Analyzing transformer energy and material efficiency under different renewable energy deployment pathways

ABSTRACT

Governments and market players around the globe are making commitments to accelerate the decarbonization of electricity supply over the next decades. As power transformers today are designed for a long operational lifetime, this article analyzes the sensitivity of the life-cycle carbon footprint of transformers with conventional and semi-hybrid insulations under different power generation decarbonization paths – reaching 95% renewable electricity target by 2030, 2035, 2040 or 2050.

KEYWORDS:

Decarbonization, Semi-hybrid design, Renewable energy, Energy-metal nexus, Grid emission factor, Carbon footprint, Ester fluids

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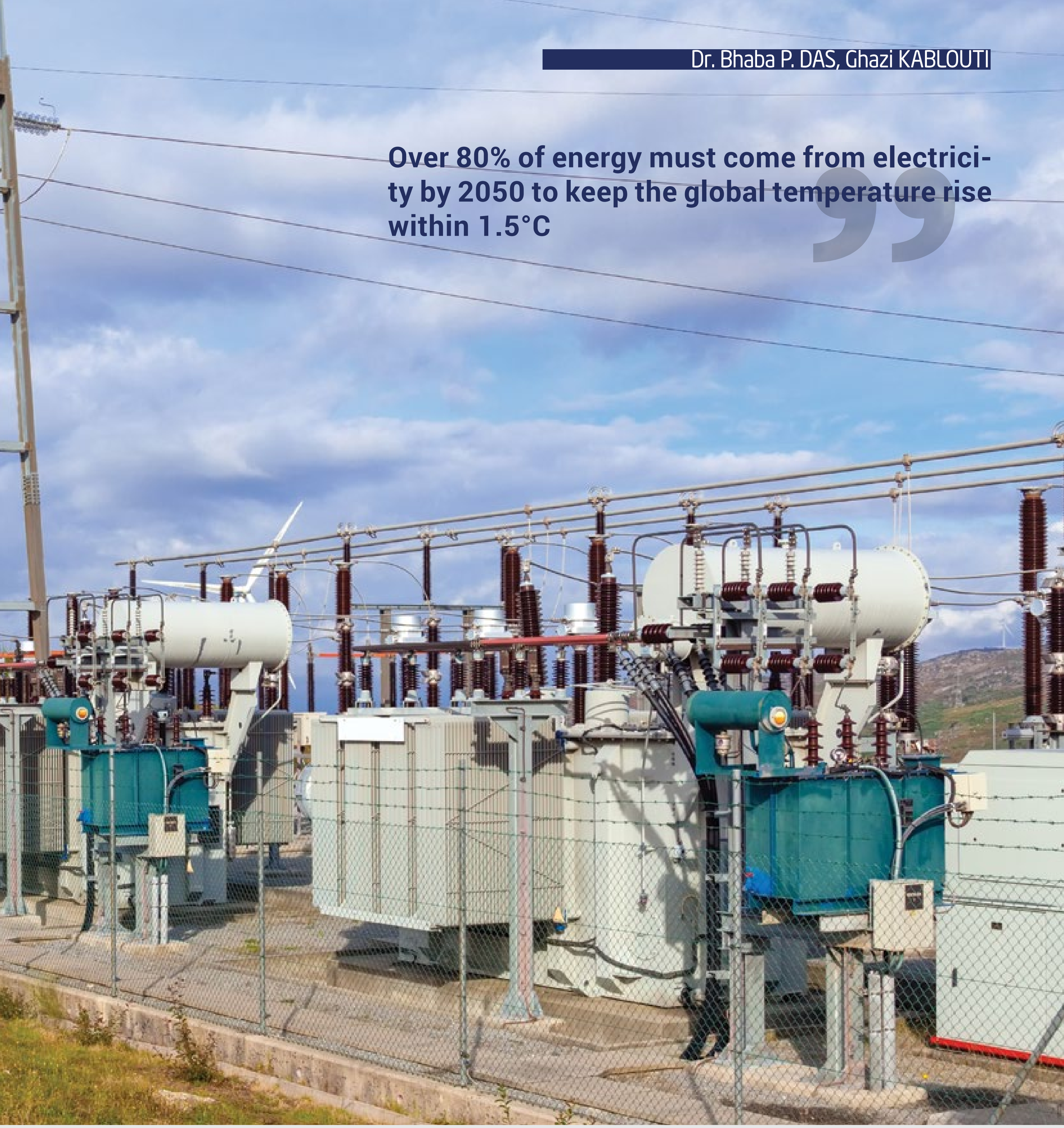
> Over 80% of energy must come from electricity by 2050 to keep the global temperature rise within 1.5°C



