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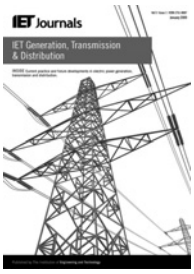

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Distribution transformer cost evaluation methodology incorporating environmental cost

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Abstract: As system investment and energy costs continue to increase, electric utilities are increasingly interested in installing energy-efficient transformers at their distribution networks. The cost evaluation of transformers is based on total owning cost (TOC) method that includes transformer purchasing price and cost of transformer losses. Similar to energy cost, greenhouse gas (GHG) emissions are also assigned a price by energy markets. That is why this study proposes an innovative distribution transformer cost evaluation methodology (DTCEM) by introducing the environmental cost (EC) into the conventional TOC method. This EC is due to GHG emissions associated with supplying transformer losses. The proposed method is applied for economic evaluation of distribution transformers for the Hellenic power system and the results are compared to the conventional TOC, indicating the importance of incorporating EC into transformer economic evaluation. A sensitivity analysis is carried out, investigating the impact of various parameters involved in the proposed DTCEM.

1 Introduction

Distribution transformers have a significant impact on the losses of a utility's transmission and distribution system [1, 2]. Based on a study conducted at the United States, distribution transformers contributed (a) about 40% of the losses for non-generating public utilities and (b) over 16% of the losses for investor-owned utilities [3]. European Copper Institute studies indicated that improving energy efficiency of existing European stock of transformers by 40% would result in about 22 TWh annual energy savings equivalent to annual reduction in greenhouse gas (GHG) emissions of about 9 million tonnes of CO_2 equivalent [4].

Energy efficient transformers have reduced total losses, that is, reduced load and no-load losses. Energy efficient transformers reduce energy consumption and consequently reduce the generation of electrical energy and GHG emissions. In deregulated electricity markets, as the price of electrical energy varies every hour, so does the cost of transformer losses. The seasonal load variations also increase the benefits associated with efficient transformers, particularly if the season of maximum load is coincident with the maximum energy prices.

As the system investment and energy costs continue to increase, electric utilities are more and more interested in installing energy-efficient transformers at their distribution networks. The transformer manufacturers have developed new manufacturing techniques and new types of core materials to provide cost-effective and energy-efficient transformers to the transformer users [1, 3, 5–8].

Energy-efficient transformers cost more but use less energy than low-efficiency transformers. The decision as to whether to purchase a low-cost, inefficient transformer or a more expensive, energy-efficient transformer is primarily an economic one. The common practice used by the electric utilities for determining the cost-effectiveness of distribution transformers is based on the total owning cost (TOC) method, where TOC is equal to the sum of transformer-purchasing price plus the cost of transformer losses throughout the transformer lifetime [3]. The TOC method for the electric utility can be found in [3, 9, 10]. The TOC method for the industrial and commercial transformer user can be found in [11, 12]. It is important to recognise that the perspective of the electric utility is different from the perspective of the industrial and commercial users of transformers. The transformer loss evaluation procedure for the electric utility involves understanding and assessing the total cost of generating, transmitting and distributing transformer losses, having complex formulas that need many input data [3, 9, 10]. On the other hand, the transformer loss evaluation procedure for industrial and commercial users requires an understanding and assessment of the electric rates they pay to the electric utility, having equations that need few input data [11, 12].

Nowadays the reduction of GHG emissions is becoming a topical issue due to the growing concern for global warming and climate change. To help developed countries achieve parts of their emission reduction commitments, Kyoto protocol includes three market-based mechanisms, one of them being emissions trading. Emissions trading scheme is a mechanism that allows participating developed countries to establish limits on pollution in a form of allowances [13]. These allowances can then be either used or traded in emissions markets. It means that similar to the cost of energy, GHG emissions are also assigned a price by the energy markets [14, 15]. The price of GHG emissions varies as a function of supply and demand. In the GHG emissions markets, those companies that do not use all their GHG emission credits can sell them to those companies that surpass them. Thus, companies who buy GHG emission credits should add this environmental cost to the cost of transformer ownership.

The innovations of GHG emissions trading and real running schemes are expanding worldwide. There are currently five GHG emissions trading schemes in force: the European Union (EU) GHG Emissions Trading scheme (which is the largest), the New South Wales GHG Reduction scheme (which is the oldest), the Chicago Climate Exchange (which was the first to encompass all GHGs), the Norwegian mandatory domestic emissions trading scheme and the Japanese Voluntary Emissions Trading scheme [16, 17]. A number of additional GHG emissions trading schemes presently in the pipeline are being designed or they have been implemented [16].

The need to undertake effective measures to protect the environment could be partially solved by improvements in energy efficiency of electrical equipment. Existing international policy instruments supporting energy efficiency of distribution transformers are summarised in Table 1 [18]. Efficiency standards and labels are effective tools that foster the development and dissemination of energy-efficient distribution transformers [18].

EPA Energy Star distribution transformer cost evaluation methodology (DTCEM) [3] is a software package that helps electric utilities to perform economic analysis in order to determine the cost-effectiveness and emission reduction potential of high-efficiency distribution transformers. Furthermore, another software tool developed by KEMA on behalf of European Copper Institute performs a life-cycle costing of transformer losses and calculates CO_2 emissions [19, 20]. However, a methodology to incorporate the environmental cost into the transformer TOC has not yet been developed.

