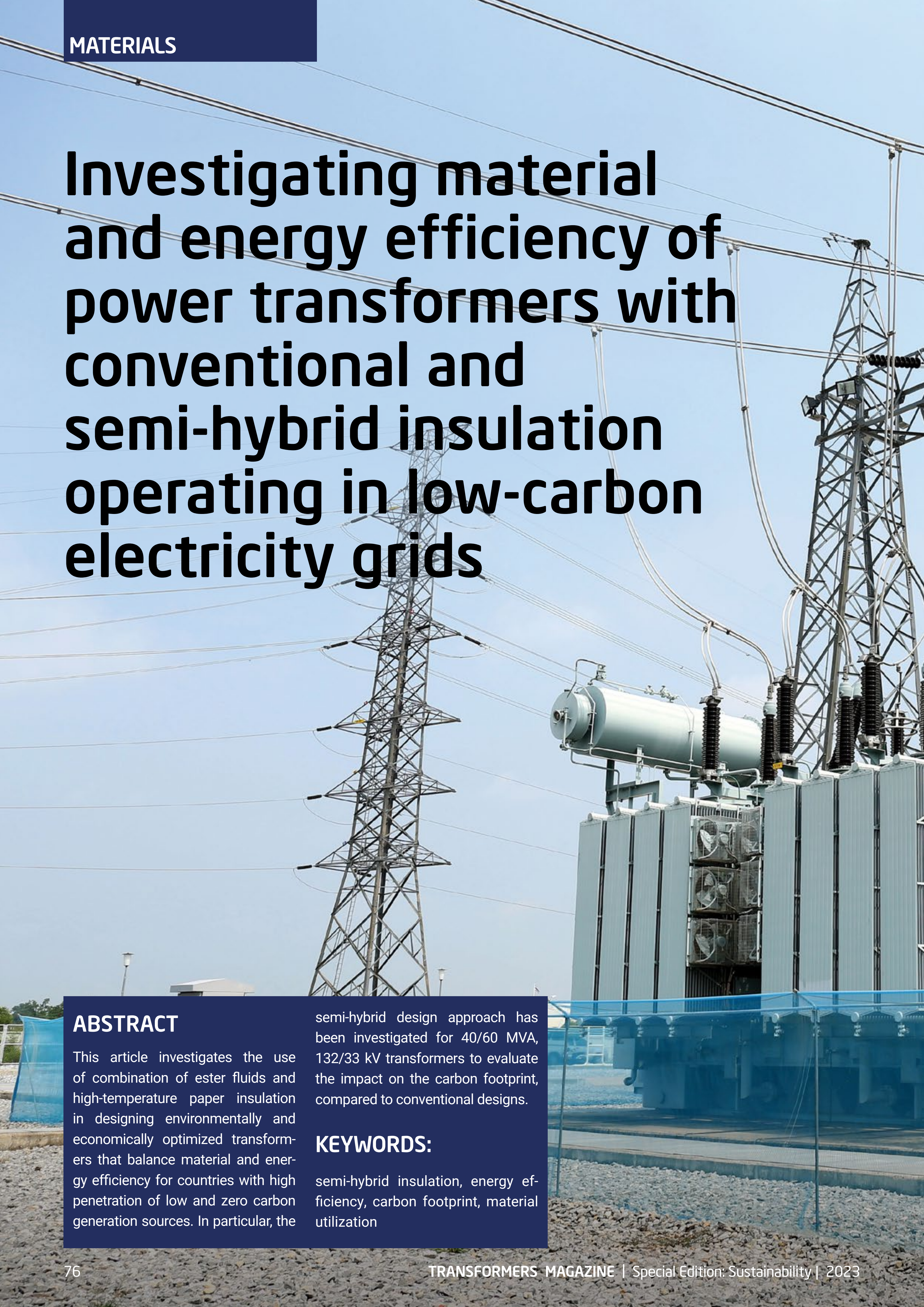

Investigating material and energy efficiency of power transformers with conventional and semi-hybrid insulation operating in low-carbon electricity grids

ABSTRACT

This article investigates the use of combination of ester fluids and high-temperature paper insulation in designing environmentally and economically optimized transformers that balance material and energy efficiency for countries with high penetration of low and zero carbon generation sources. In particular, the semi-hybrid design approach has been investigated for 40/60 MVA, 132/33 kV transformers to evaluate the impact on the carbon footprint, compared to conventional designs.

KEYWORDS:

semi-hybrid insulation, energy efficiency, carbon footprint, material utilization

Dr. Bhaba P. DAS, Ghazi KABLOUTI

Semi-hybrid insulation allows a step change in the ability to make transformers compact compared to 'conventional' designs based on cellulose insulation and mineral oil

1. Introduction

Traditionally, power transformers use an insulation system that comprises cellulose insulation immersed in mineral oil, which limits the maximum hot spot temperature to 98 °C [1]. IEC 60076-14 [2] classified new insulation systems into different categories and specified the temperature rise limitations of each category. These are referred to as hybrid insulation systems. A hybrid insulation system allows the loading capacity to increase substantially while reducing the long-term ageing of the insulation. Hybrid insulation systems with ester fluids are also becoming common. This type of system is a response to mitigate fire risk and resulting environmental damage in case of fire. One of the types of hybrid insulation systems is the semi-hybrid system, where the conductor insulation may see temperatures higher than 98 °C but the other parts remain below 98 °C since they are cooled by the bulk oil flow that will not see a significant temperature increase due to the higher thermal time constant of the oil compared to the copper. Semi-hybrid insulation allows a step change in the ability to make transformers compact compared to "conventional" designs based on cellulose insulation and mineral oil. In addition, the use of semi-hybrid insulation provides the opportunity to reduce the materials used in the transformer [3], [4], [5], which has a direct impact on the life-cycle carbon footprint of the transformer.

Transformers create environmental impacts, e.g., carbon emissions from electrical losses and materials used in their manufacturing as well as from end-of-life treatment. Thus, it becomes crucial that these environmental considerations are investigated. In this article, an investigation is conducted for a 40/60 MVA, 132/33.6 kV ONAN/ONAF with a target impedance of 14 % transformer on the life-cycle carbon footprint (tCO_{2-e} equivalent) of the three different insulation systems:

1. Conventional insulation system – mineral oil with Kraft paper (60/65 K temperature rise).
2. Conventional insulation system – ester fluid with Kraft paper (60/65 K temperature rise).
3. Semi-hybrid insulation system – ester fluid with TU paper (90/95 K temperature rise).

The article will share the comparison of the outcomes total life cycle carbon emission assessment and will demonstrate the impact of the insulation system on tCO_{2-e} equivalent emissions for:

- Design 1: Conventional insulation system in mineral oil,
- Design 2: Conventional insulation system in ester fluid,
- Design 3: Semi-hybrid insulation system in ester fluid,
- Design 4: Semi-hybrid insulation system in ester fluid considering the cost of carbon emission.

