Investigating the impact of transformer specification on the life cycle carbon emissions:

A case study for Middle East Countries

ABSTRACT

In this article, an investigation is conducted for a 50/62.5 MVA, 154/33.6kV ONAN/ONAF transformer on the carbon emission equivalent (tCO2-e equivalent) of different designs that derive from different loss requirements in the technical specification. The impact of such specifications for Middle Eastern countries will be shared. Furthermore, the article will compare the outcomes of cost, total ownership cost and total life cycle carbon emission assessment and will demonstrate that an effective and appropriate specification will impact and help procure transformers with the lowest total life cycle cost, including metrics such as tCO_{2-e} equivalent.

KEYWORDS:

carbon footprint, carbon emissions, transformer specifications, energy efficiency, Middle East countries

Middle East is warming at twice the global average and by 2050, the region could be as much as 4 °C warmer

1. Introduction

Transformer technical specification is the first step in establishing the long-term reliability of transformers. From a user perspective, a technical specification formally communicates what the manufacturer must deliver. From a manufacturer's perspective, a technical specification offers the ability to provide an appropriate and optimised solution, meeting both technical and commercial aspects while remaining a long-term profitable business [1].

The supply of a transformer comprises the design, manufacture, quality assurance and testing at the manufacturers' works and, depending on the contract, transport, complete erection, commissioning, and set to work at a site [2]. For designing and delivering a good transformer, a complete specification must be provided by the end-user with mandatory, supplementary, and additional categories. Mandatory specifications (not limited to) include – MVA rating, voltage ratio, phase and frequency, impedance, tappings, etc., whereas supplementary specifications include – Temperature Rise limits, Specific requirements of fittings and accessories such as temperature indicators, limitations of flux density and current density, dimension limitations, loss capitalisation etc. Additional categories include – the type of core construction, external clearances, bushing creepage distances, sheet thickness etc. Additional specifications are not so critical for the operation of a transformer but are necessary for a designer to know the requirements of the end-users. Routine tests, type tests and special tests (if required) are also included.

In terms of environmental considerations, the following are typically considered [2]:

- sound level,
- oil spill and pollution minimisation,
- fire hazard and risk of other by-products,
- explosion or blast hazards,
- seismic risk.

However, considerations on the impact of transformer technical specifications in the protection of the environment from greenhouse gas emissions have not been included yet. Many end-user specifications claim that they purchase transformers using some type of loss evaluation procedure. However, the total cost of ownership method incorporates only the transformer losses and not the impact on the environment. Additionally, many contractors procure transformers based on the lowest initial cost transformer without investigating the environmental impact of such selection over the entire transformer life cycle. If end users have little incentive to take into consideration any economic factors other than the transformer's purchase cost, it prevents manufacturers from offering or recommending efficient options.

Increasing carbon emissions is an existential threat to humanity [3]. The Middle East is warming at twice the global average and by 2050, the region could be as much as 4 °C warmer. This is way beyond the 1.5 °C target set by the Paris Agreement [4]. To counter increasing carbon emissions, clean and efficient energy technologies will need to be deployed at an unprecedented scale, with electrification becoming the backbone of the entire energy system. Transformers will contribute to this journey as they are the "spinal cords" of our electrified energy system. Hence selection of transformers with consideration for environmental impact is crucial more than ever before. Transformers create environmental impacts, e.g. carbon emissions from electrical losses and mining and processing materials used in their manufacturing as well as how transformer components are disposed of at the end of their lifecycle. Thus, it becomes crucial that these environmental considerations are included in the specification & procurement process.

The article will share the comparison of the outcomes of cost, total ownership cost and total life cycle carbon emission assessment for the Middle Eastern region – Egypt, Turkey, Qatar, Saudi Arabia, Kuwait, United Arab Emirates, and Iraq. The Middle Eastern energy sector is predominately based on non-renewable energy. This energy mix plays an important role as it directly affects the environmental impact of the transformer. For example, UAE's Energy Strategy for 2050 foresees shares of 44 % renewable energy, 38 % gas, 12 % "clean coal", and 6 % nuclear in the electricity mix in 2050 [5] hence increasing energy efficiency will always remain a key national strategy.

Considerations on the impact of transformer technical specifications in the protection of the environment from greenhouse gas emissions have not been included yet

An investigation of how the different transformer designs that comes from different loss requirements in the technical specification impacts the carbon emission equivalent (tCO_{2-e} equivalent) will be conducted

This article investigates a 50/62.5 MVA, 154/33.6 kV ONAN/ONAF transformer, with target design impedance = 12 %, and how the carbon footprint is impacted (tCO_{2-e} equivalent) by different designs based on different specifications from end users in the Middle Eastern region. The aim of the article is to demonstrate that an effective and appropriate specification will impact and help procure transformers with the lowest total life cycle cost, including metrics such as tCO_{2-e} equivalent. In addition to the tCO_{2-e} equivalent, there are other important sustainability-related metrics [6] which are not included in the scope of this article:

