Investigating the impact of transformer capitalization factors on the carbon footprint

ABSTRACT

The design of transformers with a low carbon footprint is a topic that is gaining significant traction in the electricity industry. In this article, an investigation is conducted for a 50/62.5 MVA, 154/33.6 kV transformer to evaluate the effect of the No Load Capitalization Factor (A) and Load Capitalization Factor (B) on the carbon footprint of the transformer. The benefit of including the cost of CO_2 in the Total Cost of Ownership (TCO) formula, i.e., the extended TCO concept, is highlighted, which results in a similar carbon footprint but with reduced material usage.

KEYWORDS:

TCO, extended TCO, carbon footprint, equivalent CO_2 emissions, transformer losses

As there are millions of transformers installed worldwide, around 5 % of global electricity is being consumed by transformers due to losses, resulting in 732 million tons of CO_2 emissions during 2020

1. Introduction

Transformers are one of the most efficient components in the electricity transmission and distribution network at efficiency values greater than 99 %. As there are millions of transformers installed worldwide, around 5 % of global electricity is being consumed by transformers due to no-load and load energy losses [1], resulting in 732 million tons of CO_2 emissions during 2020. Given the projected increase in electricity generation and consumption over the following decades, energy losses in transformers are also expected to grow by more than 60% by 2040 in case there are no changes in current energy specifications [1]. There is a significant risk of inaction if the procurement processes are not updated: lock-in decades of energy waste, given the transformers operate non-stop for 30–40 years of their service life. Any efficiency gain has a multiplier effect, which is why energy efficiency is one of the main drivers in transformer technology evolution and the main lever for decarbonizing electricity transmission and distribution (T&D) systems.

Many end users claim that the evaluation of transformers based on the purchase price is not enough during the procurement process, and the loss evaluation procedure is now well established across end users in many countries. This is now evident by the fact that the Total Cost of Ownership (TCO) method is a standard practice in the industry [2], [3]. The TCO method enables the purchase cost-optimized transformer design that will be installed and operated for many years. The TCO formula considers the purchase price (PP) and cost of losses during the transformer lifetime by specifying the No Load Capitalization Factor (A) and Load Capitalization Factor (B) [3]. It must be kept in mind that TCO is not used to minimize transformer losses but to minimize the investment required to obtain the greatest energy savings for the least cost arising from optimal transformer design. This method yields transformer designs whose losses are economically optimal but not necessarily minimal.

Typically, the TCO formula is used in “varying degrees” across the globe:

- Some end users from some countries do not specify any loss requirements and only specify the TCO formula.
- Some end users from some countries specify the desired fixed maximum values of no-load and load losses required along with the TCO formula.
- Some end users from some countries specify the peak efficiency index required of the transformer along with the TCO formula.

The ratio of the B factor to the A factor effectively defines the load factor at which losses are to be minimized. Transformers also naturally have a particular ratio of load to no-load losses inherent in their design, depending mainly on rating and impedance. In some cases, the ratio of the B factor to the A factor may not match the natural ratio of the transformer and departure from this natural ratio makes the transformer more expensive. As the TCO methodology just considers the direct use of electricity during transformers' lifetime, the article aims to investigate the environmental outcomes of TCO specifications.

A transformer can be designed using different optimization methods:

- Lowest initial purchase price of the transformer (Method 1).
- Lowest lifetime owning cost of the transformer, which includes the initial purchase price plus the lifetime operating cost considering the cost of losses (Method 2).
- Lowest lifetime owning cost of the transformer includes the initial purchase price plus the lifetime operating cost, considering the cost of losses and cost of CO_2 emissions for the lifetime (Method 3).

TCO is not used to minimize transformer losses but to minimize the investment required to obtain the greatest energy savings for the least cost arising from optimal transformer design

The extended TCO concept has been proposed where an optimum transformer design is obtained when considering sustainability metrics such as tCO_{2-e} equivalent

While transformer design optimization with consideration of the cost of carbon is ideal, it has not been included yet in the TCO method. Only recently, the extended TCO concept has been proposed [4]. In [4] it was highlighted that optimum transformer design is obtained when considering sustainability metrics such as tCO_{2-e} equivalent, which may differ when compared to the optimum based on a traditional TCO analysis. However, details were not included.

