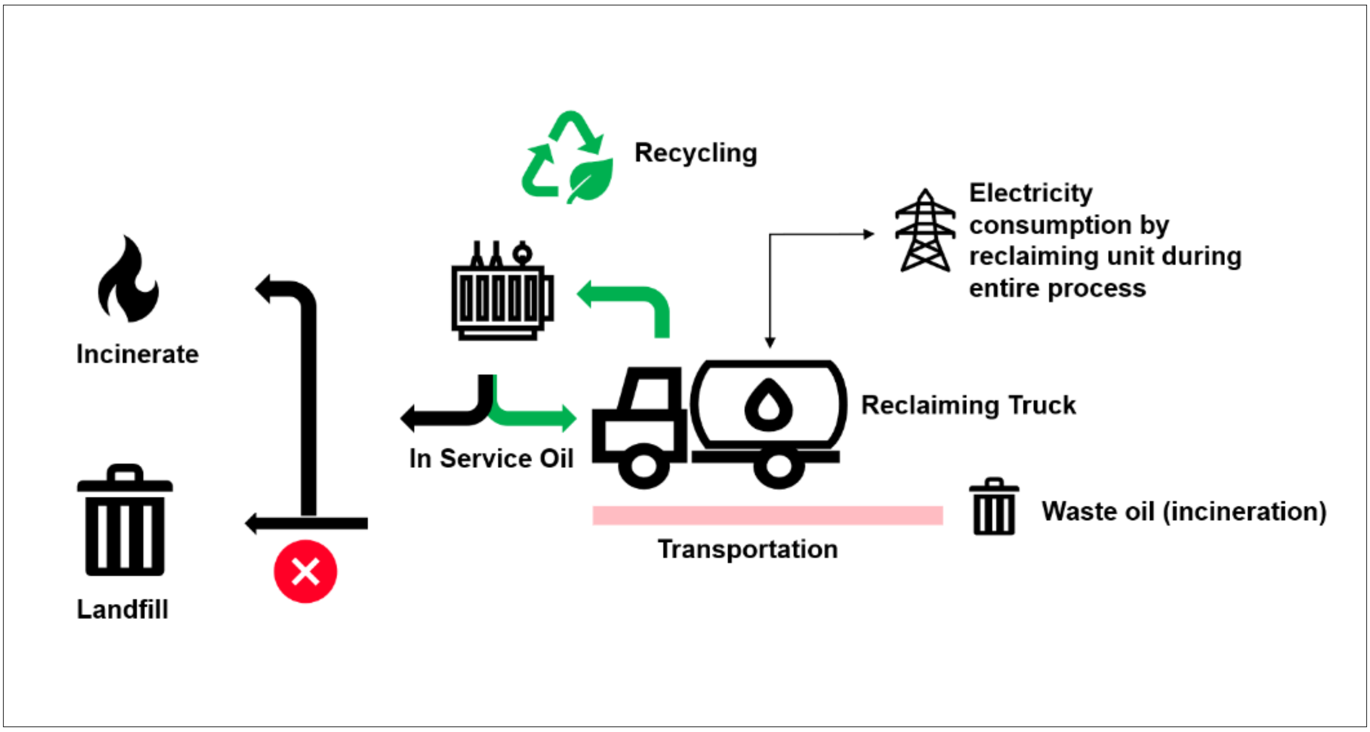

Figure 5. Boundary Conditions for Oil Reclamation vs Oil Exchange

- Return Distance to the transformer from service unit – 180 km.
- Emission factor for HGV Diesel vehicle (<20ton) – 0.988 $kgCO_{2e}$/(ton-km) [9]
- Transportation related emissions – **2.67 $tonCO_{2e}$**

3.1.2 CO_{2e} emissions due to electricity consumption.

The typical process for this 300 MVA GSU involved steps listed in Table 3.

- kWh rating of the reclaiming unit – 57 kWh
- Total electricity used = 43776 kWh
- Grid emission factor - 0.6 $kgCO_{2e}$/kWh
- Electricity related emissions – **26.26 $tonCO_{2e}$.**

3.1.3 CO_{2e} emissions due to waste oil end-of-life treatment

- Approximate amount – 200 kg
- Calorific value = 42 MJ/kg
- Emission factor = 74.1 tCO_{2e}/TJ
- Waste oil related emissions – 0.62 $tonCO_{2e}$.