1. Introduction

Transitioning to a low-carbon energy system is vital for realizing sustainable development and has already been underway for the last few decades. Over 80% of energy must come from electricity by 2050 to keep the global temperature rise within 1.5°C [1]. To meet this challenge of transition, an important nexus which currently gets little attention must be addressed – the energy-metal nexus [2]. One of the largest factors expected to make the energy-metal nexus more important is the expansion of low-carbon energy technologies. This is because these emerging technologies – which have a significant potential to mitigate global warming – require specific metal resources in significant quantities and make resource depletion a real concern. The global demand for copper is expected to increase by 51%, aluminum by 43% and steel by 35% by 2050 to meet the demands of a low-carbon energy system [3]. Reflecting this concern, a growing number of studies have examined the availability of metals for the low-carbon energy transition in recent years. These studies have largely concluded that the decarbonization of the energy and transport sectors could potentially be restricted by availability in the long term [4].

> **The impact of semi-hybrid power transformer carbon footprint is evaluated in different scenarios, with renewable energy penetration ranging from 83% to 95%, in combination with conventional transformer designs**

Transformers are going to be the backbone of the electrified energy system, which also requires significant amounts of these crucial metals. Therefore, it is paramount to investigate if options are available to reduce the usage of materials in transformers while achieving the same reliability and performance from both the operational and environmental viewpoints.

In our previous article [5], an investigation was conducted on a 40/60 MVA, 132/33.6kV ONAN/ONAF transformer with a target impedance of 14% for the life-cycle carbon footprint of the three different insulation systems:

1. conventional insulation system – mineral oil with kraft paper (60k/65k temperature rise).
2. conventional insulation system – ester fluid with kraft paper (60k/65k temperature rise).
3. semi-hybrid insulation system – ester fluid with TU paper. (90K/95K temperature rise). A hybrid insulation system uses a combination of high-temperature insulation – fluid and paper to exploit the high-temperature capability of the resulting combination. A semi-hybrid system uses ester fluid as insulation fluid and thermally upgraded paper as conductor insulation. However, spacers, strips and other solid insulation still use conventional cellulose insulation.

The results of the comparison of the total life cycle carbon emission assessment for four different designs under the New Zealand electricity mix, which is an electricity grid dominated by renewable energy, were reported in the article:

- design 1: conventional insulation system in mineral oil,
- design 2: conventional insulation system in natural ester fluid,
- design 3: semi-hybrid insulation system in natural ester fluid,
- design 4: semi-hybrid insulation system in natural ester fluid considering the cost of carbon emission.

In the previous article, we estimated the life cycle carbon emission assessment for fixed grid emission factors (GEF) of 0.101 tCO_{2e}/MWh, 0.059 tCO_{2e}/MWh and 0.024 tCO_{2e}/MWh and evaluated the outcome for a 40-year life cycle. These were based on 83% renewable electricity in 2020 and 95% renewable electricity target by 2050. As we know, the grid emission factor is a time-based varying quantity which changes with the addition of either renewable or non-renewable electricity sources.