In this article, an investigation is conducted for a 50/62.5 MVA, 154/33.6 kV transformer with a target 12 % impedance on the impact of two transformer designs on the carbon footprint from material usage and energy losses at the operation stage as these are the most relevant aspects determining the total lifecycle carbon emissions of power transformers [5]. Both transformer designs meet the same IEC Peak Efficiency Index 2 (PEI 2) requirements but at different load factors:

- Design 1 is optimized for the lowest TCO with capitalization values of A = \$7500/kW and B = \$2500/kW and a natural peak efficiency load factor.
- Design 2 is optimized for a load factor close to the desired peak efficiency load factor as inferred from the capitalization factors but with a limit of < 20 % increase in the transformer purchase price.

The outcome of such design optimization on total ownership cost and carbon footprint assessment will be shared. However, both designs are optimized for the lowest lifetime ownership cost of the transformer, excluding the cost of CO_2 emissions. The benefit of including the cost of CO_2 in the TCO formula, i.e., the extended TCO concept, is highlighted using Design 3, where design is optimized, including the cost of losses and cost of CO_2 emissions.

The paper is divided into the following sections:

- Section 2 provides a brief review of the capitalization formula.
- Section 3 lists the main transformer specifications for the comparison study.
- Section 4 provides the details of the design optimization results and comparisons of the two designs.
- Section 5 explains the extended TCO concept, which includes the CO_2 costs in the A and B factor and the outcomes of the three designs are provided.

2. Review of capitalization formula and peak efficiency index

The cost of losses comes into effect during transformer lifetime, and hence loss costs are therefore converted to the moment of purchase (Net Present Value) by assigning their capitalized values A, B. Factors A, B (\$/kW) depend on transformer loading conditions, as well as the cost of capital, energy market forecasts, expected transformer life.

The equations as defined in IEC 60076-20: 2017 [3] are:

$$A = t \times C_{n/2} \times \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \quad (1)$$

$$B = t \times C_{n/2} \times \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \times k^2 \quad (2)$$

Where:

- n is the useful economic life of the transformer in years,
- $C_{n/2}$ is the forecast cost of electricity,
- i is the discount rate,
- t is assumed to be 8760 hours of operations per year,
- k is the average loading of the transformer during its lifetime.

Once A and B factors have been evaluated, the total lifetime operating costs are evaluated as below:

$$TCO = C_{pp} + (A \times P_0) + (B \times P_k) \quad (3)$$

Where:

- C_{pp} is the purchase price of the transformer,
- P_0 is the no-load loss (kW) measured at rated voltage and rated frequency,
- P_k is the load loss (kW) due to load, measured at rated current and rated frequency at the reference temperature.

A common value for A-factor = \$7500/kW and B-factor = \$2500/kW (calculation shown in Section 5) is used as an example in this article. When purchasing a transformer, the end user will include a statement expressing this valuation of no-load and load losses. The transformer manufacturers then use this information in their transformer design process to prepare a design that trades off a higher first cost against a lower lifetime operating cost. This greatly helps the production of economically optimal designs, identifying the 'optimum point' for the most economically appropriate combination of no-load and load losses. This optimum point may result in a load factor which is different from the TCO specified load factor, which can be estimated from the A-factor = \$7500/kW and B-factor = \$2500/kW as: $\sqrt{\frac{2500}{7500}} = 57.7\ \%$. The impact of optimizing the transformer design to follow the TCO-specified load factor will be shared in this article, and the need to include the cost of CO_2 in the TCO formula is explained.