For all four designs, the life-cycle carbon footprint is estimated in the context of the New Zealand electricity mix, which is an electricity grid dominated by renewable energy.

In a hybrid insulation system, the insulation liquid can be conventional, i.e., mineral oil, or high-temperature type, i.e., ester fluid

2. Hybrid insulation systems

In a hybrid insulation system, the insulation liquid can be conventional, i.e., mineral oil, or high-temperature type, i.e., ester fluid, whereas the solid insulation is either conventional, i.e., kraft paper or a combination with high-temperature type, i.e., thermally upgraded paper (TUP). Three categories of hybrid designs have been proposed in IEC 60076-14, as listed in Table 1.

However, the reference temperature is equal to the rated average winding temperature rise + 20 °C for semi-hybrid insulation. When a comparison between

Table 1. Types of hybrid insulation vs. conventional design as per IEC 60076-14

Types	Semi-hybrid	Mixed-hybrid	Full-hybrid	Conventional
Insulation fluid	Conventional or high temperature	Conventional or high-temperature	Conventional or high temperature	Conventional or high temperature
Insulation of conductor	High temperature	Conventional and high-temperature combination	High temperature	Conventional
Spacers & strips	Conventional	Conventional and high-temperature combination	High temperature	Conventional
Other solid insulation	Conventional	Conventional	Conventional	Conventional

Table 2. Maximum temperature rise limits as per IEC 60076-14

Parameter	Semi-hybrid insulation system		Conventional insulation system
Insulation fluid	Mineral oil	Ester fluid	Mineral oil or ester fluid
Insulation of conductor	TU paper	TU paper	Kraft paper
Top oil rise	60 K	90 K	60 K
Average winding rise	75 K	95 K	65 K
Hot spot rise	90 K	110 K	78 K

the losses of transformers using conventional insulation with semi-hybrid insulation must be made, the reference temperature must be corrected to higher average winding rises. For a semi-hybrid insulation design, depending on the type of insulation fluid and conductor, the following maximum temperature rises with normal ambient temperatures as per IEC 60076-14 are listed in Table 2.

For this study, we consider the following generic transformer specification listed in Table 3.

Hydroelectricity has been a part of New Zealand's energy system for over 100 years and continues to provide most of the country's electricity needs, amounting to approximately 60 %

3. New Zealand energy mix

Hydroelectricity has been a part of New Zealand's energy system for over 100 years and continues to provide most of the country's electricity needs, amounting to approximately 60 %. Geothermal power generation is also integral to New Zealand's electricity landscape, accounting for approximately 16 % of New Zealand's electricity generation. Wind generation has grown quickly as a source of electricity in New Zealand, currently at 5 %. Electricity generation from the combustion of coal, oil, and gas provides baseload, backup, and peaking electricity supply constituting 20 % of the total electricity generation. The variation in the electricity generation mix from 2009–2020 is shown in Fig. 1 [6]. In 2016 and 2019, the Ministry of Business, Innovation & Employment (MBIE), Government of New Zealand published two reports [7] and [8], which provided insights into New Zealand's electricity demand and supply future. Electricity demand under different sensitivity analyses shows that it will exceed 50 TWh and up to more than 60 TWh in some scenarios (Fig. 2). To meet this demand, the majority of new build generation will be renewable. Renewable shares are projected to increase from the current 80 % in 2020 to around 95 % in all the scenarios. The combination of continued decline in the cost of solar and wind technology and limited supply of gas and oil will result in new build generation to be renewables. Under the different modelling scenarios presented in [7] and [8], the majority of the new builds will be wind generation (35–55 %). All the gas-fired or geothermal new builds will be operating a peaking role owing to the intermittent nature of wind power. It is mentioned that there is a limit to renewable electricity sources, and hence a maximum of 95 % of renewable electricity is estimated by 2050, as shown in Fig. 3.

Table 3: Major design parameters for the comparison study

Rating	40/60 MVA
Phases	3-phase
Impedance	14%
Voltages	132/33kV
Vector group	YNd11
Tapping	20 taps @1.25%
Cooling	ONAN/ONAF
Sound power level	83 dBA
Max flux density	1.7 T
Ambient temperature	25°C

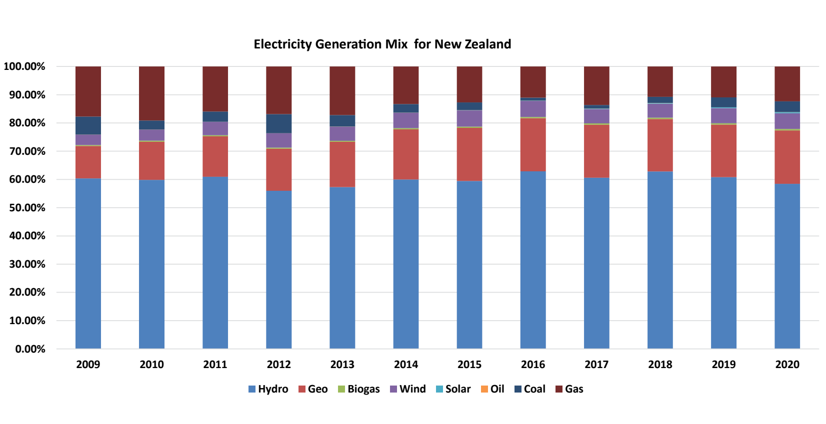

Figure 1. Electricity generation mix of New Zealand [6]

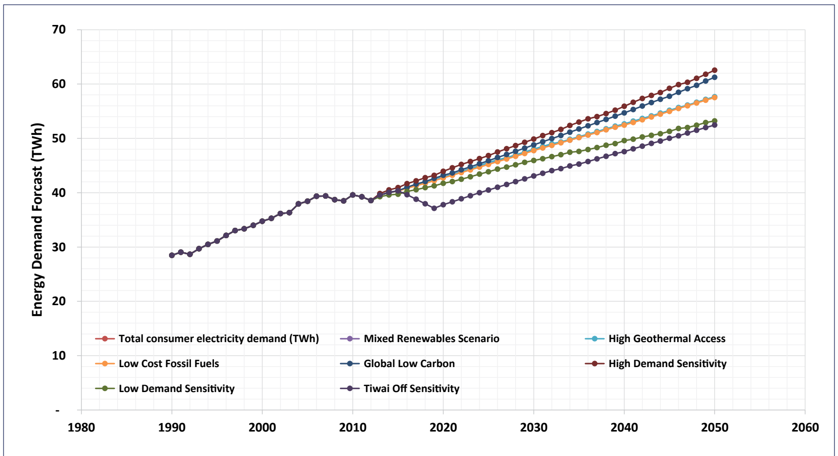

Figure 2. Electricity demand forecasts till 2050 [7]