3.1.4 CO_{2e} emissions due to transportation of waste oil

- Distance to incineration site – 200 km.
- Emission factor for HGV Diesel vehicle (<5ton) – 0.421 $kgCO_{2e}$/(ton-km) [9]
- Transportation related emissions – 0.43 $tonCO_{2e}$

In the case of oil exchange without proper cleaning of the active part, these residual degradation products can cause a substantial shortening of the life of the new oil

Table 3. Oil Reclamation Passes for 300 MVA GSU

Oil Reclamation Process	Days	Hours
Start	0	0
Pass 1: Regeneration	4	96
Pass 2: Regeneration	5	120
Pass 3: Regeneration	4	96
Pass 4: Regeneration	3	72
Pass 5: Regeneration	2	48
Pass 6: Regeneration	2	48
Passivator + 1st Filtration	4	96
2nd Filtration	3	72
3rd Filtration	3	72
Additional Passivator*	2	48
Total Time	32	768

*Additional passivator is typically not required. However, in this case, it was done as the end user was more familiar with oil passivation and requested it to be added.

The majority of the CO_{2e} emissions for the oil reclamation are due to the electricity consumption in the oil reclamation process

3.1.5 Total CO_{2e} emissions due to oil reclamation

Table 4. Total CO_{2e} emissions due to oil reclamation

Factors	tonCO_{2e} Emissions
Transportation	2.67
Electricity	26.26
Oil Waste	0.62 + 0.42
Total	29.97

This excludes emissions due to around 350 litres of DBPC inhibitor and 140 litres of passivator, as emission factors are not known. Even if it is assumed that these chemicals have high emission factors, as the volume used is very low compared to the mineral oil volume, the net impact will be marginal.

3.2 Quantifying the carbon footprint of the Oil Exchange Scenario

3.2.1 CO_{2e} emissions due to new oil production

- Amount of new oil required – 100,620 kg.
- Emission factor for mineral oil = 1.12 kgCO_{2e}/kg
- Emissions due to new oil = 112.69 tonCO_{2e}.

3.2.2 CO_{2e} emissions due to new oil transportation.

- Distance to the transformer from new oil supplier – 400 km
- Emission factor for HGV Diesel vehicle (>30ton) – 1.377 kgCO_{2e}/(ton-km)[9]
- Emissions due to transportation = 55.42 tonCO_{2e}.

3.2.2 CO_{2e} emissions due to in-service oil transportation for disposal

- Distance to incineration site – 200 km.
- Emission factor for HGV Diesel vehicle (>30ton) – 1.377 kgCO_{2e}/(ton-km)[9]
- Transportation related emissions – 27.71 tonCO_{2e}

3.2.3 CO_{2e} emissions due to incineration of in-service oil.

- Amount of in-service oil – 100,620 kg.
- Calorific value = 42 MJ/kg
- Emission factor = 74.1 tCO_{2e}/TJ
- Incineration related emissions – 313.08 tonCO_{2e}.

3.2.4 CO_{2e} emissions due to electricity usage during retro fill process

Any oil wastage is not considered in these calculations.

- kWh rating of the retro filling unit – 60 kWh
- Total electricity used = 10440 kWh
- Grid emission factor - 0.6 kgCO_{2e}/kWh
- Electricity related emissions – **6.26 tonCO_{2e}.**

Table 5. Total estimated time for Oil exchange

Oil Exchange Process	Days	Hours
Start	0	0
Oil Drain at 3000LPH	1.5	39
Mineral Oil Flushing at 3000LPH	1.5	39
Mineral Oil Retrofill at 3000LPH	4	96
Total Time (Estimated)	7	174

Table 6. Total CO_{2e} emissions due to oil exchange

Factors	tonCO_{2e} Emissions
New Oil Production	112.69
New Oil Transportation	55.42
Old Oil Incineration	313.08
Old Oil Transportation	27.17
Electricity	6.26
Total	514.62

For this 300 MVA GSU, over 480 tonCO_{2e} emissions can be avoided if we perform oil reclamation instead of oil exchange

The use of a science based LCA method gives us transparency regarding the impacts across the transformer life cycle

3.2.5 Total CO_{2e} emissions due to oil exchange

The use of LCA allows us to quantify the environmental benefits of sustainable transformer services. For this 300 MVA GSU, over 480 tonCO_{2e} emissions can be avoided if we perform oil reclamation instead of oil exchange. The DBDS concentration is also reduced, as shown in Fig 6, from 37 ppm to <5 ppm.