TCO equation calculates the value of the transformer together with the cost of the losses during its lifetime, taking into account no-load losses with factor A and factor B

There is a need to include environmental and sustainability factors into the TCO formula, including the cost of CO_2 emissions due to the manufacturing of the transformer and the transformer's losses

The peak efficiency of the transformer load is obtained when no-load loss equals load loss. The corresponding loading point is calculated as:

$$k_{PEI} = \sqrt{\frac{P_{NLL}}{P_{LL}}}$$

The formula for calculating the PEI is:

$$PEI = 1 - \frac{2 * P_{NLL}}{S_r * k_{PEI}}$$

Where P_{NLL}: no-load loss (W), P_{LL}: load loss (W), S_r: rated power of the transformer (VA). Table 1 lists the PEI values specified in IEC 60076-20 for transformers with voltage > 36 kV and rating > 3150 kVA.

Table 1: PEI values for oil-filled power transformers

MVA	PEI Level 1	PEI Level 2
20	99.639 %	99.684 %
25	99.657 %	99.700 %
31.5	99.671 %	99.712 %
40	99.684 %	99.724 %
50	99.696 %	99.734 %
63	99.709 %	99.745 %
80	99.723 %	99.758 %
> 100	99.737 %	99.770 %

3. Main transformer specifications

For this study, we consider the following transformer specification as listed in Table 2.

The case study of calculating the TCO with the cost of CO_2 emissions was carried out for 50 MVA ONAN/62.5 MVA ONAF transformer with nominal voltages equal to 154 kV/33.6 kV

Table 2. Major design parameters for the comparison study

Rating	50 MVA ONAN/62.5 MVA ONAF			
Phases	3-phase			
Impedance	12 %			
Voltages	154 kV/33.6 kV			
Max flux density	1.93 T			
Vector group	YNyn0			
Tapping	154±12*1.25 %			
Sound power level	82 dBA			
BIL	HV: 650 kV, LV: 170 kV			
Temperature limits	Ambient	Top oil rise	Winding temperature rise	Hot spot rise
	45 °C	55 K	60 K	73 K
Loss capitalization formula	C_{pp}+ (7500×P_0)+(2500×P_k)			
PEI	IEC Level 2			

Two different transformer designs were analyzed, with the same peak efficiency but with the different load factors at which the peak efficiency occurs

4. Optimized design outcomes and comparison

Under the minimum PEI IEC Level 2 requirements, the optimization objective for Design 1 is to minimize the total cost of the transformer subject to the following conditions:

- The peak efficiency of the transformer exceeds the minimum PEI Level 2 requirements.
- Other parameters are meeting the specific requirements:
  - The flux density in core is less than 1.93 T.
  - The impedance is 12 % (subject to applicable tolerance).
  - Top oil temperature rise is less than 55 K.
  - The average temperature rise of winding is less than 60 K.
  - The winding conductors withstand dynamic and thermal short-circuit stresses.
  - Sound level is less than 82 dBA
  - Others design specifics such as BIL levels, clearances etc., as applicable.

For Design 2 optimization, the peak efficiency point was moved as close as possible to the expected loading point of 57.7 % with a limit of < 20 % increase in the purchase price of the transformer. These two methods resulted in the following outcomes as listed Table 3.

4.1 Impact of optimization outcome on carbon emissions

To evaluate the impact of design variations, the following processes are included in this study:

- Equivalent tCO2e for electrical energy loss covering transformer power losses at 57.7 % load for 40 years at an average grid emission factor of 0.669 tCO2e/MWh (calculated average for Middle Eastern countries).
- Equivalent tCO2e for components such as core steel, tank steel, oil, copper, bushings, etc. (accounting for > 98 % of the material) used in the transformer.

4.1.1 Impact optimisation on CO_2 emissions from operational energy losses

The two different transformer efficiency curves for Design 1 and Design 2 are shown in Fig. 1.

It can be inferred from Fig. 1 that the PEI value for both designs is the same (99.79 %), whereas the load factor at which the peak efficiency occurs for Design 2 is 40.1 %, which is closer to the 57.7 % load factor specified in the TCO formula whereas for Design 1 it is 31.9 %.

