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SUPPLEMENT TO THE TRANSFOMERS POLICY GUIDE:
«ACCELERATING THE GLOBAL ADOPTION OF ENERGY-EFFICIENT TRANSFORMERS»

PUTTING ENERGY EFFICIENT TRANSFORMER PROCUREMENT INTO PRACTICE

# A GUIDE TO USING TOTAL COST OF OWNERSHIP WHEN PURCHASING DISTRIBUTION TRANSFORMERS

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UN Environment – Global Environment Facility | United for Efficiency (U4E)

Supplement to the Transformers Policy Guide:
"Accelerating the Global Adoption of
Energy-efficient Transformers"

# Procurement Guidelines

# A Guide to Using Total Cost of Ownership When Purchasing Distribution Transformers

UN Environment Programme – Global Environmental Facility
United for Efficiency (U4E)

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# Foreword

Transformers are a critical part of the electrical infrastructure of a country. They help to improve the efficiency of the transmission and distribution of electricity by increasing and decreasing the voltages in the network as necessary. Transformers themselves are highly energy-efficient, typically with efficiency values greater than 97%. This means that, when changing the voltage level, these transformers only consume 3% or less of the total power passing through the unit. Even though this level of efficiency is very high, there are still significant improvements in efficiency that can be made which are highly cost effective and utilize mature, proven and reliable approaches.

In addition to being energy-efficient, another defining characteristic of transformers is long lifetime. In most applications, transformers are expected to remain in service for 30 years or more. As with other products and appliances, the first cost is not fully representative of the total cost of ownership, which includes the cost of both purchasing and operating the transformer in a national network. It has been shown that the running costs (i.e., electrical energy losses in the transformer) far exceed the purchase cost (i.e., first cost) of the transformer and can be as much as four times higher.

Taking into account the cost of future losses is critical for ensuring that utilities and companies purchase and install cost-optimised transformers into their network. The International Electrotechnical Commission (IEC) has developed a methodology for doing exactly this – it is called the Total Cost of Ownership (TCO) methodology – and it capitalises the value of future losses and incorporates them into the purchasing decision process. The TCO methodology can be applied to any transformer size, from small distribution transformers right through to large network and transmission transformers.

This guide seeks to provide information about the IEC's methodology and raise awareness amongst transformer specifiers about the TCO approach. The IEC's specification and equations are all published in IEC Technical Specification (TS) IEC TS 60076-20 (Ed. 1.0) 2017 Annex A. In addition to this document, U4E has prepared an Excel spreadsheet tool[1] which puts the IEC equations into a user-friendly spreadsheet, to facilitate the derivation of the calculation of the loss evaluation factors.

For more information about this document or other energy-efficient transformer related topics, please contact:

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[1] Available at https://united4efficiency.org/resources/a-guide-to-using-total-cost-of-ownership-when-purchasing-distribution-transformers/

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# Acronyms and Abbreviations

| | |
|---|---|
| IEC | International Electrotechnical Commission |
| COP | Conference of the Parties |
| h | hours |
| Hz | hertz |
| kW | kilowatt |
| TCO | Total Cost of Ownership |
| TS | Technical Specification |
| U4E | United for Efficiency |
| UN | United Nations |
| UNEP | United Nations Environment Programme |
| UNFCC | United Nations Framework Convention on Climate Change |
| US | United States |
| W | Watts |

# 1 Executive Summary

Energy losses in transformers represent additional (incremental) load that a utility must supply and pay for over the life of a transformer. To the extent that these losses can be reduced in an economically justified way, the utility (or other business procuring a transformer) will incur lower future running costs in their electricity network and achieve a more economically optimal outcome over the lifetime of the transformer. The total cost of ownership (TCO) methodology for evaluating the purchase of a transformer enables experts and specifiers to identify and purchase cost-optimised transformer designs that will be installed and operate in a given network for decades to come. Data analysis has shown that transformers cost a utility several times more[2] to *operate* than they cost to *purchase*, however this high operating cost is not always apparent to the transformer specifying and financing team. To quantify this hidden operating cost, experts from around the world on an IEC Technical Committee developed a "total cost of ownership" methodology, which enables transformer specifiers and procurement officers to take into account the value of future losses in their purchasing decision.

The IEC TCO methodology brings together the first cost of the transformer and the future (discounted) running costs into a net present value total cost of ownership. It does so by using the following methodology:

$$TCO = Purchase\ Price + (A \times Watts_{No-Load\ Losses}) + (B \times Watts_{Load\ Losses})$$

Where:

> A-factor is the capitalisation of no-load losses, taking into account lifetime, the discount rate and the cost of electricity; the units are defined as the national currency per watt or kilowatt; and
>
> B-factor is the capitalisation of load losses, taking into account lifetime, the discount rate, the cost of electricity and the loading on the transformer; the units are defined as the national currency per watt or kilowatt.

This methodology was published in IEC's international technical specification, IEC TS 60076-20:2017, Power Transformers – Part 20: Energy Efficiency[3], on 30 January 2017, and a brief corrigendum issued in January 2018. The TCO approach is presented in Annex A of that document, titled "Capitalisation of losses".

UNEP's United for Efficiency (U4E) initiative wishes to encourage utilities and organisations that specify and procure transformers around the world to apply this TCO methodology

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[2] Operating cost for a transformer includes the cost of electricity consumed by the transformer when converting the voltage up or down. This electricity cost can be as much as 4 or 5 times higher than the initial purchase cost of the transformer, depending on the cost of electricity and the magnitude of the losses in the transformer.