This paper proposes an innovative DTCEM by introducing the environmental cost into the conventional TOC formula. This environmental cost is due to the cost to buy GHG emission credits because of the GHG

Table 1 Policy and measures supporting energy efficiency of distribution transformers in the world

Country	Labelling	BAT[a]	Efficiency standard		Test standard
			Mandatory	Voluntary	
Australia			√		
Canada	√		√ (dry-type)	√	
China			√		
EU				√ (single companies)	
India				√	√
Japan	√	√		√	
Mexico			√		√
Taiwan	√	√			
USA	√	√	√		√

[a] BAT = orientation towards best available technology.

emissions associated with supplying transformer losses throughout the transformer lifetime.

The proposed model is very important not only for energy management but also for electrical engineering because of the following main reasons:

1. It has been proven that optimal transformer capacity planning based on TOC minimisation offers significant cost reduction as compared to the conventional practice to plan the transformers with initial capacity to cover the power loading for the peak operation of the target year [21, 22]. Consequently, electrical engineers in the planning departments of electric utilities can minimise the TOC of the proposed DTCEM for optimal transformer capacity planning.

2. Engineers in the purchasing departments not only of electric utilities but also of industrial transformer users routinely use the TOC method for selecting distribution transformers [3, 4, 9–12, 23]. These engineers can use the proposed DTCEM for selecting distribution transformers, since by applying the proposed DTCEM they can determine the relative economic benefit of a high-purchasing-cost, low-loss, low-GHG transformer against one or more transformers with lower purchasing cost and higher losses and higher GHG emissions.

3. Electric utilities can benefit from the proposed DTCEM in order to increase power system efficiency, reduce energy costs and reduce GHG emissions by selecting and installing the most energy-efficient transformers.

4. The electricity regulatory framework has to consider the true cost of losses in the network so as to promote investments for energy-efficient transformers on the basis of the minimal TOC [24, 25]. The proposed DTCEM will be a valuable tool for engineers in regulatory authorities since it includes not only the cost of losses but also the environmental cost of losses.

5. Electrical engineers in the design departments of transformer manufacturers use TOC as an objective function when optimising transformer design [1, 26–28]. The usefulness of TOC objective function is also very important when new transformer materials are being introduced [29, 30]. The transformer manufacturers can use the proposed DTCEM to optimise the transformer design and provide the most economical transformer to bid and manufacture.

6. Using energy-efficient transformer has the benefit of reducing energy consumption and thus reduces the need to operate generators that dump heat and carbon dioxide into the atmosphere. Moreover, the energy-efficient transformer usually has lower TOC value in comparison with that of a less energy-efficient transformer [3]. Therefore an environment-friendly and energy-efficient distribution transformer is chosen not only due to environmental reasons but also due to economical reasons.

The proposed method is employed for the economic evaluation of distribution transformers for the Hellenic power system and the results are compared to the conventional TOC (without environmental cost) method, indicating the importance of incorporating the environmental cost into the transformer economic evaluation. A sensitivity analysis is carried out, investigating the impact of various parameters involved in the proposed DTCEM.

The paper is organised as follows. Section 2 presents the conventional TOC method. Section 3 describes the proposed DTCEM. Section 4 presents the application of the proposed DTCEM for the economic evaluation of distribution transformers for the Hellenic power system and analyses the results obtained by the proposed DTCEM in comparison with the conventional TOC method. Section 5 concludes the paper.

2 Conventional TOC technique without environmental cost

The most widely used method for the economic evaluation of distribution transformers is the TOC method, which is based on the following formula [3, 4]

$$\mathrm{TOC} = \mathrm{BP} + \mathrm{CL} \tag{1}$$

where TOC indicates the total owning cost (in \$), BP refers to transformer purchasing price (in \$) and CL is the cost (in \$) of transformer losses throughout the transformer lifetime. The cost of transformer losses CL is computed as follows

$$\mathrm{CL} = C_{\mathrm{NLL}} + C_{\mathrm{LL}} \tag{2}$$

where

$$C_{\mathrm{NLL}} = A \times \mathrm{NLL} \tag{3}$$

$$C_{\mathrm{LL}} = B \times \mathrm{LL} \tag{4}$$

where C_{NLL} is the cost of transformer no-load loss throughout the transformer lifetime (\$), C_{LL} is the cost of transformer load loss throughout the transformer lifetime (\$), A indicates the no-load loss factor (in \$/kW), NLL refers to transformer no-load loss (in kW), B indicates the load loss factor (in \$/kW) and LL refers to transformer rated load loss (in kW).

By combining (1)–(4), the conventional TOC formula is obtained

$$\mathrm{TOC} = \mathrm{BP} + A \times \mathrm{NLL} + B \times \mathrm{LL} \tag{5}$$

The factors A and B are computed according to (11) and (12), respectively.

According to the conventional distribution transformer cost evaluation method, among all transformer offers, the most cost-effective and energy-efficient transformer is the one that minimises the TOC of (5).

3 Proposed DTCEM

3.1 Overview

In this section, details of the proposed innovative DTCEM are illustrated, adopted for the evaluation of the transformer TOC so as to incorporate the environmental cost. The introduction of an additional cost component into the TOC formula is proposed by this work, representing the environmental costs that are associated with various types of GHG emissions resulting from the combustion of fossil fuels so as to compensate for transformer losses.

