

# Life-cycle loss evaluation of power transformers serving large photovoltaic plants in vertically integrated and decentralised systems

Antonis L. Lazari, Charalambos A. Charalambous ✉

School of Electrical and Computer Engineering, University of Cyprus, P.O. Box 20537, 1678, CY, Cyprus

✉ E-mail: cchara@ucy.ac.cy

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**Abstract:** This study details a comprehensive loss evaluation method of power transformers serving large-scale solar applications. The fact that these transformers are obliged to serve an intermittent energy source calls for a suitable method to evaluate their life-cycle losses and total ownership costs. These transformers may be owned by independent photovoltaic power producers or by regulated utilities. Thus, the method concurrently responds to the current efforts to address the concept of loss evaluation both in vertically-integrated and decentralised energy systems that are experiencing a high penetration of renewable energy.

## 1 Introduction

Loss evaluation is a process which accounts for the sum of the present worth of each kilowatt of loss of power transformers throughout their life, or some other selected evaluation period. The total losses in power transformers are, in principle, power losses, for example, no load (NL), load (LL) and auxiliary (AUX) losses. Under the process of loss evaluation each type of power loss is assessed on the basis of its demand (€/kW) and energy (€/kWh) components [1]. The demand component is the cost of installing system capacity in €/kW to serve the power used by the losses. The energy component is the present value of the energy that will be used by one kilowatt of loss during the life cycle of the power plant under study in €/kWh. Both demand and energy components are appropriately annuitised to provide a total loss factor figure (€/kW) which accounts for the sum of the present worth of each kilowatt of loss of power transformers throughout their useful lives. This figure represents the maximum amount that can be spent by a user on more efficient transformers to save a kilowatt of loss [1]. It subsequently determines the total ownership cost (TOC) of different transformer units. The TOC of a transformer is defined as the purchase price (PP) of the transformer plus the total cost of losses (TCL). It is a financial estimate intended to provide the transformers' buyers and owners the direct and indirect costs of their transformers' investment. To this extent, it provides a cost basis for determining the total economic value of the transformer over its estimated life cycle. TOC is typically used to compare the offerings of two or more manufacturers to facilitate the best purchase choice among competing transformers.

Thus, an appropriate loss evaluation endeavour reinforces the fact that reducing the losses, by more efficient and perhaps expensive units, would mean an overall reduction in the total operating and ownership costs of transformers. This stimulates manufacturer to modify their transformer designs (i.e. increase efficiency) and at the same time be confident that they can obtain a lucrative share in the market [2]. The net effect of such a motivation would be firstly to defer any utility rate growths and secondly to achieve significant CO<sub>2</sub> emissions reduction through energy conservation. A few options [3–8] to improve the efficiency of transformer designs are: (a) to use a core material that is more efficient, (b) to reduce eddy current losses by using thinner laminations, (c) to

ensure that air gap losses at the core joints (yoke and limbs) are minimised, (d) avoiding the use of core bolts and (e) winding materials may be more conductive or thicker.

Nevertheless, it appears that although the existing loss evaluation procedures are relatively similar in the nature, there are major fluctuations when defining and evaluating the system cost and load parameters that are used in these processes [9]. The elements engaged in the processes are: (a) the load characteristics of the system under study in terms of defining the load factor, loss load factor, peak responsibility factor and coincidence factor [10], (b) an appropriate discount rate based on the overall financial objectives of the business should the levelised annual cost method be used [11], (c) relevant capital (system capacity costs or capital fixed cost) and operating expenditures to account for the use of human and material resources, (d) future system expansion in term of forecasts, appropriate usage of future load, energy demands and fuel consumptions [12] and (e) predictions of the relevant fuel/energy prices over the life cycle of the plant under study [13].

To this extent, the picture of loss evaluations becomes more complex in the context of low carbon electricity markets. Primarily, loss evaluation methods should be adjusted for evaluating the ownership cost of transformers operated in a decentralised energy environment. For example, under liberalised electricity markets, several regulated utilities (RUs) and independent renewable power producers co-exist but have diversified ways of assessing their capital costs, system expenditures and generation profiles. Thus, the methods for capitalising their own transformer losses should be different.

Consequently the specific scope of this paper is to offer a comprehensive loss evaluation method to calculate the TOC of power transformers serving large-scale solar applications. These transformers may be owned by either Independent photovoltaic (PV) energy producers or by RUs. This paper (a) discusses the arising implications and (b) introduces a method to address these.

More specifically these implications arise from the fact that these transformers are obliged to serve an intermittent energy source with varying operational and financial characteristics. Thus, the key element in capitalising the losses of such transformers is to appreciate exactly how these losses should be evaluated, bearing in mind the ownership status of the transformer in relation to the regulatory framework of the electricity market it exists in.

## 2 Critical review of loss evaluation method

The loss evaluation method may be considered as a planning tool which its implementation depends heavily on utilities' discretion [14]. However, there is sufficient evidence in the literature that loss evaluation techniques have been used over the course of the past few decades, for defining the ownership cost including the cost of losses of power transformers [15–19]. The majority of these efforts reflected on vertically-integrated market environments where the generation, transmission and distribution facilities had been owned either by private RUs or by public companies/government agencies.