To meet New Zealand's climate change obligations, the Ministry of Business, Innovation & Employment (MBIE), Government of New Zealand, published two reports, [6] and [7], which provided insights into New Zealand's electricity demand and supply future. Electricity demand under different sensitivity analyses shows that it will exceed 50TWh and reach up to more than 60TWh in some scenarios. To meet this demand, most of the newly built generation capacity will be renewable. The share of renewables is projected to increase from the current 83% in 2020 to around 95% in all scenarios. The combination of continued decline in the cost of solar and wind technology and the limited supply of gas and oil will result in new build generation to be renewables. 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.

In this article, the impact of semi-hybrid power transformer carbon footprint is evaluated under different scenarios, with

Table 1. Transformer loss values for the different designs [5]

Parameters	Design 1 At 75°C reference temperature	Design 2 At 75°C reference temperature	Design 3 At 115°C reference temperature	Design 4 At 115°C reference temperature
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	363.3
Peak Efficiency Index (PEI) Design output	99.704%	99.706%	99.679%	99.738%
Load at Peak Efficiency (KPEI)	0.258	0.292	0.247	0.227
Total Weight (kg)	75,540	83,140	71,315	74,090

renewable energy penetration ranging from 83% to 95% in combination with conventional transformer designs.

2. Transformer designs

The outcomes for the four different transformer designs are listed in Table 1, same as published in [5].

3. Uniform variation in GEF

In this section, four scenarios are investigated, as shown in Figure 1:

1. NZ electricity mix reaches 95% renewable by 2030, target reached in 7 years.
2. NZ electricity mix reaches 95% renewable by 2035, target reached in 12 years.
3. NZ electricity mix reaches 95% renewable by 2040, target reached in 17 years.
4. NZ electricity mix reaches 95% renewable by 2050, target reached in 27 years.

4. Non-uniform variation in GEF

In this section, four scenarios are investigated as well, as shown in Figure 2:

1. Slow change in GEF till 2040 and then fast change reaching 95% in 2050.
2. Fast change in GEF till 2035 and then slow change reaching 95% in 2050.
3. Alternative change in GEF every 3 years, reaching 95% in 2050.
4. Alternative change in GEF every 6 years, reaching 95% in 2050.

5. Carbon footprint assessment: Uniform variation in GEF

Based on the analysis presented in [1], the carbon emissions tCO$_{2e}$, excluding operations, are listed in Table 2.

> **A marginal reduction in total carbon footprint (excluding operations) can be observed in conventional ester fluid design 2 when compared to conventional mineral oil design 1, which is due to the carbon emission factor used for natural ester fluid**

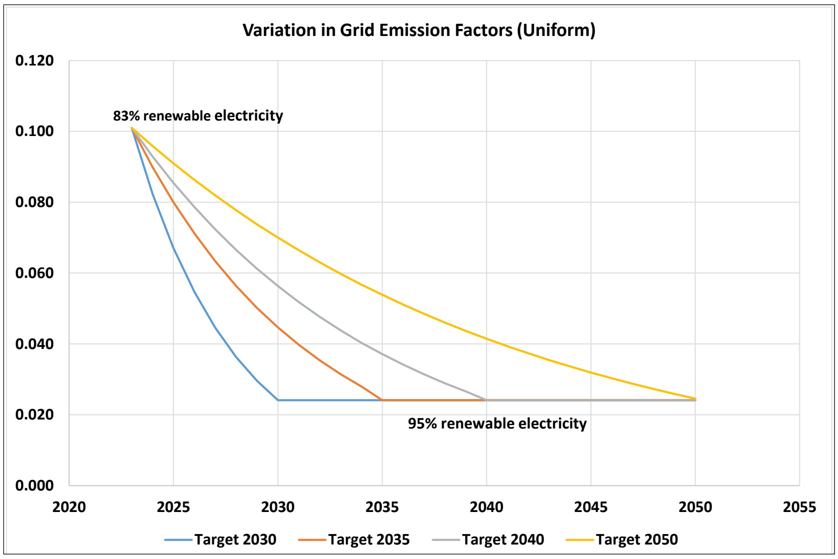


Figure 1. Variation in GEF (uniform)