3.2 Proposed TOC technique incorporating environmental cost

The objective of this paper is to redefine the TOC method to properly incorporate all the aspects of the transformer life-cycle, evaluating not only the transformer losses but also the environmental cost. It is proposed to introduce an appropriate environmental cost parameter EC into the TOC formula (1), resulting into the following proposed $\mathrm{TOC_e}$ formula

$$\mathrm{TOC_e} = \mathrm{TOC} + \mathrm{EC} \tag{6}$$

where EC is the environmental cost (in \$) throughout the transformer lifetime that results because of transformer energy losses, which is computed as follows

$$\mathrm{EC} = \mathrm{EC_{NLL}} + \mathrm{EC_{LL}} \tag{7}$$

where

$$\mathrm{EC_{NLL}} = A_e \times \Delta P_{\mathrm{NLL}} \tag{8}$$

$$\mathrm{EC_{LL}} = B_e \times \Delta P_{\mathrm{LL}} \tag{9}$$

where $\mathrm{EC_{NLL}}$ is the environmental cost due to transformer no-load loss throughout the transformer lifetime (\$), $\mathrm{EC_{LL}}$ is the environmental cost due to transformer load loss throughout the transformer lifetime (\$), A_e is the no-load loss environmental factor (in \$/kW), ΔP_{NLL} is the no-load loss difference (in kW) between an evaluated transformer and a reference transformer, B_e is the load loss environmental factor (in \$/kW) and ΔP_{LL} is the rated load loss difference (in kW) between an evaluated transformer and a reference transformer. The importance of the reference transformer is highlighted in Section 3.4.2.

By combining (5)–(9), the proposed $\mathrm{TOC_e}$ formula is obtained

$$\begin{aligned}\mathrm{TOC_e} = \mathrm{BP} + A \times \mathrm{NLL} + B \times \mathrm{LL} + A_e \times \Delta P_{\mathrm{NLL}} \\ + B_e \times \Delta P_{\mathrm{LL}}\end{aligned} \tag{10}$$

In the context of environmental protection, EU countries have set GHG emission limits, and electric utilities that violate these limits have to pay GHG emission penalties or to buy GHG emission credits from other utilities [17]. This means that each electric utility has to assess this cost and to take care so as not to pay GHG emission penalties. This can be done by assessing the GHG emissions of its installed electrical equipment and specifying accordingly its new equipment. More specifically, in case of distribution transformers, the electric utility has to compute the reference transformer (see Section 3.4.2) for each power rating. When evaluating a transformer, it is important for the electric utility to compute the no-load loss difference between an evaluated transformer and a reference transformer, that is, the term ΔP_{NLL} using (25). The electric utility has to pay GHG emission penalties due to transformer no-load loss only if $\Delta P_{\mathrm{NLL}} > 0$. Similarly, the electric utility has to pay GHG emission penalties due to transformer load loss only if $\Delta P_{\mathrm{LL}} > 0$. That is why the terms ΔP_{NLL} and ΔP_{LL} are included in (10).

The factors A and B are computed according to (11) and (12), respectively. The factors A_e and B_e are computed according to (27) and (28), respectively. The values of ΔP_{NLL} and ΔP_{LL} are computed using (25) and (26), respectively.

This paper proposes that among all transformer offers, the most cost-effective and energy-efficient transformer is the one that minimises the $\mathrm{TOC_e}$ of (10). The flowchart of the proposed DTCEM is shown in Fig. 1.

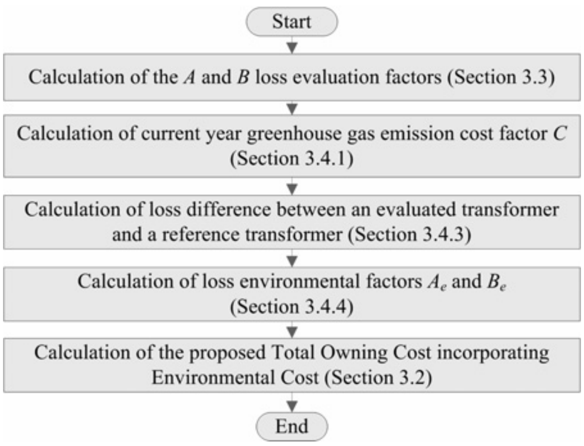

Figure 1 *Flowchart of the proposed DTCEM*

3.3 Calculation of loss evaluation factors A and B

In this paper, the A and B factors that are used in TOC formula (5) and in TOC_e formula (10) are computed as follows [31]

$$A = \frac{\text{LIC} + \text{LECN}}{\text{ET} \times \text{FCR} \times \text{IF}} \tag{11}$$

$$B = \frac{\text{LIC} \times \text{PRF}^2 \times \text{PUL}^2 + \text{LECL} \times \text{TLF}^2}{\text{ET} \times \text{FCR} \times \text{IF}} \tag{12}$$

where LIC is the levelised annual generation and transmission system investment cost (in \$/kW-yr), LECN is the levelised annual energy and operating cost of transformer no-load loss (in \$/kW-yr), ET is the efficiency of transmission, FCR is the fixed charge rate that represents the 'cost of ownership', IF is the increase factor (it represents the total money that the user must pay to acquire the transformer, including the purchase price, overhead, fee and tax), PRF is the peak responsibility factor that derives from the transformer load at the time of the power system peak load divided by the transformer peak load, PUL is the peak per unit transformer load that derives from the average of the annual peaks throughout the transformer lifetime divided by the transformer rated load loss, LECL is the levelised annual energy and operating cost of load loss (in \$/kW-yr) and TLF is the transformer loading factor.