The investigation performed in [20] presents a comparison of transformers' loss evaluation factors (both no-load and load) of several countries with diverse economic conditions. The study acknowledges that not all of these loss factors seem rational. Hence, the two key elements identified within the study that impact on the published loss factors, are: (a) different economic conditions of each country and (b) credibility of the method employed to calculate these factors. It is true that the different economic conditions of each country may have an impact in loss evaluations of transformers. However, is it meaningful to classify loss evaluation figures on a country basis? It should become clear that the classification of loss factors must be based on a utility/entity basis rather than on a country basis. Even within the same country, different entities may have diverse operation targets and financial objectives.

Moreover, the credibility of the published loss factors is, in most of the times, counteracted by the fact that the methodologies employed to determine these factors, are not disclosed. To this end, it is marked that although a standardised methodology for loss evaluations (IEEE Std. C57.120-1991) exists [1], there is a clause in the standard that states that nothing specified within, is mandatory and that many transformer users may develop their own techniques that are suitable for their intended purpose.

However, it is our belief that because the loss factors are of eminent influence in the design/manufacturing and purchasing processes [20], these should be calculated accordingly and the method of calculation should be disclosed. Transparency could lead to win-win scenarios for RUs, transformer manufacturers as well as for independent power producers (IPPs).

Since the majority of loss evaluation methods refer to transformer users who own their own transmission and generation facilities, particular attention should be given where these facilities are 'dis-integrated' into multiple businesses. One should also add the imminent need of independent renewable power producers to define the TOC of their own plants' transformers.

Therefore in the light of disintegrated electricity markets and renewable energy penetration, the standardised methods [1] for evaluating transformer losses may not be suitable for assessing the transformers' life-cycle cost. A preliminary step towards addressing these concerns can be found in [21] where a market-specific loss evaluation technique, for distribution transformers, is presented. Our previous work [12, 13] has proposed a method to evaluate the cost of losses of power transformers in vertically integrated systems. The method proposed, subject to specific modifications, may be applied in

cases where a system is 'dis-integrated' into multiple businesses that operate under the auspices of a regional transmission operators (RTOs). For instance, in the case of transmission companies that receive orders from RTOs to install a set of power transformers and no generation is necessarily added to the system in the conjunction.

However, the decisive step to fully address the emerging challenges would be the proper unbundling of the demand and energy components of the cost of losses. This will firstly ensure that each component is assigned to the appropriate entity that participates in a decentralised energy market. It will subsequently facilitate the understanding of the implications arising when evaluating the losses of transformers serving large scale renewable energy sites. To this extent, Fig. 1 proposes how the concept of loss evaluation should be approached in the modern era of power systems operation.

Thus, within this paper, a method is specifically developed to evaluate the losses (and the TOC) of power transformers serving PV plants, owned by IPPs or RUs. The fact that these transformers are obliged to serve an intermittent energy source sets a special case when it comes to evaluating their life-cycle losses and TOCs. To this extent, we believe that some key modifications are needed to account for an appropriate loss evaluation method of transformers serving other renewable energy sites. This is because the energy generation profile and characteristics of a PV plant, for example, are very different to the specifics of a wind farm. More specifically, the generation profile of a wind farm is extremely volatile and may have multiple ON and OFF states during a day. In a liberalised energy market the hourly profile of wholesale electricity prices may vary significantly, thus complicating the capitalisation of losses of transformers serving such an unbalanced energy source.

## 3 General technical background for PV plant specifics

### 3.1 Large-scale PV plant characteristics

A large-scale PV plant can either be part of a RU or it can be owned by an IPP/investor. The plant is comprised by a large number of PV modules connected in series. These modules are subsequently connected to a centralised inverter that performs a DC to AC conversion. In addition, a step-up power transformer is required to increase the inverter's output voltage to the transmission level voltage. For example, a 4 MW PV plant, supplying at the transmission level, may occupy a field area that equals to 90 000 m<sup>2</sup>. Finally, the transformers serving large-scale PV plants are permanently connected to the main grid, to ensure that the plant is supplied with energy when the PVs are not generating [22]. Based on [22] the transformers remain permanent connected to: (a) satisfy plants' auxiliary losses, (b) track any sunshine and start the PV generation and (c) help the system for reactive power compensation.

### 3.2 PV generation profile

Fig. 2 illustrates a characteristic 24 h generation (pu) profile of a PV plant as obtained by field measurements [23]. This profile is heavily dependent on the daily solar irradiation profile, on the PV panels' effective area as well as on the solar technology used [24]. As illustrated in Fig. 2, the operation of a PV plant can be broadly classified in one of two different 'states'. The sun is down and there is no PV production (non-generating state – NGS). The sun is up and there is – a solar irradiation dependent – PV production (generating state – GS).