- The calculated equivalent tCO_{2e} due to Design 1, for an operational life of 40 years and an average load factor of 57.7 % with an average grid emission factor of 0.669 tCO_{2e}/MWh equals 20,649 tCO_{2e}.
- The calculated equivalent tCO_{2e} due to Design 2, for an operational life of 40 years and an average load factor of 57.7 % with an average grid emission factor of 0.669 tCO_{2e}/MWh equals 18,582 tCO_{2e}.

4.1.2 Impact of optimisation on CO_2 emissions from material usage

The transformer core coil assembly consists of the following – copper windings, core steel, core frame, conductor paper insulation, pressboard insulation, 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. The emission factors used for the different components are available in [6]. The calculated equivalent tCO_{2e} due to components used in Design 1, equals 227.03 tCO_{2e}. An increase of 19 % in core coil assembly weight can be observed, and a total of 12 % increase in total installed mass is seen in Table 3. The calculated equivalent tCO_{2e} due to components used in Design 2, as listed in Table 3, equals 257.37 tCO_{2e}.

Table 3. Design outcome comparisons between Design 1 and Design 2

Parameters	Design 1	Design 2
No-load loss	20.6kW	26kW
Load loss	202.7kW	160kW
Total loss	223.3kW	186kW
PEI design output	99.793%	99.794%
KPEI	31.9%	40.3%
Core coil assembly (kg)	45,000	53,760
Tank, tank shunts and covers (kg)	14,154	16,400
Radiator, pipes, flanges (kg)	7,270	4,660
Oil (kg)	18,945	20,830
Total weight (kg)	86,704	96,985
Transformer purchase price	1 PU	1.18 PU

Design 1 has an emission of 20,876 tCO_{2e} while Design 2 has an emission of 18,839 tCO_{2e}, a reduction of 2,037 tCO_{2e}, which is approximately a 9.76 % reduction in carbon emission

4.2 Total equivalent lifetime CO_2 emissions

Fig. 2 shows the total equivalent tCO_{2e} emissions from transformer operation at 57.7 % load and transformer components. Design 1 has an emission of 20,876 tCO_{2e} while Design 2 has an emission of 18,839 tCO_{2e}, a reduction of 2,037 tCO_{2e}, which is approximately a 9.76 % reduction in carbon emission.

4.3 Total cost of ownership

The total cost of ownership without considering the cost of carbon is shown in Table 4.

The purchase price will vary from country to country, manufacturer to manufacturer. Assuming a value of $8000/MVA, Design 1 will cost = $500,000 (1 pu) and Design 2 will cost = $590,000 (1.18 pu). Thus $TCO_{(Design1)}$ = $1,161,250 and $TCO_{(Design2)}$ = $ 1,185,000 resulting in an increase of purchase price by $23,750. However, Design 2 will reduce around 2,037 tCO_{2e} emissions. If a carbon price of $50/$tCO_{2e}$ is used to monetize the carbon costs, then 2,037 tCO_{2e} emissions equal $102,000 (assuming the generation mix and carbon price remains the same), which indicates

