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Techno-Economic Modelling of Solar Photovoltaic (PV) Power Transformers in South Africa

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Abstract: The increasing demand for electricity in South Africa has led to a rise in the deployment of solar photovoltaic systems. The integration of these systems requires the installation of power transformers to convert the generated DC power into AC power that can be fed into the grid. However, the high cost of these transformers can hinder the widespread adoption of solar PV systems. Consequently, the primary objective of this work is to introduce a novel service-lifetime loss estimation method that acknowledges the unique requirements of transformers facilitating solar photovoltaic applications. In reality, these transformers are required to facilitate a sporadic energy source, which advocates for an appropriate method to assess the cost of their service-lifetime losses and total ownership cost. Thus far, the energy elements of classical coal-power generation are inadequate, and in conformity with operational and financial considerations of solar PVs, a novel method incorporating the outcomes of a transformer facilitating a solar PV plant is proposed. The proposed approach has been benchmarked with existing methods and the distinction between proposed and existing methods is highlighted. The study further proposes various regression models for estimating the purchase price for transformers specifically intended to exclusively serve in solar PV applications, which are not available in the current South African standards. The percentage errors between the conventional method and the proposed solar PV method are relatively high, ranging from 34.66% to 44.03%. This indicates that the two methods produce significantly different results, and the proposed solar PV method may not be an accurate replacement for the conventional method.

Keywords: transformer; solar photovoltaic; economic evaluation; service life; total ownership cost

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1. Introduction

In South Africa, a great deal of research is currently being undertaken to study the effects of introducing alternative energy into conventional electrical networks, notably concerning electric power quality and power system stability [1,2]. Notwithstanding, this work pinpoints a separate but equally significant topic, which is the economic analysis of the transformer service lifetime losses in the new dawn of the renewable energy market. This scope of research has piqued global interest from utility owners and manufacturers. Subsequently, the primary target of this work is to establish a holistic and translucent technique for determining the cost of transformer losses over its planned in-service life. To a fuller extent, the methods developed in this work aim to facilitate independent power producers (IPPs) to carry out more feasible vendor jurisdiction procedures [3]. Additionally, these methods will most notably come to the aid of manufacturers to produce optimised designs that will be competitive in the renewable energy market. It is generally acknowledged that the amount of loss is far from optimal in the current low-carbon power generation markets, and at any point in time, the alleviation of the transformer losses is advisable. This would inescapably increase the initial transformer purchase price. However, the methods proposed in this work intend to underpin that the alleviation of the losses by a low-loss high-transformer price implies that there would be an extended reduction in the solar PV operational and ownership costs. A practical effect of such a method is firstly for the solar PV plant to delay an increase in the annual rates and secondly, to achieve considerable power savings.

Recent related works have been reported in [4–6]. These methods, however, are based on transformers operated in coal power stations. In [7], the fuel-type pricing has been assessed for transformers in vertically integrated systems. This work, however, primarily underlines that, in the recent multifaceted transformation dawn of low-carbon power generation markets and escalated growth of renewable energy technologies in South Africa, there is a lack of investigation in the service life economic evaluation (SLEE) methods for transformers, which are scheduled to particularly facilitate solar PV plants in South Africa that take part in the country's energy market. The following complexities were revealed:

- The classical SLEE methods do not appropriately contemplate the distinct characteristics, both operational and economic, between various power utilities.
- The existing SLEE methods should be fittingly reworked for determining the TCO of transformers in service to solar PV plants.
- There is a lack of investigation into the SLEE methods for transformers, which are scheduled to particularly facilitate solar PV plants in South Africa.

The graphical abstract of this work has been illustrated in Figure 1.

Figure 1. Graphical abstract.

A general critique of exiting SLEE methods: In the recent multifaceted transformation dawn of low-carbon power generation markets and escalated growth of renewable energy technologies in South Africa, a comprehensive analysis of the technical and economic performance of transformers has been under-explored as a result of insufficient knowledge in this study area. Given the government's plans to deregulate the country's vertically integrated generation system, guessing or estimating the economic benefits of transformer expenditure and, by and large, of energy supply systems is becoming ever more important. After the recent developments of renewable energy technologies in South Africa, the following general critiques have been formulated:

- It has been noted that the current SLEE methods do not thoroughly acknowledge the operational and economic hallmarks of distinctly integrated power utilities. This results from the fact that these benchmarked methods are not sufficiently comprehensive to be readily adapted to the needs of renewable energy systems. They hinge on estimates that for the most part do not contemplate the requirements that may be applicable for the appropriate transformer loss evaluation.
- By and large, the loss evaluation procedures are critical for utility owners; therefore, their comprehensive and translucent delineation matters. The SLEE methods should be capable of capturing the specific characteristics, both operational and economical, of a power system to provide the soundest decision for the parties concerned. This indicates the necessity to establish comprehensive transformer SLEE methods that will be able to capture the needs of a transformer operating under renewable energy systems.
- Predominantly, the existing SLEE methods contemplate vertically integrated generation systems. These methods are not suitable to meet the operational and economic requirements of the decentralised generation systems.
- The SLEE approach increases in complexity in the setting of renewable energy technologies in South Africa. The SLEE methods should be modified for determining the TCO of transformers facilitating decentralised generation systems. For instance, in South Africa, regulated and deregulated electricity markets exist simultaneously but have distinct generation profiles and approaches to evaluating their operational and economic characteristics. As a result, the approaches for capitalising on the

transformer losses must be distinct. The approaches need to be able to ascertain the individual loss elements designated to the parties concerned, who may be involved in the deregulated electricity markets, from the perspective of determining who is accountable for the supply of the transformer's losses.