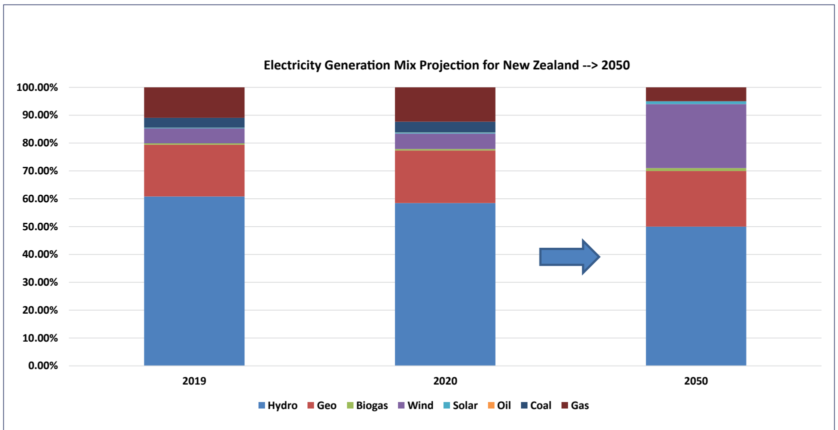

Figure 3. Electricity generation forecast for New Zealand in 2050: 95 % Renewable Target [8]

Table 4. GEF for carbon emission calculations (New Zealand)

Year	% Share of renewables	Grid emission factor
2020	~83 % (actual)	0.101 tCO_{2e}/MWh
2040	~90 % (estimated)	0.059 tCO_{2e} /MWh
2050	~95 % (target)	0.024 tCO_{2e} /MWh

3.1 Calculating the GHG (greenhouse gas) grid emission factor

To estimate the equivalent $CO_{2\text{-}e}$ impact due to the type of generation, the following formula is used [9]:

$$GHG_{fuel} = (G_{CO2} + 21 \times G_{CH4} + 310 \times G_{N2O}) \times \frac{0.0036}{\eta_{fuel}\,(1 - J_{T\&D})}$$

Where GHG is the emission factor of each fuel type in tons of equivalent carbon dioxide (tCO_{2e}) /MWh, GCO_2 is the CO_2 emission factor in kg/GJ, GCH_4 is the CH_4 emission factor in kg/GJ, GN_2O is the N_2O emission factor in kg/GJ, JT&D represents the transmission and distribution losses in %, and η_{fuel} is the fuel conversion efficiency in %. Using this equation, the Grid Emission Factor (GEF) can be calculated as listed in Table 4.

The New Zealand Emissions Trading Scheme (NZ ETS) is New Zealand's principal policy response to climate change

3.2 Estimating the cost of CO_2 per MWh ($/MWh) at mid-life

The New Zealand Emissions Trading Scheme (NZ ETS) is New Zealand's principal policy response to climate change. Originally designed to cover the whole economy, it has the broadest sectoral coverage of any ETS by directly covering forestry, waste, liquid fossil fuels, power, and industry [10]. A Fixed Price Option of NZ$ 25 (US$ 17.68) per tCO_{2e}, which acted as a form of price ceiling, was introduced in 2009 and raised to NZ$ 35 (US$ 24.76) for emissions that occurred in 2020. Several reforms were introduced in 2021 in line with the approval of the Climate Change Response (Emissions Trading Reform) Amendment Act 2020. The current price is NZ$ 76 (US$53) per tCO_{2e} (Figure 4) and is expected to rise by

Table 5. The cost of emission from fossil-based power generation at mid-life of transformer

	Hydro	Geo	Biogas	Wind	Solar	Oil	Coal	Gas
Fuel %	55%	19%	0.75%	14%	0.80%	1.95%	0%	8.50%
G_{CO2}	0	0	0	0	0	74.1	94.6	56.1
G_{CH4}	0	0	0	0	0	0.002	0.002	0.003
G_{N2O}	0	0	0	0	0	0.002	0.003	0.001
η_{fuel}	100%	100%	100%	100%	100%	30%	35%	45%
$J_{T\&D}$	7%	7%	7%	7%	7%	7%	7%	7%
GHG_{fuel}	0	0	0	0	0	0.9646	1.068	0.4857
Ceq –factor (tCO_{2e} /MWh)	0	0	0	0	0	0.018	0	0.041
Price of CO_{2e} ($/$tCO_{2e}$)	120	120	120	120	120	120	120	120
Emission cost ($/MWh)	0	0	0	0	0	2.25	0	4.95
Total Emission cost ($/MWh)	$7.2/MWh							

With semi hybrid design, higher temperature rises are allowed, which would allow the design to have lower masses compared to a conventional insulation system in ester fluid

2 % per year in line with projected inflation. However, the revised calculation projected it to reach NZ$110 (US$77.8) per tCO_{2e} by 2026. For our calculation, a value of NZ$ 180 (US$120) per tCO_{2e} is used.

Table 5 shows the emission cost calculation, which results in a value of $7.2/MWh for the NZ generation mix of 2040, i.e., the mid-life of the transformer. Table 6 shows the resulting capitalization factors considering only the emission cost (excluding the cost of losses).

4. Design outcomes

Four designs were completed with the following design strategies

1. Design 1: Optimization of transformer design for cheapest manufacturing price for Conventional insulation system in mineral oil, without the total cost of ownership considerations and standard temperature rise limits.
2. Design 2: Optimization of transformer design for cheapest manufacturing price for Conventional insulation system in ester fluid, without the total cost

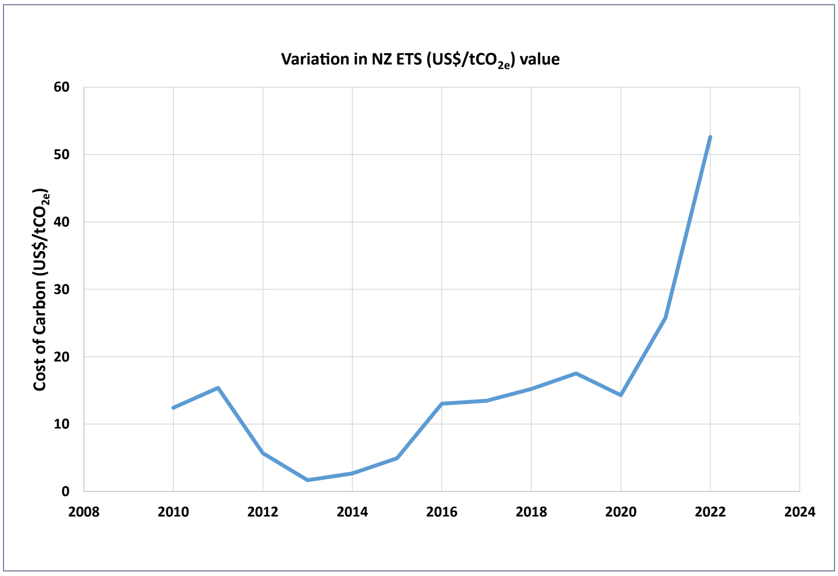

Figure 4. NZ ETS price variation 2010-2022 [10]

Table 6. TCO formulation with environmental impact only

Parameters	No load loss (A) factor	Load loss (B) factor
Cost of carbon = $7.2/MWh Discount rate = 4% Life of power transformer = 40 years Estimated loading = 50 %	$1,248/kW	$312/kW

of ownership considerations and standard temperature rise limits.