Moreover, Fig. 3 illustrates the power-output duration curve of a PV unit over a year, as obtained by field data [23]. It specifically illustrates that the PV plant considered, is at its GS for ~4380 h (i.e. 50%) in a year. The loss evaluation method proposed in this paper is applicable to PV energy producers (independent or part of

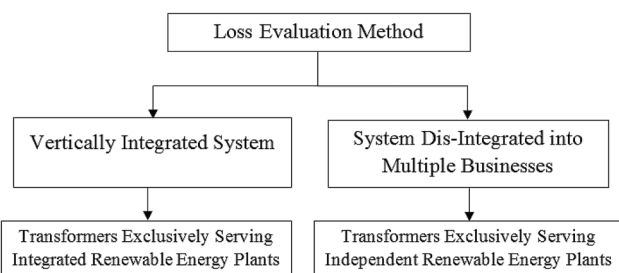


Fig. 1 Concept of loss evaluation in the modern era of systems' operation

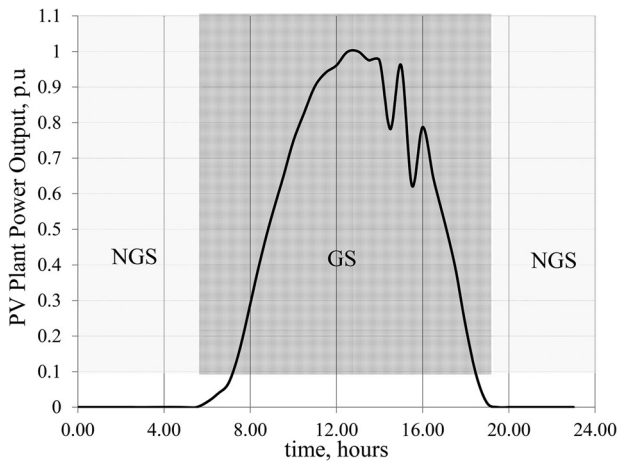


Fig. 2 Two operation states of PV plant power output [23]

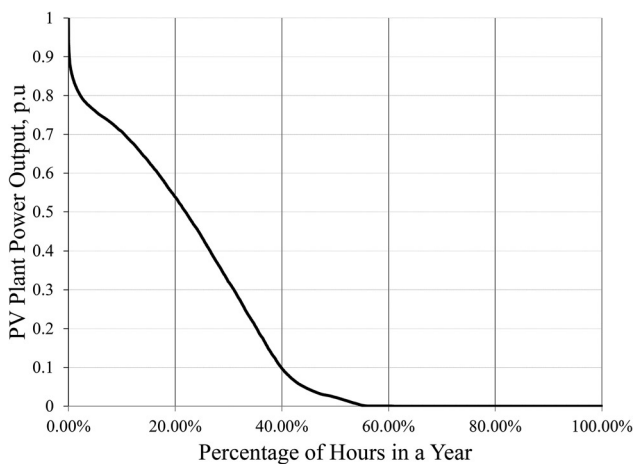


Fig. 3 Load duration curve of a PV unit [23]

a RU) that supply power to the grid through a step-up power transformer.

### 3.3 Size selection of step-up transformers

The size (MVA) selection of a step-up power transformer, suitable for large PV plants, is not a trivial task. It results from a dynamic assessment of several technical and financial constraints. These include, besides the initial installation cost, energy losses due to transformers' efficiency, energy storage systems (if applicable),

core saturation due to harmonics and the reliability of the PV plant connection to the grid [25].

## 4 Description of the methodology

The loss evaluation method proposed in this paper is applicable to PV energy producers (independent or part of a RU) that supply power to the grid through a step-up power transformer. The key element in capitalising the losses in these step-up transformers is the proper definition of the demand and the energy components of the cost of losses. The demand component is the cost of capacity in €/kW to serve the power used by the losses. The energy component is the present value of the energy that will be used by one kilowatt of loss during the life cycle of the plant under study in €/kWh. To this extent, it is important to appreciate exactly how these components should be evaluated, bearing in mind: (a) who is the owner of the PV plant and transformer, (b) what are his/her enforced regulatory obligations and (c) what are the operational and financial characteristics of each individual large-scale PV plant.

### 4.1 Case A: loss evaluation method for independent PV power producers

As previously explained, through the course of the day, a PV plant will most likely operate in one of two different states. When operated in its GS, the PV plant is responsible to cover its own energy needs and losses, as well as to supply energy to the collector grid. When operated in the NGS, its auxiliary needs and losses should be covered from the main grid supply (i.e. buy energy from a supplying utility, when its generation potential is low).

Thus, Fig. 4 illustrates the fundamental logic of the transformers' loss evaluation method applicable to independent PV power producers. It is merely based on the two different PV plant operating states (GS and NGS) which concurrently define two loss evaluation elements. These are the 'PV element' and the 'system element'. Under the 'PV element', the transformer owner should capitalise a significant part of his transformer losses, by considering the overall costs distributed over the lifetime of its PV plant. This calculation should be based on a PV related levelised cost of electricity (LCOE – €/kWh) calculation [26]. The LCOE is often cited as a suitable measure for the cost of electricity produced by different generating technologies. It represents the per-kilowatt-hour cost of building and operating a generating plant over its assumed financial life and duty cycle. The LCOE can account for (a) the cost of capacity to serve the power used by the losses and (b) the value of the energy that will be used by one kilowatt of loss during the life cycle of the plant under study.