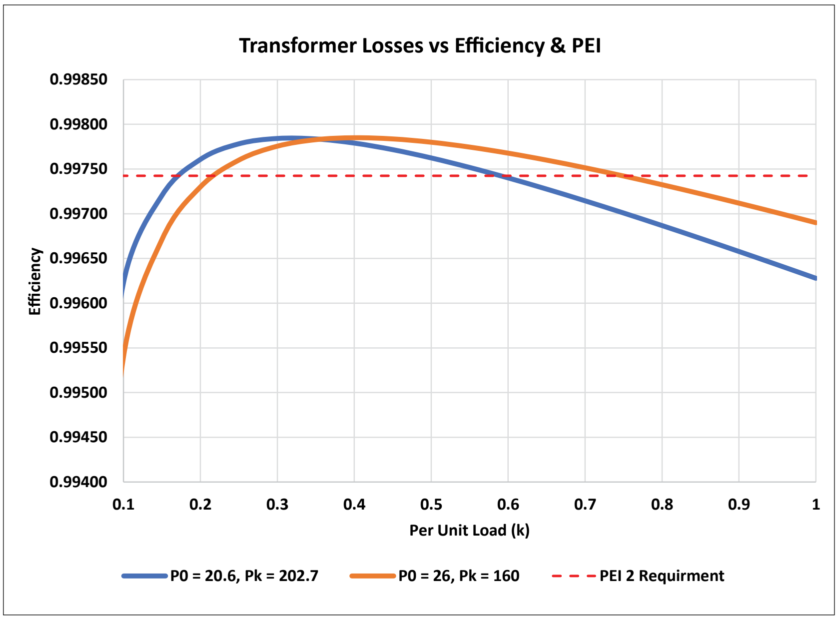

Figure 1. Transformer efficiency curves: Design 1 and Design 2

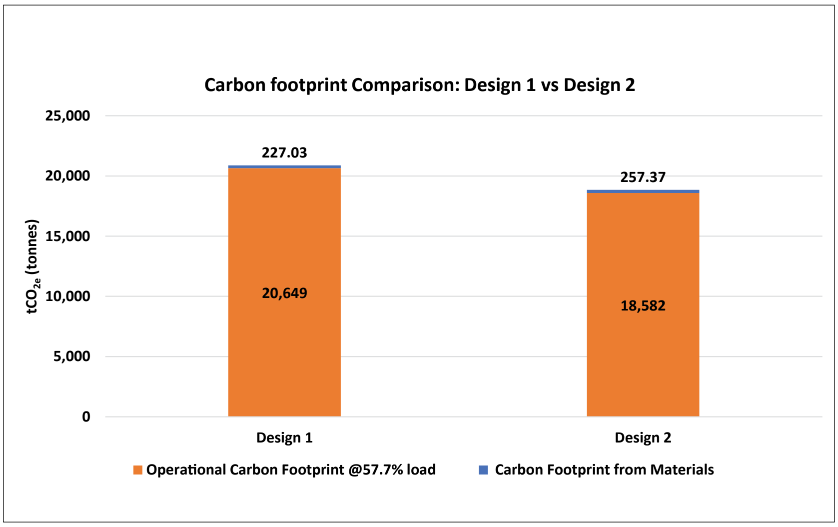

Figure 2. Carbon footprint comparison: Design 1 and Design 2

It is crucial that the TCO formula is updated to include carbon costs related to the entire transformer lifecycle, such as components / raw materials used, operation, transportation, end-of-life disposal, etc.

Table 4. TCO formulation based on two different designs – without environmental impact

Design	No-load loss (kW)	Load loss (kW)	Purchase price	Capitalized cost A = $7500/kW & B = $2500/kW	TCO
Design 1	20.6	202.7	1 PU	$661,250	1PU + $661,250
Design 2	26	160	1.18 PU	$595,000	1.18PU + $595,000

Table 5. TCO formulation is based on two different designs: without environmental impact

Parameters	A-factor	B-factor
Cost of electricity = 0.05$/kWh **Discount rate = 5 %** **Life of power transformer = 40 years** **Estimated loading = 57.7 %**	$7516/kW (~ $7500/kW)	$2502/kW (~ $2500/kW)

In 2022, 68 carbon pricing instruments, including taxes and emissions trading schemes, are operating worldwide, with carbon prices ranging from 1 USD/tCO_2 in the Shenzhen (China) ETS up to 137 USD/tCO_{2e} as a carbon tax in Uruguay

that Design 2 is cheaper to own and operate by $78,000 even when it costs $90,000 more!

Hence it is crucial that the TCO formula is updated to include carbon costs related to the entire transformer lifecycle, such as components / raw materials used, operation, transportation, end-of-life disposal, etc. Corresponding to finding the optimal economic point is likely to see an increase in transformer costs due to the extra material used and the increase in dimensions and mass. However, the optimum design would be to find the lowest lifetime ownership cost of the transformer, which includes the initial purchase price plus the lifetime operating cost, considering the cost of losses and cost of CO_2 emissions for the lifetime.

