Hidden cross-subsidies of net energy metering practice: energy distribution losses reallocation due to prosumers’ and storsumers’ integration

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Abstract: This study evidently discloses a hidden cross-subsidy that is embedded in the traditional net energy metering (NEM) practice with regard to how energy distribution losses are reallocated when NEM customers (i.e. prosumers and storsumers) are integrated at the distribution level. This cross-subsidy springs from the fact that the NEM customers receive a one-for-one credit for the energy they export to the grid against their time-diversified consumption that is imported from the grid. Even though such practices are appealing due to their relatively simple form, it is shown that this one-for-one credit exchange may entail additional losses-related costs to the ones recovered from NEM customers through their net billing processes. Subsequently, a different net billing scheme is examined, bearing in mind the limitations of the existing metering infrastructure at the distribution level, in order to assess the effect of alternative practices on this hidden cross-subsidy. Both practices are applied on a real system that benefits from prosumers and storsumers. For the scope of this work, the authors label storsumers as retail grid-connected customers that exhibit increased energy controllability over their net demand profiles, owing to the pairing of their photovoltaic systems with energy storage devices.

1 Introduction

Net energy metering (NEM) practices that support rooftop photovoltaic (PV) rely on compensation mechanisms based on retail tariffs. This is because NEM prosumers receive a one-for-one credit for the electricity they export to the grid against their time-diversified consumption that is imported from the grid [1]. The term prosumers (i.e. wordplay between the words ‘producers’ and ‘consumers’) is currently widely adopted to describe a class of electricity customers that simultaneously act as PV energy producers and grid-energy consumers. Even though NEM practices are appealing to prosumers, due to their relatively simple form, there exist major concerns regarding these practices’ impact on utilities revenue collection mechanisms. The concern is mainly that the NEM practice entails utility incurred costs that are in addition to the electricity costs recovered from NEM customers. Recent studies have demonstrated this financial implication – also known as the electricity rate death spiral [2, 3] – on utility fixed costs recovery. As a result, rate re-design endeavours are being undertaken in order to minimise such cost-shifting issues through alternative ways of recovering fixed costs, e.g. increased fixed customer charges or demand (i.e. per kVA) charges [4, 5]. The latter suggests that fixed cost recovery could, in principle, be decoupled from energy consumption volumes.

However, a subsequent concern that has received no thorough attention yet – but will persist even if fixed costs are recovered independently from the energy volumes of customers – pertains to the losses-related expenditures of utilities accommodating NEM prosumers (i.e. prosumers with net-energy metered electricity bills). We will elaborate this by discussing and demonstrating, through the course of this paper, cases where NEM prosumers cause utilities to incur more losses than those reflected in their net billing amounts. This inevitably entails additional costs caused by NEM prosumers but are borne by regular customers that do not have net-metered PV systems.

Moreover, the aforementioned rate re-design efforts may provide incentives for the uptake of yet another energy class of retail customers. Thus, besides NEM prosumers, we investigate potential implications associated with an emerging class of energy users that we label, for the scope of this work, as NEM storsumers. Storsumers fundamentally amalgamate the simultaneous actions to ‘store’ their excess solar energy and ‘consume’ it at later times. This new label is introduced to directly distinguish this class of energy users from typical NEM prosumers who do not have storage capabilities.

1.1 Specific contribution of this work

The primary objective of this paper is to evidently disclose the hidden financial implication of the NEM practice with regard to the recovery of load losses-related expenditures of utilities. In general, utilities incur non-technical (e.g. theft) and technical losses [6]. Technical losses are further divided into no-load and load losses [6]. Load losses are dependent on power flows and thus are affected by the integration of NEM customers. On the contrary, non-technical and no-load losses are considered independent from power flows and hence are not within the scope of the present analysis.

The need for defining a diligent as well as practical loss allocation practice rests with the limitations of the existing metering and monitoring infrastructure at the low voltage (LV) level. Smart grid concepts that allow real-time monitoring of line flows, demand profiles and LV distribution network configuration information to support more sophisticated losses pricing schemes, e.g. marginal or flow-tracing methods [7], are still far from being practically and cost-effectively implementable. This is due to the existence of significant computational, techno-economical, regulatory and behavioural obstacles that tamper the optimism of rapidly migrating to the smart grid era [8]. Therefore, until advanced metering and monitoring capabilities become a factual and not a theoretical reality, cross-subsidies or hidden financial implications associated with the NEM practice will persist.