- **Ozone depletion (kg CFC-11 equiv.).** This category concerns the depletion of stratospheric ozone, which can have adverse effects on human health, animal health, terrestrial and aquatic ecosystems, biochemical cycles and materials.
- **Depletion of abiotic resources-mineral and metals (kg Sb equiv.) and Depletion of abiotic resources-fossil fuels (MJ).** These impact categories relate to the protection of human well-being, human health and ecosystem health and the extraction of minerals and fossil fuels. The abiotic depletion factor is determined for each mineral and fossil fuel extraction (kg of antimony equivalents / kg of extraction) based on reserves and the de-accumulation rate.
- **Acidification (mol H+ equiv.).** This impact category covers acidifying substances that cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems, and materials (buildings).
- **Eutrophication aquatic freshwater (kg PO43- equiv.).** Eutrophication includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to the water.
- **Water use (m3 world eq. deprived).** The indicator measures the Relative Available WAter REmaining (AWARE), or the amount of water remaining in a basin, after the demand for water resources for human and ecosystem activities has been met. This indicator evaluates the potential for deprivation of water resources, both for humans and ecosystems.

2. Typical transformer loss specifications in Middle Eastern Countries

According to transformer specification reviews from different end-users in Egypt, Turkey, Qatar, Saudi Arabia, Kuwait, UAE, and Iraq, the following four categories can be inferred for typical loss requirements, as listed in Table 1.

Based on Table 1, four different designs resulting from the four different categories of transformer loss specification are analysed for a common transformer rating of 50/62.5 MVA, 154/33.6 kV as below:

We analyse 4 different design strategies, raging from optimised design which does not take into account taking efficiency, up to the cases where designs were optimised for efficiency with no-load and load capitalisation factors

Table 1. Transformer loss specification categories from the literature review

Category	Specification type
1	This is a type of specification with no transformer loss limitations, no loss cost ($/kW) considerations and no IEC 60076-20 Peak Efficiency Index (PEI) requirement.
2	This is a type of specification where the end-user requires maximum transformer losses to comply with certain maximum no Load loss and Load Loss and comply with IEC “PEI 1” requirement. However, no loss cost ($/kW) is provided.
3	This is a type of specification where the end-user requires maximum transformer losses to comply with certain maximum no Load loss and Load Loss and comply with IEC “PEI 2” requirement. However, no loss costs ($/kW) are considered.
4	This is a type of specification where the end-user requires the transformer to comply with IEC “PEI 2” and design optimised according to loss cost ($/kW).

Table 2. Major design parameters for the comparison study

Rating	50 MVA ONAN/62.5 MVA ONAF			
Phases	3-phase			
Impedance	12%			
Voltages	154kV/33.6kV (Voltage level selected from Turkish Specification)			
Max flux density	1.63T (Max flux density selected from Turkish Specification)			
Vector group	YNyn0			
Tapping	154 ±12 * 1.25 %			
Sound Power Level	82 dBA			
BIL	HV: 650 kV, LV: 170 kV			
Max flux density	1.63 T, overexcitation = 1.193 pu with 1.93 T limit			
Temperature limits	Ambient	Top oil rise	Winding temperature rise	Hot spot rise
	45°C	55 K	60 K	73 K

- **Design #1:** A design optimised with no transformer loss limitations, no loss costs ($/kW), and no Peak Efficiency Index requirement.
- **Design #2:** A design optimised for: no-load loss < 30 kW, load loss < 250 kW and IEC 60076 -20 Peak Efficiency Index 1.
- **Design #3:** A design optimised for: no-load loss < 30 kW, load loss < 250 kW and IEC 60076-20 Peak Efficiency Index 2.
- **Design #4:** A design optimised for: no-load loss < 30 kW, load loss < 250 kW, IEC 60076-20 Peak Efficiency Index 2 and where the total cost of ownership (TCO) is included with No-Load Capitalisation factor, A = 7500$/kW and Load Capitalisation factor, B = 2500$/kW.