[3] Visit the IEC webstore to purchase IEC TS 60076-20:2017: https://webstore.iec.ch/publication/28063

when purchasing transformers, as it will result in more economically optimised transformers being installed and reduce powerplant $CO_2$ emissions.

This guide is intended to function as a supporting document to an Excel spreadsheet tool published by U4E, which was developed to help utilities derive their A and B factors, and thereby enable better economic optimisation of distribution transformers using the IEC standard methodology.

In addition, U4E has developed a second TCO methodology which elevates the cost of carbon in the calculation. U4E is offering this tool as a resource to help demonstrate the increased value of more energy-efficient transformers. The U4E Excel spreadsheet tool offers a second TCO methodology (developed by U4E) which reflects the value of carbon – i.e., a ton of $CO_2$. – by which this factor can be calculated for different transformer designs and introduced to the TCO calculation.  This ensures that when looking at the total cost of ownership, utilities would not only capture the total direct cost of ownership from an equipment and losses perspective, but also the value of the $CO_2$ emissions associated with those losses.

Irrespective of whichever method transformer procurement officers select, the consideration of future losses through the use of the TCO methodology when making a purchasing decision of a transformer will result in more economically rational outcomes which are better for the utility, the country and ultimately the planet.

# 2 Introduction and Context

When purchasing distribution transformers, utilities will often use a purchasing practice referred to as total cost of ownership or whole life costing, which involves the capitalisation of losses. This approach to specifying and purchasing transformers is used to minimise the total investment over the lifetime of a transformer, enabling a utility to maximise its energy savings at the lowest cost. Loss capitalisation takes time to calculate the correct factors to apply but helps provide answers to the following questions:

- At what cost should the lost energy be evaluated?
- What is the load factor that should be applied?
- What is the societal discount rate that should be applied to any benefits?
- What is the weighted average cost of capital that should be applied to the capital purchase?

The biggest issue with loss capitalisation is that it seeks to quantify the typical life of a transformer – which spans several decades, and which represents the length of time that utilities could use for discounting asset values in their accounts.

This whole life costing approach is intended to assign a present value to the value of future losses that will occur over the life of the transformer in a given installation. To achieve this, the loss factors typically developed for an annualised cost method can be used as inputs to a discounted present value calculation method looking into the future to develop the whole life costing model. However, each purchaser may prefer different approaches based on historical methodologies.

By using this whole life costing approach, future changes such as load growth or reductions can be factored into the purchasing decision. In this method the discounted present value of the cost of energy consumed over the life of the transformer is added to the purchase price. The lowest total lifetime cost being the preferred option (which is often not the lowest first cost design).

When purchasing a transformer, a utility will include a statement expressing its valuation of no-load and load losses. These two valuations are expressed on a cost per Watt basis, where the cost is in the same currency as the purchase order. For example, in the United States, a utility would specify its no-load and load-loss valuation in dollars per Watt of losses ($/W). The transformer manufacturer then uses this information in their transformer design process for that customer to prepare a design that trades off higher first cost against lower lifetime operating cost. The higher the valuation of the transformer's losses, the more efficient a manufacturer will make the transformer design – this is the core principle of how the TCO approach works.

The availability of A and B capitalisation rates allows the transformer manufacturer to optimise their transformer design, as this information about the cost of an extra Watt of loss reduction allows for an assessment of precisely when the extra costs match the extra benefits as expressed by the capitalisation rate for the A and B factors. This greatly facilitates the production of economically optimal designs, identifying the 'sweet spot' for the most economically appropriate combination of core and coil losses taking into account the load factor, transformer design and the loss capitalisation rates.

Thus, when assessing the various bids received in response to a request for tenders, the transformer specifier will apply the following equation and select the option which has the lowest TCO for the transformer designs specified (Note: the design options with the lowest TCO are not necessarily the ones with the lowest purchase price):

$$TCO = Purchase\ Price + Valuation\ of\ Core\ Loss + Valuation\ of\ Load\ Loss$$

In this equation, the purchase price represents what the manufacturer would charge the utility for the purchase. This price is a reflection of the materials and construction techniques, and thus more efficient transformers will tend to have higher purchase prices.

The valuation of core loss is a calculation that assigns a value to each watt of loss in the core of the transformer. In other words, if core losses are valued at for example $5 per watt and a transformer design has 100 watts of core loss, then the valuation of core loss entered into the TCO calculation will be $500. Adding valuation of losses allows the overall design assessment to result in the most cost-optimised purchase decision for the utility. It serves to offset the higher first cost of an energy-efficient design because the lower losses associated with the more efficient design will result in a lower operating cost added to the TCO calculation.

The valuation of load loss is very similar to that of valuing core loss. Each watt of load loss is multiplied by the value of the load losses to arrive at a total cost associated with the load loss that should be incorporated into the purchasing decision. In other words:

Valuation of core loss = A x core loss (W)

Valuation of load loss = B x load loss (W)

The total cost of ownership equation is therefore written as follows:

$$TCO = Purchase\ Price + (A \times Watts_{No-Load\ Losses}) + (B \times Watts_{Load\ Losses})$$

Where:

A-factor is the capitalisation of no-load losses, taking into account lifetime, the discount rate and the cost of electricity; the units are defined as the national currency per watt or kilowatt; and

B-factor is the capitalisation of load losses, taking into account lifetime, the discount rate, the cost of electricity and the loading on the transformer; the units are defined as the national currency per watt or kilowatt.