There is a lack of investigation into the SLEE methods for transformers, which are scheduled to particularly facilitate the solar PV plants in South Africa that participate in the country's energy market. The pain points arise from the reality that these transformers are indebted to service a spasmodic source of energy with irregular operational and economic characteristics. Therefore, a critical factor in capitalising on the losses of these transformers is to recognise an entirely appropriate methodology to appraise these losses by contemplating the inherent nature of the solar PV supply and the proprietorship status of these transformers regarding electricity regulation in South Africa. Consequently, loss capitalisation for transformers in service to spasmodic energy sources indicates the necessity for re-examining the classic coal power generation system SLEE methods in the context of South Africa.

The manuscript is organised as follows: Section 2 introduces the materials and methods comprising of the discounted total cost of service losses, ABB SLEE tool, transformer total cost of ownership, general critique of existing SLEE methods, and proposed transformer techno-economic evaluation. Section 3 presents the results, which cover various case studies based on the classical and proposed method. Section 4 provides the conclusion.

2. Materials and Methods

In the transformer manufacturing industry, the service lifetime loss evaluation (SLEE) is a procedure that rationalises the totalling of the present worth or value of every loss-per-kilowatt (kW) of a transformer during its operational life. As discussed earlier, the transformer total losses ($P_{TOT}-$kW) comprise the no-load ($P_{NL}-$kW) and load loss ($P_{LL}-$kW). Consequently, under the SLEE method, individual transformer loss components (P_{NL} and P_{LL}) are examined based on the energy element ($ZAR/$kWh) of the utility that will be consumed by each loss-per-kW of the transformer during its operational life. So far, the energy element of the losses is a predominant factor in the procedure of determining the cost of electrical energy necessitated to supply the service lifetime losses on the units in service.

No-load loss refers to the power that is consumed by the transformer when it is energised but not connected to any load. This loss is primarily due to the magnetising current that flows through the core, which creates a magnetic field and causes the core to become magnetised. The no-load loss also includes losses due to eddy currents and hysteresis in the core material. The no-load loss is typically measured in watts and is a function of the transformer's rated voltage and frequency.

Load loss, by contrast, refers to the power that is lost in the transformer when it is under load. This loss is primarily due to the resistance of the transformer's windings, which causes a drop in voltage across the windings and leads to power dissipation. The load loss is typically measured in watts and is a function of the transformer's rated current and impedance.

2.1. Discounted Total Cost of Service Losses

The energy element is fittingly annualised to furnish a total loss determinant value ($ZAR/$kWh), which accounts for the totalling of the present worth value of every loss-per-kW consumed by a transformer during its operational life. The SLEE method thereupon produces the discounted total cost of service losses ($T_{CSL} - ZAR$) of the transformer during its operational life. The total cost of service losses can be expressed as follows in Equation (1) as the arithmetic sum of the no-load and load cost [8,9].

$$T_{CSL} = P_{NLcost} + P_{LLcost} \tag{1}$$

Here, P_{NLcost} presents the service life cost of no-load loss (in ZAR), and P_{LLcost} presents the service life cost of load loss (in ZAR). Note: The cost of maintenance is not considered as it is subject to the volatility of air flight, accommodation, meals, and local travel costs where the unit is located.

It follows that the service life cost of the no-load loss can be expressed as follows in Equation (2).

$$P_{NLcost} = F_{NL} \times NLL \quad (2)$$

Here, F_{NL} presents the no-load loss capitalisation factor, while NLL presents the no-load losses (in kW), and LL presents the load losses (in kW). Subsequently, the service life cost of load loss can be expressed as follows in Equation (3).

$$P_{LLcost} = F_{LL} \times LL \quad (3)$$

Here, F_{LL} presents the load loss capitalisation factor.

The capitalisation factors in Equations (2) and (3) can be evaluated as follows in Equations (4) and (5) [9,10].

$$F_{NL} = \frac{\left(\left(1+\frac{i_{ACOE}}{100}\right)^{n} - 1\right) \times 100}{\left(1+\frac{i_{infl.}}{100}\right)^{n} \times i_{ACOE}} \times 8760 \times ACOE \quad (4)$$

$$F_{LL} = \frac{L^2 \times 8760 \times ACOE}{\left(1+\frac{i_{infl.}}{100}\right)^{n}} \times \frac{\left[\left(1+\frac{i_L}{100}\right)^2 \times \left(1+\frac{i_{ACOE}}{100}\right)\right]^{n}}{\left(1+\frac{i_L}{100}\right)^2 \times \left(1+\frac{i_{ACOE}}{100}\right) - 1} \quad (5)$$

Here, $ACOE$ is the annualised cost of energy by power utility (ZAR/kWh), 8760 is the operational hours per year (hours), n is the designed service life of the transformer (years), i_{ACOE} is the annual increase in energy cost (%), $i_{infl.}$ is the annual inflation rate (%), while L is the transformer loading at the moment of very first energisation (%), and i_L is the annual increase in loading (%)

2.2. ASEA Brown Boveri (ABB) SLEE Tool

The ABB has issued an online SLEE estimator on their website [9,10] for evaluating the TCO under vertically integrated generation systems. The online estimator alludes to transformers that are indebted to be in-service to vertically integrated generation systems. The estimator furnishes a client application as shown in Figure 2 to evaluate the loss capitalisation factors of these transformers. The TCO method for this estimator integrates the annual cost of carbon dioxide (CO_2) emission, which is typically for coal power generation systems in South Africa.