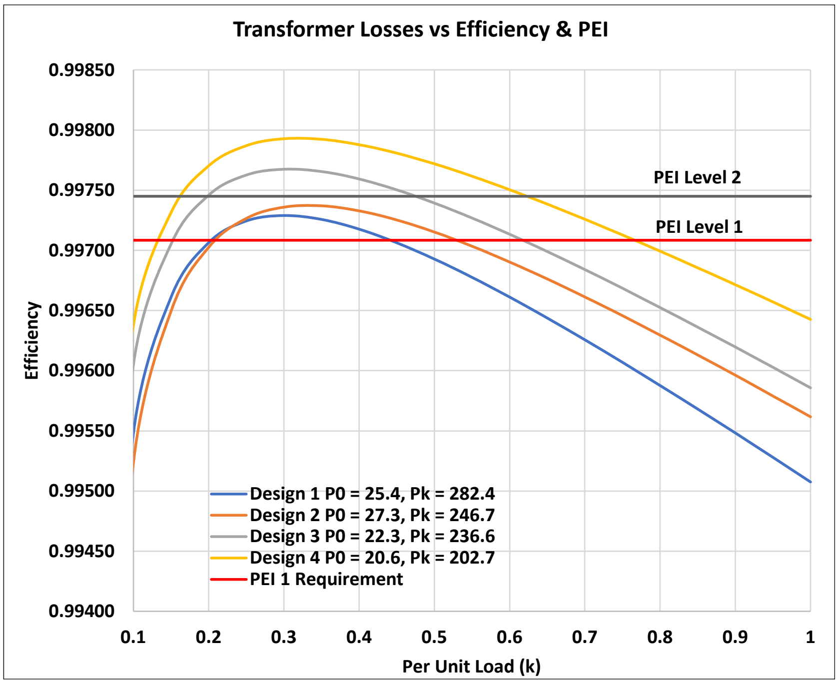

Figure 1. Transformer efficiency curves: Design 1 to Design 4

3. Transformer under investigation

For this study, we consider the following transformer specification (as listed in Table 2) which is based on typical specifications from different end-users in Egypt, Turkey, Qatar, Saudi Arabia, Kuwait, UAE, and Iraq.

Table 3 lists the parameter values used to calculate the A-factor and B-factor using equations in IEC 60076-20 [7].

Table 3. TCO parameters used for Design 4

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)

Table 4: Design outcomes based on transformer loss requirements

Parameters	Design 1	Design 2	Design 3	Design 4
No load loss	25.4 kW	27.3 kW	22.3 kW	20.6 kW
Load loss	282.4kW	246.7 kW	236.6 kW	202.7 kW
Total loss	307.8 kW	274 kW	258.9 kW	223.3 kW
Loss reduction achieved?	--	10.98 %	15.89 %	27.45 %
IEC PEI Level 1 required	99.709 %	99.709 %	99.709 %	99.709 %
IEC PEI Level 2 required	99.745 %	99.745 %	99.745 %	99.745 %
PEI Design output	99.729 %	99.737 %	99.768 %	99.793 %
IEC PEI Level 1 achieved?	Yes	Yes	Yes	Yes
IEC PEI Level 2 required?	No	No	Yes	Yes
K_{PEI}	30 %	33.3 %	30.7 %	31.9 %

If the transformer selection is only based on the transformer's first cost, it discourages manufacturers and contractors from offering or recommending efficient options to end-users who do not specifically request them

Table 5. Component mass outcomes based on transformer loss requirements

Component mass	Design 1	Design 2	Design 3	Design 4
Core coil assembly (kg)	39,350	41,990	43,690	45,000
% Change from Design 1	--	↑7 %	↑11 %	↑14 %
Tank, (kg)	12,880	13,195	13,310	14,154
Transport mass (kg) without radiators	52,230	55,895	57,000	59,864
% Change from Design 1	--	↑6.56%	↑8.37%	↑12.75%
Radiator (kg)	11,975	11,345	9,115	7,270
% Change from Design 1	--	↓5.55%	↓16.48%	↓23.37%
Oil (kg)	19,280	19,065	19,280	18,945
Total weight (kg)	83,485	86,305	86,020	86,704
% Change from Design 1	--	↑3.27%	↑2.95%	↑3.71%

4. Design outcomes

4.1 Transformer efficiency outcomes

The transformer loss specification requirements result in four different design outcomes, as in Table 4.

The efficiency curves for Design 1 to Design 4 are shown in Fig. 1 against IEC PEI Level 1 and PEI Level 2 requirements. All the four different designs meet PEI Level 1, whereas only Design 3 and Design 4 meet PEI Level 2. From Design 1 to Design 4, the total loss is reduced by almost 27.45 %, which has a significant implication for the environmental performance of the transformer. However, if the transformer selection is only based on the transformer's first cost, it discourages manufacturers and contractors from offering or recommending efficient options to end-users who do not specifically request them. Transformer specifications must include sustainability-related metrics such as tCO_{2-e} equivalent to select the most sustainable transformer.

4.2 Transformer component mass outcomes

The transformer loss specification requirements result in four different component mass outcomes, as in Table 5.

In Fig. 2, the effect of transformer loss specification on the main transformer components are shown. With the increase in efficiency, the weight of the core coil assembly increases from Design 1 to Design 4 by around 14 %, while the weight of the radiators used decreases from Design 1 to Design 4 by 36 %. The net variation in the weight of the oil used remains within ± 2 % and the total installed mass also remains at ± 3 %. The environmental impact of the changes in components used in the transformer will be evaluated in the next section.

5. Impact of design outcomes on equivalent tCO_{2e} emissions

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

- Variation in the quantity of components used in designs 1 to 4, such as core steel, tank steel, oil, copper, etc.
- Electrical energy loss covering transformer power losses for designs 1 to 4 at 50 % load for 40 years.