3. Design 3: Optimization of transformer design for cheapest manufacturing price for Semi-hybrid insulation system in ester fluid, without the total cost of ownership considerations and high-temperature rise limits.
4. Design 4: Optimization of transformer design for cheapest manufacturing price for Semi-hybrid insulation system in ester fluid with high-temperature rise limits and capitalization factors derived from the cost of CO_2 emissions (based on Table 6).

Typically, active parts for ester transformers are heavier than those for mineral oil-filled transformers because of the following reasons:

1. Depending on the voltage class, stress levels, and technology used, the dielectric performance of ester is different from mineral oil and requires potentially lower stresses and modified solid insulation structures. This results in slightly larger dielectric distances and more solid insulation between and within the windings. This increases the winding and core dimensions which leads to increased mass.
2. The higher viscosity of the ester (compared to mineral oil) means that it flows more slowly within the labyrinth ducts within the windings. This results in a longer duration when in contact with the heat source (winding conductors), and hence the increase in fluid temperature is greater. If it is required to achieve the same temperature rise limits, then either some or all of the following need to be implemented:
   1. The cooling ducts within the windings need to be modified (increased in cross-section area or quantity) to allow faster flow of the higher viscosity fluid.
   2. The losses are reduced by an increased cross-section of copper in the windings to reduce the heat.
   3. The quantity of external cooling equipment needs to be increased.

However, with semi hybrid design, higher temperature rises are allowed, which would allow the design to have lower masses compared to a conventional insulation system in ester fluid. The results are presented next sections. This would lower the manufacturing carbon footprint of the transformer.

4.1 Transformer temperature rise outcomes

For an ambient temperature of 25 °C, the following limitations in Table 7 apply:

4.2 Transformer efficiency outcomes

The transformer loss outcomes for the four different designs are listed in Table 8, and the efficiency vs. load curves are shown in Fig. 5.

Table 7. Maximum ambient corrected temperature rise limitations

	Conventional insulation system	Semi-hybrid insulation system
Insulation fluid	Mineral oil or ester fluid	Ester fluid
Insulation of conductor	Kraft paper	TU paper
Top oil rise	55 K	85 K
Average winding rise	60 K	90 K
Hot spot rise	73 K	105 K

Table 8. Transformer loss values for the different designs

Parameters	Design 1 at 75 °C (reference)	Design 2 at 75 °C (reference)	Design 3 at 115 °C (reference)	Design 4 at 115 °C (reference)
Type	Conventional mineral oil	Conventional ester fluid	Semi hybrid ester fluid	Semi hybrid ester fluid optimized at $120/tCO$_{2e}$
No load loss (kW)	22.9	25.8	23.8	17.8
Load loss (kW)	344.9	302.0	388.9	345.5
Total loss	367.8	327.8	412.7	363.35
Peak efficiency index (PEI) design output	99.704 %	99.706 %	99.679 %	99.738 %
IEC PEI Level 1 achieved?	No	No	No	Yes
IEC PEI Level 2 required?	No	No	No	No
Load at peak efficiency (KPEI)	0.258	0.292	0.247	0.227

4.3 Transformer component mass outcomes

The resulting component weights are listed in Table 9.

4.3.1. Material efficiency comparison between conventional insulation and semi-hybrid insulation in ester

The resulting component mass comparison between conventional insulation and semi-hybrid insulation in ester fluid is shown in Fig. 6. The use of semi-hybrid insulation allows a reduction of core coil assembly weight by ~9 %, a reduction in tank weight by ~3 %, radiator mass by ~40 %, oil by around 12 % and the total transformer weight by 14 % for the 40/60 MVA between design 2 and 3.

Operating transformers at higher temperatures than conventional values allow the designer to increase material efficiency by reducing the weight and dimensions. This can be a valuable approach in some applications, even though the losses generated by such hybrid designs may be higher. The suitability of this approach for reducing the life-cycle carbon footprint is investigated for a low-carbon electrical system, as in the case of the New Zealand

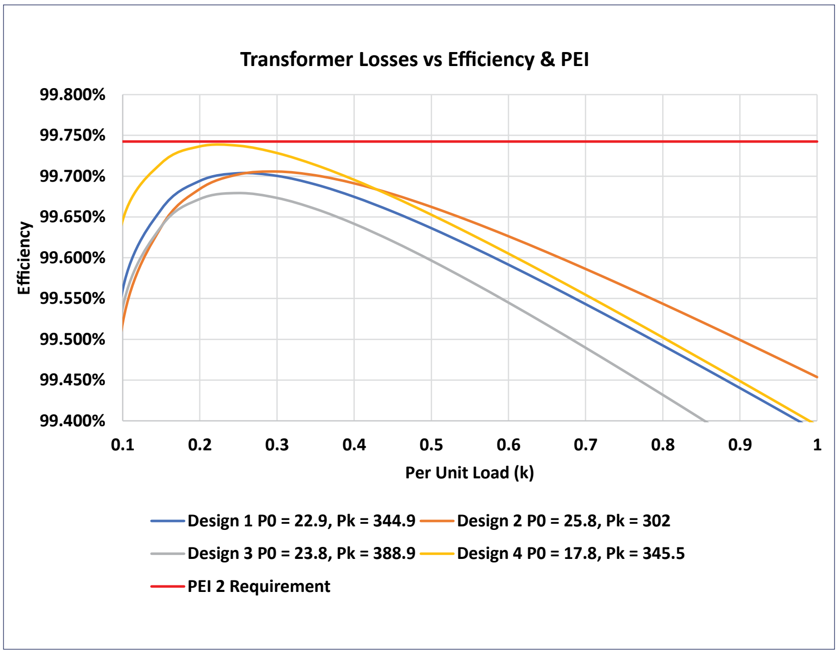

Figure 5. Transformer efficiency curves: designs 1, 2, 3 and 4

The use of semi-hybrid insulation allows a reduction of core coil assembly weight by ~9 %, a reduction in tank weight by ~3 %, radiator mass by ~40 %, oil by around 12 % and the total transformer weight by 14 %