This approach, estimating the net present value of future electricity losses, is a prediction and involves a degree of uncertainty. For this reason, the calculation requires some professional judgement, and relevant experts with specialist knowledge of the issues should be involved. Also, it should be noted that the loss-evaluation factors may be subject to regional variation due to factors such as differences in the cost of electricity production and distribution, as well as the cost of capital.

If the loss evaluation formulae can be provided to suppliers at the time of tendering for new transformers, the tender of designs proposed can then be assessed on the basis of the initial cost plus the capitalized value of the future no-load and load losses of that transformer. This approach enables the customer to achieve the lowest overall lifecycle cost (i.e., first cost plus running cost) for the transformer they are purchasing.

**Case study: Comparison of two 1600 kVA Transformers**

If we assume a utility has established their A value as €3.74/Watt and B value as €1.58/Watt, they can use the TCO equation above to compare two design options – a standard transformer design and an efficient transformer design. The standard transformer costs €14,451 and has 2,800W of core loss and 15,207W of winding loss. The efficient design costs €14,990 and has 2,670W of core loss and 14,218W of winding loss.

Plugging these into the TCO equation, we calculate the following:

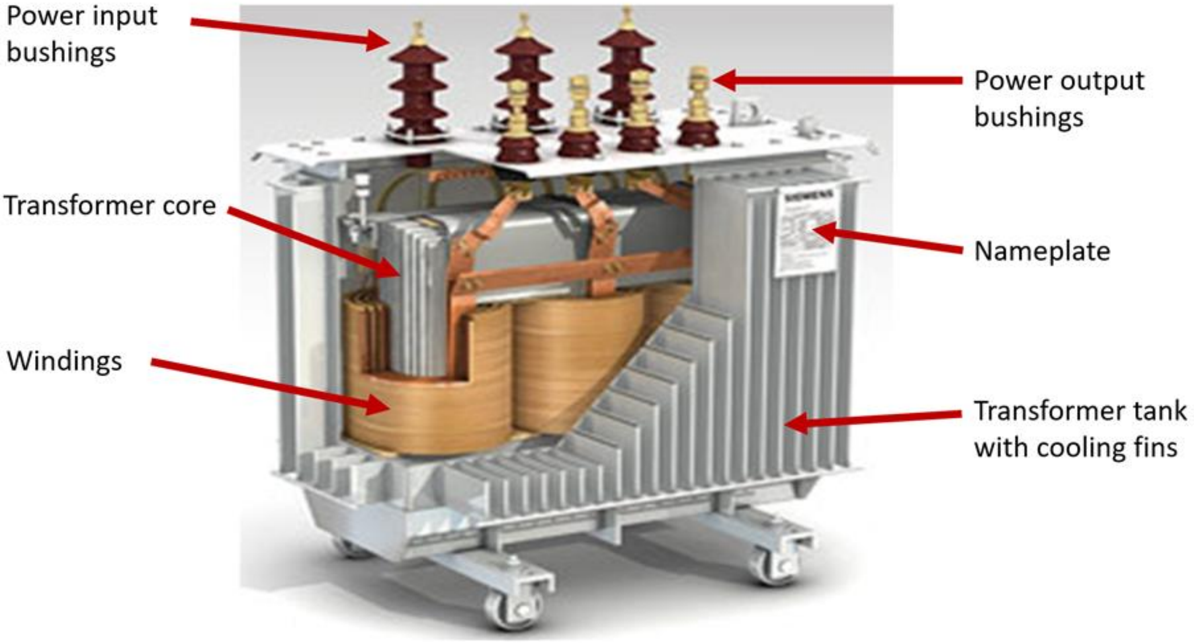
- Standard transformer: €14,451+€3.74/W*2,800W+€1.58/W*15,207W = **€48,950**
- Efficient transformer: €14,990+€3.74/W*2,670W+€1.58/W*14,218W = **€47,440**

Thus, the efficient design has a TCO of around €1,500 less than the standard transformer and has a payback period of approximately 5 years. (Leonardo Energy, 2015)

# 3 Transformer Losses

Losses in the transformer core (see Figure 1) are often called “no-load losses” or “iron losses” because they are present whenever the transformer is energised, even when the transformer is not actively supplying a load. No-load losses are independent of the loading on the transformer, meaning they do not change as the loading on the transformer varies. No-load losses come from two sources – hysteresis and eddy currents. Hysteresis losses are created by the magnetic lag or reluctance of the molecules in the core material to reorient themselves at the operating frequency of the transformer [i.e., 50 or 60 hertz (Hz)]. Eddy currents occur in the core due to the induction of the alternating magnetic field—the same way that field induces current in the secondary winding. These circulating electrical currents do not leave the core; they simply circulate within the material and become waste heat.