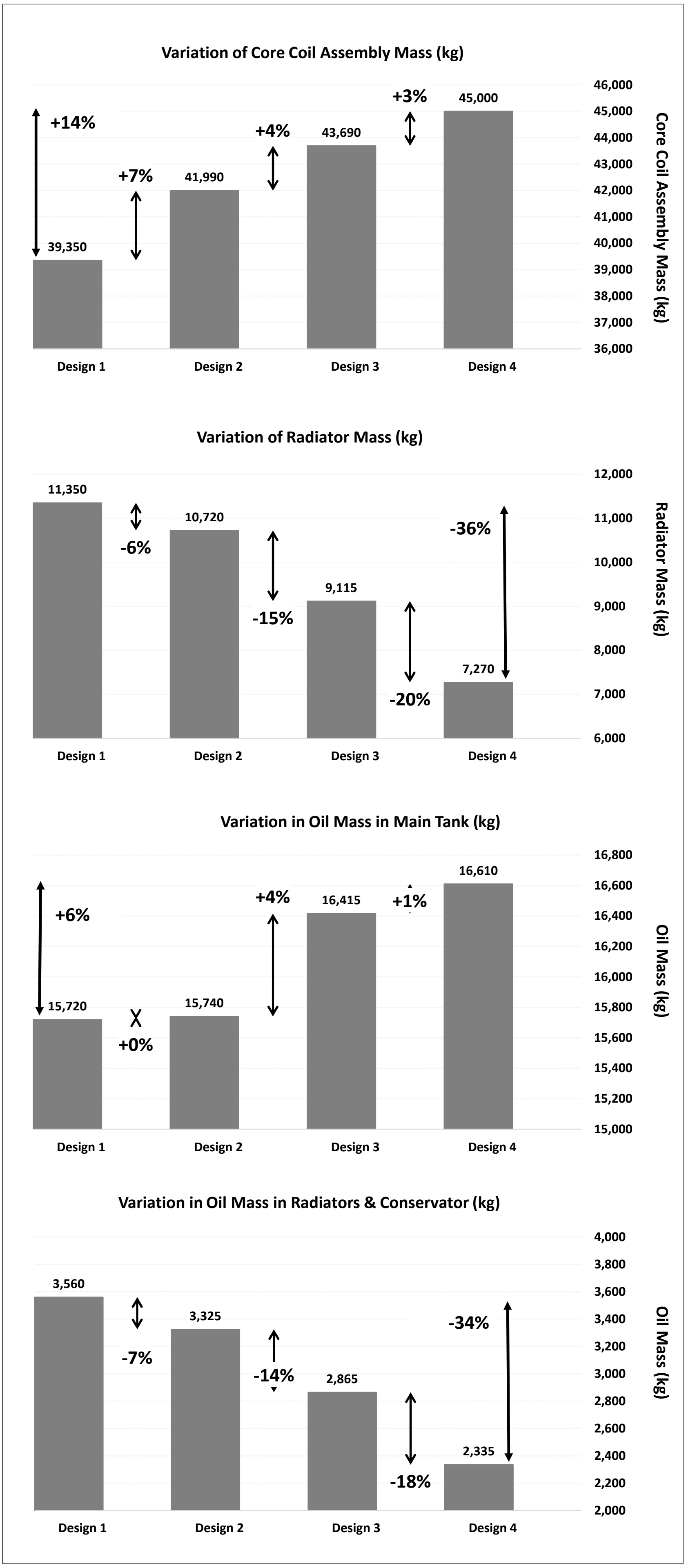

Figure 2. Impact of transformer efficiency specifications – core coil assembly, radiator and oil weight

To evaluate the impact of transformer efficiency on global warming potential, an average grid emission factor of 0.668 tCO_{2e}/MWh is used in our calculations

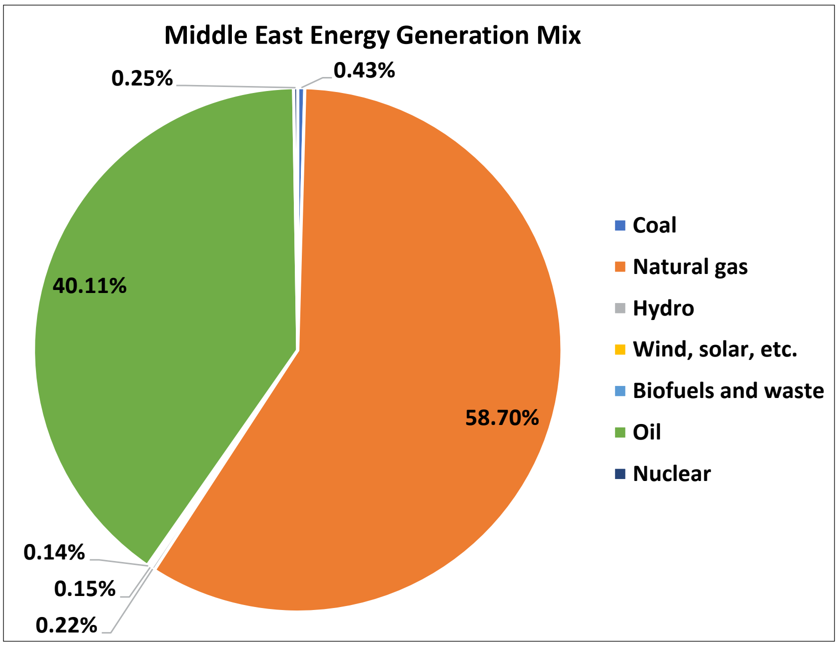

Figure 3. Energy generation mix of Middle East

Processes not included in this study are transportation of raw materials to component manufacturing, energy used for component manufacturing processes at suppliers, transportation of components to the transformer factory, electricity used in transformer factory during production of the transformer, transportation of transformer to the end-user, end of life management including landfill and recycling.