The levelised costs LECN and LECL are computed as follows

$$\text{LECN} = \text{CRF} \times \text{HPY} \times \text{AF} \times \sum_{j=1}^{\text{BL}} \text{CYEC} \times \frac{(1+\text{EIR})^j}{(1+d)^j} \tag{13}$$

$$\text{LECL} = \text{CRF} \times \text{HPY} \times \sum_{j=1}^{\text{BL}} \text{CYEC} \times \frac{(1+\text{EIR})^j}{(1+d)^j} \tag{14}$$

where CRF is the capital recovery factor that is computed by (18), HPY indicates the hours of transformer operation per year (typically 8760 h), AF represents the transformer availability factor (i.e. the proportion of time that the transformer is predicted to be energised, which may be less than unity due to failures), BL is the number of years of transformer lifetime, EIR (in %) is the annual escalation rate of the energy cost (cost of electricity), d (in %) refers to the discount rate (interest rate) and CYEC refers to the current year energy cost (in \$/kWh). It should be noted that throughout this paper, the current year (or year 0) is defined as the year before the first year of transformer operation.

Since

$$\sum_{j=1}^{\text{BL}} \frac{(1+\text{EIR})^j}{(1+d)^j} = \left(\frac{1+\text{EIR}}{d-\text{EIR}}\right)\left[1 - \left(\frac{1+\text{EIR}}{1+d}\right)^{\text{BL}}\right] \tag{15}$$

(13) and (14) can be further simplified as follows

$$\text{LECN} = \text{CRF} \times \text{HPY} \times \text{AF} \times \text{CYEC} \times \left(\frac{1+\text{EIR}}{d-\text{EIR}}\right) \times \left[1 - \left(\frac{1+\text{EIR}}{1+d}\right)^{\text{BL}}\right] \tag{16}$$

$$\text{LECL} = \text{CRF} \times \text{HPY} \times \text{CYEC} \times \left(\frac{1+\text{EIR}}{d-\text{EIR}}\right) \times \left[1 - \left(\frac{1+\text{EIR}}{1+d}\right)^{\text{BL}}\right] \tag{17}$$

The capital recovery factor, CRF, is computed as follows

$$\text{CRF} = \frac{d \times (1+d)^{\text{BL}}}{(1+d)^{\text{BL}} - 1} \tag{18}$$

The peak per-unit load, PUL, derives from the following equation

$$\text{PUL} = \frac{\sum_{j=1}^{\text{BL}} \text{ITL}_{\text{TPL}} \times (1+\text{TPLIF})^j}{\text{BL}} \tag{19}$$

that can be simplified as follows

$$\text{PUL} = \frac{\text{ITL}_{\text{TPL}} \times (1+\text{TPLIF})[(1+\text{TPLIF})^{\text{BL}} - 1]}{\text{BL} \times \text{TPLIF}} \tag{20}$$

where ITL_{TPL} indicates the initial (year 0) transformer load as a percentage of transformer peak load and TPLIF indicates the transformer peak load annual incremental factor (in %). ITL_{TPL} and TPLIF are computed based on transformer load curve.

The transformer loading factor, TLF, is calculated by

$$\text{TLF} = \sqrt{\text{LF} \times \text{PUL}^2} \tag{21}$$

where LF refers to the loss factor that derives from the load factor l_f, that is, the mean transformer loading throughout its lifetime, represented as an equivalent percentage of its nominal power, according to the following equation [3]

$$\text{LF} = 0.15 l_\text{f} + 0.85 l_\text{f}^2 \tag{22}$$

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3.4 Calculation of environmental factors A_e and B_e

In order to calculate the environmental factors A_e and B_e, the following steps should be followed: (i) calculation of the current year GHG emission cost factor C, (ii) computation of loss difference between an evaluated transformer and a reference transformer and (iii) calculation of the environmental factors A_e and B_e.

3.4.1 Calculation of current year GHG emission cost factor C: The current year GHG emission cost factor C (in \$/MWh) is computed as follows

$$C = C_{cy} \times \sum_{i=1}^{N} f_i \times e_i \tag{23}$$

where C_{cy} is the current year GHG emission cost value in $\$/t_{CO_2}$, where t_{CO_2} denotes the tonnes of equivalent CO2 emissions, e_i is the emission factor (in t_{CO_2}/MWh) for fuel type i, f_i is fraction (in %) of end-use electricity coming from fuel i and N is the number of fuels in the electricity mix.

In particular, three greenhouse gases: (i) carbon dioxide (CO_2), (ii) methane (CH_4) and (iii) nitrous oxide (N_2O) are considered [32]. According to the type of fuel (i.e. coal, diesel, natural gas, wind, nuclear, propane, solar, biomass, geothermal, etc.), GHG emissions are converted into equivalent CO_2 emissions (expressed in t_{CO_2}) in terms of their global warming potential. In order to estimate the emission factor of each fuel type, the following equation is used

$$e_i = (e_{CO_2,i} + e_{CH_4,i} \times 21 + e_{N_2O,i} \times 310) \times \frac{0.0036}{n_i \times (1 - \lambda_i)} \tag{24}$$

where e_i is the emission factor (in t_{CO_2}/MWh) for fuel type i, $e_{CO_2,i}$ is the CO_2 emission factor (in kg/GJ) for fuel i, $e_{CH_4,i}$ is the CH_4 emission factor (in kg/GJ) for fuel i, $e_{N_2O,i}$ is the N_2O emission factor (in kg/GJ) for fuel i, n_i is the conversion efficiency (in %) for fuel i and λ_i represents the fraction (in %) of electricity lost in transmission and distribution for fuel i. The factor 0.0036 in (24) is used so as to convert kg/GJ into t_{CO_2}/MWh. It can be seen from (24) that CH_4 and N_2O emissions are converted into equivalent CO_2 emissions by multiplying their emission factors with 21 and 310, respectively, since CH_4 is 21 times more powerful GHG than CO_2 and N_2O is 310 times more powerful than CO_2 [33].