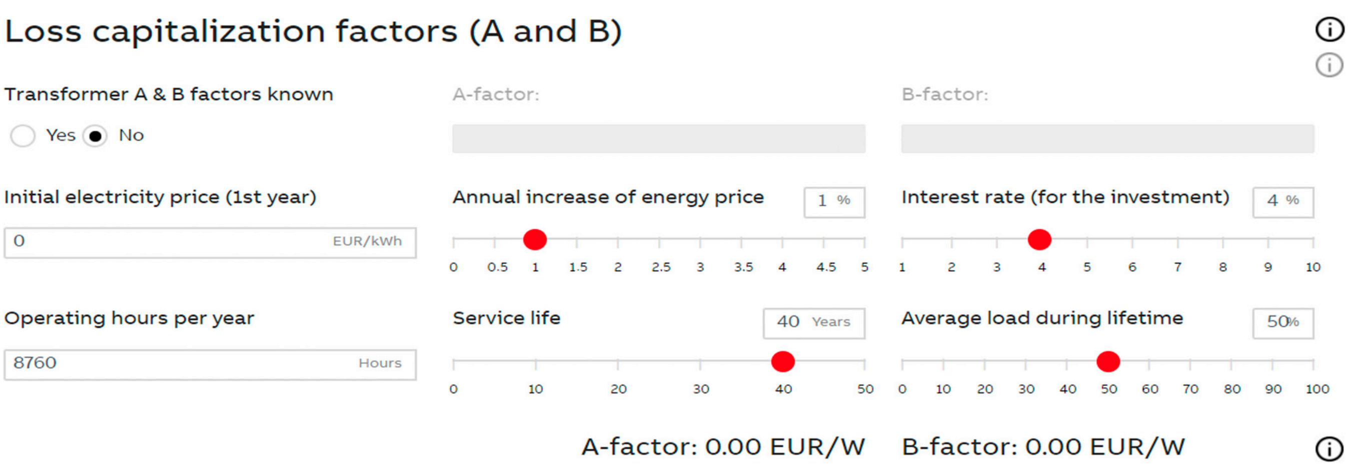

Figure 2. ABB loss capitalisation tool.

In the pursuance of latter-day measures taken by the South African government for energy conservation, the external environmental expenses should be reflected in the transformer's SLEE procedures per their corresponding TCO. The environmental expenses are related to the charges that are related to the carbon credits. To reimburse the transformer losses during its operational life, the ABB SLEE procedure integrates the CO_2 emission charges emanating from the combustion of coal.

It is important to bear in mind that the reference transformer on the ABB estimator must be designed per the Institute of Electrical and Electronics Engineers (IEEE) or International Electro-technical Commission (IEC)/European Norm (EN) standards.

2.3. Transformer Total Cost of Ownership

The transformer total cost of ownership ($TCO - ZAR$) is henceforth deduced by taking the initial transformer purchase price ($TP - ZAR$) and the ($T_{CSL} - ZAR$) as follows in Equation (6) [11,12].

$$TCO = TP + T_{CSL} \tag{6}$$

Therefore, the transformer's total cost of ownership can be identified as a financial projection applied to furnish the IPPs with the techno-economic evaluation of the expenditure of their transformer acquisition. The TCO method can be applied by the IPP as a techno-economic-based purchase decision tool in subsequent conditions:

- The SLEE procedure and the ensuing TCO facilitate the IPPs during the jurisdiction phase of a bid to compare offers of participating manufacturers in making the best procurement call between competing transformers and subsequently uphold the acquisition of the techno-economically sound transformer. By applying the capitalisation formula in Equations (4) and (5), the techno-economic benefit of low-loss and initially high-TP transformers can be compared with low-TP and high-loss transformers over the intended operational lifetime of the units.
- It is generally acknowledged that the loss levels of transformers, especially in modern power grids where centralised and decentralised energy markets co-exist, do not achieve cost-optimal levels, and under all circumstances, a minimisation of the service losses is advisable. The latter will inescapably increase the transformer EX WORKS price of the manufacturers. Having said that, the TCO methodology underpins the notion that minimising the service losses by purchasing low-loss and high-TP transformers implies that the TCO and operational costs will be reduced. The net result of the technique would be foremost to shelve the necessity for the rates to increase and secondly to conserve power on the power utility.
- The SLEE procedure delivers information to demonstrate the appropriate time to replace an existing transformer in service with lower -loss units. This information contemplates the economic feasibility of paralleling the load profile increase effects under the existing and prospective transformer replacement.