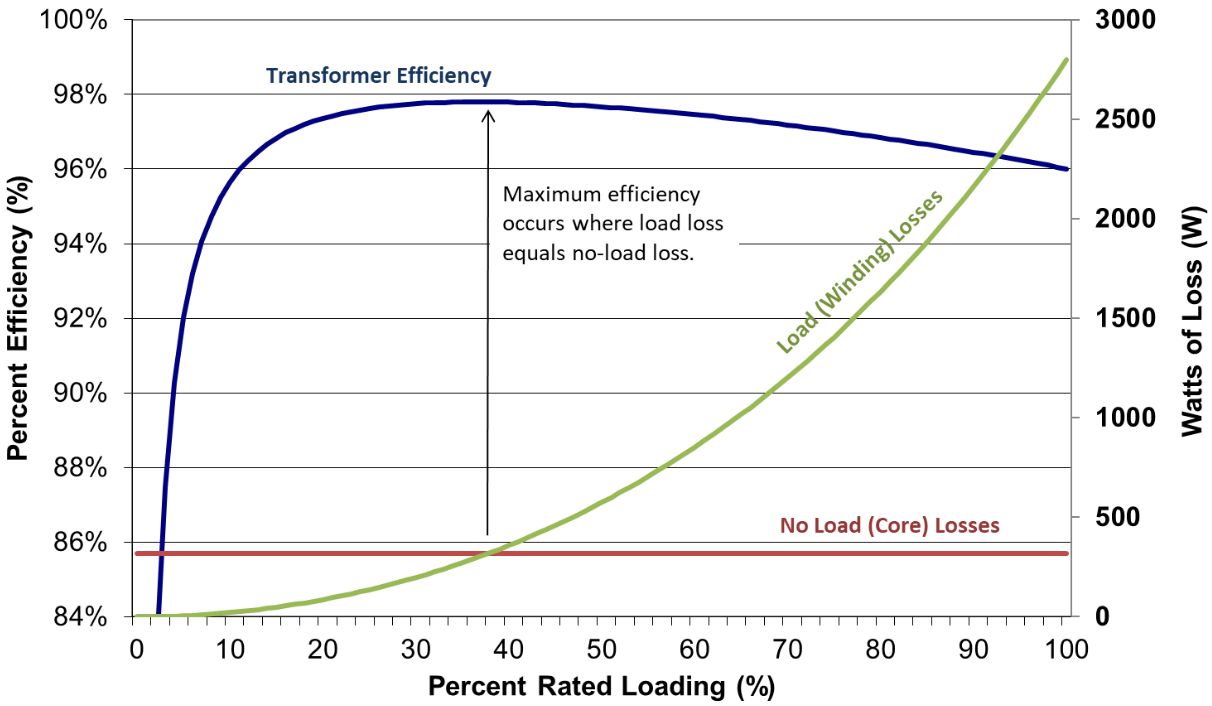
Figure 1. Cut-away view of a distribution transformer with key components labelled



Losses in the transformer windings (see Figure 1) are often called “winding losses” or “copper losses.” They are associated with the current flowing through the windings. Load losses are primarily caused by the electrical resistance of the windings. The magnitude of these losses varies with the square of the current being carried. There are also stray eddy losses in the conductor that are caused by the magnetic flux. The resistive losses in the windings mean that as the loading on the transformer increases, the losses also increase, by approximately the square of the load. This impact is visible in Figure 2 which shows the no-load losses and load losses described over loading points from 0 to 100 per cent of rated capacity transformer loading. Peak efficiency of the transformer occurs at the point where no-load losses are equal to load losses, and this is always less than the rated nameplate capacity of the transformer.

In addition to the losses in the core and the winding of a transformer, certain transformers could have other sources of losses if they incorporate active cooling systems engaged while the transformer is operating. Active cooling systems include pumps and/or fans that operate when the transformer gets above a certain temperature. The energy used by these active cooling systems is considered an operating loss of the transformer.

Figure 2. Example of the relationship between transformer losses and efficiency



A transformer can be made more energy-efficient by improving the materials of construction (e.g., better-quality core steel or winding material) and by modifying the geometric configuration of the core and winding assemblies. Making a transformer more energy efficient (i.e., reducing electrical losses) is often a trade-off between more expensive, lower-loss materials and designs, and the value a customer attaches to those losses. For a given efficiency level, the no-load and load losses are generally inversely related: reducing one usually increases the other, as shown in Table 1. The table shows five approaches to reducing no-load losses, one of which is a material-substitution option and four are transformer-design options, and five approaches to reducing load losses.

Table 1. Loss-reduction interventions for transformers

| Goal | Approach | No-load (core) losses | Load (winding) losses | Effect on price |
|---|---|---|---|---|
| Decrease no-load losses | 1. Use lower-loss core materials | Lower | No change | Higher |
| | 2. Use better core construction techniques | Lower | No change | Higher |
| | 3. Decrease flux density by increasing core cross-sectional area | Lower | Higher | Higher |
| | 4. Decrease flux density by decreasing volts/turn | Lower | Higher | Higher |
| | 5. Decrease flux path length by decreasing conductor cross-sectional area | Lower | Higher | Lower |
| Decrease load losses | 1. Use lower-loss conductor materials | No change/ lower | Lower | Higher |
| | 2. Decrease current density by increasing conductor cross-sectional area | Higher | Lower | Higher |
| | 3. Decrease current path length by decreasing core cross-sectional area | Higher | Lower | Lower |
| | Decrease current path length by increasing volts/turn | Higher | Lower | Lower |
| | 4. Reduce core cross-section by increasing flux density through better core steels, reducing conductor length | Higher/ no change | Lower | Higher |

### *Options for decreasing no-load losses*

Each of the approaches to reducing no-load losses shown in Table 1 are discussed briefly below:

1. The use of lower-loss material to construct the core of the transformer will decrease the no-load losses, and very often it will have no impact on load losses. This can include, for example, using a laser-scribed thinner lamination of silicon steel in place of a standard one, or using amorphous material in the core instead of silicon steel. In general, however, substituting with a lower-loss core material will result in higher manufacturing costs. Over the last 50 years, considerable advances have been made in the materials used for transformer cores offering lower watts of loss per unit magnetic flux.

2. The use of better core-construction techniques can also reduce no-load losses as a result of how the joints between the metal laminations are formed. These techniques can include, for example, using a distributed gap in a wound core, or a step-lap core. These solutions, however, involve the use of sophisticated core-manufacturing equipment that may, in turn, lead to an increase in price.