3.4.2 Reference transformer: The definition of the reference transformer, that is, a transformer with reference no-load loss $\mathrm{NLL_r}$ (in kW) and reference rated load loss $\mathrm{LL_r}$ (in kW) is important because the $\mathrm{NLL_r}$ and $\mathrm{LL_r}$ are required for the computation of ΔP_{NLL} and ΔP_{LL} [(25) and (26)] that are involved in the proposed $\mathrm{TOC_e}$ formula (10). The selection of the reference transformer losses $\mathrm{NLL_r}$ and $\mathrm{LL_r}$ is based on the contribution of the transformer losses to the total GHG emissions of the power system of the considered electric utility and their responsibility to the violation of the maximum GHG emission values imposed by international standards or protocols concerning each country.

3.4.3 Loss difference between an evaluated transformer and a reference transformer: The no-load loss of the evaluated transformer, NLL (in kW), and the rated load loss of the evaluated transformer, LL (in kW), are given by the transformer manufacturer. On the other hand, the no-load loss of the reference transformer, $\mathrm{NLL_r}$ (in kW), and the rated load loss of the reference transformer, $\mathrm{LL_r}$ (in kW), are defined by the electric utility.

The no-load loss difference between an evaluated transformer and a reference transformer, ΔP_{NLL} (in kW), and the rated load loss difference between an evaluated transformer and a reference transformer, ΔP_{LL} (in kW), are computed as follows

$$\Delta P_{\mathrm{NLL}} = \mathrm{NLL} - \mathrm{NLL_r} \tag{25}$$

$$\Delta P_{\mathrm{LL}} = \mathrm{LL} - \mathrm{LL_r} \tag{26}$$

It should be noted that if $\Delta P_{\mathrm{NLL}} > 0$, that is, if the no-load loss of the evaluated transformer is greater than the no-load loss of the reference transformer, then, since A_e is always positive as implied by (27), the quantity $A_e \times \Delta P_{\mathrm{NLL}}$ that is added to the $\mathrm{TOC_e}$ formula of (10) is positive, thus partially affecting negatively the decision to purchase from the considered transformer manufacturer. On the other hand, if $\Delta P_{\mathrm{NLL}} < 0$, that is, if the no-load loss of the evaluated transformer is smaller than the no-load loss of the reference transformer, then this partially affects positively the purchasing decision. Similar conclusions can be drawn if the quantity $B_e \times \Delta P_{\mathrm{LL}}$ takes positive or negative values.

3.4.4 Calculation of environmental factors A_e and B_e: The no-load loss environmental factor A_e and the load loss environmental factor B_e are computed as follows

$$A_e = \frac{\mathrm{LECN_e}}{\mathrm{ET} \times \mathrm{FCR} \times \mathrm{IF}} \tag{27}$$

$$B_e = \frac{\mathrm{LECL_e} \times \mathrm{TLF}^2}{\mathrm{ET} \times \mathrm{FCR} \times \mathrm{IF}} \tag{28}$$

where $\mathrm{LECN_e}$ is the levelised annual environmental cost of no-load loss (in \$/kW-yr) and $\mathrm{LECL_e}$ is the levelised annual environmental cost of load loss (in \$/kW-yr) that are computed as follows

$$\mathrm{LECN_e} = \mathrm{CRF} \times \mathrm{HPY} \times \mathrm{AF} \times \sum_{j=1}^{\mathrm{BL}} C \times \frac{(1+\mathrm{EIR_e})^j}{(1+d)^j} \tag{29}$$

$$\mathrm{LECL_e} = \mathrm{CRF} \times \mathrm{HPY} \times \sum_{j=1}^{\mathrm{BL}} C \times \frac{(1+\mathrm{EIR}_e)^j}{(1+d)^j} \tag{30}$$

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where $\mathrm{EIR_e}$ is the annual escalation rate (in %) of the current year GHG emission cost C_{cy}. Equations (29) and (30) can be further simplified as follows

$$\mathrm{LECN_e} = \mathrm{CRF} \times \mathrm{HPY} \times \mathrm{AF} \times C \times \left(\frac{1+\mathrm{EIR_e}}{d-\mathrm{EIR_e}}\right) \times \left[1-\left(\frac{1+\mathrm{EIR_e}}{1+d}\right)^{\mathrm{BL}}\right] \tag{31}$$

$$\mathrm{LECL_e} = \mathrm{CRF} \times \mathrm{HPY} \times C \times \left(\frac{1+\mathrm{EIR_e}}{d-\mathrm{EIR_e}}\right) \times \left[1-\left(\frac{1+\mathrm{EIR_e}}{1+d}\right)^{\mathrm{BL}}\right] \tag{32}$$

4 Results and discussion

4.1 Overview

The proposed DTCEM is applied for the economic evaluation of the three different transformer models of Table 2 (model 1 to model 3 is denoted as D1 to D3). These models correspond to three-phase oil-immersed distribution transformer, 50 Hz, 1000 kVA. The typical distribution transformer loading profile of the Hellenic distribution system of Fig. 2 is used, that is, domestic profile (type of load). The following subjects are analysed

1. In Section 4.2, the economic evaluation of the models of Table 2 is implemented using the conventional TOC method. The transformer loading profile is that of the domestic load of Fig. 2.