Bearing the above remarks in mind, this paper associates: (i) the effect – on the incurred energy distribution losses – of small-scale distributed energy resources (DER) such as PV and storage units with (ii) the compensation mechanisms entailed by the traditional NEM practice (i.e. one-for-one credit exchange). To this extent, the present work differs from other relevant archived literature (see [6,
2 Revealing the hidden financial implication of NEM practice on energy distribution losses reallocation

2.1 Losses allocation through retail rates and one-for-one credit exchange practice for NEM customers

Utilities incur losses-related costs when distributing electricity and, therefore, these have to be recovered by appropriately charging their customers. To this extent, the most commonly met practice for allocating and recovering losses’ costs from electricity end-users is the pro rata method [7, 11, 15]. By definition, the pro rata method would allocate the total losses of the system to customers based on their individual active power demand level, ignoring their relative location on the grid [7, 11]. This is mathematically expressed in (1), where AL refers to the losses allocated to customer \( n \) from the total number of customers (NoC) whereas TL and \( D \) are the total incurred losses and demand level at time interval \( t \), respectively.

\[
AL_n^t = TL \times \frac{D_n^t}{\sum_{i=1}^{n} D_i^t}
\]  

Thus, the total allocated losses (TAL) to each individual consumer \( (n) \) during an examination time period \( (T) \) would be the sum of his allocated losses at each time interval as expressed in the following equation:

\[
TAL_n = \sum_{t=1}^{T} AL_n^t
\]  

However, the existing metering infrastructure at the distribution level provides measured data with limited temporal resolution. Specifically, a significant number of utilities are able to obtain information regarding their customers’ individual behaviour merely on a volumetric basis (i.e., consumed kWh per billing period). This limitation has forced such utilities to adopt variations of the pro rata method, such as the one described in (3) (e.g., [17, 18]). This equation shows that the incurred energy losses allocation could be achieved through the use of distribution loss factors (DLFs) [15]. Hence, DLFs account for the average energy losses that are incurred as electricity travels through the distribution system to reach the customers’ premises [15].

\[
DLF = \frac{\text{[Energy losses]}}{\text{[Energy sales]}} = \frac{\text{[Total imported energy]}}{\text{[Total exported energy]}}
\]  

At this point, it should be made clear that demand variations will result in varying losses and, consequently, to different DLF calculation due to the fact that losses are dependent on power levels, not merely on energy levels [7, 11]. To deal with this effect, the usual regulatory approach is to set a standard DLF which will be kept constant for a specified time period based on relevant assumptions (resulting either from forecasting or historical data) with respect to the expected conditions of the system [6]. Thus, utilities have to procure adequate energy to cover the actual system losses but they receive compensation that is equal to the metered final electricity sales (kWh) times a standard DLF [6]. It should, however, be noted that the subsequent analysis of this paper refers to the planning stage, i.e., when studying the expected conditions of the system in order to determine the corresponding DLF and losses allocation strategy.

DLFs are used in billing arrangements as per-unit scaling factors that are applied to the metered energy (i.e., imported energy or, equivalently, energy sales – in kWh) of each customer, thus yielding their billed consumption (e.g., [19]). Therefore, the billed consumption (in kWh) of each consumer, which would be used to calculate his energy charges, is shown in the following equation:

\[
\text{[Billed consumption]} = \text{[Imported energy]} + \text{[Allocated losses]}
\]  

(4)

Where the term allocated losses (in kWh) is calculated as in the following equation:

\[
\text{[Allocated losses]} = \text{DLF}_1 \times \text{[Imported energy]}
\]  

(5)

Bearing in mind the formulations shown in (3)–(5), the billed consumption formulation shown in (6) resembles the traditional ‘net energy’ metering practice. That is, NEM customers receive a one-for-one credit exchange for the electricity they export to the grid against their consumption that is imported from the grid. This exchange is a volumetric aggregation process (e.g., on a monthly basis) that essentially ignores the time diversity between the import and export activities of NEM customers.

\[
\text{[Billed consumption]} = \text{[Imported energy]} - \text{[Allocated losses]}
\]  