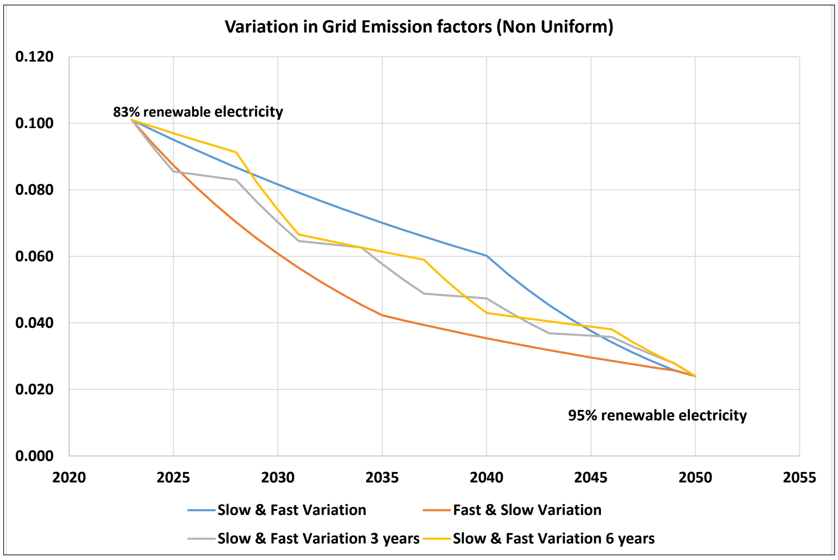


Figure 2. Variation in GEF (non-uniform)

A marginal reduction can be observed in Design 2 when compared to Design 1. This is due to the carbon emission factor used for natural ester fluid. However, there is a wide variation in the reported emission factors for natural ester transformers due to the type of plant crop used (soybean, canola/rapeseed, sunflower, etc.). A detailed verified life cycle analysis report for the fluid must be requested from the fluid supplier for the natural ester used. In this study, the values reported by the NIST BEES study have been used for calculation purposes [8].

Table 2. tCO$_{2e}$ emissions excluding operations for the four designs [1].

Parameters	Design 1	Design 2	Design 3	Design 4
tCO2$_e$ excluding Operations	222.12	218.61	187.19	196.2

> **Under uniform variation of GEF, the semi-hybrid design D4 (with carbon cost included at \$120/tCO_{2e}) is able to reduce around ~6% to 5.58% of tCO_{2e} emissions compared to the conventional mineral oil design D1**

The operational carbon emissions tCO_{2e} (2023-2050) at 50% load for the four scenarios under uniform variation in GEF are listed in Table 3.

The total carbon emissions tCO_{2e} (2023-2050) for the four scenarios under uniform variation in GEF can now be calculated and are listed in Table 4.

5.1 Comparing tCO_{2e} emissions: Semi-hybrid vs conventional mineral oil design

It can be clearly observed from Table 4 and Figure 3 that, in all four scenarios, the semi-hybrid design D4 (with carbon cost included at \$120/tCO_{2e}) is able to reduce around ~6% to 5.58% of tCO_{2e} emissions compared to the conventional mineral oil design D1. The total weight of the semi-hybrid design D4 is 74.09 tons, compared to the conventional design D1 with a weight of 75.5 tons, which suggests that transformer weight has not increased despite using ester fluid.

5.2 Comparing tCO_{2e} emissions: Semi-hybrid vs conventional ester fluid design

It can be clearly observed from Table 4 and Figure 4 that, in all four scenarios, the semi-hybrid design D4 (with carbon cost included at \$120/tCO_{2e}) is within ± 1% of tCO_{2e} emissions compared to the conventional ester fluid design D2. The total weight of the semi-hybrid design D4 is 74.09 tons versus the conventional ester design D2, with a weight of 83.14 tons, which means that a 9-ton reduction has been achieved.

