Environmental impact assessment of transportation in distribution transformer life cycle analysis

Investigating the local vs global supply question?

ABSTRACT

Questions to compare localized and globalized distribution transformer supply has contributed to debate around the 'Transformer Miles' concept, i.e., 'the distance a distribution transformer (raw materials and the finished unit) travels, from the supplier/factory to factory/installation site". A relatively new question related to this issue seeks to answer the question of carbon footprint due to the transportation of raw materials to the factory and delivery of the finished transformer to the end user. Within this framework, this article investigates the question - What is the carbon footprint due to transportation: distribution transformers made in New Zealand (as an example), in comparison with importing distribution transformers from overseas into New Zealand? Are there advantages or otherwise from a carbon footprint point of view?

KEYWORDS:

greenhouse emissions, CO_2 equivalent, environmental impact, transportation, transformer miles, efficiency

Dr. Bhaba P. DAS, Ghazi KABLOUTI

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1. Introduction

An increase in greenhouse gas (GHG) emissions in the atmosphere is currently one of the most serious environmental threats, which will have far-reaching consequences in the next few decades. GHG emissions are categorized into three groups [1]:

- Scope 1 covers direct emissions from owned or controlled sources.
- Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the reporting company.
- Scope 3 includes all other indirect emissions that occur in a company's value chain.

There are various references that evaluate the life cycle analysis (LCA) for transformers [2], [3], [4]. For a transformer, the typical scope 3 boundary conditions (as shown in Fig. 1) include:

- Raw material extraction and production for manufacturing
- Transportation of components to the manufacturing site
- Transportation of transformer to the customer
- Electricity production covering for power losses at transformer operation
- End-of-life management including landfill and recycling

This study aims to assess the environmental impact of transportation in transformer LCA and answer questions to compare localized and globalized transformer supply. Questions to compare localized and globalized transformer supply has contributed to debate around the 'Transformer Miles' concept, i.e., 'the distance transformer (raw materials and the finished unit) travels, from the supplier/factory to factory/installation site'. A relatively new question related to this issue seeks to answer the question of carbon footprint due to the transportation of raw materials to the factory and delivery of the finished transformer to the end user.

It is well known that the transportation sector generates an enormous amount of environmental emissions. Globally, transportation has the highest reliance on fossil fuels GHG emissions for any sector and it accounted for 37 % of global CO_2 emissions from all the end-use sectors in 2021. Most of these emissions are associated with road transportation (5.9 $GtCO_2$), followed by shipping (0.8 $GtCO_2$) and aviation (0.7 $GtCO_2$) [5]. There are essentially three variables that drive CO_2 emissions from transportation, and these are the distance travelled, the mass transported, and the mode used. To investigate this question, a commonly used 300 kVA oil-filled distribution transformer (with High-Efficiency Performance Standard, HEPS efficiency) manufactured in Vietnam and transported to New Zealand (NZ) is compared to a 300 kVA oil-filled distribution transformer (HEPS efficiency as per AS 2374.1.2 [6]), manufactured in New Zealand and transported within New Zealand, assuming identical design