2. In Section 4.3, the economic evaluation of the models of Table 2 is implemented using the proposed DTCEM.

3. In Section 4.4, a sensitivity analysis is carried out, investigating the impact of various parameters involved in the proposed DTCEM.

4. In Section 4.5, the proposed DTCEM is applied for the optimal design of an actual distribution transformer.

Table 2 Three different transformer models for the 1000 kVA distribution transformer

Transformer model	CENELEC category [34]	Bid price, $	No-load loss, kW	Load loss, kW
D1	BA′	35 251	1.7	13.0
D2	AB′	36 654	1.4	10.5
D3	CC′	39 974	1.1	9.5

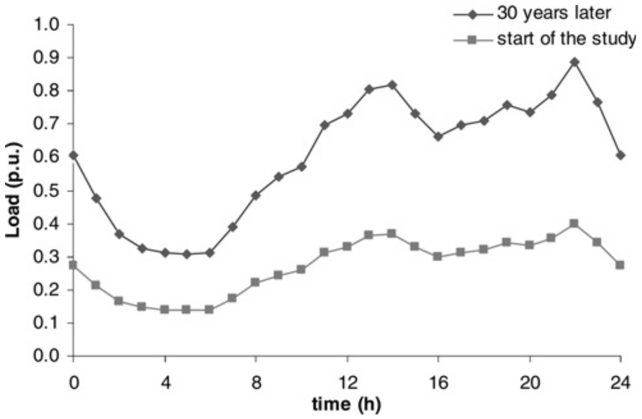

Figure 2 *Typical daily transformer loading profile of the Hellenic distribution system*

4.2 Evaluation without incorporating environmental cost

It is supposed that the transformer loading profile is that of the domestic load of the Hellenic interconnected power system of Fig. 2 with the characteristics shown in Table 3. In order to compute the A and B loss evaluation factors, the 14 input parameters of Table 3 are required. Based on the input data of Table 3 and using the equations with numbers shown in the calculations part of Table 3, it is found that $A = \$13391.1/\mathrm{kW}$ and $B = \$2093.3/\mathrm{kW}$.

The TOC (without the environmental cost) results for the three different transformer models of Table 2 are presented in Table 4. These results are based on the A and B factors of Table 3, the bid price as well as the losses of each transformer model of Table 2, implementing TOC formula of (5). Table 4 shows that despite the fact that transformer design D1 is the cheapest one concerning the bid price, the transformer model D1 is the worst investment in long-term, since it has the highest TOC. In contrast, it is clear that transformer model D3 is the best investment in long-term, since it has the lowest TOC. Although the bid price of D1 is 11.8% cheaper than the bid price of D3, the TOC of D1 is 14.3% more expensive than the TOC of D3 throughout the 30 years of transformer lifetime. The above-mentioned difference in the TOC of D1 and D3 is attributed to the difference in the cost of losses of D1 and D3, as Table 4 shows. That is why it is very important to incorporate the cost of losses into the economic evaluation of distribution transformers.

4.3 Evaluation incorporating environmental cost

In this section, the economic evaluation of the models of Table 2 is implemented using the proposed DTCEM, that is, the $\mathrm{TOC_e}$ formula of (10) that incorporates the environmental cost. Table 5 presents the required input data values so as to compute the current year GHG emission cost factor C of the Hellenic interconnected

Table 3 Calculation of *A* and *B* loss evaluation factors

Input data			Computed parameters			
Symbol	Value	Unit	Symbol	Value	Unit	Equation
AF	0.97	–	CRF	0.0931	–	(18)
HPY	8760	h/yr	LF	0.4924	–	(22)
BL	30	yr	PUL	0.60	–	(20)
CYEC	0.084	\$/kWh	TLF	0.4210	–	(21)
EIR	0.027	per year	LECN	949.75	\$/kW-yr	(16)
FCR	0.0931	\$/\$/yr	LECL	979.12	\$/kW-yr	(17)
d	0.085	per year				
ITL_{TPL}	0.40	–				
TPLIF	0.025	–				
PRF	0.369	–				
l_f	0.678	–				
IF	1	–				
ET	0.95	–	A	13391.1	\$/kW	(11)
LIC	234	\$/kW-yr	B	2093.3	\$/kW	(12)

power system in which the domestic load of Fig. 2 is connected. It is considered that the current year GHG emission cost value is $C_{cy} = \$50/t_{CO_2}$. As can be seen from Table 5, $C = \$44.66$/MWh.

Table 6 presents the required input data values so as to compute the environmental factors A_e and B_e for the domestic load of the Hellenic interconnected power system. As can be seen from Table 6, $A_e = \$6261.3$/kW and $B_e = \$1144.3$/kW. Table 7 presents the TOC$_e$ results for the three different transformer models of Table 2, with the incorporation of the environmental cost, based on the values of the A and B factors of Table 3 and the values of the A_e and B_e factors of Table 6. As reference transformer, the transformer with loss category AC′ according to

Table 4 Calculation of TOC values without environmental cost

Parameter	Model			Remarks
	D1	D2	D3	
BP, \$	35 251	36 654	39 974	Table 2
NLL, kW	1.7	1.4	1.1	Table 2
LL, kW	13	10.5	9.5	Table 2
C_{NLL}, \$	22 765	18 748	14 730	Equation (3)
C_{LL}, \$	27 213	21 980	19 887	Equation (4)
CL, \$	49 978	40 728	34 617	Equation (2)
TOC, \$	85 229	77 382	74 591	Equation (5)
BP/TOC, %	41.4	47.4	53.6	
CL/TOC, %	58.6	52.6	46.4	