5.1 Outcome of transformer efficiency

To evaluate the impact of transformer efficiency on global warming potential, an average grid emission factor of 0.668 tCO_{2e}/MWh is used in our calculations. The average grid emission factor is derived for an energy generation mix as shown in Fig. 3, where 58.7 % natural gas and 40.11 % oil is used [8]. It should be noted that the grid emission factor will change in time when more renewables are added to the generation mix, e.g., UAE's Energy Strategy for 2050. In this article,

With the increase in efficiency, the weight of the core coil assembly increases from Design 1 to Design 4 by around 14 %, while the weight of the radiators used decreases from Design 1 to Design 4 by 36 %

Power losses have the highest contribution to the total impact on carbon emissions for transformer specifications in the Middle East

the analysis is carried out using the current generation mix.

The estimated global warming potential 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 %, 50 %, and 100 % are shown in Fig. 4. The following can be inferred:

- At 25 % average load, 23 % tCO2e can be reduced i.e., from 10,092 tCO2e to 7,799 tCO2e if Design 4 is used instead of Design 1.
- At 50 % average load, 26 % tCO2e can be reduced i.e., from 22,504 tCO2e to 16,708 tCO2e if Design 4 is used instead of Design 1.
- At 100 % average load, 27 % tCO2e can be reduced i.e., from 72,154 tCO2e to 52,345 tCO2e if Design 4 is used instead of Design 1.

5.2 Outcome of components used in the core coil assembly

The transformer core and coil assembly consist of 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 various remaining 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 [9] and listed in Table 6. Fig. 5 shows the impact of transformer loss specification – a 15 % increase in CO_{2e} can be seen, i.e., from 125.18 tCO_{2e} to 146.23 tCO_{2e} if Design 4 is used instead of Design 1.

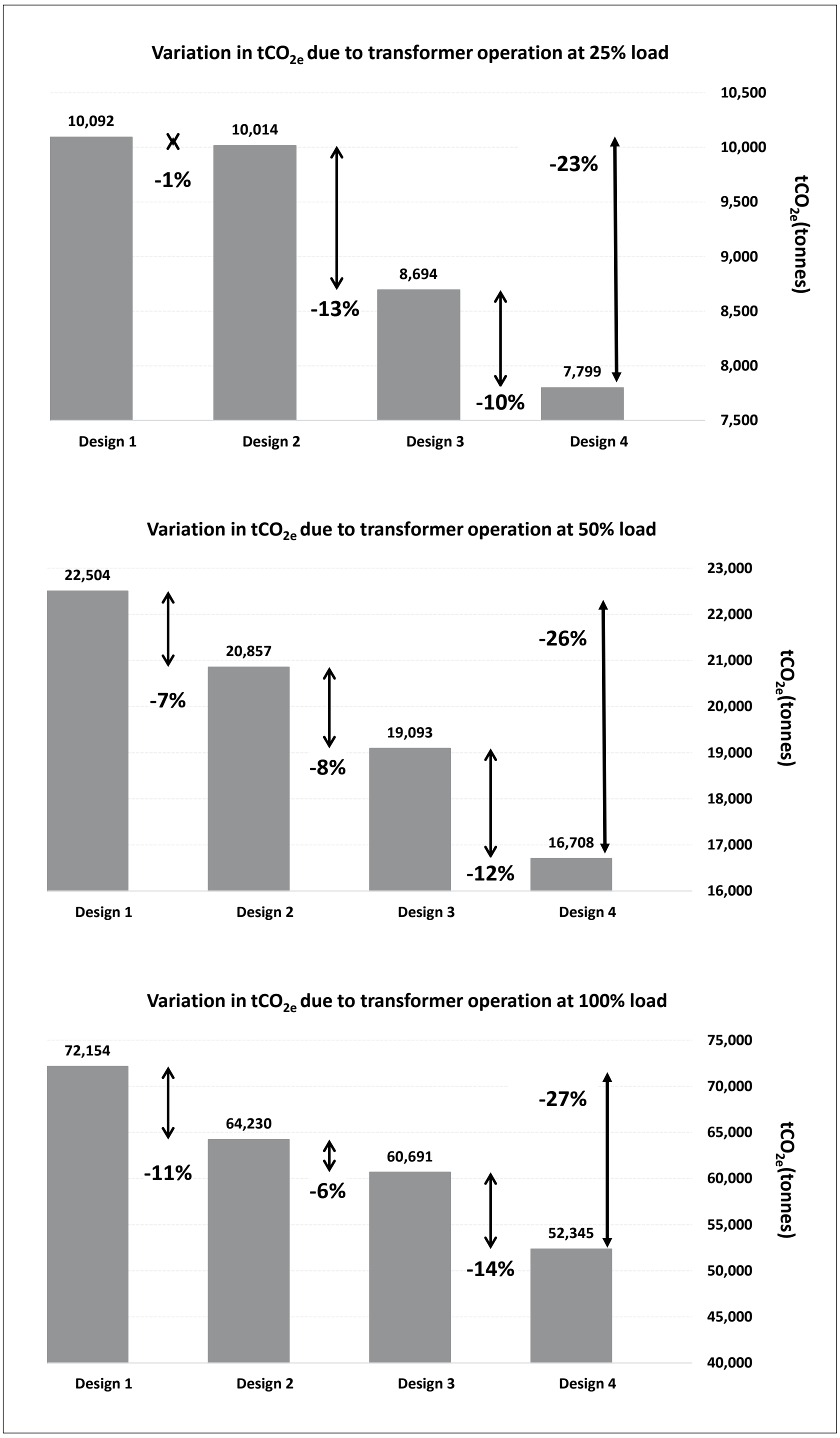

Figure 4. Impact of transformer loss specification: operational carbon footprint

Table 6. Average emission factors ($kgCO_{2e}/kg$) [9]