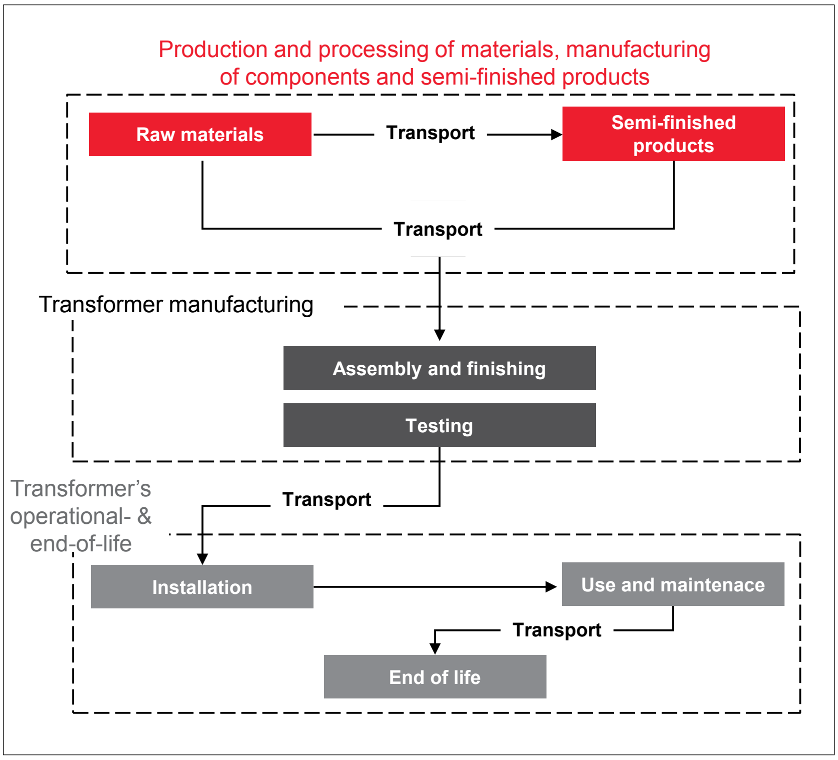

Figure 1. Typical transformer life cycle stages

Table 1. The material composition of a 300 kVA oil-filled distribution transformer

Material	Mass (kg)	Mass (%)
Core coil assembly	701	49.58 %
Oil	327	23.13 %
Tank	289	20.44 %
Tank cubicles (Al)	82	5.80 %
Miscellaneous	15	1.06 %
Transformer's total transport mass	1,414	

process. Only the transportation distances from the component supplier to the factory and transportation distances from the factory to the end user installation location are different.

Emission factors derived as part of the Ministry for the Environment, Government of New Zealand, are used in this paper [7]. They are given as $kgCO_2$ emitted per ton-kilometer (ton-km) for a given mode. A ton-km is a measure of both the mass of the transformer and the distance the transformer has been transported.

2. Life cycle analysis (LCA)

LCA is a methodology widely used in environmental assessment (ISO 14040:2006) [8]. LCA is used to assess, compare, and calculate the environmental impact of products and/or processes, acting as a support tool for their choice.

- For the production phase of the transformer, there are three main parts – procurement/transport of components and material (electrical steel, copper, steel, oil, pressboard, etc.), transformer manufacturing at the factory and transport to the customer.
- For the use phase, transformer losses are required.
- For the end of the life cycle phase, three potential end-of-life scenarios are possible: recycling, disposal, and incineration.

For procurement, the amount of material needed per transformer is required. Table 1 presents the transformer component mass distribution for the 300 kVA distribution transformer used in this article. It is assumed that both factories (in Vietnam and New Zealand) produce identical designs using similar design and manufacturing processes.

2.1 Transformer losses

Transformer losses represent an important part of transformer use, and they must be taken into consideration in the calculation of the environmental impact for the use phase. The operation of the 300 kVA oil-filled distribution transformer is modelled over a 30-year lifetime and an average load of 50 %. The resulting load losses and no-load losses are presented in Table 2.

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Table 2. Transformer losses (assumed identical for both factories)

Losses	Value
No load losses	0.425 kW
Load losses	2.960 kW
Peak Efficiency Index (PEI)	99.253 %
Load at PEI, k_{PEI}	37.9 %
Efficiency at 50 % load	99.200 %
HEPS limit at 50 % load (AS/NZ 2374.1.2)	99.179 %

Shipping distribution transformers over large distances using a container ship has the least impact in terms of CO_2 emissions, while the highest amounts of CO_2 are produced if long-haul air freight is used

2.2 Component transport to Vietnam

Component transportation to the manufacturing site in Vietnam with the transportation means and distances are presented in Table 3, to calculate the impact of component transfer to the factory.

2.3 Component transport to New Zealand

Component transportation to the manufacturing site in New Zealand with the transportation means and distances are presented in Table 4. All major components are assumed to be sourced from the same suppliers, except the tank and tank cubicles which are sourced from China. Actual supplier locations may differ, however, for comparison purposes, values in Table 4 have been used.

Table 3. Component transportation distances from the supplier to the Vietnam factory

Component	Distance from the supplier to the Vietnam factory (km)	Means of transport to the factory	Country of origin
Core Steel	~3,000 km	Ship	Singapore
Winding (Al)	~3,300 km	Ship	Korea
Pressboard	~9,500 km	Ship	Germany
Paper	~9,500 km	Ship	Germany
Oil	~9,800 km	Ship	Belgium
Core inactive parts	~10 km	Truck	Vietnam (local)
Radiator	~3,200 km	Ship	India
Tank	~10 km	Truck	Vietnam (local)
Tank cubicles (Al)	~10 km	Truck	Vietnam (local)
Miscellaneous	~5,000 km	Air	Australia

Table 4. Component transportation distances from the supplier to the New Zealand factory