5. Extended TCO concept

In the original TCO concept, loss capitalization factors are based on some input parameters such as the useful economic life of the transformer in years, forecast cost of electricity, and discount rate. The influence of the life of the transformer in years and discount rate are very well explained in [7]. For estimating the cost of electricity associated with operational energy losses, operators typically select the following three approaches:

- using forecasted electricity costs from government departments or authorized agencies,
- using the wholesale cost of electricity,
- using the levelized cost of electricity using the forecast of fuel prices.

Particularly when using forecasted electricity prices or conventional estimations of the levelized cost of electricity, the cost of carbon emitted from fossil-fuel-based power generation processes incurred during the electricity generation process is not considered. According to the International Energy Agency (IEA), 29 % of global electricity generation is based on renewables [8]. Driven by the need for decarbonizing the electricity sector, there is increasing use of carbon pricing as a major instrument to achieve the different climate change commitments at the regional and global levels. As in 2022, 68 carbon pricing instruments, including taxes and emissions trading schemes (ETS), are operating worldwide, with carbon prices ranging from 1 USD/tCO_2 in the Shenzhen (China) ETS up to 137 USD/tCO_{2e} as a carbon tax in Uruguay [9]. More ambitious carbon prices are expected to close the gap between the existing climate pledges and the need to limit global average temperature increase within the range of 1.5–2 °C.

In countries where fossil-fuel-based fuels dominate the energy mix, there is a need to include carbon pricing in estimating the loss capitalization factors for new transformers. In those countries, fossil fuel plants will be required; accordingly, a reduction in losses will continue to be the dominant factor in cutting CO_2 emissions by burning fossil fuels. Furthermore, it is reasonable to assume that the transition to greater penetration of renewable energy will continue for the next 20–30 years, i.e., till 2050 and beyond. Including the cost of carbon in the A-factor and B-factors will ensure that we will be able to capture the total direct cost of ownership plus the value of the CO_2 emissions associated with that

Table 6. Estimating the cost of electricity: no CO_2 cost included (average Middle East)

Type of technology	% Mix	Cost $/MWh	CO_2 emission?
Solar photovoltaic	1.19 %	20	No
Hydro electric	0.00 %	0	No
Wind generation	0.00 %	0	No
Coal	0.00 %	0	Yes
Natural gas	58.70 %	59	Yes
Oil	40.11 %	38	Yes
Cost of electricity		50.1128 ~0.05 $/kWh	

Table 7. The cost of CO_2 emission from fossil-based power generation

	Solar	Hydro	Wind	Coal	Natural gas	Diesel
Fuel %	1.19 %	0.00 %	0.00 %	0.00 %	58.70 %	40.11 %
G_{CO2}	0	0	0	94.6	56.1	74.1
G_{CH4}	0	0	0	0.002	0.003	0.002
G_{N2O}	0	0	0	0.003	0.001	0.002
N_{fuel}	100 %	100 %	100 %	35 %	45 %	30 %
$J_{T\&D}$	8 %	8 %	8 %	8 %	8 %	8 %
GHG_{fuel}	0	0	0	1.068507	0.491	0.975
C_{eq} – factor (tCO_{2e} /MWh)	0	0	0	0	0.288	0.391
Price of CO_{2e} ($/$tCO_{2e}$)	50	50	50	50	50	50
Emission cost ($/MWh)	0	0	0	0	14.41	19.55

transformer loss into the current procurement policy.

Table 5 lists the parameter values used to calculate the A-factor and B-factor using equations (1) and (2).

The cost of electricity typically consists of annualized capital costs, variable O&M costs, fixed O&M costs, and fuel costs [10]. The costs of electricity generation from a given technology vary widely across countries, even at different locations in the same country. For the purpose of this article, the cost of generation and the generation mix used is listed in Table 6.