(6)

This one-for-one credit exchange suggests that utilities accommodating NEM customers would calculate their DLFs for all their customers based on the formulation shown in (7) in order to recover the entirety of the incurred energy losses. Within (7), the term ‘total imported energy’ refers to the cumulative amount of energy (in kWh) that flows from the grid to all utility customers. Conversely, the term ‘total exported energy’ refers to the cumulative amount of energy (in kWh) that explicitly flows from NEM customers to the grid.

\[
\text{DLF}_i = \frac{\text{[Energy losses]}}{\text{[Net energy sales]}} = \frac{\text{[Total imported energy]}}{\text{[Total exported energy]}}
\]  

(7)

Therefore, with reference to (6) and (7) the term allocated losses would be calculated as in the following equation:

\[
\text{[Allocated losses]} = \text{DLF}_i \times \text{[Imported energy]}
\]  

(8)

Thus, it should be noted that by virtue of the traditional NEM practice: (i) DLF depends on the net sales of a utility, (ii) DLF is uniformly used for all grid-connected customers (i.e., both regular and NEM customers) and (iii) the one-for-one credit exchange ignores the time-diversified interaction of NEM customers with the grid which inevitably incurs losses and, therefore, has a hidden impact that is not currently accounted in the DLFs calculation nor the billed consumption of all customers.

2.2 Small-scale example

To make the losses-related hidden impact of the current NEM practice more explicit, a small-scale example is hereby modelled. The aim of this example is to qualitatively demonstrate the hidden financial implication when NEM prosumers and subsequently NEM storsumers are integrated in an LV feeder. The example is based on a simple four-node feeder shown in Fig. 1. The simple...
four-node feeder is simulated under three different scenarios. The first scenario (Fig. 1a) serves as the benchmark case and considers a pure consumer at node C and a pure consumer at node D. The second scenario (Fig. 1b) pertains in having the same pure consumer at node D (as in the first scenario) and a NEM prosumer at node C. Finally, the third scenario (Fig. 1c) benefits from the same pure consumer at node D (as in the first scenario) but a NEM storsumer at node C.

2.2.1 Scenario 1 (SC1-benchmark) – losses incurred by pure consumers: The benchmarking scenario (SC1) considers the case where the consumer at node C constantly demands one unit of electricity ($D_C$ in kW) whereas the consumer at node D constantly demands two units of electricity ($D_D$ in kW) over a specified period ($T$), for example 24 h. The demand profile of consumer C is marked in Fig. 2, for illustration purposes. For facilitating the subsequent analysis, the 24 h period is divided into five segments, $\Delta T_1$ to $\Delta T_5$ (see Fig. 2). This time division applies to all scenarios (SC1–SC3). To this extent, Table 1 summarises the volumetric grid interaction of both consumers in SC1, which corresponds to the data that would be available to the utility in order to determine the DLF.

Therefore, to simulate the total losses ($\sum P_L$) incurred on the feeder (Fig. 1a) for each time step $t$, the formulation shown in (9) is used. For simplicity, line losses are assumed to be equal to $aJ^2$ where $a$ is determined by the voltage and resistance of the respective line (i.e., AB, BC, BD) whilst $J^2$ is the square of the power flowing through that line

$$\sum_{t=1}^{T} P_L = \sum_{t=1}^{T} [(J'_{AB})^2 \times a_{AB} + (J'_{BC})^2 \times a_{BC} + (J'_{BD})^2 \times a_{BD}]$$

(9)

Based on (9), Table 2 shows the calculated total losses for SC1 as described above.

2.2.2 Scenario 2 (SC2): losses incurred by NEM prosumer and pure consumer: The second scenario considers the case where the consumer at node D constantly demands two units of electricity over a 24 h period ($T$), as in SC1, whereas the customer at node C becomes a NEM prosumer. The net demand profile of the NEM prosumer at each time step $t$ is simulated as per (10), and it is also shown in Fig. 2

$$ND'_{Prosumer} = D' - G'_{PV}$$

(10)

With reference to (10), the net demand (ND) of the NEM prosumer is calculated as per his actual demand ($D$) minus the PV generation ($G_{PV}$) at each time step ($t$). In SC2, the NEM prosumer imports electricity during $\Delta T_1$ and $\Delta T_4 + \Delta T_5$. Conversely, the NEM prosumer exports electricity during $\Delta T_2 + \Delta T_3$. It should be noted that the profile shown in Fig. 2 assumes that the NEM prosumer benefits from a PV system that constantly generates two units of electricity for 12 h. Table 3 summarises the grid interaction (i.e., import/export) activities of both the NEM prosumer and the consumer in order to calculate the net sales of the utility in SC2.