3. Lowering the magnetic flux density by making the cross-sectional area of the core larger is also an option available to transformer designers. However, by increasing the size of the core, the length of the windings also increases, and thus resistive losses will increase. The overall impact on price is higher because more material is used in the transformer, in both the core and the coil, which also makes the transformer larger and heavier[4].

4. Lowering the magnetic flux density by decreasing the volts per turn involves maintaining the same turns ratio of primary to secondary but having more of each. This design approach results in longer windings, which will tend to increase the load losses. The impact on price tends to be higher on account of the increased material being used in the design.

5. Decreasing the distance of the magnetic flux has to travel by reducing the wire size will also reduce no-load losses; however, it tends to increase load losses because the current density per unit cross-sectional area of the conductor increases. This design option tends to lower the price of the transformer because it reduces the conductor material used in the design.

***Options for decreasing load losses***

Five approaches are outlined in Table 1 as techniques for decreasing load losses. For these design options, one is a material-substitution option and the other four are design techniques. Each of these options is discussed briefly below:

1. The use of lower-loss conductor materials—specifically, using copper instead of aluminium windings—will decrease the winding losses and would either have no impact or reduce no-load losses by improving the flux linking, allowing a designer to use a slightly smaller core. However, depending on material prices, this approach can lead to an increase in price.

2. Load losses can be decreased by lowering the current density in the conductor through an increase in the cross-sectional area. This option of using a larger-gauge conductor will reduce load losses but will also tend to increase no-load losses as the core must be made larger for the additional conductor. This design option also tends to increase price because more material is used in the transformer.

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[4] The weight of a transformer can have an impact on installation. For example, a pole-mounted installation may be rated for a specific weight, and in certain situations, it may be replaced by a more efficient transformer that is heavier, requiring modifications to the installation site thereby increasing costs.

3. Load losses can also be decreased by reducing the current path length through a reduction in the cross-sectional area of the core. By having a smaller core, the transformer becomes more compact, and winding lengths can be reduced, lowering resistive losses in the conductor. This will, however, tend to increase the losses in the core, as the magnetic flux intensity increases per unit area. Overall, this design option would tend to reduce the price, as there is less physical material being incorporated into the finished transformer design.

4. Load losses can also be reduced by proportionally reducing the length of conductor used in both windings, so as to keep the same turns ratio. This design option will tend to increase the volts per turn of the transformer, which (within the same insulation class) will decrease conductor losses but tend to increase losses in the core. As with design option 3, this approach would also tend to result in a lower price as there is less material incorporated into the finished product.

5. Increasing flux density (achieved through the use of better materials), can result in a smaller-diameter core with lower load losses due to smaller-diameter windings. This would increase no-load loss in terms of watts per kilogram, but the weight of core would be less and could also reduce core losses.

### ***Additional considerations***

All of the above provides information on the engineering behind how to make an efficient transformer designed for a given load factor, but the biggest impact on actual performance in the field will be determined by how well the transformer design matches the pattern of the load it experiences.

This is because, as discussed earlier and shown in Figure 2, the core losses are constant regardless of the load, but the winding losses increase with the square of the load. Thus, winding losses can be very high relative to the core losses during peak times.

This means that, for installations that have only sporadic loading such as those installed in rural areas or newly electrified areas, the core losses which are constant and on consistently will be more important. Any short peaks caused by small loads on the transformer will be less important. Generally, rural transformers are designed to minimise core losses rather than winding losses.

The situation in urban areas is different. Here, due to the higher number of connections, a transformer is likely to be heavily loaded for longer periods of time, therefore reducing the winding losses is given priority over reducing the core losses. Therefore, transformers designed for use in urban areas (with high loading for long periods of time) will tend to be designed with a preference for lower winding losses.

As shown in Table 1, it is difficult to improve transformer performance in both the core and coil simultaneously because, in general, minimising one factor generally causes the other one to increase. For example, increasing the core size will lower core losses by having a lower magnetic flux intensity, however it will also increase losses in the winding because the winding will have to be larger (longer) to accommodate the larger core. These relationships between core and coil losses are non-linear, and thus can change the relative marginal cost of reducing either iron or copper losses, as one is traded off against the other.

Another design aspect to keep in mind is that where high peak loads are expected but which may only be on occasion and for short periods, is to use ester cooling fluid in the transformer which can tolerate higher temperature than mineral oil. Such designs cope well with high loads in that the insulation in the windings does not deteriorate as rapidly, and if the peaks are high and not too frequent, the savings in core losses from the smaller kVA rating used could outweigh the high winding losses caused by short duration peaks when the load exceeds the nominal rating.

For example, instead of installing a 1,000 kVA transformer to accommodate an occasional peak a few times a year for a short period, but then having higher core losses from the larger transformer for 40 years, the utility could install a 630kVA transformer with ester coolant which could cope with short peak load occurrences of over 900kVA without any physical deterioration. This approach would allow physically smaller and less expensive transformers to be used in such installations, as well as reducing energy consumption from the higher core losses associated with larger transformer ratings.

In practice, a combination of the above options is used by transformer designers to meet the desired energy performance level at the minimum initial cost, depending on the relative material costs prevailing at the time.

More information on energy-efficient transformers and losses can also be accessed in the U4E policy guide “Accelerating the global adoption of energy-efficient transformers”[5].

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[5] The policy guide can be accessed here: https://united4efficiency.org/resources/accelerating-global-adoption-energy-efficient-transformers/

# 4 Loss Evaluation

This section provides an overview of the IEC TS 60076-20:2017 Annex A methodology for developing the loss evaluation factors, A and B. The objective in offering this overview is to facilitate and encourage transformer procurement officers to apply this methodology when issuing and evaluating tenders for transmission and distribution transformers.