To estimate the equivalent $CO_{2\text{-}e}$ impact due to type of generation, the following formula is used [11]:

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

Where GHG is the emission factor of each fuel type in tCO_{2e} /MWh, G_{CO2} is the CO_2 emission factor in kg/GJ, G_{CH4} is the CH_4 emission factor in kg/GJ, G_{N2O} is the N_2O emission factor in kg/GJ, $J_{T\&D}$ represents the transmission and distribution losses in %, and n_{fuel} is the fuel conversion efficiency in %. Once the emission factor is tCO_{2e} /MWh and using the price for CO_2 emission at $50/ tCO_{2e} [12], the emission cost for natural gas and diesel can be calculated.

Table 8 lists the cost of electricity with the cost of carbon emission included, resulting in a new cost of electricity = 0.066$/kWh. Equations (1) and (2) can now be used to calculate the new A-factor and B-factor (Table 9), which would result in a new optimized transformer suited for the generation mix of Table 6.

Using the new A-factor = $9,980/kW and B-factor =$3,320/kW, a new transformer

Table 8. The cost of electricity: CO_2 – cost included

Type of technology	% Mix	Cost ($/MWh)	CO_2 emission?	Emission cost ($/MWh)	New cost ($/MWh)
Solar photovoltaic	1.19 %	20	No	0	20
Hydro electric	0.00 %	0	No	0	0
Wind generation	0.00 %	0	No	0	0
Coal	0.00 %	0	Yes	0	0
Natural gas	58.70 %	59	Yes	14.41	73.41
Oil	40.11 %	38	Yes	19.55	57.55
Cost of electricity		50.1128 ~0.05 $/kWh			66.41 ~0.066 $/kWh

design (Design 3) was optimized, resulting in the carbon footprint result shown in Fig. 3.

Fig. 3 shows the total equivalent tCO_{2e} emissions from transformer operation at 57.7 % load and transformer components. Design 1 has an emission of 20,876 tCO_{2e}, Design 2 has an emission of 18,839 tCO_{2e}, and Design 3 has an emission of 19,270 tCO_{2e}. Fig. 4 shows the variation in transformer price for the three designs: Design 2 achieves 2.3 % less tCO_{2e} but at a price increased by ~ 14 %. Design 3 achieves a total transformer mass of 89.2 tons, whereas Design 2 has 96.9 tons. This reflects that fewer materials are used in Design 3 while almost achieving similar CO_2 emissions (~ 2.3 % difference). Thus, incorporating CO_2 costs in the A and B factor is a good process to follow! Table 10 shows TCO values for the three designs.