2.4. Proposed Transformer Techno-Economic Evaluation

2.4.1. Generation Profile for Photovoltaic Panels

In South Africa, large-scale solar PV plants are privately owned entities under the framework of an unbundled market, generating electricity and then selling it to the national power utility, municipalities, and end users. The plant is composed of a vast array of photovoltaic panels coupled in series. These panels are thereupon connected to a central inverter that executes a DC to AC transformation. Moreover, a step-up transformer is necessary to enhance the output of the inverter to the transmission voltage magnitude. For instance, a 100 MW solar PV plant, powering at the transmission level, might take up a site area equal to 1100 hectares. It should be emphasised that the transformers facilitating solar PV plants are coupled to the electric grid permanently to guarantee that the PV plant is provided with energy if it is in a non-generating mode.

Figure 3 demonstrates a distinguishing 24 h generation profile of photovoltaic panels at three distinct field measurements. Nonetheless, the measurements demonstrate a similar pattern over 24 h [13]. This content is critically dependent on the day-by-day availability of emitted radiation from the sun and the effective surface of the photovoltaic panels. As demonstrated in Figure 3, the operation of photovoltaic panels can in the broadest sense be categorised into two operating modes. The first one is the non-generating mode (NGM) when there is no solar radiation available on the effective area of the photovoltaic panels. The second one relates to available solar radiation and the photovoltaic panels are productive, that is, in a generating mode (GM).

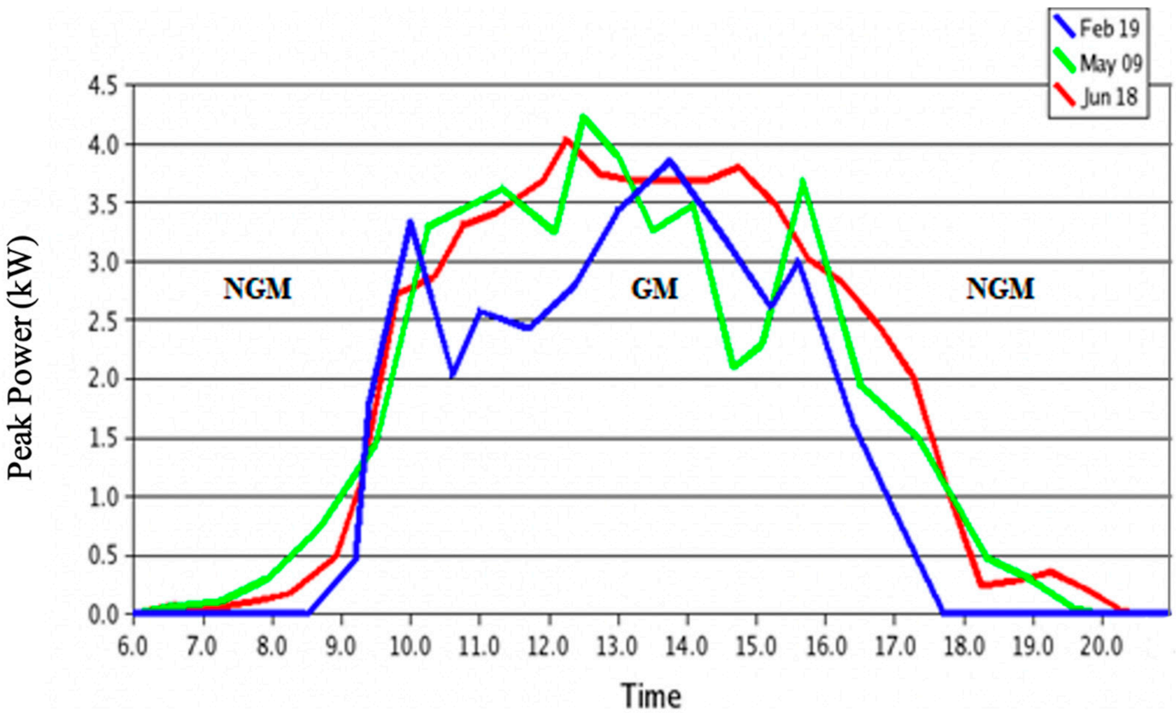

Figure 3. Hourly generation modes for solar PV.

It can be observed that the fraction of the hours that the photovoltaic panels are in a GM range from 06:00 am to 8:00 pm constituting a fraction of 0.542% on a 24 h basis. Consequently, the NGM of the photovoltaic panels on a 24 h basis will be 45.8%. The peak power of the solar panels is 4.25 kW, and the curves in Figure 3 are valid for 5 months where solar PV is at peak. These curves give an average of normal sunny and cloudy days during these periods.

The relationship of the availability of solar radiation and months where the measurements were taken in Figure 3 are also discussed. The Northern Cape province is in the arid west of South Africa and is known for its high levels of solar radiation. The region receives an average of around 2800 h of sunlight per year, making it an ideal location for solar energy generation.

In February, the Northern Cape experiences high levels of solar radiation due to the region's position in the Southern Hemisphere and the high incidence of clear skies. However, the month can also be characterised by sporadic rainfall and occasional cloud cover, which can reduce the amount of solar radiation received. February is a summer month in the Northern Cape and experiences hot and dry weather conditions. The average temperature during this month is around 30 °C. The solar PV profile during February is typically characterised by high solar irradiation levels, with an average of around 7.5 kWh/m^2/day. The daily solar radiation is highest around midday and gradually reduces towards the evening. The solar PV generation profile during this month is generally consistent and predictable.