Table 9. Component weight outcomes for the different designs

Parameters	Design 1	Design 2	Design 3	Design 4
Core coil assembly (kg)	31,565	35,465	32,290	33,750
% Change from Design 1	--	↑12.3%	↑2.3%	↑6.9%
Tank, tank shunts & covers (kg)	10,385	11,110	10,715	13,600
Turrets & bushings (kg)	615	580	580	560
Radiator (kg)	13,100	13,760	8,205	6,930
% Change from Design 1	--	↑5%	↓37.3%	↓47.1%
oil (kg)	19,250	21,600	18,900	18,720
% Change from Design 1	--	↑12.2%	↓1.8%	↓2.7%
Total weight (kg)	75,540	83,140	71,315	74,090
% Change from Design 1	--	↑10%	↓5.6%	↓1.9%

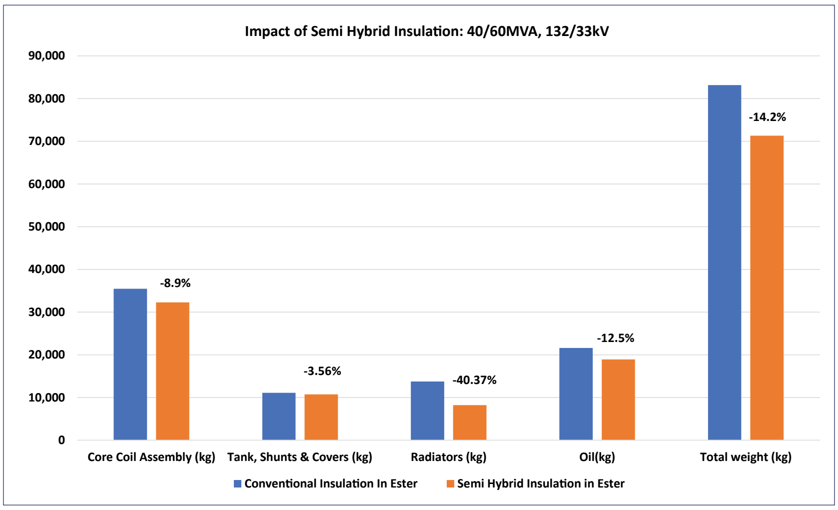

Figure 6. Mass comparison between Design 2 and Design 3

energy mix, which has a predominantly renewable energy mix.

5. Impact of semi-hybrid insulation on transformer life cycle carbon emissions

5.1 System boundaries of the life-cycle assessment

To evaluate the impact of design variations, the assessment is based on international LCA standards and particularly on the product category rules for liquid-filled power transformers [13]. The following processes are included in this study

The following processes are included in the system boundaries:

- Raw material extraction and production for manufacturing
- Transportation of components to transformer factory
- Transportation of product to the end user (operator)
- Electricity production covering power losses at operation
- End-of-life management

The following processes are not included in the system boundaries:

- Preventative maintenance activities
- Raw material extraction and production for operation/service activities
- Transportation of raw materials to component manufacturing
- Energy used for component manufacturing processes at suppliers
- Manufacturing and operation of heavy machinery used at installation
- Construction of infrastructure
- Final end-of-life treatment (recycling, incineration, disposal)
- Human labour and employee transport

5.2 Operational energy efficiency comparison between the 4 design options

Typically, most transformers have N-1 contingency, and hence the maximum expected load is around 50 %. Thus, the estimated carbon emissions due to designs 1, 2, 3, and 4 for an operational life due to variation in designed losses for 40 years and average load factors of 25 % and 50 % are listed in Table 11 with a GEF = 0.024 tCO_{2e}/MWh for 2050. The impact of variation in GEF is illustrated in Section 6.9.

5.3 Comparison of GHG emissions from the dielectric fluid used

The impact of using ester fluid on the carbon emission equivalent is listed in Table 12.

5.4 Comparison of GHG emissions from materials of the core coil assembly

The transformer core coil assembly consists of the following – copper windings, core steel, core frame, conductor paper insulation, pressboard insulation, on-load tap changer (OLTC), leads, and other miscellaneous components. The major components account for more than 98 % of the material used, while the remaining miscellaneous components account for less than 2 %. In this section, we calculate the impact of the major core coil assembly components, as shown in Table 13. The emission factors used for the different components are available in [11].

5.5 Comparison of GHG emissions from materials used in cooling assembly

The resulting tCO_{2e} for the amount of steel used in radiators and conservators is shown in Table 14.

5.6 Comparison of GHG emissions from materials used in tank/covers and bushings

The outcome of the tCO_{2e} for the amount of steel used in the tank and covers and due to bushings is listed in Table 15.

As a summary, Fig. 7 provides an overview of the tCO_{2e} emissions impact of used materials by main transformer components.

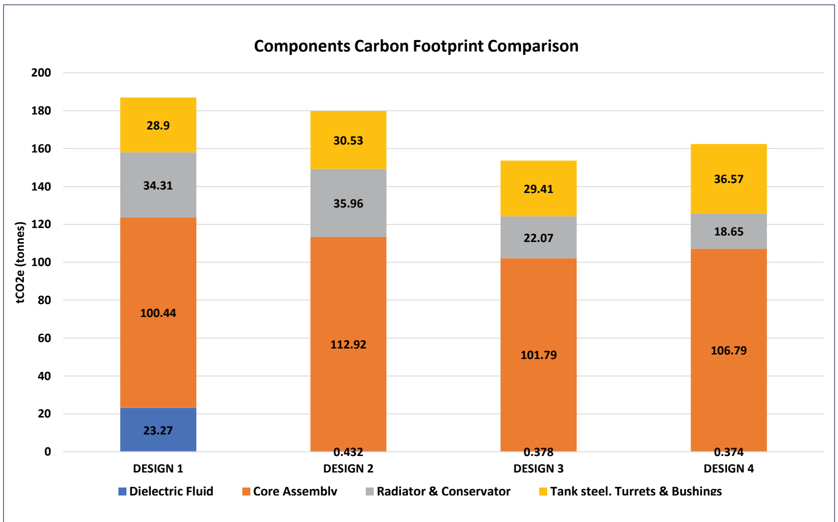

Figure 7. tCO_{2e} emissions impact due to the main transformer components

Table 11. Impact of transformer efficiency on tCO_{2e} emissions from operational losses at different load