Furthermore, under the 'system element', the corresponding transformer losses should be capitalised by considering the electric rates payable to the supplying electric utility. In such a case the evaluation should be based on a levelised figure of the commercial/industrial electricity rates (CIER – €/kWh) that are likely to be charged to the independent owner of the transformer,

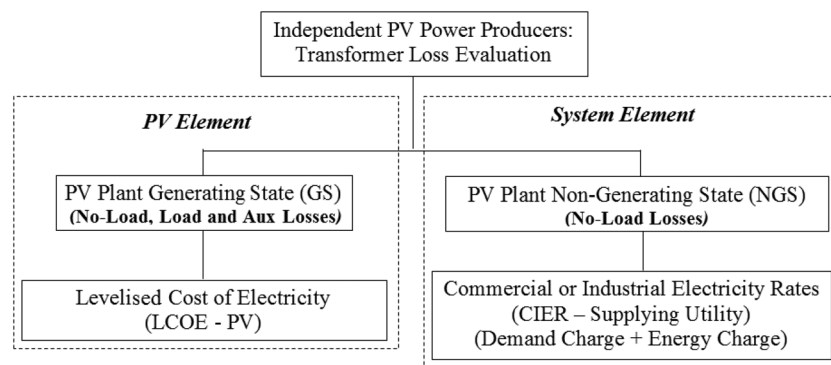


Fig. 4 Loss evaluation method applicable to IPPs

over the life cycle of the PV plant. The CIERs may contain both a demand and an associated energy charge as per a time of use tariff.

Bearing in mind, the principles described above, the total losses (i.e. no-load, load and AUX losses) of the step-up transformer, should be evaluated as per the two elements defined (see Fig. 4). To this end, the NLL should be proportionally evaluated under both the PV and system elements, respectively. The LL and the AUX may be evaluated under the PV element only. This is because the LL and AUX losses will be dominant during the GS of the PV plant. This may be verified by assessing the ratio of the total exported energy during the GS to the total imported energy during the NGS of the PV plant. For example, a 100 MW PV plant may generate ~191.6 GWh of energy per year. The auxiliary energy needs of the PV plant during the NGS would be significantly lower (e.g. lighting, air-conditioning, telemetry/telecommunication systems etc.). A rough estimate suggests that the PV plant may import 124.23 MWh to cover these needs. Thus, 99.9352% of the total annual energy is served during the GS of the PV plant. Since losses are proportional to the square of the load it is logical to assume that the LL and AUX may be evaluated under the PV element only (i.e. during the GS of the PV plant). In contrast the NLL will occur whenever the transformer is energised (i.e. during both GS and NGS).

Hence the two loss evaluation elements (PV and system) should be appropriately levelised to provide a total €-per-kilowatt-year figure as proposed in the following equation

$$\begin{aligned} \text{TCL}_{\text{IPP}} = & [\text{CIER}_{\text{UT}} \times 8760 \times \text{NGS}_{\text{FACTOR}} \times \text{AF}] \cdot \text{NLL} \\ & + [\text{LCOE}_{\text{PV}} \times 8760 \times \text{GS}_{\text{FACTOR}} \times \text{AF}] \cdot \text{NLL} \\ & + [\text{LCOE}_{\text{PV}} \times \text{PQE}^2 \times \text{LLF}_{\text{PV}} \times 8760 \times \text{GS}_{\text{FACTOR}}] \cdot \text{LL} \\ & + [\text{LCOE}_{\text{PV}} \times \text{FOW} \times 8760 \times \text{GS}_{\text{FACTOR}}] \cdot \text{AUX} \end{aligned} \quad (1)$$

This figure represents the TCL ( $\text{TCL}_{\text{IPP}}$ ) and accounts for the sum of the present worth of each kilowatt of transformer loss (NLL, LL and AUX) over the life time of the PV plant. The TOC of the step-up transformer is subsequently defined as the PP of the transformer plus the  $\text{TCL}_{\text{IPP}}$ . Table 1 tabulates the further particulars of the nomenclature used.

Four terms are present in (1), namely the no-load (NLL) cost component that falls under the system loss evaluation element, the no-load loss (NLL) cost component for the PV loss evaluation element, the load loss (LL) cost attributed to PV energy and the load loss auxiliary (AUX) cost component. It is reiterated that the first term reflects on the system loss evaluation element, while the remaining three account for the PV loss evaluation element (see Fig. 4).

## 4.2 PV loss evaluation element

As far as the PV loss evaluation element is concerned, it is important to properly define the  $\text{LCOE}_{\text{PV}}$ ,  $\text{PQE}$  and  $\text{LLF}_{\text{PV}}$  factors found in (1). The PV plant's LOCE ( $\text{LCOE}_{\text{PV}} - \text{€}/\text{kWh}$ ) is the cost of generating PV electricity by considering the overall associated costs (capital and

operating) distributed over the lifetime of the PV plant as given in (2). Hence, it is applied to estimate the present value of the energy (€/kWh) that will be used by one kilowatt of loss during the life cycle of the transformer

$$\text{LCOE}_{\text{PV}} = \frac{\text{IC} + \sum_{y=1}^n \text{OM}_y \cdot \text{pwf}_y}{\sum_{y=1}^n \text{Gpv}_y \cdot \text{pwf}_y} \quad (2)$$

Within (2), IC is the initial PV capacity investment cost in €,  $n$  is the life-cycle evaluation in years,  $\text{pwf}_y$  is the present worth factor of each equivalent year ( $y$ ),  $\text{Gpv}_y$  is the calculated annual PV energy generation in kWh and  $\text{OM}_y$  is the operation and maintenance cost of each year considered in the evaluation.