In May, the Northern Cape experiences cooler temperatures compared to February, but the amount of solar radiation received remains high. May is also characterised by a lower incidence of cloud cover and rainfall, which further increases the amount of solar radiation received. May is a transitional month in the Northern Cape, marking the start of the autumn season. The weather during this month is typically warm and mild, with an average temperature of around 20 °C. The solar PV profile during May is characterised by declining solar irradiation levels as the days become shorter and the sun's angle decreases. The average daily solar radiation during this month is around 5.5 kWh/m^2/day. The solar PV generation profile during this month is still relatively consistent, but there may be some variability due to weather conditions, such as cloud cover and rainfall.

In June, the Northern Cape experiences its winter season, which is characterised by colder temperatures and shorter days. However, the region still experiences high levels of solar radiation due to its location in the Southern Hemisphere and the low incidence of cloud cover. The amount of solar radiation received during June is still sufficient for solar energy generation, and the colder temperatures can even improve the efficiency of solar panels.

It is reaffirmed that the SLEE method proposed in this work should apply to IPPs in South Africa that supply energy to the national grid via a step-up transformer. The cornerstone in capitalising on the losses in these transformers is the correct interpretation of the F_{NL} and F_{LL} factors. Furthermore, the applicable annualised cost of energy (ACOE) must be appropriately applied for each energy tariff in South African rand (ZAR/kWh) that will be consumed by one kW of loss over the designed service life of the transformer.

2.4.2. SLEE Method

As demonstrated in Figure 3, during the day the solar PV plant will undoubtedly operate in two distinct generation modes. At the time that the plant is in a GM, it is accountable for its energy demands and losses, along with supplying power to the grid. When the plant is in NGM, its ancillary services and losses must be supplied from the grid. The solar PV plant in this case will purchase energy from a power utility when its generation capacity is low.

Thus, Equation (7) demonstrates the intrinsic rationale of the transformer SLEE method that should apply to IPP. Consequently, the SLEE method proposed in this work is purely based on two distinct solar PV operating modes (GM and NGM), which at the same time characterise two SLEE components. Under the GM, the IPP must capitalise a large portion of the transformer losses by bearing in mind the total expenditure spread over the lifespan of the solar PV plant. This should be based on correctly defining solar PVs $ACOE_{PV}$ (ZAR/kWh), which indicate the kilowatt-hour cost of operating a solar PV plant subject to annual escalations. The $ACOE_{PV}$ considers the cost incurred to provide power consumed by the losses and the rate of energy that will be consumed by each kilowatt of loss over the lifetime of the solar PV.

Moreover, under the NGM in Equation (7), the related no-load losses must be capitalised by considering the energy tariff commissioned by the supplying power utility. In the aforementioned case, the calculations must be based on the annualised cost of energy of the supplying utility, that is the $ACOE_{coal}$ that the utility will charge the IPP over the lifespan of the plant.

$$SLLE\ method = GM(NLL,\ LL,\ ACOE_{PV}) + NGM(NLL,\ ACOE_{coal}) \tag{7}$$

Taking into consideration the above-indicated rudiments, the total losses of the transformer must be calculated for each of the two components illustrated in Equation (7). From that perspective, the no-load losses (NLL) must be proportionately determined under both the GM and NGM components, respectively. The NLL will materialise each time the unit is energised (i.e., in the course of GM and NGM). It follows that the LL must be determined under the GM only since they will be predominant during the GM of the solar PV plant.

That being the case, the two SLEE components should be fittingly specified to furnish the total cost of service losses (T_{CSL}) in ZAR for IPPs as proposed in Equation (8).

$$T_{CSL} = NLL_{cost} + LL_{cost} \tag{8}$$

where

$$NLL_{cost} = F_{NL} \times NLL$$

and

$$LL_{cost} = F_{LL} \times LL$$

Two terms are present in Equation (8): Firstly, the no-load losses, which are the arithmetic sum of the cost elements, are associated with SLEE under GM and cost elements under NGM, F_{NL} (ZAR/kW), and are shown in Equation (9).

$$F_{NL} = \frac{\left(\left(1 + \frac{i_{ACOE}}{100}\right)^n - 1\right) \times 100}{\left(1 + \frac{i_{infl.}}{100}\right)^n \times i_{ACOE}} \times F_{NGM}$$

where

$$F_{NGM} = \left(8760 \times NGM_{factor} \times ACOE_{coal} + 8760 \times GM_{factor} \times ACOE_{PV}\right). \tag{9}$$

When the PV plant is not independently generating power, the auxiliary components will be supplied by the coal (i.e., $8760 \times NGM_{factor} \times ACOE_{coal}$), and during the day when the plant can sustain itself, then the factor ($8760 \times GM_{factor} \times ACOE_{PV}$) will prevail. It should be taken into account that the PV transformer is permanently connected to the grid to guarantee that the plant is supplied with power when the PVs are on a NGM. Hence, the F_{NGM} will be composed of the NGM_{factor} and GM_{factor} as the unit will be in operation during both these conditions.