Core steel	Copper	Paper	Steel	Pressboard	OLTC
2.765	4.738	0.817	2.5	1.183	7.5

5.3 Outcome of components used in radiators / conservator

The transformer radiator assembly consists of radiator banks and headers, pipes, fans, and a conservator. Almost all the components are made of steel, the emission factor used for steel = 2.5 $kgCO_{2e}/kg$ [9]. Fig. 6 shows the impact of transformer loss specification – a 36 % decrease in CO_{2e} can be seen, i.e., from 29.93 tCO_{2e} to 19.73 tCO_{2e} if Design 4 is used instead of Design 1.

5.4 Outcome of total oil used

As shown in Section 4.2, the net variation in the weight of the oil used remains within ± 2 %. The emission factor used for mineral oil = 1.209 $kgCO_{2e}/kg$ [9]. Fig. 7 shows the impact of transformer loss specification – the global warming potential due to the amount of mineral oil used in the four different specification, for all practical purposes, is equivalent, i.e., 23 tCO_{2e}.

5.5 Outcome of total tank steel and bushings

Fig. 8 shows the impact of transformer loss specification – the global warming potential due to the amount of steel used in the transformer tank and the global warming potential due to bushings used. Total emission for Design 1 = 33.2 tCO_{2e} increases to 38.157 tCO_{2e} for Design 4.

5.6 Outcome of total components used

Fig. 9 shows the impact of transformer loss specification – the global warming potential due to components used in the four different specifications, for all practical purposes, is equivalent, i.e., 219 ± 8 tCO_{2e}.

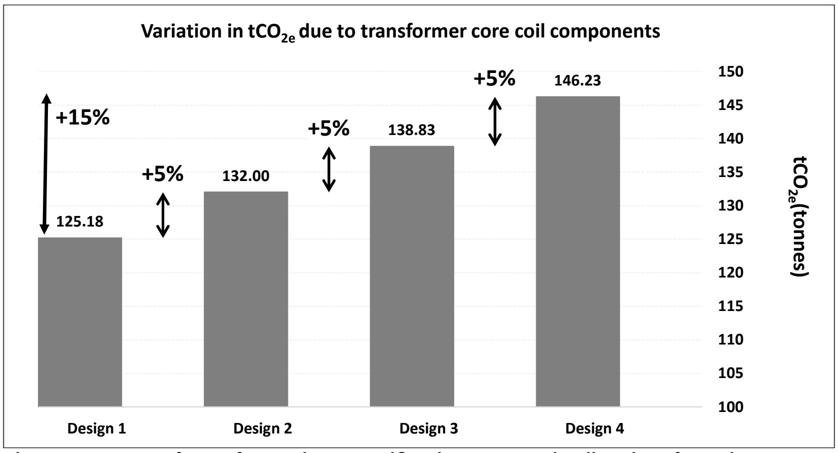

Figure 5. Impact of transformer loss specification: core and coil carbon footprint

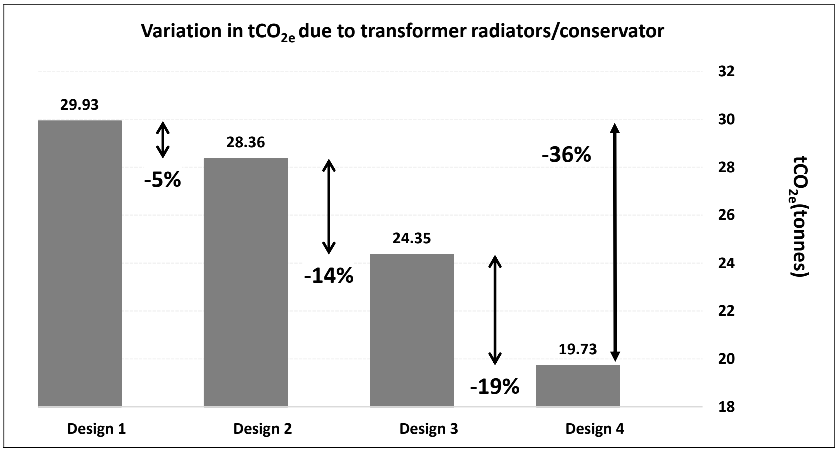

Figure 6. Impact of transformer loss specification: radiator / conservator carbon footprint