The annual PV energy generation ( $\text{Gpv}_y$ ), can be calculated as given in (3), by taking into consideration the annual predicted solar potential ( $\text{sp}_y - \text{kWh}/\text{m}^2$ ) and the annual degradation rate ( $n_d$ ) of the maximum rated output power of the PV panels [27]. The total effective area ( $A - \text{m}^2$ ) occupied by the PV panels and the efficiency ( $n_{\text{ef}} - \%$ ) of the PV system are also considered

$$\text{Gpv}_y = A \times \text{sp}_y \times n_{\text{ef}} \times (1 - n_d)^{y-1} \quad (3)$$

Furthermore, the levelised annual peak load of the transformer as per its life cycle ( $\text{PQE}$ ) is calculated based on the following two assumptions: (a) the transformer loading is coincident to the PV plant's power profile and (b) the PV plant's power profile is subject to the PV technology used, as it will be further discussed. It is highlighted that the levelised annual peak load of the transformer ( $\text{PQE}$ ) may concurrently account for the levelised annual transformer losses ( $\text{PQE}^2$ ) as given in the following equation

$$\text{PQE}^2 = \left[ \sum_{y=1}^n P_y^2 \cdot \text{pwf}_y \right] \cdot \text{crf}_n \quad (4)$$

$P_y$  is the annual transformer peak load (pu) that captures the changes in the PV modules' power performance. This performance can be initially improved and subsequently reduced depending on the PV technology used and its corresponding response to the 'light soaking effect' [28]. Moreover, in both (2) and (4) a nominal discount rate ( $d$ ) is utilised [11] to determine (a) the present worth factor ( $\text{pwf}_y$ ) for each year  $y$  considered and (b) the capital recovery factor ( $\text{crf}_n$ ) found in (4) – for the  $n$  years of the evaluation period.

A subsequent factor that needs to be properly defined is the loss load factor of the PV plant system ( $\text{LLF}_{\text{PV}}$ ). It can be considered as the ratio of the PV plant's average power loss ( $L_{\text{average}}$ ) to the PV plant's peak power loss ( $L_{\text{peak}}$ ) over a given period of time ( $T$ ) as in (5). In the absence of any measured loss values ( $L(t)$ ) it may be assumed that the PV losses are proportional to the square of the PV plant's generation load ( $P_{\text{PV}}$ ) as shown in the following equation

$$\begin{aligned} \text{LLF} = \frac{L_{\text{average}}}{L_{\text{peak}}} &= \frac{\int_0^T L(t) dt}{L_{\text{peak}} \times T} \simeq \frac{\int_0^T [P_{\text{PV}}(t)]^2 dt}{(P_{\text{PV PEAK}})^2 \times T} \quad (5) \\ \rightarrow T &= 8760 \times \text{GS}_{\text{FACTOR}} \end{aligned}$$

## 4.3 System loss evaluation element

As far as the system loss evaluation element is concerned (see Fig. 3), it is important (for the PV plant owner) to estimate the CIERs that are likely to be paid to the supplying utility over the life cycle of the PV plant. That is for capitalising the associated portion of the NLL that falls under the NGS of the PV plant.

Therefore the applied CIERs should reflect on that proportion of hours per year that the PV plant is operated in its NGS. To this extent, the CIERs would, most likely, be associated to some demand and energy charges for base load generation (i.e. off-peak or night tariffs). A simple method to calculate the levelised CIER

**Table 1** Nomenclature

$\text{CIER}_{\text{UT}}$ , €/kWh	levelised commercial or industrial electricity rates charged by supplying utility
$\text{LCOE}_{\text{PV}}$ , €/kWh	solar PV LCOE
$\text{NGS}_{\text{FACTOR}}$ , pu	proportion of hours per year that the PV plant is operated in its NGS
$\text{GS}_{\text{FACTOR}}$ , pu	proportion of hours per year that the PV plant is operated in its GS
$\text{PQE}$ , pu	levelised annual peak load of transformer as per its life-cycle
$\text{LLF}_{\text{PV}}$ , pu	PV plant loss load factor
$\text{FOW}$ , pu	average hours per year the transformer cooling is operated
$\text{AF}$ , pu	availability factor, the proportion of time in a year that a transformer is predicted to be energised

rates over the evaluation period is given in the following equation

$$CIER_{UT} = \sum_{y=1}^n [CIER_0 \times (1 + er(y))^{y-1} \times pwf_y] \cdot crf_n \quad (6)$$

where  $CIER_0$  is an average value of the electricity charge rate (demand + energy) that applies in the first year of the evaluation,  $er$ , is a nominal constant or variable escalation electricity charge rate (base load) for each year ( $y$ ) considered in the analysis. The values are levelised through the use of the  $pwf_y$  and  $crf_n$ , as shown in (6).