As the calculated value of these loss evaluation factors increase, they will result in a decrease in the losses and usually an increase in the cost, size and weight of the transformer. The capitalisation values represent the avoided costs associated with the marginal cost of electricity due to the no-load and load losses saved.

The formula provided by the IEC for TCO is given in Annex A, equation A.1 and includes the forecast cost of energy for each year of the transformer's service life and the projected losses during this period, and it discounts those future costs to today's money using the appropriate discount rate. The equation is written to include both the losses and any energy consumption associated with active cooling system, if it is used:

$$\mathrm{TCO} = IC + A \times (P_0 + P_{C0}) + B \times (P_k + P_{CS} - P_{C0}) \qquad \text{Equation. A.1}$$

where:

$IC$ is the initial cost of the transformer; this cost may include installation costs such as foundation and erection costs (requires a more sophisticated evaluation);

$P_0$ is the no-load loss (kW) measured at the rated voltage and rated frequency, on the rated tap;

$P_k$ is the load loss (kW) due to the load, measured at the rated current and rated frequency on the rated tap at a reference temperature;

$P_{CS}$ is the total cooling power (kW) needed for operation at the rated power (including three winding operation if any) (note: this variable is set to zero for passively cooled transformer designs);

$P_{C0}$ is the cooling power (kW) needed for no-load operation (note: this variable is set to zero for passively cooled transformer designs);

$A$ is the cost of capitalisation of no-load losses in cost per kW;

$B$ is the cost of capitalisation of the losses due to load in cost per kW.

The IEC notes that if different transformer technologies are used, additional differences related to installation costs may also need be considered.

In the following the derivation of the A and B factor are explained. This guide is, as mentioned, complemented by a Microsoft Excel tool which shows how to derive the A and B factors, and calculate the TCO.

## 4.1 Derivation of the A-factor (valuation of future core losses)

The A-factor is the valuation (capitalisation) of the future no-load losses in cost per kW. As discussed in Chapter 2, no-load losses (and any associated cooling losses for actively cooled transformers) are present whenever the transformer is energized. Thus, the A-factor is calculated as the cost of energy multiplied by the operating time divided by the full life expectancy of the transformer, as shown in equation A.2:

$$A = \sum_{j=1}^{n} \frac{O_{0j} \times C_j}{(1+i_j)^j} \qquad \text{Equation (A.2)}$$

where:

$O_{0j}$ is the operating time of the transformer at year j in hours (h);

$C_j$ is the valorisation of the energy at year j in cost per Wh if losses are expressed in W;

$i_j$ is the real discount rate at year j in per unit;

$n$ is the life expectancy of the transformer in years.

The IEC notes that discount rates can be expressed in either real terms (excluding inflation) or nominal terms (including inflation). Both approaches will lead to the same result, provided that the associated cash flows are also expressed in similar terms. The IEC uses real discount rates because it simplifies the calculations since it assumes costs increase at the rate of inflation. Thus, all discount rates used in the analysis of this guide and in- the associated Excel spreadsheet model are real.

The IEC offers a simplified calculation of the A-factor, if the discount rate is considered constant and the cost of energy (in real terms) is equal to that halfway through the service life of the transformer, then assuming the transformer is energized for a whole year, the equation A.2 can be simplified as shown below:

$$A = 8760 \times C_{n/2} \times \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \qquad \text{Equation (A.3)}$$

where:

$C_{n/2}$ is the evaluation of the energy at mid-life of the transformer in cost per kWh if losses are expressed in kW;

$i$ is the discount rate fixed over the whole life of transformer (n years);

$n$ is the useful economic life of the transformer in years, which in the past has been close to the transformer's physical life expectancy (usually 30 to 50 years).

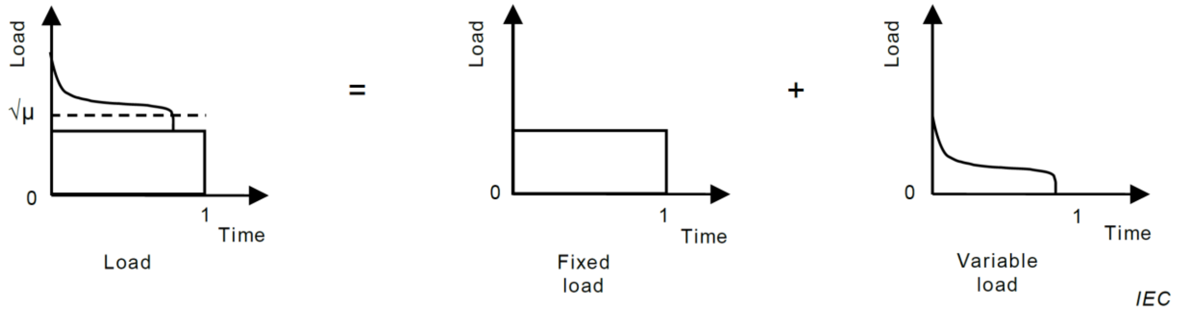
The IEC notes that the use of $C_{n/2}$ is an approximation and overvalues the losses somewhat, but it is deemed by the IEC to be acceptable in the context of other uncertainties.

## 4.2 Derivation of the B-factor (valuation of future coil losses)

The “B-factor” represents the capitalisation value of the load losses of the transformer. To determine this value accurately, information is needed about the load profile that the transformer will experience during its service life.