Thus, the semi-hybrid design helps in addressing the energy-metal nexus issue from a transformer design point of view. It is also apparent that the earlier we reach the 95% renewable target, the benefit of the semi-hybrid design is more pronounced.

Table 3. tCO_{2e} emissions due to operations at 50% load – Uniform variation in GEF

Parameters	Design 1	Design 2	Design 3	Design 4
tCO_{2e} due to Operations 95% renewable by 2030	881.49	818.28	977.62	840.49
tCO_{2e} due to Operations 95% renewable by 2035	1042.48	967.72	1156.16	993.99
tCO_{2e} due to Operations 95% renewable by 2040	1171.77	1087.75	1299.55	1117.27
tCO_{2e} due to Operations 95% renewable by 2050	1455.97	1351.57	1614.74	1388.26

Table 4. Total tCO_{2e} emissions – Uniform variation in GEF

Parameters	Design 1	Design 2	Design 3	Design 4
Total tCO_{2e} 95% renewable by 2030	1103.61	1036.89	1164.81	1036.7
Total tCO_{2e} 95% renewable by 2035	1264.60	1186.33	1343.35	1190.2
Total tCO_{2e} 95% renewable by 2040	1393.89	1306.36	1486.74	1313.47
Total tCO_{2e} 95% renewable by 2050	1678.09	1570.18	1801.93	1584.46

> **Under uniform variation of GEF, the semi-hybrid design D4 (with carbon cost included at $120/tCO$_{2e}$) is within ± 1% of tCO$_{2e}$ emissions compared to the conventional ester fluid design D2**

6. Carbon footprint assessment: Non-uniform variation in GEF

The operational carbon emissions tCO$_{2e}$ (2023-2050) at 50% load for the four scenarios with non-uniform variation in GEF are listed in Table 5.

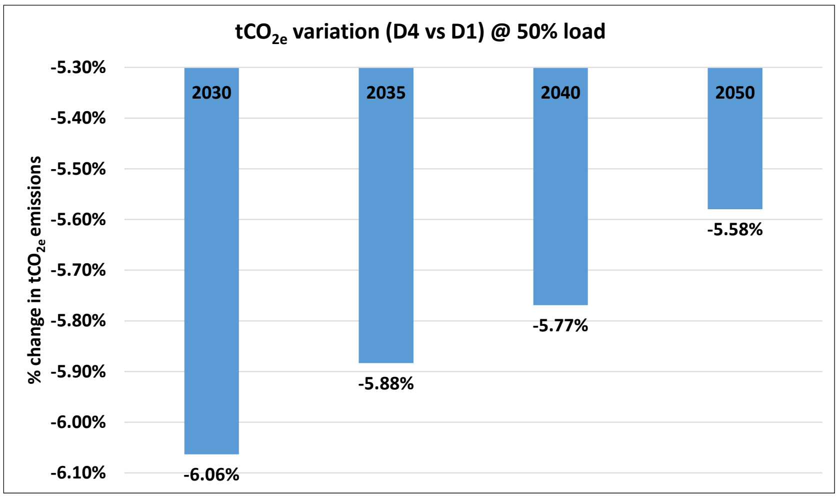


Figure 3. Semi-hybrid vs. conventional mineral oil design (uniform variation in GEF)