#### 4.4 Case B: loss evaluation method for RUs

The method proposed for this second case is based on the assumption that a RU possesses its own generation and transmission networks. Thus, the RU should perceive the PV plant as another generation facility, having although different operational and financial characteristics. The arising question is however, what sort of loss evaluation method should be used to calculate the total ownership of the transformer serving this PV plant? To this end the RU could choose to evaluate the losses of such a transformer as it evaluates the losses in any other power transformer installed in its transmission network. This could be achieved by using the methods detailed in [1] or [6]. However, these methods may not reflect the specific conditions that would influence the loss evaluation of a transformer serving a PV plant. Thus the following should be considered:

- (a) PV plant GSs: As in Case A (i.e. for IPPs) the LL, NLL and AUX losses should be capitalised according to the two operating states (GS and NGS) of the PV plant. In fact during the PV GS, the NLL (part), LL and AUX losses of the transformer would be served locally by the PV energy generation, rather than accounted by any other generation facility of the RU that is remotely located.
- (b) Transformer load and PV generation profiles: The transformer loading coincides (as in Case A) to the PV plant's generation profile. Therefore the peak responsibility factor [1] of the PV plant's transformer would be close to unity. This will offer the means to avoid adjusting for the difference between the PV plant's load and the transformer's peak load.
- (c) Energy component of the cost of losses: As previously noted nearly all the LL and AUX losses of the transformer will be served locally by the PV plant. Thus the present value of the energy (€/kWh) that will be used by one kilowatt of loss during the life cycle of the transformer should be based on the LCOE for PV generation.
- (d) Demand and energy components of the cost of losses for NLL: The NLL during the NGS of the PV plant should be evaluated as per an appropriate demand ( $D_{BASE}$ ) and energy ( $E_{BASE}$ ) charges for the cost of losses. Thus, they should account for the related

costs and energy for base load generation. These costs should be classified under the RUs base load generation and transmission expenses (capital and operating), as will be further discussed.

Bearing in mind the above discussion, Fig. 5 illustrates the PV plant's transformer loss evaluation method proposed for RUs. The method accounts for all four conditions (a)–(d) detailed above.

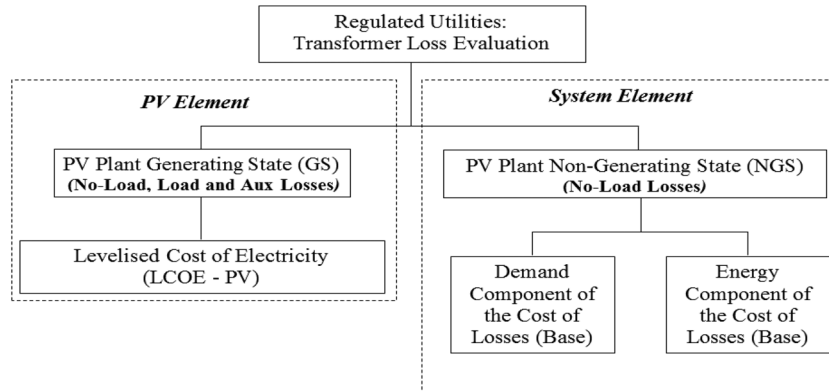
It is obvious that the methodology illustrated in Fig. 5 is similar to methodology proposed for the IPPs (Fig. 4), as far as the 'PV element' is concerned. The fundamental difference arises in the 'system element' where the evaluation is based on the demand ( $D_{BASE}$ ) and energy ( $E_{BASE}$ ) components of the cost of losses attributed to the base load generation specifics of the RU.

Therefore the TCL ( $TCL_{RU}$ ) of a power transformer serving a PV plant that is owned by a RU is given in (7). The TOC of the transformer is defined as the PP of the transformer plus the  $TCL_{RU}$ . Table 2 tabulates the further particulars of the nomenclature used. The two components  $D_{BASE}$  and  $E_{BASE}$  appearing in (7) are explicitly defined in Table 2. As part of our previous work, a comprehensive method to calculate these two components is presented in [12], whereas in [13] a numerical evaluation is provided for a specific small-scale system.

$$\begin{aligned} TCL_{RU} = & [D_{BASE} + 8760 \times NGS_{FACTOR} \times AF \times E_{BASE}] \cdot NLL \\ & + [LCOE_{PV} \times 8760 \times GS_{FACTOR} \times AF] \cdot NLL \\ & + [LCOE_{PV} \times PQE^2 \times LLF_{PV} \times 8760 \times GS_{FACTOR}] \cdot LL \\ & + [LCOE_{PV} \times FOW \times 8760 \times GS_{FACTOR}] \cdot AUX \end{aligned} \quad (7)$$

**Table 2** Nomenclature

$D_{BASE}$ , €/kW	annual fixed cost (associated with the generation and transmission category's related expenses of the RU) required to serve a kW of loss occurring at the time of the PV plant's NGS (e.g. base load demand)
$E_{BASE}$ , €/kWh	annuitised variable cost (associated with generation and transmission category's related expenses of the RU) required to serve the energy consumed by the losses occurring at the time of the PV plant's NGS (e.g. base load demand)
$LCOE_{PV}$ , €/kWh	solar PV LCOE as given in (2)
$NGS_{FACTOR}$ , pu	proportion of hours per year that the PV plant is operated in its NGS
$GS_{FACTOR}$ , pu	proportion of hours per year that the PV plant is operated in its GS
$PQE$ , pu	levelised annual peak load of transformer as per its life cycle as given in (4)
$LLF_{PV}$ , pu	PV plant loss load factor as given in (5)
$FOW$ , pu	average hours per year the transformer cooling is operated
$AF$ , pu	availability factor, the proportion of time in a year that a transformer is predicted to be energised



**Fig. 5** Loss evaluation method applicable to RUs

## 5 Application of method and numerical results

The proposed methods are numerically evaluated by using a set of realistic data and characteristics. Table 3 tabulates the technical and financial specifics of the PV plant considered in this evaluation example.