Secondly, the load losses characterised by the GM component (F_{LL}) of the solar PV will be capitalised as follows in Equation (10).

$$F_{LL} = \frac{{L_{PV}}^2 \times F_{GM}}{\left(1 + \frac{i_{infl.}}{100}\right)^n} \times \frac{\left[\left(1 + \frac{i_L}{100}\right)^2 \times \left(1 + \frac{i_{ACOE}}{100}\right)\right]^n}{\left(1 + \frac{i_L}{100}\right)^2 \times \left(1 + \frac{i_{ACOE}}{100}\right) - 1} \tag{10}$$

where

$$F_{GM} = 8760 \times ACOE_{PV} \times GM_{factor} \tag{11}$$

Here, $ACOE_{coal}$ is the annualised cost of energy by the power utility (ZAR/kWh), $ACOE_{PV}$ presents the annualised cost of energy by solar PV plant (ZAR/kWh), GM_{factor} is the generating mode factor, NGM_{factor} is the non-generating mode factor, 8760 is the hours per year (hours), n is the designed service life of the transformer (years), i_{ACOE} is the annual increase in energy cost (%), $i_{infl.}$ annual inflation rate (%), and L_{PV} is the load loss factor of the PV plant, i.e., the ratio of the PV plant's mean power loss to its peak power loss over given time. In the unavailability of the measured power values, this factor can be presumed that the PV loss is equal to the square of the PV plant generation load and i_L is the annual increase in loading (%)

Considering the SLEE of the NGM, it is pivotal for the IPP to ascertain the $ACOE_{PV}$ that will be paid to the supplying power utility over the designed life of the solar PV plant to capitalise the appropriate portion of the no-load losses associated with the NMG of the plant. As a result, the $ACOE_{coal}$ must contemplate the number of yearly hours for which the solar PV operated in its NGM.

3. Results

The proposed methods are methodically appraised by applying a set of practical data and specific characteristics. Table 1 tabulates the techno-economic specifics of the solar PV plant and the studied transformer. The studied transformer herein is a 40 MVA, 88/11 kV, transformer, which operates in a solar PV plant in the Northern Cape. The initial loading of the unit is 65%.

Table 1. Techno-economic specifics.

Specifics	Value
No-load losses, NLL (kW)	12.97
Load losses, LL (kW)	258.5
Service lifetime, n (Years)	30
Transformer initial loading, L (%)	65%
The annual increase in loading, i_L, (%)	2%
The annualised cost of energy of the solar PV plant, $ACOE_{PV}$, (ZAR/kWh)	0.62
Generating mode factor, GM_{factor}	0.542
Non-generating mode factor, NGM_{factor}	0.458
The annualised cost of energy of the coal power plant, $ACOE_{coal}$, (ZAR/kWh)	1.65
Energy cost inflation, i_{ACOE}, (%)	3%
The annual inflation rate, $i_{infl.}$, (%)	2%

Consequently, by applying the data tabulated in Table 1 and the proposed methods in Equations (9) and (10), the capitalisation of the losses for 30 years is shown in Table 2.

Table 2. Capitalisation of losses: proposed method (Equations (9) and (10)) vs. conventional (Equations (4) and (5)).

Capitalisation Factors	Conventional Method	Proposed Solar PV Method
F_{NL}	405,974	225,145
F_{LL}	74,768	11,686

Furthermore, by contemplating the losses provided in Table 1 and the capitalisation of these losses in Table 2, as calculated in Equations (9) and (10) the total cost of the service losses over the 30 years is calculated and presented in Figure 4.

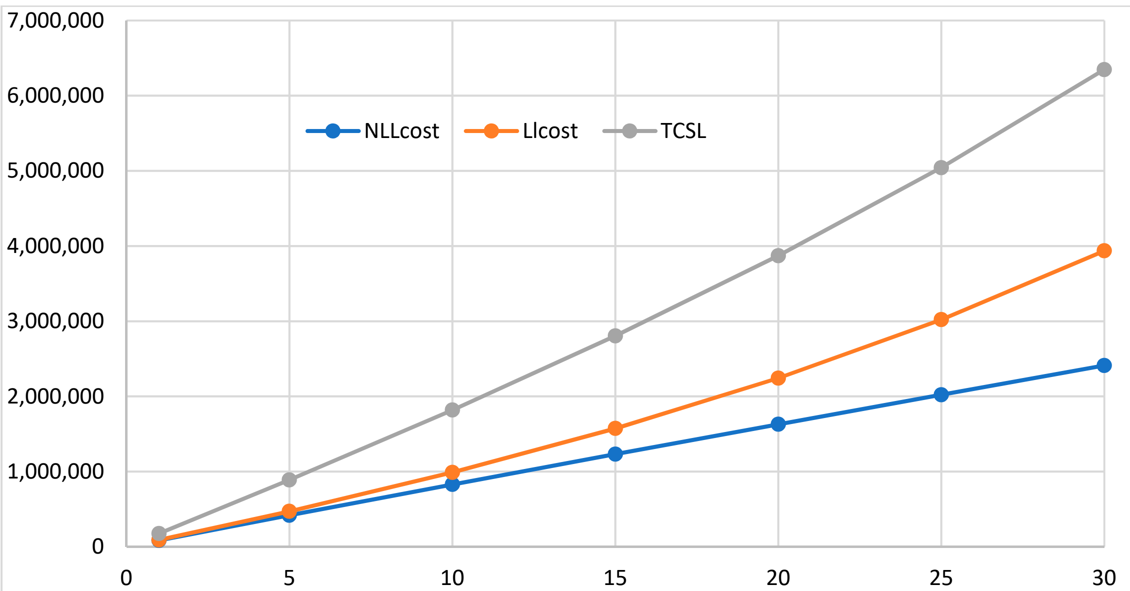

Figure 4. The total cost of service losses (T_{CSL}): proposed method.