Component	Distance from the supplier to the Vietnam factory (km)	Means of transport to the factory	Country of origin
Core Steel	~8,500 km	Ship	Singapore
Winding (Al)	~9,500 km	Ship	Korea
Pressboard	~18,000 km	Ship	Germany
Paper	~18,000 km	Ship	Germany
Oil	~18,300 km	Ship	Belgium
Core inactive parts	~10 km	Truck	New Zealand (local)
Radiator	~11,580 km	Ship	China
Tank	~11,580 km	Ship	China
Tank cubicles (Al)	~4,000 km	Air	Australia
Miscellaneous	~5,000 km	Air	Australia

2.4 Product transport from Vietnam to New Zealand

Transformer transportation to the customer site from Hanoi, Vietnam, with the transportation means and distances, is presented in Table 5.

2.5 Product Transport within New Zealand

Transformer transportation to the customer site from New Zealand with the transportation means and distances is presented in Table 6.

2.6 Emission factors

Some of the emission data are sourced from databases of the NZ Ministry for the Environment. The datasets used are presented in Table 7.

It can be seen from Fig. 2 that shipping distribution transformers over large distances using a container ship has the least impact in terms of CO_2 emissions. Considering the impact of a container ship as the base, it can be inferred that:

- Transportation using rail has almost 1.35 times higher carbon emissions than container ships.
- Trucks add almost 7 times more carbon emissions than transportation using container ships.
- If transformers are transported large distances by air freight, the CO_2 emissions increase by a factor of 30 when compared to a container ship. This is a significant increase.

The choice of mode of transportation is thus crucial in determining the outcome of the "transformer miles" result. For transformer components, the emission factors listed in [9] are used.

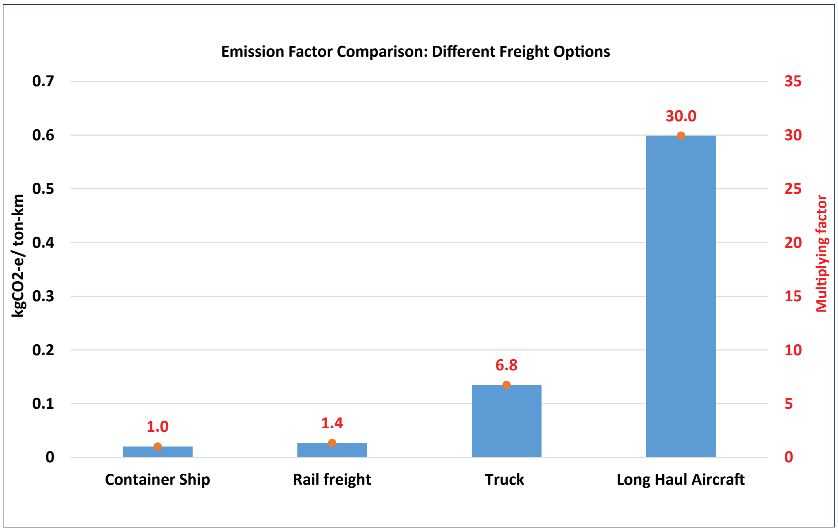

Figure 2. Comparison of emission factors for different freight options

Table 5. Transport distances to the site from Vietnam

Component	Distance (km)	Means of transport to the customer site	Place of origin
300 kVA transformer	~14,000 km	Ship	Vietnam
300 kVA transformer	~300 km	Truck	Auckland port/ Lyttleton port

Table 6. Transport distances to the site within New Zealand

Component	Distance (km)	Means of transport to the customer site	Place of origin
300 kVA transformer	~600 km	Truck	NZ

Table 7. Emission factors for fuel type and electricity consumption [7]

Type	Dataset
Electricity	NZ: Electricity Grid Emission Factor (GEF) = 0.101 $kgCO_{2\text{-}e}$/kWh
Truck	Emission factor for freighting goods by road on the truck, emission factor = 0.135 $kgCO_{2\text{-}e}$/ton-km
Rail freight	Emission factor for freighting goods by rail, Emission factor = 0.027 $kgCO_{2\text{-}e}$/ ton-km
Container ship	Emission factor for freighting goods by ship on the sea, emission factor = 0.02 $kgCO_{2\text{-}e}$/ ton-km
Long haul air freight	Emission factor for freighting goods by airplane, emission factor = 0.539 $kgCO_{2\text{-}e}$/ ton-km

Importing raw materials to NZ has a higher $kgCO_{2e}$ than importing to Vietnam, however, $kgCO_{2e}$ for transporting the assembled transformer is lower for transformers made locally in NZ