Thus, by the use of data tabulated in Table 3 and the method described in (3), the annual calculated PV energy generation for 30 years is shown in Table 4.

Further on, by combining the data provided by both Tables 3 and 4, as dictated in (2) the PV Plant's LCOE ( $LCOE_{PV}$ ) is calculated at 0.1784 €/kWh. A further set of data referring to a suitable step-up transformer is given in Table 5. The value of the levelised annual peak transformer losses ( $PQE^2$ ) can be calculated as defined in (4), based on a series of estimates of the transformer's annual peak load, over its life cycle.

Finally, Table 6 tabulates some example values for  $CIER_{UT}$  as well as for demand ( $D_{BASE}$ ) and energy ( $E_{BASE}$ ) charges that apply to a small-scale real system [7].

Hence, the TCL ( $TCL_{IPP}$ ) generic formula (1) defined for IPPs is numerically evaluated as given in the following equation

$$TCL_{IPP} = 1297.16 \cdot NLL + 125.98 \cdot LL + 237.43 \cdot AUX \quad (8)$$

Similarly the TCL ( $TCL_{RU}$ ) formula (7) applicable to a RU is numerically evaluated in the following equation

$$TCL_{RU} = 1365.58 \times NLL + 125.98 \times LL + 237.43 \times AUX \quad (9)$$

Subsequently, the TOC of the transformer is given in (10) and (11)

**Table 3** Technical and financial data – PV plant specifics

PV plant capacity, MWp	100
life-time evaluation, years	30
PV initial investment, IC – €, million	300
annuitised operation and maintenance cost, €, million	3.9
annual PV panels power degradation rate ( $n_d$ ), % [27]	0.50
total PV panels effective area ( $A - m^2$ ) [27]	1 055 600
PV module efficiency ( $n_{ef} - \%$ ) [27]	14.70
annual solar potential ( $kWh/m^2$ ) [23]	1300
proportion of hours per year that the PV plant is operated in its GS ( $GS_{FACTOR} - pu$ ) [23]	0.5064
proportion of hours per year that the PV plant is operated in its NGS ( $NGS_{FACTOR} - pu$ ) [23]	0.4936
PV plant loss load factor ( $LLFPV - pu$ ) [23]	0.2222
nominal discount rate ( $d_i$ ), % [9]	10

**Table 4** Annual energy generation for the 100 MWp PV plant

Year	Calculated PV energy generation, kWh
1	191638902
2	190680707.49
3	189727303.95
4	188778667.43
.	.
.	.
30	165711640.04

**Table 5** Transformer loading and cooling characteristics

transformer availability factor ( $AF - pu$ ) [1]	0.99
transformer cooling operation per year ( $FOW - pu$ ) [1]	0.30
initial transformer annual peak load ( $Po - pu$ )	0.80
levelised annual peak losses of transformer as per its life cycle ( $PQE^2 - pu$ )	0.7164

for the two cases examined, by considering a given PP

$$TOC_{IPP} = PP + TCL_{IPP} \quad (10)$$

$$TOC_{RU} = PP + TCL_{RU} \quad (11)$$

### 5.1 PV specific loss figures against system loss figures

To demonstrate the difference between the system loss evaluation method [12] and the PV specific method (9) proposed in this paper, the following example is considered. It is highlighted that system loss evaluation method pertains to 'system' unit costs, whereas the PV specific method pertains to PV related costs. In the context of this work, a 'system' includes all power related facilities from generation down to transmission level.

In our previous work, we have evaluated the loss factors (NLL, LL and AUX) of power transformers under the specific characteristics of a small-scale real system, where the generation and transmission facilities are possessed by a RU [13]. These loss factors are tabulated in Table 7. Thus the RU may choose to apply these factors to evaluate the losses of a transformer that is entitled to serve one of its owned PV plants. Alternatively, the utility may choose to utilise the loss factors derived under the PV specific method that is introduced in this paper. These are the loss factors appearing in (9) and are also tabulated in Table 7.

To facilitate a valid comparison the loss factors shown in Table 7 are applied to a set of an example selling prices (SP) and guaranteed losses (see Table 8), assuming that these are the bid offers of different transformer manufacturers. In this example, all four bids are assumed to represent size-adequate power transformers with comparable features.

Therefore Table 9 tabulates the calculated TOC ( $TOC_{RU}$ ) of each of the bid offers described above. The results show that when the loss factors of the system loss evaluation method [13] are applied, the offering from manufacturer B is seen to be the most cost-effective. However, when the loss factors of the PV specific method (9) are applied then the offering of manufacturer D appears to be the most cost effective. Although the absolute values in Table 9 should be interpreted with care, as these are quite dependent on the specifics of each PV plant, it is clearly demonstrated that under certain conditions, the TOC of the transformer serving a PV system can be different depending on which method of loss evaluation is applied.