The results in this section are benchmarked in the next section and discussed.

3.1. Benchmark Test of Proposed Solar PV Method

To illustrate a distinction between the conventional SLEE method and the proposed method, a benchmarking test is carried out. It is underlined that the conventional SLEE method considers the operational conditions of a coal power plant, whereas the proposed solar PV SLEE method considers the operational conditions detailed in this section. The computation of the transformer capitalisation factors in the previous section considers only the annualised cost of energy of the coal power plant ($ACOE_{coal}$), where energy generation and transmission are possessed by the utility throughout the year (8760 h). Therefore, the coal power plant owner may choose to apply these capitalisation factors for transformers in the South African grid. It follows that IPPs may choose the factors formulated under solar PV plant operational conditions developed in this work. The capitalisation factors for each of the methods are tabulated in Table 3.

Table 3. Capitalisation of losses: proposed method (Equations (9) and (10)).

Service Lifetime, n (Years)	F_{NL}	F_{LL}	Ratio, F_{NL}/F_{LL}
1	6522.10	351.81	18,539
5	32,300.25	1819.80	17,749
10	63,906.09	3826.77	16,700
15	94,948.88	6086.44	15,600
20	125,554.64	8675.84	14,472
25	155,844.65	11,686.37	13,336
30	185,936.02	15,227.21	12,211

To facilitate a bona fide benchmarking test of these factors shown Table 3, they are applied to a set of real techno-economic data in Table 4 of bid offers supplied by transformer manufacturers to utility owners for evaluation during the tender stage. In these case scenarios, all bidding offers to correspond with the transformers of the same-sized design according to the same technical specification.

Table 4. Competing transformer manufacturers offer.

Offer	TPP (*ZAR*)	NLL (*kWh*)	LL (*kWh*)
X	4,470,465.00	7.78	49.88
Y	4,480,465.00	8.24	60.20
Z	4,495,465.00	7.00	34.40

TPP—transformer purchase price.

Consequently, Table 5 tabulates the computed TOC (ZAR) of the individual bid offerings presented above. The results indicate that when the capitalisation factors of the conventional methods (Equations (5) and (6)) are applied, the bid offer supplied by manufacturer Z is observed to be the most economical. By contrast, when the proposed solar PV methods (Equation (8) to Equation (10)) are applied, bid offer Y emerges to also be the most economical but with a significant drop in the TOC.

Table 5. TOC of competing offers.

Offer	Conventional Method	Proposed Solar PV Method
X	11,358,370.56	6,804,990.78
Y	12,326,724.36	7,039,157.00
Z	9,909,302.20	6,473,478.40

Even though thorough values in Table 5 must be interpreted with the utmost precision, as these are wholly dependent on the particulars of the individual solar PV plant, it is revealed that when subjected to specific conditions, the TOC of the transformer facilitating a solar PV plant may differ in concordance with which SLEE method is employed.

The percentage errors between the conventional method and the proposed solar PV method are relatively high, ranging from 34.66% to 44.03%. This indicates that the two methods produce significantly different results, and the conventional method may not be used for solar PV application.

3.2. Sensitivity Study of the Proposed Method

One of the critical factors in the proposed SLEE method is the effect of the harmonic current contents to which the transformer will be susceptible during service because the harmonic current contents will yield an increase in the load losses.

To address this effect, a sensitivity study is carried out to demonstrate the variations in the cost of losses over 30 years for the studied methods of evaluating the winding eddy current losses under both harmonic load current and rated conditions presented in [14], respectively. The winding eddy losses and stray load losses are considered by the formulae shown in Figure 5. Therefore, Figure 5 demonstrates the cost of these losses in the calculated capitalisation factors that apply to solar PV plants.