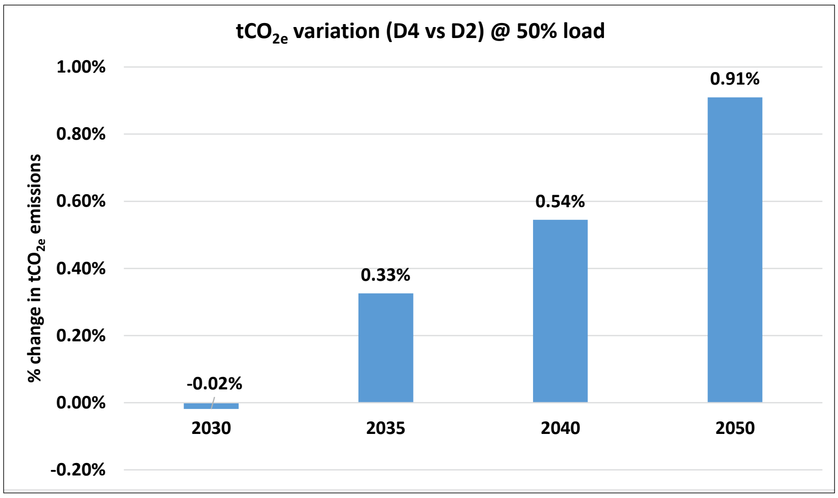


Figure 4. Semi-hybrid vs. conventional ester fluid design (uniform variation in GEF)

Table 5. tCO$_{2e}$ emissions due to operations at 50% load – non-uniform variation in GEF

Parameters	Design 1	Design 2	Design 3	Design 4
tCO$_{2e}$ due to Operations Slow and Fast Variation	1713.97	1591.07	1900.88	1634.26
tCO$_{2e}$ due to Operations Fast and Slow Variation	1302.89	1209.46	1444.97	1242.30
tCO$_{2e}$ due to Operations Slow and Fast Variation (3-year cycle)	1509.22	1401.00	1673.80	1439.03
tCO$_{2e}$ due to Operations Slow and Fast Variation (6-year cycle)	1598.82	1484.18	1773.18	1524.47

Table 6. Total tCO_{2e} emissions – non-uniform variation in GEF

Parameters	Design 1	Design 2	Design 3	Design 4
Total tCO_{2e} Slow and Fast Variation	1936.098	1809.684	2088.075	1830.467
Total tCO_{2e} Fast and Slow Variation	1525.015	1428.079	1632.165	1438.502
Total tCO_{2e} Slow and Fast Variation (3-year cycle)	1731.34	1619.61	1860.99	1635.23
Total tCO_{2e} Slow and Fast Variation (6-year cycle)	1820.94	1702.79	1960.37	1720.67

Transformers, as the key long-lasting energy- and material-intensive components of the electricity grid, need to be designed to address the energy-materials nexus challenge of the transition towards a more sustainable energy grid

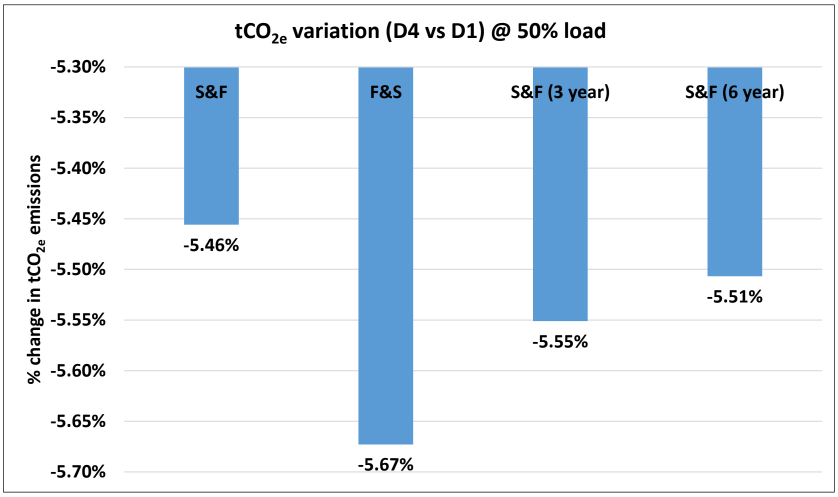


Figure 5. Semi-hybrid vs. conventional mineral oil design (non-uniform variation in GEF)