Parameters	Design 1	Design 2	Design 3	Design 4
Emission factor ($kgCO_{2e}$/kg)	0.024	0.024	0.024	0.024
Carbon emission at 25% load (tCO_{2e})	374 tCO_{2e}	376 tCO_{2e}	405 tCO_{2e}	331 tCO_{2e}
Change from Design 1	--	↑2 tCO_{2e}	↑31 tCO_{2e}	↓ 43 tCO_{2e}
Carbon emission at 50% load (tCO_{2e})	918	852	1018	876
Change from Design 1	--	↓66 tCO_{2e}	↑100 tCO_{2e}	↓42 tCO_{2e}

Table 12. Impact of total oil quantity on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Total Oil (kg)	19,250	21,600	18,900	18,720
Emission factor ($kgCO_{2e}$/kg)	1.209	0.02	0.02	0.02
Carbon emission (tCO_{2e})	23.27 tCO_{2e}	0.432 tCO_{2e}	0.378 tCO_{2e}	0.374 tCO_{2e}
Change from Design 1	--	↓22.84 tCO_{2e}	↓22.89 tCO_{2e}	↓22.89 tCO_{2e}

Table 13. Impact of core coil assembly on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Core coil assembly (kg)	31,565	35,465	32,290	33,750
Carbon emission (tCO_{2e})	100.44 tCO_{2e}	112.92 tCO_{2e}	101.79 tCO_{2e}	106.79 tCO_{2e}
Change from Design 1	--	↑12.48 tCO_{2e}	↑1.36 tCO_{2e}	↑6.35 tCO_{2e}

Table 14: Impact of cooling assembly on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Cooling assembly (kg)	13,725	14,385	8,830	7,460
Carbon emission (tCO_{2e})	34.31 tCO_{2e}	35.96 tCO_{2e}	22.07 tCO_{2e}	18.65 tCO_{2e}
Change from Design 1	--	↑1.65tCO_{2e}	↓12.23 tCO_{2e}	↓15.66 tCO_{2e}

Table 15. Impact of tank steel, turrets, and bushings on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Tank & bushings (kg)	11,000	11,695	11,295	14,160
Carbon emission (tCO_{2e})	28.9 tCO_{2e}	30.53 tCO_{2e}	29.41 tCO_{2e}	36.57 tCO_{2e}
Change from Design 1	--	↑1.63tCO_{2e}	↑0.51 tCO_{2e}	↑7.67 tCO_{2e}

The transformer transportation to the customer site from the factory using the transportation means and distances was taken into account

Table 16. Transportation distance and mode of transport

Component	Distance (km)	Means of transport to the customer site
40/60 MVA transformer	~150 km	Truck
40/60 MVA transformer	~14,000 km	Ship
40/60 MVA transformer	~300 km	Truck

5.7 Comparison of GHG emissions from transportation of transformer to New Zealand

Transformer transportation to the customer site from the factory with the transportation means and distances are presented in Table 16.

The impact of transporting the transformer from the factory to the customer site is listed in Table 17.

5.8 Comparison of GHG emissions from transportation of materials and components to transformer factory

Transformer component transportation to the factory from suppliers with the

Table 17. Impact of transformer transportation to customer site on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Emission factor ($kgCO_{2e}/kg$)	Ship – 0.02 $kgCO_{2e}$/ton-km [12] Truck - 0.135 $kgCO_{2e}$/ton-km [12]			
Carbon emission (tCO_{2e})	25.74 tCO_{2e}	28.33 tCO_{2e}	24.3 tCO_{2e}	25.24 tCO_{2e}
Change from Design 1	--	↑2.43 tCO_{2e}	↓1.35 tCO_{2e}	↓0.5 tCO_{2e}

transportation means and distances are presented in Table 18.

The impact of transporting the transformer components from suppliers to the factory is listed in Table 19.

5.9 Comparison of GHG emissions from End-of-life (EOL) management

Power transformers are designed to remain in use for a very long time. At end-of-life, decommissioning is a natural part of the life cycle, and units are disassembled much in the same way as they were assembled. For liquid-filled transformers, almost 95 % of the materials are recoverable for either 1st-degree (recycled into the same material needed for the manufacture of new transformers) or 2nd-degree recycling (downgraded for use in a different context with lower quality requirements). 2-3 % of the initial transformer weight [13] consists of pressboard, Kraft paper, wood, and other organic materials ends up being incinerated with energy recovery, and the rest goes to a landfill. Typically, recyclable parts which are impregnated with the dielectric oil are cleaned and treated before entering the recycling process. Other parts are directly incinerated or finally disposed of without

Table 18. Component transportation distances and mode of the transformer to the factory

Component	Distance from supplier to factory (km)	Means of transport to factory
Core Steel	~3000 km	Ship & Truck
Winding	~3300 km	Ship & Truck
Pressboard/wood	~9500 km	Ship & Truck
Paper	~9500 km	Ship & Truck
Oil	~9800 km	Ship & Truck
Core inactive parts	~10 km	Truck
Radiators	~3200 km	Ship & Truck
Tank	~10 km	Truck
OLTC	~5000 km	Ship & Truck
Bushings	~2000 km	Ship & Truck
Miscellaneous	~100 km	Truck

For liquid-filled transformers, almost 95 % of the materials are recoverable for either 1st-degree or 2nd-degree recycling

Table 19: Impact of component transportation to factory on tCO_{2e} emissions.

Parameters	Design 1	Design 2	Design 3	Design 4
Carbon Emission (tCO_{2e})	6.67 tCO_{2e}	7.44 tCO_{2e}	6.33 tCO_{2e}	6.3 tCO_{2e}
Change from Design 1	--	↑0.77 tCO_{2e}	↓0.33 tCO_{2e}	↓0.37 tCO_{2e}

Table 20. Impact due to estimated landfill mass on tCO_{2e} emissions

Parameters	Design 1	Design 2	Design 3	Design 4
Emission factor ($kgCO_{2e}$/ton)	Landfill – 1200$kgCO_{2e}$/ton			
Total Weight (ton)	75,540	83,140	71,315	74,090
Estimated landfill weight (ton)	2.26	2.49	2.13	2.2
Carbon emission (tCO_{2e})	2.71 tCO_{2e}	2.99 tCO_{2e}	2.56 tCO_{2e}	2.66 tCO_{2e}
Change from Design 1	--	↑0.28 tCO_{2e}	↓0.15 tCO_{2e}	↓0.05 tCO_{2e}