Table 5 Calculation of the current year GHG emission cost factor *C*

Fuel type	Coal	Diesel	Hydro	Natural gas	Wind
Indicator of fuel type, i	1	2	3	4	5
f_i, %	69.77	7.6	7.6	15	0.03
$e_{CO_2,i}$, kg/GJ [32]	94.6	74.1	0	56.1	0
$e_{CH_4,i}$, kg/GJ [32]	0.002	0.002	0	0.003	0
$e_{N_2O,i}$, kg/GJ [32]	0.003	0.002	0	0.001	0
n_i, % [32]	35	30	100	45	100
λ_i, %	8	8	8	8	8
e_i (t_{CO_2}/MWh) (24)	1.069	0.975	0.000	0.491	0.000
C, \$/MWh (25)	44.66				

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Table 6 Calculation of A_e and B_e environmental factors

Input data			Computed parameters			
Symbol	Value	Unit	Symbol	Value	Unit	Equation
AF	0.97	–	CRF	0.0931	–	(18)
HPY	8760	h/yr	LF	0.4924	–	(22)
BL	30	yr	PUL	0.60	–	(20)
C	44.66	\$/MWh	TLF	0.4210	–	(21)
EIRe	0.035	per year	$LECN_e$	553.49	\$/kW-yr	(31)
FCR	0.0931	\$/\$/yr	$LECL_e$	570.60	\$/kW-yr	(32)
d	0.085	per year				
ITL_{TPL}	0.40	–				
TPLIF	0.025	–				
PRF	0.369	–				
l_f	0.678	–				
IF	1	–	A_e	6261.3	\$/kW	(27)
ET	0.95	–	B_e	1144.3	\$/kW	(28)

Table 7 Calculation of TOC_e values incorporating environmental cost

Parameter	Model			Remarks
	D1	D2	D3	
BP, \$	35 251	36 654	39 974	Table 2
NLL, kW	1.7	1.4	1.1	Table 2
LL, kW	13	10.5	9.5	Table 2
ΔP_{NLL}, kW	0.6	0.3	0.0	Equation (25)
ΔP_{LL}, kW	2.5	0.0	-1.0	Equation (26)
C_{NLL}, \$	22 765	18 748	14 730	Equation (3)
C_{LL}, \$	27 213	21 980	19 887	Equation (4)
C_L, \$	49 978	40 728	34 617	Equation (2)
TOC, \$	85 229	77 382	74 591	Equation (5)
EC_{NLL}, \$	3757	1878	0	Equation (8)
EC_{LL}, \$	2861	0	-1144	Equation (9)
EC, \$	6618	1878	-1144	Equation (7)
TOC_e, \$	91 847	79 260	73 447	Equation (10)
BP/TOC_e, %	38.4	46.2	54.4	
CL/TOC_e, %	54.4	51.4	47.1	
EC/TOC_e, %	7.2	2.4	-1.6	
TOC/TOC_e, %	92.8	97.6	101.6	

CENELEC [34] is selected, which means that $NLL_r = 1.1$ kW and $LL_r = 10.5$ kW. Fig. 3 presents the TOC_e results of Table 7. Table 7 shows that the environmental cost due to transformer load loss is positive for D1 and negative for D3, and the ratio of the environmental cost over the TOC_e is +7.2% and −1.6% for D1 and D3, respectively. It can be concluded from Table 7 and Fig. 3 that the best investment is model D3 since it has the lowest TOC_e.

4.4 Sensitivity analysis

In the TOC economic analysis, it is helpful to determine how sensitive the TOC_e is to several parameters of concern so that proper consideration may be given to them in the decision process (distribution transformer cost evaluation process).

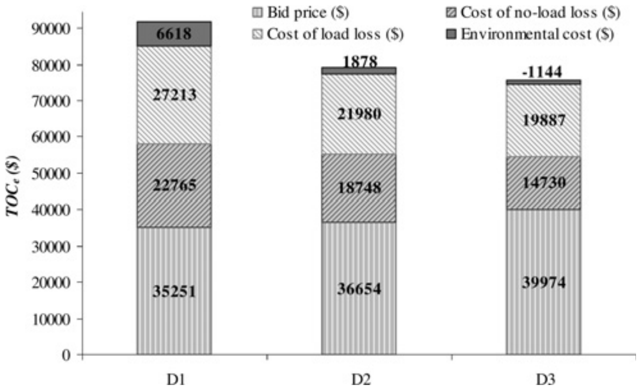

Figure 3 *Graphical representation of TOC_e results of Table 7*

The six parameters that have been selected are (i) the discount rate (d), (ii) the cost of electricity (CYEC), (iii) the levelised annual generation and transmission system investment cost (LIC), (iv) the current year GHG emission cost factor (C), (v) the number of years of transformer lifetime (BL) and (vi) the load factor (l_f). These parameters consist the most versatile factors in the equations yielding the A, B, A_e and B_e factors of the TOC_e calculation.

Before investigating the sensitivity of the above six parameters, a base case should be developed. The model D3 for the domestic load is considered as the base case, which means that the TOC_e of the base case is equal to \$73 447, as Table 7 shows. This base case corresponds to $d = 8.5\%$, CYEC = \$0.084/kWh, LIC = \$234/kW-yr, $C = \$44.66$/MWh, BL = 30 years and $l_f = 0.678$, as can be seen from Tables 3 and 5.