Transformer loading is usually divided into two components: (1) a fixed load that is present year-round and (2) a variable load that fluctuates with time depending on customer demand for electricity. Figure 3 illustrates these two component parts of transformer loading.

Figure 3. Transformer Load Profile Component Parts: Fixed and Variable Loading (IEC, 2017)



One of the critical inputs to the B-factor calculation is the average load loss factor ($\mu$) which is calculated as the square of the root mean square value of the instantaneous load factors by the following equation:

$$\mu = \frac{1}{T}\int_{O}^{T}(k(t))^2 dt \qquad \text{Equation (A.4)}$$

where:

*T* is equal to one year in the same units of time as the load factor k(t); thus if k(t) is defined in hours, then T is 8760 hours, or if k(t) is defined in minutes, then T is 525,600 minutes; and

*k(t)* is the load factor as a function of time, combining both the fixed load and variable load shown in Figure 2.

The load losses capitalisation cost is then calculated as the sum of the two load factors (fixed and variable) multiplied by the cost of energy and corrected by the increase in the load and the increase in the transformer installed base. The following equation presents the overall equation for calculating the B-factor, where the losses are split into two parts – one fixed and one variable – with each one weighted by its appropriate time base utilisation:

$$B = \sum_{j=1}^{n} \frac{\mu \times c_j \times (O_{aj} \times T_{aj} + O_{fj} \times T_{fj})}{(1+i_j)^j} \left(\frac{1+C_{\mu j}}{1+C_{aj}}\right)^{2j} \qquad \text{Equation (A.5)}$$

where:

$\mu$ is the average load loss factor defined above in Equation A.4;

$c_j$ is the total cost of the energy in year j in cost per watt-hour if units are expressed in watts, or in cost of kilowatt-hour if units are expressed in kilowatts;

$i_j$ is the discount rate in year j;

$O_{aj}$ is the operating time that the transformer experiences variable loading in year j, and is usually expressed in hours;

$O_{fj}$ is the operating time that the transformer experiences the fixed loading in year j, and is usually expressed in hours; this value is normally 8760 hours if the transformer is operated year round;

$T_{aj}$ is the share of the variable load in the total load loss factor in year j;

$T_{fj}$ is the share of the fixed load in the total load loss factor in year j; and it should be noted that $T_{aj} + T_{fj} = 1$, meaning that the shares of variable and fixed load as proportions of the total load loss sum to one;

$n$ is the life expectancy of the transformer in years;

$C_{\mu j}$ is the rate of load loss factor increase at year j;

$C_{aj}$ is the rate of the installed power increase at year j.

For these last two terms, $C_{\mu j}$ *and* $C_{aj}$, the IEC notes that these terms are usually taken to equal zero, which corresponds to a situation where the average transformer loading is not expected to change. If this is not the case, then special care must be taken to avoid overloading the transformer in any given year, because if $C_{\mu j}$ *is greater than* $C_{aj}$, then the final factor is greater than one.

If the transformer is connected to the grid (i.e., is energized) all year, the cost of energy is considered constant and equal to the energy evaluation at the mid-life of the transformer, the usage of the transformer is assumed to be constant (i.e., invariant) during its service life, and the discount rate is held constant, then equation A.5 can be simplified to equation A.6:

$$B = \mu \times C_{n/2} \times (O_a \times T_a + 8760 \times T_f) \times \frac{\frac{(1+C_\mu)^2}{(1+i)\times(1+C_a)^2} \times \left[1 - \left(\frac{(1+C_\mu)^2}{(1+i)\times(1+C_a)^2}\right)^n\right]}{1 - \frac{(1+C_\mu)^2}{(1+i)\times(1+C_a)^2}}$$

Equation (A.6)

where:

$\mu$ is the average load loss factor defined above in Equation A.4;

$C_{n/2}$ is the valorisation of the energy at the mid-life of the transformer in cost per watt-hour if units are expressed in watts, or in cost of kilowatt-hour if units are expressed in kilowatts;

$i$ is the discount rate;

$O_a$ is the operating time of the transformer experiences variable loading, and is usually expressed in hours;

$O_f$ is the operating time that the transformer experiences fixed loading, and is usually expressed in hours; this value is normally 8760 hours if the transformer is operated year round;

$T_a$ is the share of the variable load in the total load loss factor;

$T_f$ is the share of the fixed load in the total load loss factor; and it should be noted that $T_a + T_f = 1$, meaning that the shares of variable and fixed load as proportions of the total load loss sum to one;

$n$ is the life expectancy of the transformer in years;

$C_\mu$ is the rate of load loss factor increase;

$C_a$ is the rate of the installed power increase.

Finally, as a further simplification, the IEC notes that if the load factors and load profile are assumed to remain constant in the future, then Equation A.6 can be simplified to Equation A.7:

$$B = \mu \times C_{n/2} \times (O_a \times T_a + 8760 \times T_f) \times \frac{1-\left(\frac{1}{1+i}\right)^n}{i} \qquad \text{Equation (A.7)}$$

where:

The variables and symbols in Equation A.7 are defined in Equations A.5 and A.6.

# 5 Total Cost of Ownership Including Carbon Factor

With the urgency to adopt policy measures that will reduce carbon emissions being heightened by the recent United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties 26 (COP26) in Glasgow, U4E developed a second calculation methodology in the spreadsheet model which represents a minor departure from the IEC standard TCO calculation methodology, but which is designed to reflect and embed the cost of carbon in the A- and B-factors. This departure is simply to add the value of carbon to the price of electricity so that it is accounted for in the TCO calculation.