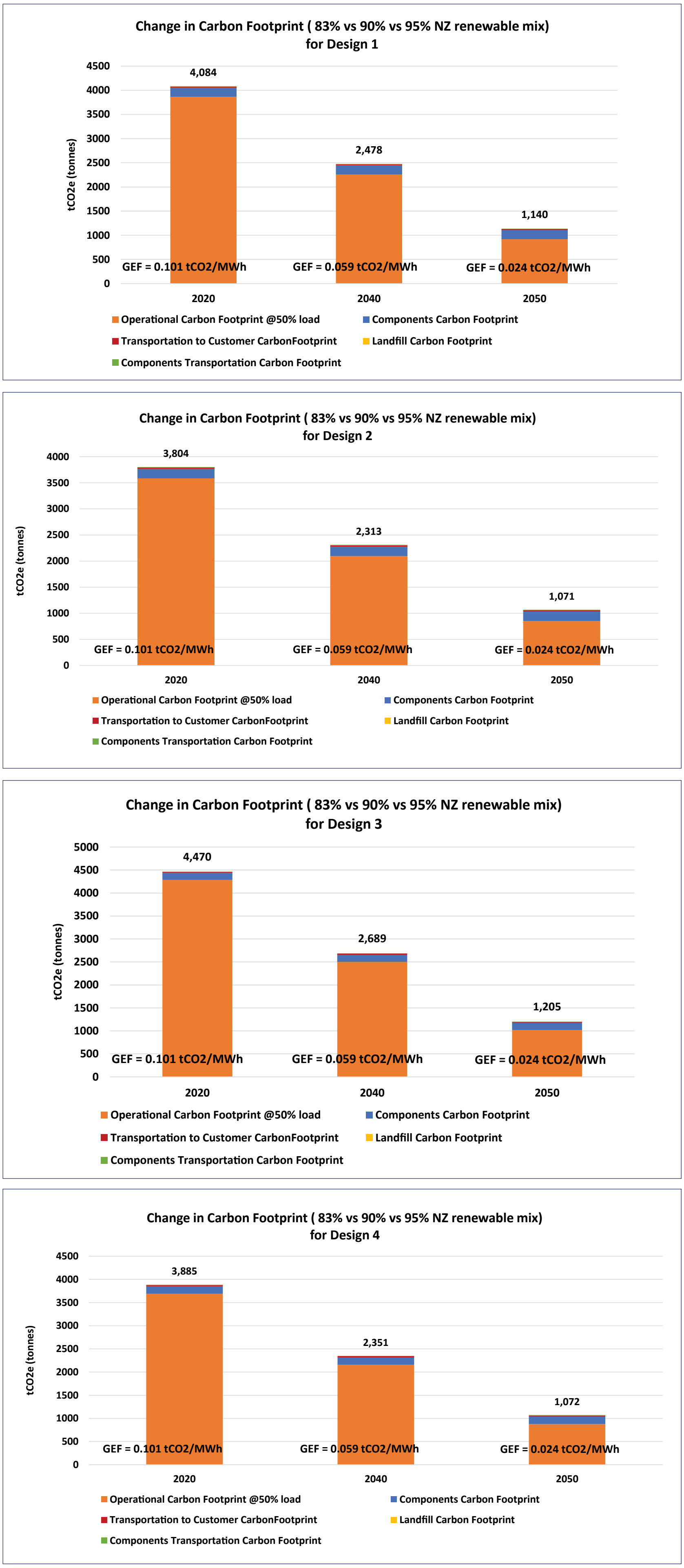

Figure 8: Evaluating the effect of grid emission factor on the tCO_{2e} emissions

Design 2 and Design 4 offer almost identical final carbon footprints, while Design 4 achieves a significantly lower transformer weight

further treatment. The following carbon emission can be calculated according to Table 20.

5.10 Summary: Life-cycle carbon footprint outcome

The overall carbon footprint is illustrated in the two following paragraphs.

5.10.1 Effect of GEF

In this section, the impact of GEF on the overall carbon footprint for all the different transformer designs in 2020, 2040, and 2050 is shown in Fig. 8. With the improvement in the GEF, the overall carbon footprint reduces for all the designs. The impact of the operational carbon footprint reduces significantly, which contributes to the improvement. The total difference between each design also decreases!

5.10.2 Comparison between the designs

The overall carbon footprint due to the four different designs is shown in Fig. 9 and 10 for the years 2040 and 2050, respectively. Design 2 and Design 4 offer almost identical final carbon footprints, while Design 4 achieves a significantly lower transformer weight, around ~9 tons lower than Design 2. The difference in the carbon footprint between Design 2 and Design 4 even reduces to a negligible level in 2050.

Key inferences can be drawn:

- The use of high-temperature insulation (the combination of ester fluids and high-temperature paper insulation) in the design of transformers can be one of the most effective tools for balancing material and energy efficiency as electricity grids continue to decarbonize.

The use of high-temperature insulation in the design of transformers can be one of the most effective tools for balancing material and energy efficiency as electricity grids continue to decarbonize

This is particularly the case today in countries with high penetration of zero and low-carbon generation sources, as in New Zealand.

- Transformer material shortages and price volatilities are occurring more frequently due to supply chain issues such as increasing energy and carbon costs and growing demand. As supply chains progress towards decarbonizing their production processes and increasing the share of recycled content, the design of transformers with hybrid insulation in ester fluids is a key lever for reducing the total life-cycle carbon footprint and towards a net-zero future.
- Transformer consultants and end users should reflect on the choice of temperature rise limits specified with conventional insulation in mineral oil and ester fluids. If it is required to achieve the same temperature rise limits, the amount of material that goes into the ester transformer increases. The ability of esters transformers to achieve higher temperatures is thus negated with such an approach.
- The approach of co-creating transformers will be invaluable in developing sustainable transformer balancing material and energy efficiency and optimizing the TCO in a carbon-constrained world.

Summary

The use of high-temperature insulation (the combination of ester fluids and high-temperature paper insulation) proves to be an essential approach in designing environmentally and economically optimized transformers.

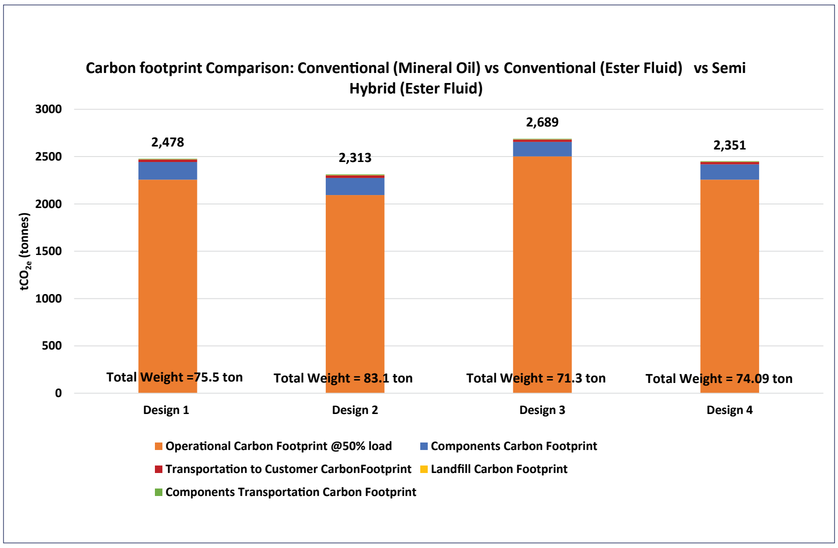

Figure 9: Overall tCO_{2e} emissions comparison: Design 1 vs. Design 2 vs. Design 3 vs. Design 4 (the year 2040)