Subsequently, to calculate the total losses incurred on the feeder shown in Fig. 1b, at each time step $t$, the formulation shown in (11) is used whilst Table 4 tabulates the SC2 losses-related results

$$\sum_{t=1}^{T} P_L = \sum_{t=1}^{T} [(J'_{AB})^2 \times a_{AB} + (J'_{BC})^2 \times a_{BC} + (J'_{BD})^2 \times a_{BD}]$$

$$J'_{AB} = J'_{BC} + J'_{BD} \quad J'_{BC} = D'_{Prosumer} \quad J'_{BD} = D'_{D}$$

$$a_{AB} = a_{BC} = a_{BD} = a = 0.01$$

(11)

2.2.3 Scenario 3 (SC3) – losses incurred by NEM storsumer and pure consumer: The third scenario considers the case where the consumer at node D constantly demands two units of electricity over a 24 h period ($T$), whereas the customer at node C now becomes a NEM storsumer, i.e., a grid-connected customer that benefits from a PV system paired with a battery energy storage

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Calculated losses during each time segment in SC1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time period</td>
<td>$\Delta T_1$ (6 h)</td>
</tr>
<tr>
<td>SC1 losses, kWh</td>
<td>0.84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Volumetric grid interaction for SC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node C</td>
<td>Node D</td>
</tr>
<tr>
<td>Imported energy, kWh</td>
<td>12</td>
</tr>
<tr>
<td>Exported energy, kWh</td>
<td>12</td>
</tr>
<tr>
<td>Net sales, kWh</td>
<td>(48 + 12) − (12) = 48</td>
</tr>
</tbody>
</table>
system (BESS). The NEM storsumer's net demand profile is generically simulated as shown in the following equation:

\[ ND_{\text{Storsumer}} = D - G_{\text{PV}} + P_{\text{BESS}} \]

\[ P_{\text{BESS}} > 0 \text{ (when charging)} \]

\[ P_{\text{BESS}} < 0 \text{ (when discharging)} \]

\[ P_{\text{BESS}} = 0 \text{ (when idle)} \]  \hspace{1cm} (12)

Within (12), the net demand (ND) of the NEM storsumer is calculated as the actual demand (D) minus the PV generation (G_{PV}) plus the BESS's power at each point in time (t). As shown in (12), the BESS's power is positive when it charges, negative when it discharges and zero when it is idle. A detailed formulation of the BESS utilised in the modelling process can be found in [20].

The simulated NEM storsumer's net demand profile is superimposed in Fig. 2. The profile shown suggests that the NEM storsumer imports electricity during ΔT_1. During ΔT_2, its excess PV generation is directly exported to the grid during ΔT_3. Subsequently, during ΔT_4 (i.e. PV generation is not available), the BESS discharges energy to cover the NEM storsumer's demand. When the BESS is discharged, importing electricity from the grid is resumed during ΔT_5. Table 5 tabulates the grid interaction of the NEM storsumer and the pure consumer in order to calculate the utility net sales in SC3.

Table 5 Volumetric grid interaction for SC3

<table>
<thead>
<tr>
<th>Node</th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>imported kW</td>
<td>9</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>exported kW</td>
<td>9</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>net sales kWh</td>
<td>(48 + 9)−9 = 48</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.3 Implication of the one-for-one credit practice on energy losses reallocation

Table 6 shows that the total incurred losses in SC1 (i.e. 3.36 kWh) are allocated to the two pure consumers at nodes C and D as per their cumulative imported energy. That is, 1.12 and 2.24 kWh, respectively. In SC2, the total incurred losses are 2.4 kW (less than in SC1). However, the DLF under SC2 is 0.05. This suggests that the DLF has been increased although the absolute incurred losses of the system have been reduced. The impact is that the pure consumer at node D, even though maintaining the same demand pattern in both SC1 and SC2, is forced under SC2 to pay 7% more for losses when compared with SC1 (i.e. 2.4 kWh compared with 2.24 kWh).