The incremental increase in cost for electricity will vary with the carbon intensity of the electricity generated by the utility, and the projected change in the $CO_2$ emissions factor over time. By including the value of carbon in the electricity price, it ensures that utilities not only capture the total direct cost of ownership from an equipment and losses perspective, but also factor the value of the $CO_2$ emissions associated with those losses into the current purchasing decision.

The following section discusses the approach which underpins how to account for the value of carbon in the TCO calculation methodology.

## 5.1 Valuation of $CO_2$ emissions

A methodology is proposed in this section to set out how the price of carbon can be incorporated into the price of electricity that is then used to determine the A- and B-factors for the electric utility. It is understood that by adding the price of carbon to the calculation method, there will be an increase in the numerical values of both the A- and B-factors because these factors will now be taking into account the value of carbon which in many markets has not yet been done.

The methodology is based on two key inputs:

1) **Carbon emissions factor** – this is the average rate of carbon emissions per kilowatt hour emissions from the utility, given the current and future projected $CO_2$ emissions associated with the generation of electricity. The units on this metric are kilogrammes of $CO_2$ that are emitted divided by the kilowatt-hours of electricity produced.

2) **Price of carbon** – this is the cost per tonne of $CO_2$ emissions, set at a level either by national regulations, a national or regional carbon market, trading in off-sets or other policy decision in a given country. The price is given in a unit of currency per tonne of $CO_2$ emissions and is based on the World Bank's Carbon Pricing Dashboard.

The World Bank's Carbon Pricing Dashboard offers a comprehensive summary of the various carbon valuation initiatives in the world. Launched in May 2017, the Dashboard offers an online platform that presents current data existing and emerging carbon pricing initiatives around the world. The data is taken from other analyses and studies of national markets, and calculates to a global average of US$24.27/tonne of $CO_2$. More information about the Dashboard and access the latest data, can be found on the World Bank website at: https://carbonpricingdashboard.worldbank.org/map_data.

The valorisation of energy is the marginal cost of a kWh (not the average cost), and it reflects the marginal generation cost for producing electricity during peak times, such as from a hydroelectric facility or a natural gas turbine (see also Tab 2 of the excel spreadsheet for more detailed information). Both of these are generating assets that can be adjusted up and down as required to follow the load. Coal and nuclear power stations are not part of the valorisation of energy calculation because they are considered base load power plants and aren't used to follow load. The marginal cost of renewable resources is close to zero, whereas the marginal cost of natural gas supplied kWh will vary with the efficiency of the system.

If a utility had a carbon emissions factor of 0.400 kg $CO_2$/kWh and the price of carbon in their country was US$24.27/tonne (the simple average price of all the programmes captured in the Carbon Pricing Dashboard for 2021), then the calculation per kilowatt hour would be the following:

$$(0.400 \text{ kg } CO_2/\text{kWh}) \times (1 \text{ tonne}/1000 \text{ kg}) \times (24.27 \text{ USD/tonne}) = 0.0097 \text{ USD/kWh}$$

In this way, this new approach introduced by U4E enables the inclusion of the value of carbon into the TOC calculation. Less efficient transformer designs will have higher energy consumption, and thus will have higher carbon factors (i.e., costs in the TOC calculation). More efficient transformer designs will consume less energy and will have lower carbon factors in the TOC. Ultimately, less efficient models will reflect the higher cost of carbon emissions associated with the higher losses they will incur over their lifetime. As the world moves toward systems that will take into account carbon emissions to the global commons, this new metric will help to ensure utility planners and transformer specifiers can capture those costs and incorporate them into their purchasing decisions.

# 6 Conclusions

The approach of the total cost of ownership will help utilities to procure transformers that are more cost-effective to own and operate in their networks. This paper provides the methodology that IEC recommends for deriving the A- and B-factors which are used to assign value to the core and coil losses respectively.

When issuing a call for tenders, transformer customers should give their values of A and B in terms of the monetary value (for example, US$/kW) as this will enable the manufacturers to develop and offer the most economically optimal transformer designs, taking into account the value of future core and coil losses of each design in their network. During the tender evaluation process, the transformer procurement officer will evaluate each bid according to equation A.1 using the losses that are guaranteed in the transformer supplier’s bid.

$$TCO = Purchase\ Price + (A \times Watts_{No-Load\ Losses}) + (B \times Watts_{Load\ Losses})$$

In following this approach, the TCO calculation will ensure that the resultant design selected by the procurement officer reflects the unique economic situation and anticipated loading for that transformer purchase over its service life. By applying this formula, the procurement officer is helping to ensure that they are installing economically optimised units into their network, improving the financial position of the overall utility or business.

In response to the heightened urgency to adopt policy measures that will reduce carbon emissions highlighted at the UNFCCC COP26 in Glasgow in November 2021, U4E developed and is offering for consideration an innovation which adds a ‘carbon factor’ to the standard IEC TCO calculation methodology. This new factor is based on calculating a small incremental carbon supplement which is included with the price of electricity when calculating the A-and B-factors. By including this additional factor in the TCO equation, it ensures that utilities not only capture the total direct cost of ownership from an equipment and losses perspective, but also the value of the $CO_2$ emissions associated with those losses.

By incorporating total cost of ownership, including the carbon emissions factor, into purchasing decisions, utilities and other transformer consumers will be better able to understand the full life-cycle cost of the procurement choices being made. The cost of the losses of a transformer most often outweighs the initial capital cost, thus it is critical to take the running and the emissions costs into account, to ensure economically optimal choices are made.

# 7 References

IEC, 2017. Power Transformers – Part 20: Energy efficiency. Technical Specification, IEC TS 60076-20. Edition 1.0 2017-01.