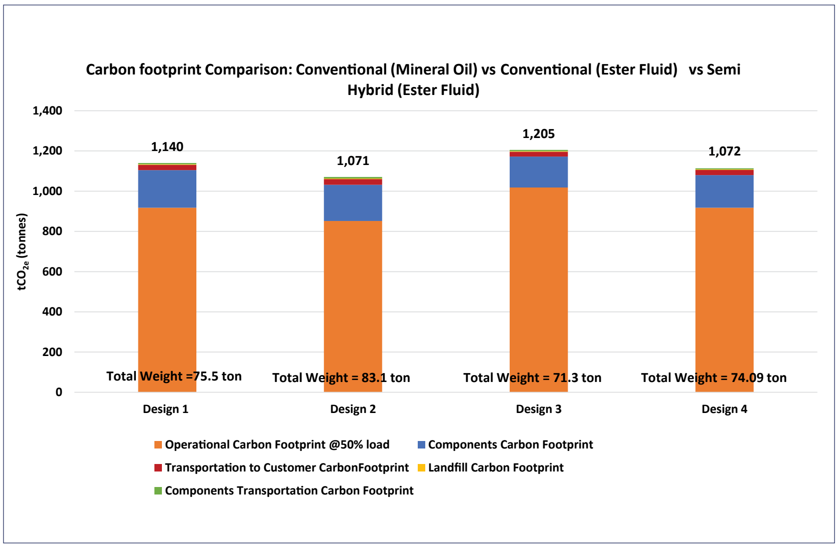

Figure 10: Overall tCO_{2e} emissions comparison: Design 1 vs. Design 2 vs. Design 3 vs. Design 4 (the year 2050)

Particularly in countries with high penetration of low and zero carbon generation sources, such as the case of New Zealand. This can be a valuable approach even though the operational energy losses generated by such high-temperature designs may be slightly higher. For the 40/60 MVA transformer investigated in this article, semi-hybrid insulation reduces the total transformer weight by ~9 tons when compared to conventional insulation in ester fluid when the design is optimized for lowering the total cost of ownership considering the cost of carbon. This also highlights that transformer specifications must include the cost of carbon in the total cost of ownership considerations.

Bibliography

[1] IEC 60076-2:2011, Power Transformers – Part 2: Temperature rise for liquid-immersed transformers

[2] IEC 60076-13:2013, *Power Transformers – Part 14: Liquid-immersed power transformers using high-temperature insulation materials*

[3] R. Marek, J. C. Duart, T. Prevost, *High-temperature insulation systems: an option for resilient transformers*, IEEE/PES Transmission and Distribution Conference and Exposition, 2018

[4] R. Szewczyk, J. C. Duart, R. Van Schevensteen, *Comparison of various technologies used for distribution transformers from an eco-standpoint*, CIRED 22nd International Conference on Electricity Distribution, Paper 0725, 2013

[5] J. C. Duart et al., *Using high-temperature insulation to reduce key transformer materials*, Mat Post 2007

[6] https://www.mbie.govt.nz/building-and-energy/energy-and-natural-resources/energy-statistics-and-modelling/energy-statistics/electricity-statistics

[7] *New Zealand's Energy Outlook: Electricity Insight, Exploring the uncertainty in future electricity demand and supply*, Ministry of Business, Innovation and Employment, ISSN 1179-4011 (online)

[8] *Electricity demand and generation scenarios: Scenario and results summary*, Ministry of Business, Innovation and Employment, ISBN: 978-1-98-857091-4 (online), July 2019

[9] E. Amoiralies et al., *Energy efficient transformer selection Implementing life cycle costs and environmental externalities*, IEEE 9th International Conference on Electrical Power Quality and Utilization, 2007

[10] https://carbonpricingdashboard.worldbank.org/

[11] B. P. Das, R. Milledge, *Investigating the impact of transformer specification on the life cycle carbon emissions: A case study for Middle East Countries*, TRANSFORMERS MAGAZINE, Volume 9, Issue 3, 2022

[12] Ministry for the Environment, Government of New Zealand, *Measuring Emissions: A Guide for Organizations*, 2020

[13] B. De Wachter, T. Jezdinsky, *The circularity of medium-power electrical transformers*, TRANSFORMERS MAGAZINE, Volume 9, Issue 1, 2022

PEER REVIEWED

Authors

Dr. Bhaba P. Das is the Lead Digital Business Developer for Transformers Business Line, HUB (Asia-Pacific, Middle East and Africa), at Hitachi Energy, based in Singapore. He is part of the Application Engineering Team and spearheads the digital transformation efforts of transformers in the Asia-Pacific region. He has been awarded the Hitachi Energy Global Transformers Excellence Award for Customer Cooperation for 2020 and 2021 in Sales & Marketing. Prior to Hitachi Energy, he worked as an R&D engineer for a major transformer manufacturer in New Zealand. He was awarded the Young Engineer of the Year 2017 by the Electricity Engineers Association of New Zealand for his work on the design and development of smart distribution transformers, fibre-optics-based sensors for transformers, and diagnostic software for fleet condition monitoring. He is a Senior Member of IEEE and a Young Professional of IEC. He completed his PhD in Electrical Engineering at the University of Canterbury, New Zealand.

Ghazi Kablouti is the Global Portfolio Sustainability Manager for the Transformers business of Hitachi Energy. In this role, he is in charge of defining the sustainability value proposition across the transformers portfolio and driving the implementation of sustainability principles and tools in product management and innovation processes. He has more than 20 years of international and interdisciplinary experience at industry-leading corporations in the energy infrastructure sector on pioneering and implementing global corporate programs and driving the development and commercialization of cleantech and decarbonization solutions. He also served as senior advisor to the World Bank on the water-climate-energy nexus and to leading corporations in the chemical and automotive sectors on digitizing and standardizing product carbon accounting in global supply chains. Ghazi has a degree in Mechanical and Aerospace Engineering from the University of Stuttgart (in Germany) and a PhD in Systemic Management from the University of St. Gallen (in Switzerland). He is a former post-doc visiting scholar at the Massachusetts Institute of Technology (MIT, USA) and a senior lecturer at engineering and business schools on international business ethics and corporate responsibility management across the value chain.