The above example, although small in scale, clearly reveals that the current NEM practice (i.e. one-for-one credit exchange) may entail losses-related costs that are in addition to the ones included in the billing process of NEM customers (prosumers or storsumers) and, consequently, are borne by regular customers. In other words, it illustrates that hidden losses-related cross-subsidies may arise as NEM customers penetrate the system due to the one-for-one credit exchange of the traditional NEM practice.

2.4 Sensitivity of arising implication to network topology

Table 7 DLF calculation for the three examined scenarios under the one-for-one practice

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>formula used</td>
<td>(3)</td>
<td>(7)</td>
<td>(7)</td>
</tr>
<tr>
<td>DLF (per unit)</td>
<td>0.0467</td>
<td>0.05</td>
<td>0.0475</td>
</tr>
</tbody>
</table>

The results of this table (i.e. allocated losses) correspond to the specific net demand profiles shown in Fig. 2. If different net demand profiles were used, the allocated losses (kwh) calculated would vary accordingly.

Table 8 Allocated losses for each scenario under the one-for-one practice

<table>
<thead>
<tr>
<th>Scenario</th>
<th>SC1</th>
<th>SC2</th>
<th>SC3</th>
</tr>
</thead>
<tbody>
<tr>
<td>allocated losses kWh</td>
<td>node C</td>
<td>1.12</td>
<td>0</td>
</tr>
<tr>
<td>node D</td>
<td>2.24</td>
<td>2.40</td>
<td>2.28</td>
</tr>
</tbody>
</table>

The above example, although small in scale, clearly reveals that the current NEM practice (i.e. one-for-one credit exchange) may entail losses-related costs that are in addition to the ones included in the billing process of NEM customers (prosumers or storsumers) and, consequently, are borne by regular customers. In other words, it illustrates that hidden losses-related cross-subsidies may arise as NEM customers penetrate the system due to the one-for-one credit exchange of the traditional NEM practice.
Following the analysis of Sections 2.3 and 2.4, an alternative exchange practice that could be adopted is hereby presented, bearing in mind the network topology may have an impact on the losses-related NEM implication. More explicitly, the alternative DLF calculation can be derived when considering the following factual principles. Point 1: at the distribution level, the current metering capabilities of utilities allow them to measure the cumulative imported energy needs of all of their customers. Point 2: NEM customers benefit from bidirectional electricity meters that are able to record both their cumulative imported and exported energy amounts.

By capitalising on the above two points, the DLF calculation could be performed as in the following equation:

$$DLF = \frac{[\text{Energy losses}]}{[\text{Total imported energy}]}$$  \hspace{1cm} (14)$$

Within (14), the term ‘total imported energy∗’ refers to the cumulative amount of energy that flows from the grid to all customers’ premises (including NEM customers). Thus, the DLF shown in (14) takes into account the fact that NEM customers continue to import energy from the grid, similarly to other pure consumers. However, an important note is that the ‘total imported energy∗’ inherently excludes the self-consumed energy of NEM customers. The self-consumed energy of NEM customers refers to the direct satisfaction of their demand through the use of their own resources (i.e. PV and BESS systems). Through the self-consumed energy, NEM customers effectively reduce the amounts of energy that they import from the grid. Thus, the direct self-consumption through privately-owned DER (PV or PV + storage units) does not incur any energy losses since the use of grid is avoided.

To this extent, the alternative, ‘one-for-one plus losses’ practice takes the above remarks into account and uses the DLF calculation shown in (14) to introduce a revised energy netting process for NEM prosumers and NEM storsumers as per the following equation:

$$[\text{Billed consumption}] = [\text{Imported energy}] + [\text{Allocated losses}] - [\text{Exported energy}]$$  \hspace{1cm} (15)$$

where the term allocated losses is now calculated as in the following equation:

$$[\text{Allocated losses}] = DLF \times [\text{Imported energy}]$$  \hspace{1cm} (16)$$

Based on (16), the allocated losses to NEM customers are now a function of their imported energy volume and not of their aggregate net energy (as in (8)). Table 10 shows the comparison between the current and the alternative practice in: (i) DLF calculation, (ii) allocated losses and (iii) billed consumption. The comparison is undertaken for SC2 and SC3 that account for the integration of NEM prosumers and NEM storsumers, respectively.