**Table 6** Example values of system charges

$D_{BASE}$ , €/kW <sup>a</sup>	140.30
$E_{BASE}$ , €/kWh <sup>a</sup>	0.103
Levelised commercial or industrial electricity rates charged by supplying utility ( $CIER_{UT} - €/kWh$ ) <sup>b</sup>	0.12

<sup>a</sup>Calculated as per methodology defined in [12] and evaluated as per the system's characteristics described in [13].

<sup>b</sup>Assumed value.

**Table 7** Benchmarking of loss factors

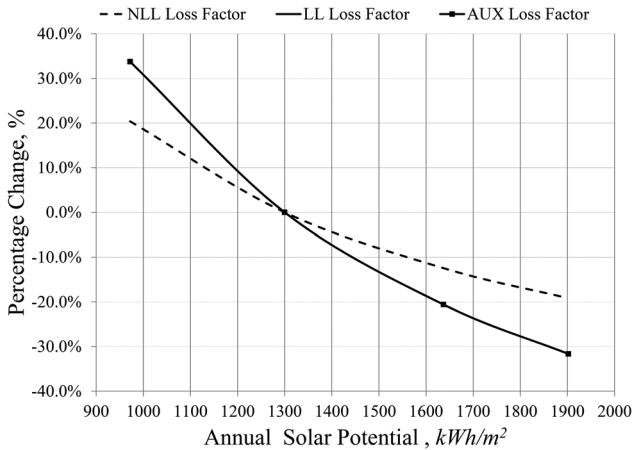
Loss factors	System method [12]	PV specific method (9)
NLL loss factor, €/kW	1018.48	1365.58
LL loss factor, €/kW	71.75	125.98
AUX loss factor, €/kW	417.62	237.43

**Table 8** Example of selling prices and guaranteed losses

Manufacturer	SP, €	NLL, kW	LL, kW	AUX, kW
A	1 325 000	50	290	8
B	1 315 000	53	350	9
C	1 305 000	61	410	12
D	1 340 000	45	200	3

**Table 9** Evaluation of TOC of transformers

Manufacturer	TOC <sub>RU</sub> , €	
	System method [12]	PV specific method (9)
A	1400071.46	1431712.64
B	1397849.46	1433605.61
C	1401555	1442801.34
D	1410647.64	1427359.39

**Fig. 6** Influence of annual solar potential on calculated loss factors (the LL and AUX loss factors are identically reliant on the annual solar potential)

### 5.2 Effect of solar irradiation – a sensitivity analysis

One of the dominant factors in the loss evaluation method proposed in this paper is the LCOE for the PV generation. This is because the LCOE relies on the PV energy output as determined by the available solar resources (i.e. the annual solar potential).

To address this influence, a sensitivity analysis is performed to illustrate the percent variation in the calculated loss factors (NLL, LL and AUX) over a range of different annual solar potential values (kWh/m<sup>2</sup>). Hence, Fig. 6 illustrates the percent change in the calculated loss factors that apply for the RU case study (Case B). These are the loss factors appearing in (9) and have been calculated for an annual solar potential of 1300 kWh/m<sup>2</sup>. The results in Fig. 6, (which are benchmarked over the 1300 kWh/m<sup>2</sup> case), show that the LL and AUX loss factors are identically influenced by the annual solar potential, while the NLL factor is less influenced. For example, there is a +36% increase in the LL and AUX loss factors when the available annual solar potential changes from 1300 to 972 kWh/m<sup>2</sup>. In the case of the NLL loss factor, a +20% change is observed. This is expected, since the LL and AUX are heavily influenced by the calculated LCOE value. The NLL loss factor is less influenced owing to the fact that it is partly determined by some of the RUs demand and energy components of the cost of losses. These components are independent from the available annual solar potential.

Finally, it can be shown that under the same conditions tabulated in Tables 3–6, but with an annual solar potential of 1902 kWh/m<sup>2</sup> (instead of 1300 kWh/m<sup>2</sup>), the most cost effective offering, out of those tabulated in Table 8, changes (see Table 9—third column) from manufacturer D to manufacturer A.

## 6 Conclusions

This paper has introduced a method for evaluating the losses of transformers serving large-scale PV applications. The method is proposed separately for IPPs and for RUs. Under each of the two cases, the capitalisation of losses accounts for the appropriate

capital and future operating costs of the transformer over its lifetime brought back into a present day cost.

The specific operational characteristics of a PV plant have been integrated in the proposed method through two operating states (GS and NGS). A further element that influences the proposed loss evaluation method is the fact that the losses in these transformers will be served locally by the PV plant, rather than remotely by any other generation facilities. Hence the LCOE for PV generation is utilised to estimate the cost value of the energy that will be used by the losses of the transformer. Furthermore, it is clearly demonstrated that under certain conditions, the TOC of the transformer serving a PV system can vary depending on which method of loss evaluation is employed. Finally, it is shown that the annual solar potential has an impact on the loss factors calculation. This is a feature that should be properly accounted for, as it may affect the tender evaluation processes to select the transformer that has the lowest TOC over its lifetime.

## 7 Acknowledgment

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