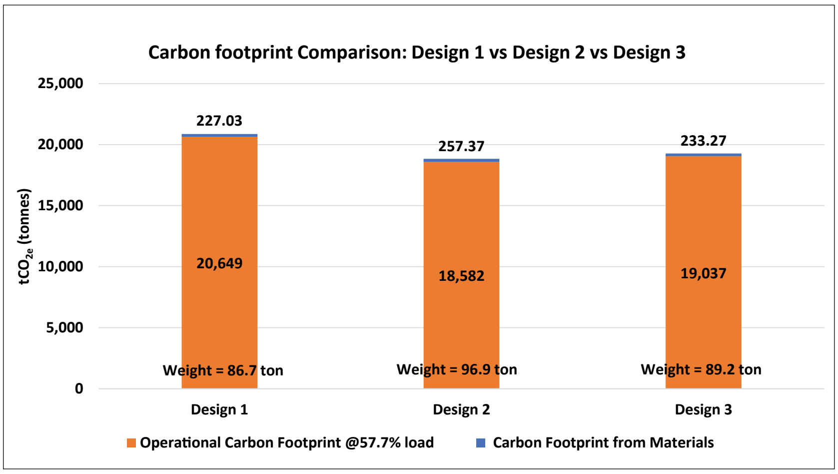

Figure 3. Carbon footprint comparison: Design 1, Design 2 and Design 3

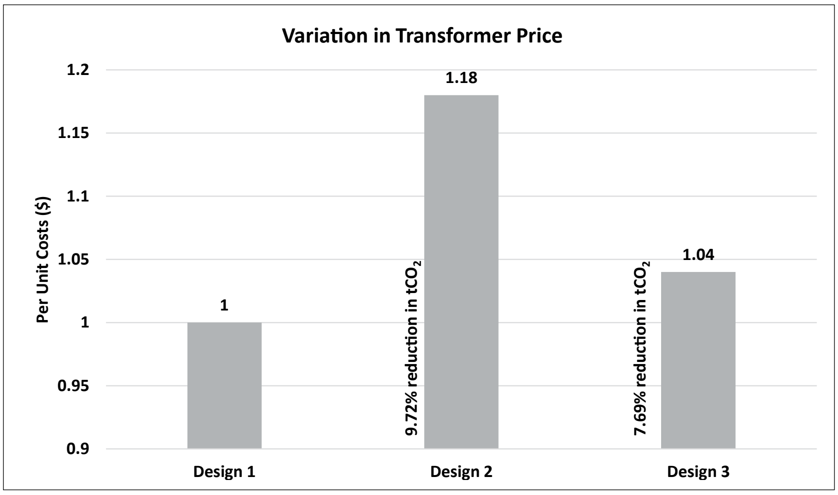

Figure 4. Carbon footprint comparison: Design 1, Design 2 and Design 3

6. Summary

The TCO methodology considers the lifetime costs of a power transformer and takes the price of losses into consideration by specifying the no-load capitalization factor (A) and load capitalization factor (B). These factors determine how the transformer designs are optimized and subsequently impact the carbon footprint of the transformer. In this article, three transformers are designed – Design 1 optimized without considering the carbon costs in the A and B factors, Design 2 where the efficiency point was moved as close as possible to the expected loading point using the A and B factors with a limit of < 20 % increase in the purchase price of the transformer, Design 3 optimized incorporating the carbon costs in the A and B factors. The impact of incorporating the carbon costs in the A and B factors clearly shows that the carbon footprint can be reduced without significantly increasing the purchase price of the transformer. Capitalization factors play a vital role in the optimization and procurement of transformers. Incorporating the costs of CO_2 in the A and B factors will assist in optimizing the design of new transform-

Table 9. TCO formulation is based on two different designs – with environmental impact:

Parameters	A-factor	B-factor
Cost of electricity = 0.066$/kWh **Discount rate = 5 %** **Life of power transformer = 40 years** **Estimated loading = 57.7 %**	$9,981/kW (~ $9,980/kW)	$3,323/kW (~ $3,320/kW)

Table 10. TCO formulation for three different designs with environmental impact

Design	No-load loss (kW)	Load loss (kW)	Purchase price	Capitalized cost A = $9980/kW and B = $3320/kW	TCO	TCO at $8000/ MVA
Design 1	20.6	202.7	1.00 PU	$878,552	1.00PU + $878,552	$1,378,552
Design 2	26	160	1.18 PU	$790,680	1.18PU + $790,680	$1,380,680
Design 3	21	180.8	1.04 PU	$821,474	1.04PU + $809,836	$1,329,836

ers to reduce their operational losses and the resulting CO_2 emissions while reducing the total cost of ownership.

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Rob Milledge, based in Sydney, Australia, graduated from the University of NSW with 1st Class Honours and University Medal. He has been involved with Power Transformer design since 1974, starting as an Electrical Design Engineer and progressing to Engineering Management in 1995 with direct engineering design and manufacturing experience for units up to 1,125 MVA and 550 kV since 1979. Since 2001, Mr. Milledge has been involved in both Customer and factory technical support, including tender and order designs to 765 kV, alternate opportunity assessment, Customer design review and FAT Support throughout the Asia-Pacific region. This also included technology transfer and implementation programs for various factories. Following a period within the company's Global "Top Gun" Design Team, he is focusing on his Application Engineering role for the Asia-Pacific region applying his extensive power transformer knowledge to Customer technical support, training and technical co-ordination with factories. Rob retired in July 2022.

Ghazi Kablouti is the Global Portfolio Sustainability Manager for the Hitachi Energy Transformers business. 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, 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.

PEER REVIEWED