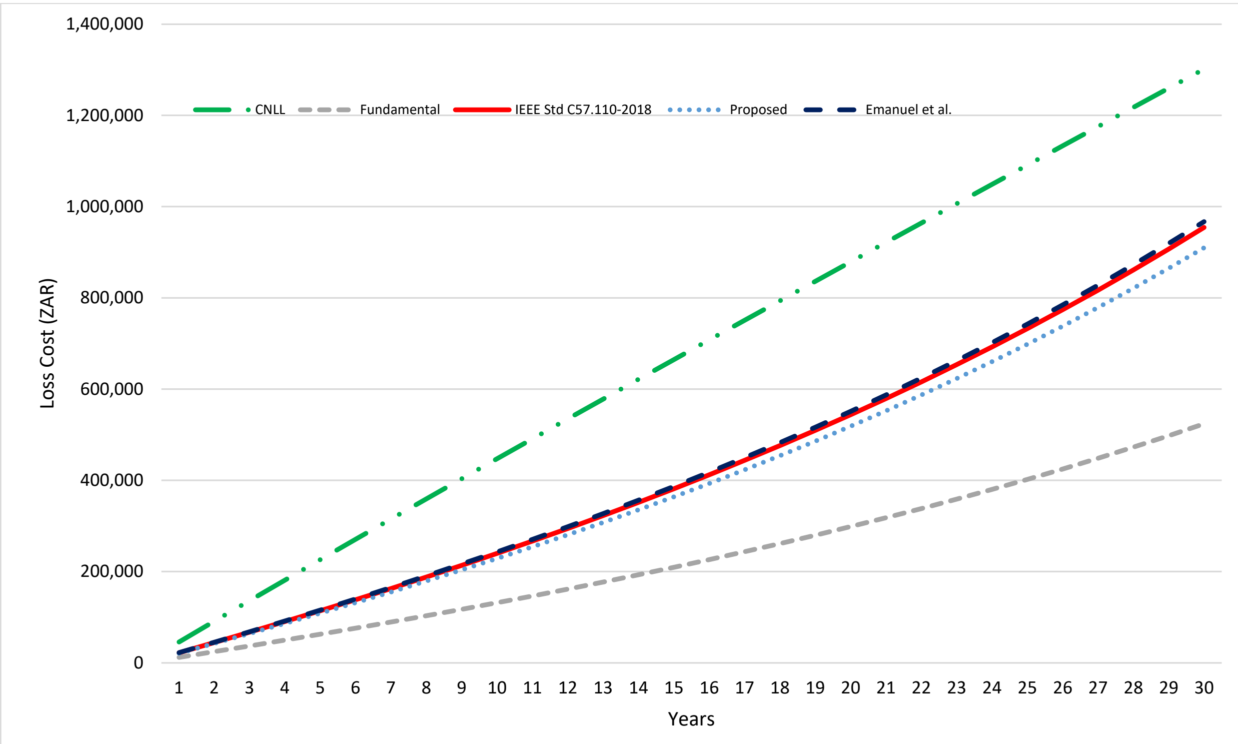

Figure 5. The influence of harmonic load current on the proposed SLEE method.

Finally, it could be demonstrated that under the different operational conditions above, the proposed method for evaluating the winding eddy losses under harmonic conditions is the most cost-effective.

In this sub-section, a broad-based study on solar PV transformers in the South African grid was carried out to establish some techno-economic limits. This study is executed by developing regression models to develop some guidelines for transformers ranging from 100 kVA to 40 MVA with a maximum primary voltage of 132 kV. It is underlined that the regression models developed for the compass of this work revert to the pending measures of developing techno-economic-based jurisdiction processes for IPPs in the new dawn of South Africa's renewable energy market.

Table 6 shows the transformer price regression models for a large sample of mineral oil-immersed transformers collected locally. The units are three-phase, 50 Hz, ratings ranging from 100 kVA to 40MVA with the highest system voltage of 132 kV. The prices used to formulate these models are based on recent prices from manufacturers for 2022–2023 year, with an anticipation of a 5% increase yearly.

Table 6. Proposed regression models for the transformer purchase price.

Rating Range	Price	R^2
Up to 100 kVA	$13244 + 508 \times kVA + 396 \times HV$	0.9104
100.1–315 kVA	$8127 + 404 \times kVA + 417 \times HV$	0.9667
315.1–5 MVA	$-22749 + 300 \times kVA + 1328 \times HV$	0.9591
10 MVA–40 MVA	$1884799 + 55689 \times MVA + 3752 \times HV + 1630 \times LV$	0.9918

The proposed models yield a good correlation coefficient of no less than 0.91 between a particular transformer rating and the corresponding transformer price. These models can be employed by IPPs as budgetary estimates for the transformers that will be required during the planning phase of erecting new renewable projects.

4. Conclusions

In this work, methods for evaluating the capitalisation factors for a solar PV plant environment are developed. The methods proposed in this work integrate the operational requirements of solar PV application, including the annualised cost of energy, the intermittent features of solar irradiation, and the generation modes of the solar PV plant during the day. It subsequently provides a comprehensive benchmarking test by using philosophical discussions and pragmatic examples for both the conventional and proposed SLEE methods. It is determined that where transformers are intended to facilitate a solar PV application, the SLEE method must be customised in the light of the particular features of the solar PV plant. Additionally, the SLEE methods must appreciate the actual annualised cost of energy (ZAR/kWh) responsible for supplying the service losses of the transformer at GM and NGM.

The percentage errors between the conventional method and the proposed solar PV method are relatively high, ranging from 34.66% to 44.03%. This indicates that the two methods produce significantly different results, and the conventional method may not be used for solar PV application.

Further, this work proposed various regression models that may serve as guidelines for solar PV transformers in the South African grid to establish some techno-economic limits. The developed regression models serve as guidelines for transformers ranging from 100 kVA to 40 MVA with a maximum primary voltage of 132 kV. It was emphasised that the regression models that were developed for the compass of this work revert to the pending measures of developing techno-economic-based jurisdiction processes for IPPs in the new dawn of South Africa's renewable energy market.

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