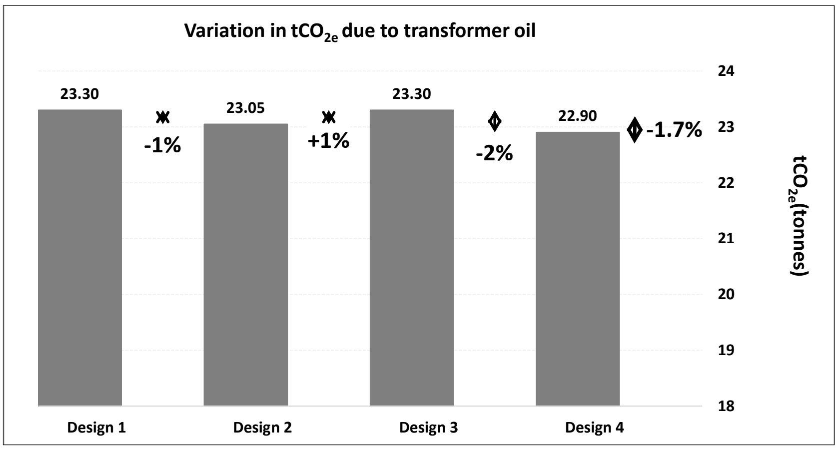

Figure 7. Impact of transformer loss specification: insulating fluid carbon footprint

6. Comparison between operational and component carbon footprint

Fig. 10 presents the emissions comparison between operation and components used. Power losses have the highest contribution (> 99 %) to the total impact on climate change for transformers used in the Middle Eastern countries. Therefore, energy efficiency is a key focal point for environmental performance under the Middle Eastern average electricity grid mix. If end-users specify a type of specification where the transformer is required to comply with IEC "Peak Efficiency Index 2" and the design optimised according to loss cost ($/kW), then 5,780 tCO_{2e} emissions can be saved by one 62.5 MVA transformer alone in the next 40 years.

7. Impact on the transformer purchase price

An estimated impact on the transformer purchase price (based on 2021 component pricing) is shown in Fig. 11. It can be estimated that the transformer's first cost will increase (approx. 17 % if Design 4 is used). However, there is a significant benefit in terms of reducing around 5,780 tCO_{2e} emissions. At a carbon price of US$50/$tCO_{2e}$, this approximates to ~US$289,000.

The adoption of Peak Efficiency Index 2 and TCO considerations for transformer specifications can contribute to the move towards net-zero emissions

In the Middle East, governments are grappling with a simple question: What is the right price to reduce greenhouse gas emissions and should market forces set this or should it be through direct government legislation, such as taxation, to change behavior? However, there are certain unusual factors in the Middle East:

- A high level of energy-intensive industries, with a risk of becoming uncompetitive under carbon pricing.
- A high degree of firm concentration in energy and heavy industry is mostly state-owned, usually including monopoly state oil and utility companies.
- Low application of income and corporate taxes, preventing the use of the tax system.

Thus, it is extremely important for end-users to include the TCO evaluation method in specifications. This is a type of specification where the end-user requires the transformer to comply with IEC "Peak Efficiency Index 2", and the transformer design is optimised according to the loss cost ($/kW) specified. The evaluation criteria is an important element to start doing things differently, with a TCO evaluation which can be later extended to include environmental impact, on top of losses once the governments in the Middle East decide on the policy implementations.

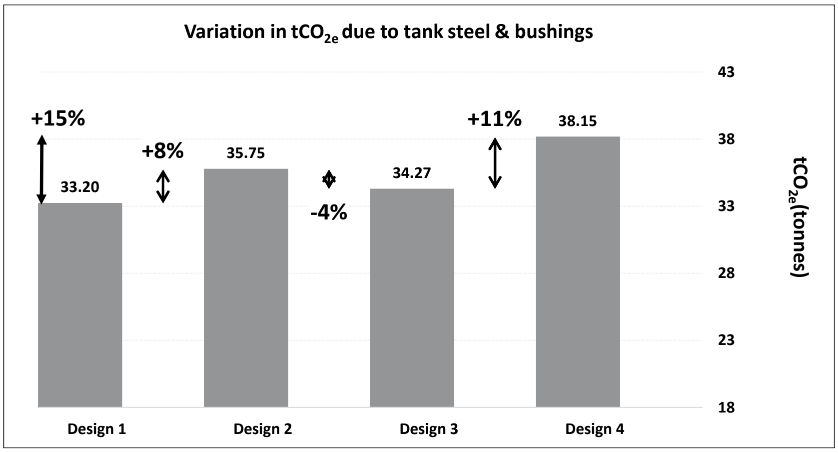

Figure 8. Impact of transformer loss specification: tank steel and bushings carbon footprint

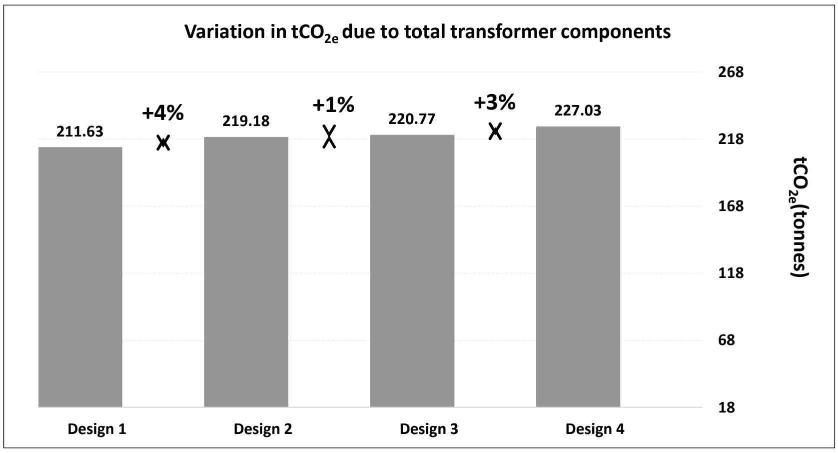

Figure 9. Impact of transformer loss specification: transformer component carbon footprint