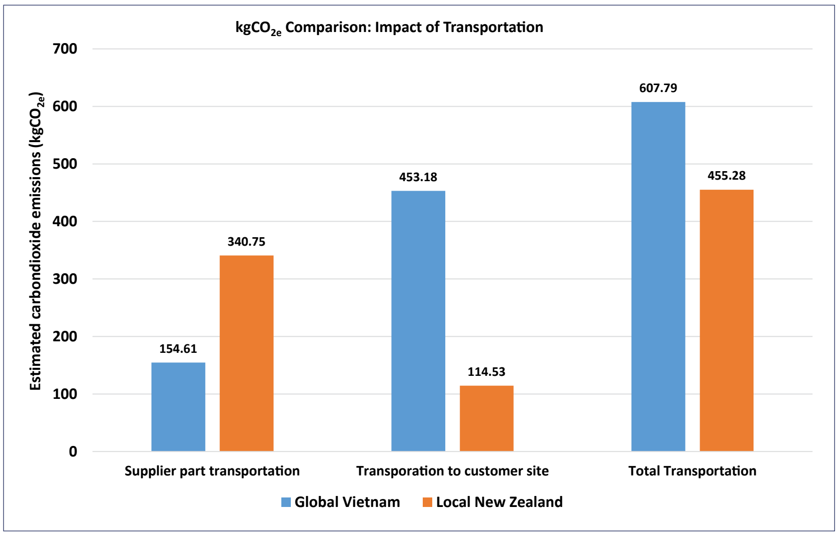

Figure 3. $kgCO_{2e}$ emission comparison due to transportation

3. Results

3.1 Transportation impact

Fig. 3 presents the estimated $kgCO_{2e}$ contribution due to the transportation of raw materials from suppliers to factories –global in Vietnam and local in New Zealand and the final transportation to the customer site. Importing raw materials to NZ has a higher kgCO2e than importing to Vietnam. However, $kgCO_{2e}$ for transporting the assembled transformer is lower for transformers made locally in NZ. The net difference due to transportation is only ~150$kgCO_{2e}$ equivalents. Now let's look at the rele-

vance of this $kgCO_{2e}$ savings from transportation compared to carbon emissions from the other life cycle stages, especially due to transformer operation and transformer materials used.

3.2 Comparison with operational and material $kgCO_{2e}$ emissions

Fig. 4 presents the $kgCO_{2e}$ equivalents emissions by life cycle phases – operations, manufacturing and transportation. Quantification of carbon emission during the operational phase is calculated as:

$$tco_{2e}\ (\textit{tonnes of carbon dioxide equivalent}) = (P_{NLL} + k^2 \cdot P_{LL}) \cdot t_{years} \cdot Lifetime \cdot GEF$$

Operation has the highest contribution of 88.5 % to the total impact on climate change, while combined transportation is less than 2 %, which means that efficiency is much more crucial than transformer miles

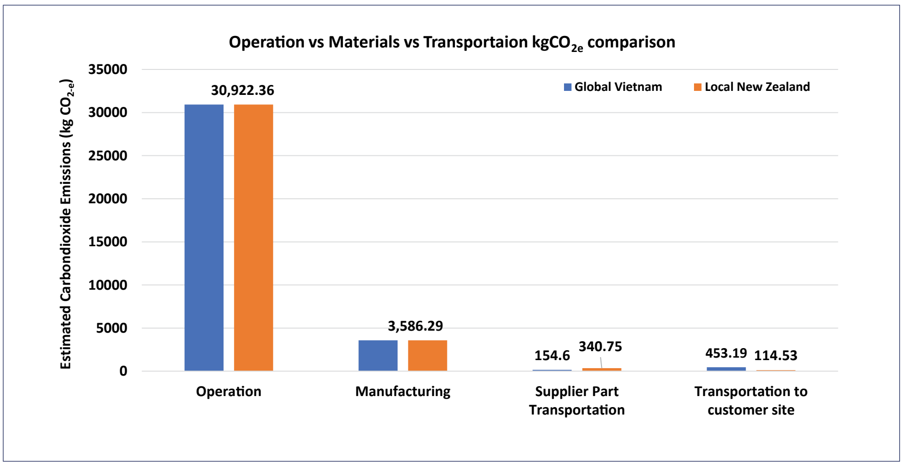

Figure 4. $kgCO_{2e}$ emission comparison under NZ electricity mix: operation vs manufacturing vs transportation

Where:

- P_{NLL}: power dissipated due to transformer no-load loss
- P_{LL}: power dissipated due to transformer load loss at a reference temperature of 75 °C.
- the total amount of hours during a year, typically 8760 hours.
- Lifetime: the expected service life of the transformer, 30 years is used here,
- GEF: Grid emission factor.
- K: load factor, typically at 50 %.