4. Summary

The objective of enhancing the sustainable performance of transformers is to minimize any adverse social and environmental impacts across its life cycle, encompassing associated activities in the business value stream. The challenge is to achieve the above in a sustained way, as "sustainable performance" itself is a moving target based on the evolution of technology, scientific knowledge and, finally, the shifting values held by society. The use of a science based LCA method gives us transparency regarding the impacts across the transformer life cycle. That's why cocreation with customized and optimized solutions informed by a scientific assessment of the associated environmental and climate impacts and benefits drives the sustainability journey based on the specific application, site conditions and other requirements. The approach of co-creating transformers will be invaluable in extending the life of existing transformers using sustainable services in a carbon-constrained world.

Previous LCA work in the electricity industry has predominantly focussed on electricity generation technologies, comparing the energy generated by and carbon emitted over the operational lifetime relative to the energy and carbon required to procure the fuel, build, operate, and decommission the power plants. It's recommended to focus on the carbon intensity of the power grid infrastructure as well, starting with the highest contributor, the transformer, by not only focusing on new transformers but also by valuing the contribution of "sustainable services" to decarbonizing and reducing the need for new materials as the demand for grid infrastructure will continue to grow.

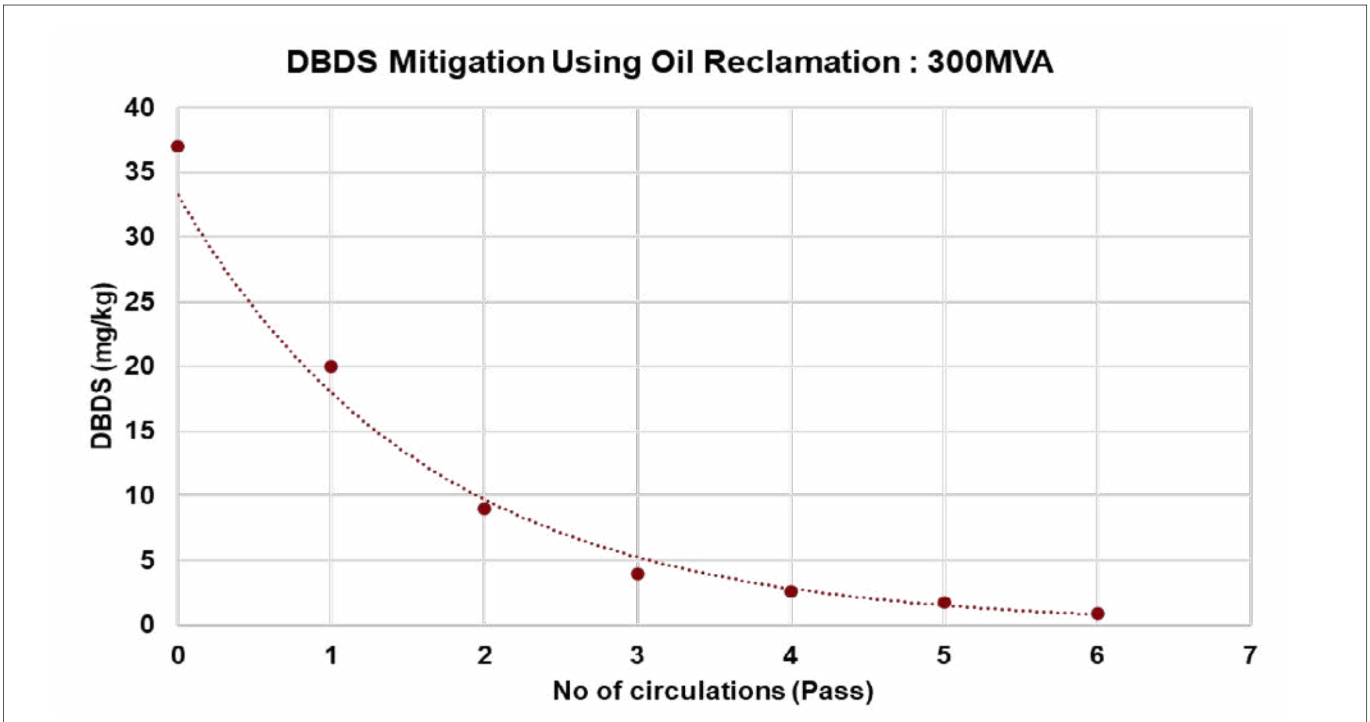

Figure 6. DBDS removal using Oil Reclamation

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