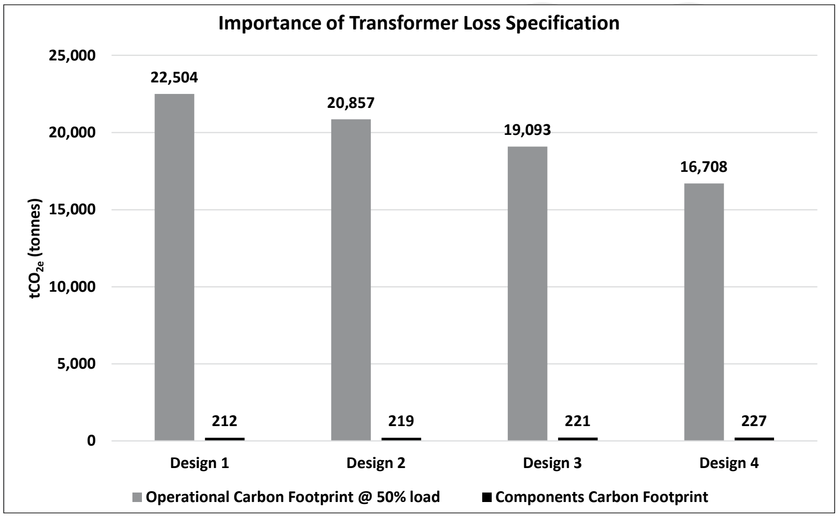

Figure 10. Transformer carbon footprint comparison: operation (40 years) vs components

8. Summary

Climate change is affecting the Middle East in far-reaching ways. Temperatures are set to rise in the region by at least 4 °C by 2050—that is, if greenhouse gases continue to increase at the current rate. A holistic approach is required to tackle this problem, and transformers can play a sustainable role in this journey.

In this article, a transformer specification review from different end-users in Egypt, Turkey, Qatar, Saudi Arabia, Kuwait, UAE, and Iraq was completed, and four categories of transformer loss requirements were identified. The article shared the comparison of the outcomes of total life carbon footprint assessment and cost for four different transformer designs based on these four categories. For the average Middle Eastern power generation mix, transformer efficiency specifications towards losses reduction are the most important effort towards sustainability as losses are the major contributor to the carbon footprint. At 50 % average load for a typical 62.5 MVA transformer, a 25 % reduction of tCO_{2e} emissions is expected, from 22,716 tCO_{2e} to 16,935 tCO_{2e} over a period of 40 years if – the transformer specification requires the transformer design to comply with IEC "Peak Efficiency Index 2" and be optimised according to loss cost ($/kW) specified instead of no transformer loss limitations, no loss cost ($/kW) considerations and no IEC Peak Efficiency Index requirement. The adoption of Peak Efficiency Index 2 and TCO considerations for transformer specifications can contribute to the move towards net-zero emissions. Therefore, this should be an integral part of transformer specifications in the future.

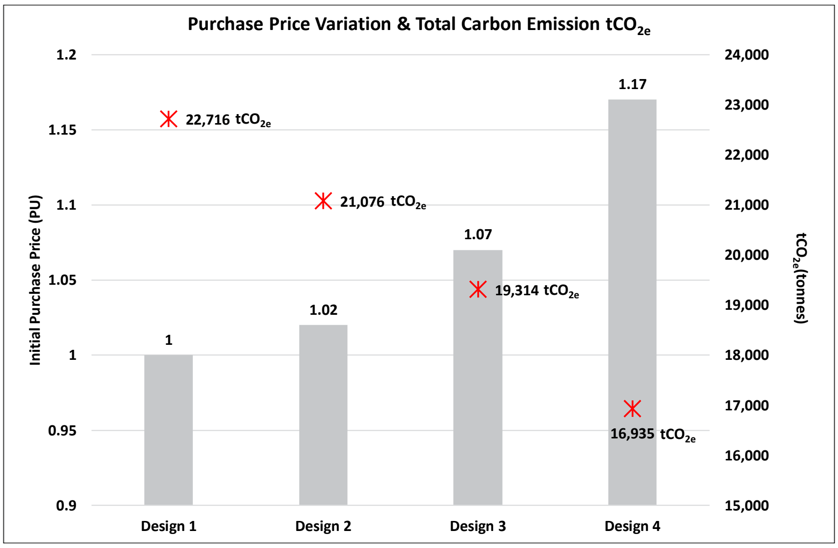

Figure 11. Impact of transformer loss specification: transformer purchase price and total carbon emission

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