Emissions due to transformer operation contribute to ~30.9 tCO_{2e}, materials used contribute to ~ 3.5 tCO_{2e}, while transportation contributes to only ~0.6 tCO_{2e}. Operation (power losses) has the highest contribution of 88.5 % to the total impact on climate change, while combined transportation is less than 2 %. This implies that the design of the transformer efficiency and material efficiency is much more crucial than transformer miles.

3.3 Effect of change in GEF

Based on the estimated share of renewables to be achieved by 2050 [10], the following GEF can be calculated in Table 8:

Fig. 5 shows the estimated percentage of $kgCO_{2e}$ contribution for the years: 2020, 2040 and 2050. By 2050 as New Zealand's electricity generation reaches around 95 % renewables, the contribution of the power losses would reduce from 88 % to around 60 %. The contribution from materials would increase from 10 % to almost 32 %, while transportation would remain below 5 % in all the scenarios.

Specification improvement in terms of enhancing energy efficiency, material use and carbon content of materials can be a more effective means of lowering transformer-related carbon footprint rather than "buying local"

Table 8. Estimated grid emission factors for New Zealand

Year	% Share of renewables	GEF [10]
2020	~83 % (actual)	0.101 tCO_{2e}/MWh
2040	~90 % (estimated)	0.059 tCO_{2e} /MWh
2050	~95 % (target)	0.024 tCO_{2e} /MWh

4. Conclusions

Despite significant recent utility concerns on the environmental impacts of global transformer supply, few studies have systematically compared the $kgCO_{2e}$ emissions associated with transformer design and manufacturing against long-distance distribution "transformer-miles." In this article, we find that although transformer is transported through long distances in general (14,000 km delivery compared to 600 km locally), the $kgCO_{2e}$ emissions associated with transformers are dominated by the operational losses and manufacturing phase contributing over 95 % of the total footprint. Transportation represents only 2 % of life cycle $kgCO_{2e}$ emissions. With a reduction in GEF till 2050, the contribution of transportation will remain below 5 % for distribution transformers (as for existing transportation technologies today and would even further decrease as the transportation sector is expected to decarbonize further to contribute to meeting the global ambitions on limiting global warming below 1.5–2 °C by 2050). Similar calculations can be carried out to investigate the impact of transportation on power transformers to check the impact of the increase in weight of the components and the overall transformer.

Hence, we suggest that specification improvement in terms of enhancing energy efficiency, material use and carbon content of materials can be a more effective means of lowering an average utilities' transformer-related carbon footprint rather than "buying local." If the utility has the necessary means to service/repair the transformer locally, the source location of the transformer is immaterial from a carbon footprint viewpoint.

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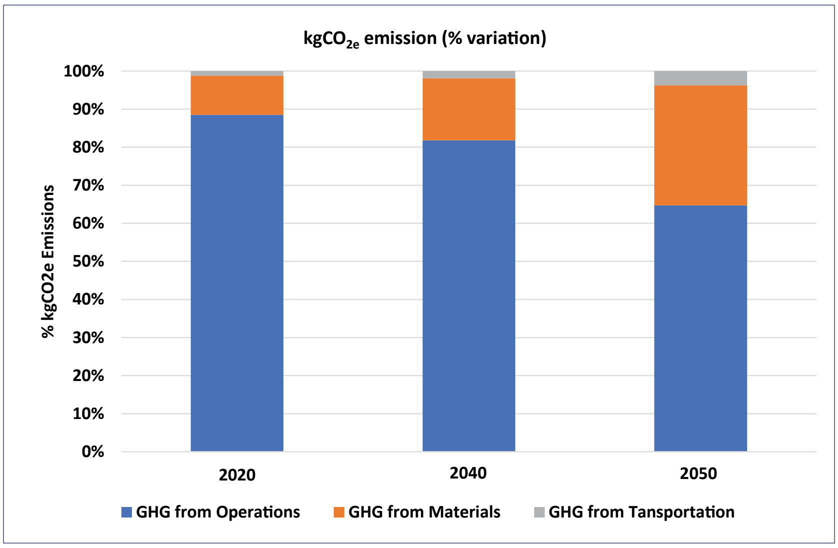

Figure 5. Estimated % of $kgCO_{2e}$ emission comparison - 2020 vs 2040 vs 2050

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.