Table 10 shows that under the one-for-one credit practice that is collectively embraced by (6)–(8) the NEM customer at node D (i.e. prosumer in SC2 and storsumer in SC3) would be allocated no losses due to the fact that he exhibits a zero net energy. Thus, all incurred losses in the feeder would be recovered by the pure consumer at node D. Conversely, under the alternative practice, that is collectively embraced by (14)–(16) the NEM customer at node C (i.e. prosumer in SC2 and storsumer in SC3) would be allocated 0.48 and 0.36 kWh, respectively. Under this practice, the pure consumer at node D would be now assigned 1.92 kWh of losses. This is ~14.29% less than the benchmark scenario SC1 (i.e. 2.24 kWh). Table 11 provides a comparison of the allocated losses to the pure consumer (at node D) under each scenario.

### 3 Realistic case study

As previously stated, the actual impact of NEM customers on the incurred losses of distribution feeders is a function of several factors and, hence, is deemed as system specific. The key factors are: (i) the penetration level of NEM customers, (ii) the interaction of NEM customers with the grid and (iii) the feeder’s technical

| Table 9 | Allocated losses per each examined scenario for varying \( a_{AB} \) values |
|---------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| \( a_{AB} \) | SC1 | \( \text{Node C} \) | \( \text{Node D} \) | \( \text{SC2} \) | \( \text{Node C} \) | \( \text{Node D} \) | \( \text{SC3} \) | \( \text{Node C} \) | \( \text{Node D} \) |
| 0.01 (Reference) | 1.12 | 2.24 | 0 | 2.4 | 0 | 2.28 |
| 0.005 | 0.76 | 1.52 | 0 | 1.8 | 0 | 1.71 |
| 0.02 | 1.84 | 3.68 | 0 | 3.6 | 0 | 3.42 |

| Table 10 | Comparison of the one-for-one and one-for-one plus losses NEM practices |
|----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Scenario | NEM practice | SC2 | SC3 |
|----------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| Comparison of calculated DLF | \( DLF \) (per unit) | 0.05 | 0.04 | 0.0475 | 0.04 |
| Comparison of allocated losses, kWh | \( \text{Node C} \) | 0 | 0.48 | 0 | 0.36 |
| \( \text{Node D} \) | 2.40 | 1.92 | 2.28 | 1.92 |
| Comparison of billed consumption, kWh | \( \text{Node C} \) | 0 | 0.48 | 0 | 0.36 |
| \( \text{Node D} \) | 50.40 | 49.92 | 50.28 | 49.92 |

### 2.5 Alternative practice – one-for-one plus losses credit exchange

Following the analysis of Sections 2.3 and 2.4, an alternative practice that could be adopted is hereby presented, bearing in mind that utilities possess data with limited temporal resolution regarding their customers’ actual behaviour. To this end, this alternative practice relies on a different DLF calculation and net billing procedure. The examination of this alternative practice is based on the premise that the import and export activities of NEM customers could, in principle, be treated differently. Specifically, the alternative practice accounts for the grid use – to import energy, NEM customers effectively reduce the amounts of energy they import from the grid. Thus, the direct self-consumption through privately-owned DER (PV or PV + storage units) does not incur any energy losses since the use of grid is avoided.

Within the above two points, the DLF calculation could be performed as in the following equation:

$$DLF = \frac{[\text{Energy losses}]}{[\text{Total imported energy}]}$$  \hspace{1cm} (14)$$

By capitalising on the above remarks, the DLF calculation shown in (14) takes into account the fact that NEM customers continue to import energy from the grid, similarly to other pure consumers. However, an important note is that the ‘total imported energy∗’ inherently excludes the self-consumed energy of NEM customers. The self-consumed energy of NEM customers refers to the direct satisfaction of their demand through the use of their own resources (i.e. PV and BESS systems). Through the self-consumed energy, NEM customers effectively reduce the amounts of energy they import from the grid. Thus, the direct self-consumption through privately-owned DER (PV or PV + storage units) does not incur any energy losses since the use of grid is avoided.