Fig. 4 presents the sensitivity parameter analysis results based on various parameter values. Each time one parameter is modified, while the other parameters are assumed to remain at their base case values. For example, by changing the cost of electricity (CYEC) by +10%, the TOC_e changes by +4.15% in comparison with the TOC_e of the base case. The slope of each curve of the sensitivity graph of Fig. 4 indicates the relative degree of sensitivity of the TOC_e to each parameter: the steeper the slope of a curve, the more sensitive the TOC_e is to the parameter [35]. Based on this, as can be observed from Fig. 4, the GHG emission factor (C) and the cost of installing transmission systems (LIC) have small impact on TOC_e. On the other hand, the discount rate (d), the cost of electricity (CYEC), the load factor (l_f) and the number of years of the transformer lifetime (BL) have large impact on TOC_e.

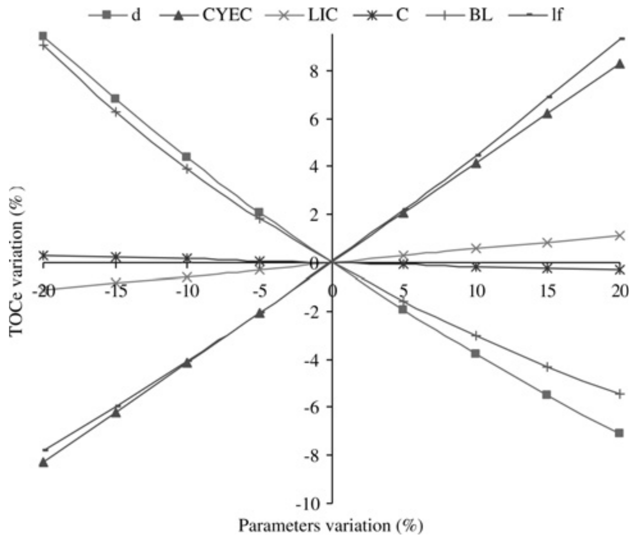

Figure 4 *Sensitivity graph of TOC_e to changes in each parameter*

4.5 Application to transformer design optimisation

The proposed DTCEM has been applied for the optimal design of an actual transformer with the following main specifications: three-phase distribution transformer, rated power 630 kVA, rated primary voltage 20 kV, rated secondary voltage 0.4 kV, rated frequency 50 Hz, vector group Dyn11, prescribed no-load loss 1.1 kW, prescribed load loss 8.9 kW and prescribed impedance 6%. The no-load loss, load loss and impedance tolerances are according to IEC 60076-1 international standard, that is, the maximum no-load loss is 1.265 kW, the maximum load loss is 10.235 kW, the maximum total loss is 11 kW, the minimum impedance is 5.4% and the maximum impedance is 6.6%. The loss factors involved in the calculation of TOC and TOC_e using (5) and (10), respectively, have the following values: $A = \$13391.1$/kW, $B = \$2093.3$/kW, $A_e = \$6261.3$/kW and $B_e = \$1144.3$/kW. The reference transformer has $\text{NLL}_r = 0.8$ kW and $\text{LL}_r = 6.75$ kW.

The above transformer design is optimised twice using an advanced recursive genetic algorithm – finite-element method [36], considering two different objective functions: (i) the minimisation of TOC and (ii) the minimisation of TOC_e. The optimisation results are presented in Table 8. Analysing the results of Table 8, the following conclusions are drawn:

- Although the D2 (design with minimum TOC_e as objective) has 7.6% higher bid price and 0.2% higher TOC, finally it has 1.2% lower TOC_e in comparison with the D1 (design with minimum TOC as objective). Consequently, if the objective is the minimum TOC_e, then the D2 has to be selected.

- The D2 has 6.7% lower no-load loss and 3.4% lower load loss in comparison with the D1. Consequently, the proposed DTCEM (minimum TOC_e as objective) helps to decrease transformer losses and increase transformer efficiency.

Table 8 Comparison of optimisation results using as objective function the minimisation of TOC and TOC_e

Parameter	Objective		Difference between D2 and D1, %
	Minimum TOC (D1 – design 1)	Minimum TOC_e (D2 – design 2)	
BP, \$	21 850	23 500	7.6
NLL, kW	1.05	0.98	−6.7
LL, kW	8.8	8.5	−3.4
TOC, \$	54331.70	54416.33	0.2
TOC_e, \$	58242.84	57545.89	−1.2

5 Conclusion

This paper proposes a novel DTCEM that takes into account the environmental cost associated with GHG emissions because of transformer energy losses. In particular, this paper introduces the incorporation of environmental cost into the conventional TOC formula, yielding the proposed TOC_e formula. The proposed DTCEM can be very useful for the electric utilities so as to select, among alternative transformer offers, the optimal distribution transformer that will minimise the TOC_e during the transformer lifetime. The introduction of the environmental cost is quite substantial, as it reinforces the optimal transformer choice, indicating considerable differences in the TOC_e values, compared to the values based on the conventional TOC formula. The proposed method was employed for the economic evaluation of distribution transformers for the Hellenic power system. Sensitivity analysis was conducted so as to investigate the impact of various parameters involved in the proposed DTCEM and the conclusion was that the discount rate, the cost of electricity, the load factor and the number of years of the transformer lifetime have large impact on TOC_e. The proposed DTCEM was also applied for the optimal design of an actual distribution transformer.

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