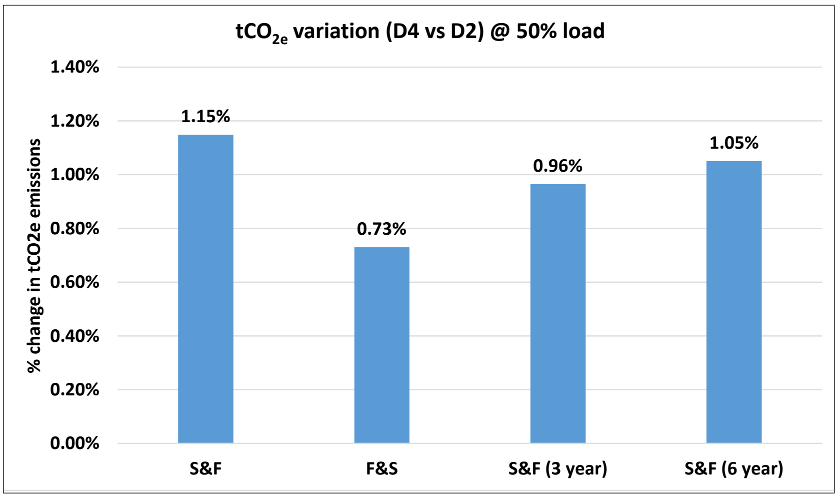


Figure 6. Semi-Hybrid vs Conventional Ester Fluid Design (Non-Uniform Variation in GEF)

The total carbon emissions tCO_{2e} for the four scenarios with uniform variation in GEF can now be calculated and are listed in Table 6.

6.1 Comparing tCO_{2e} emissions: Semi-hybrid vs conventional mineral oil design

It can be clearly observed from Table 6 and Figure 5 that, in all four scenarios, the semi-hybrid design D4 (with carbon cost included at $120/$tCO_{2e}$) is able to reduce around 5% of tCO_{2e} emissions compared to conventional mineral oil design D1.

6.2 Comparing tCO_{2e} emissions: Semi-hybrid vs conventional ester fluid design

It can be clearly observed from Table 6 and Figure 6 that, in all non-uniform GEF variation scenarios, the semi-hybrid design D4 (with carbon cost included at $120/$tCO_{2e}$) is within +1.15% tCO_{2e} emissions compared to the conventional ester design D2, with an ~11% reduction in total transformer weight.

Conclusions

Material production and energy supply are increasingly becoming interlinked and interdependent. Solar energy, wind turbines, electric vehicles, fuel cells, and other key infrastructure must be deployed on a large scale to keep the global temperature rise within 1.5°C. However, such infrastructure is very material intensive. Solar power requires up to 40 times more copper than fossil fuel combustion power. Copper is also one of the main metals used in transformers. Metal constraints may become severe as we move towards 2050.

Transformers, as the key long-lasting energy- and material-intensive components of the electricity grid, need to be designed to address the energy-materials nexus challenge of the transition towards a more sustainable, low-carbon energy system. The analysis proves that the sooner a lower grid EF can be achieved, the lower the operational and total life-cycle carbon footprint of a connected transformer. Accelerating the energy transition is, therefore, the main lever to reducing the carbon footprint of transformers due to operational energy losses.

At the same time, designing transformers in a way that reduces the quantity of main materials, such as steel and copper, enables making these materials available for manufacturing lower-carbon power generation technologies.

Thus, hybrid insulation in transformers is key in designing environmentally optimized transformers in the future. It addresses the energy-metal nexus concerns for future low-carbon energy technologies by allowing transformer designers to take advantage of higher operating temperatures. By using high-temperature insulation and ester fluids, these semi-hybrid designs reduce the quantity of metals used in the transformer.

In this article, the variation in the grid emission factor (both uniform and non-uniform) shows that semi-hybrid insulation designs have advantages over both the conventional mineral oil and ester fluid designs – around 5% reduction in carbon emissions with a similar total weight when compared to the conventional mineral oil designs or within ±1% carbon emission from conventional ester transformers but with an almost 11% reduction in transformer weight. It is time for transformer end users and manufacturers alike to embrace alternative design methods to support the transition to low carbon.

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