To this extent, the alternative, ‘one-for-one plus losses’ practice takes the above remarks into account and uses the DLF calculation shown in (14) to introduce a revised energy netting process for NEM prosumers and NEM storsumers as per the following equation:

$$[\text{Billed consumption}] = [\text{Imported energy}] + [\text{Allocated losses}] - [\text{Exported energy}]$$  \hspace{1cm} (15)$$

where the term allocated losses is now calculated as in the following equation:

$$[\text{Allocated losses}] = DLF \times [\text{Imported energy}]$$  \hspace{1cm} (16)$$

Based on (16), the allocated losses to NEM customers are now a function of their imported energy volume and not of their aggregate net energy (as in (8)).
characteristics (e.g. voltage level, topology, conductor type and length etc.). To comprehensibly appraise this impact, a more systematic analysis is performed through a realistic test system. The case study relies on an actual LV feeder that is considered representative for the LV system of Cyprus. The details of the LV feeder were directly taken from the geographical information system database of the Distribution System Operator of Cyprus (DSOCY). Moreover, a set of average daily profiles for the demand and PV generation characteristics in Cyprus are used (see Fig. 4) and, to this extent, the case study pertains in capturing the effect of NEM practice on losses allocation based on these typical 24 h patterns.

### 3.1 Description of LV feeder

The LV feeder (see Fig. 3) serves 36 single-phase residential and two three-phase commercial customers (located at nodes 3 and 5). All 38 customers are uniformly distributed among the three phases of the feeder.

![Realistic test LV feeder single-line diagram (all distances are scaled)](image)

**Fig. 3** Realistic test LV feeder single-line diagram (all distances are scaled)

### 3.2 Examined cases

The examined cases are shown in Table 12. In particular, the 36 residential customers served by the representative feeder are simulated under four different cases: Case 0 refers to serving 100% pure consumers, case 1 refers to serving 50% pure consumers and 50% NEM prosumers, case 2 refers to 50% pure consumers, 25% NEM prosumers and 25% NEM storsumers and case 3 refers to serving 50% pure consumers and 50% NEM storsumers.

![Average daily consumption profiles of commercial and residential consumers in Cyprus](image)

**Fig. 4** Average daily consumption profiles of commercial and residential consumers in Cyprus

<table>
<thead>
<tr>
<th>Case</th>
<th>Commercial customers</th>
<th>Residential customers</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pure consumers</td>
<td>Pure consumers</td>
</tr>
<tr>
<td>0</td>
<td>2</td>
<td>36</td>
</tr>
<tr>
<td>1</td>
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<td>18</td>
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<td>18</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>18</td>
</tr>
</tbody>
</table>

### 3.3 Description of consumption profiles, PV generation profiles and BESS

Each customer served by the feeder is assigned to a daily consumption profile (i.e. residential or commercial). The demand profiles are shown in Fig. 4 and were directly provided by the DSOCY. It is noted that the annual consumption of residential and commercial customers is $\sim 10$ and $70 \text{ kWh}$, respectively. Thus, the total demand that is served by the feeder sums up to 500 kWh.

To facilitate the subsequent analysis, it is also necessary to have characteristic net demand profiles for residential prosumers and residential storsumers. These are shown in Fig. 5. In particular, the net demand profile of NEM prosumers is derived by combining the demand profile of the pure residential consumer (Fig. 4) with a PV generation profile (see Fig. 5). The PV generation used in this case study is based on real-measured data that are representative of the solar potential characteristics in Cyprus [23]. The average daily energy yield is $\sim 4.56 \text{ kWh per each installed kWp}$ [23]. Thus, when the prosumer installs a 2.2 kWp PV system, the corresponding net demand profile is that shown in Fig. 5.

![Daily net demand profiles of a residential prosumer and storsumer](image)

**Fig. 5** Daily net demand profiles of a residential prosumer and storsumer

Furthermore, the residential storsumer, besides the 2.2 kWp PV system benefits from a BESS with an energy rating equal to 50% of the residential customer's average daily consumption (i.e. 5 kWh). The further particulars of the BESS are provided in Table 13. By using these characteristics, the storsumers’ net demand profile, shown in Fig. 5, can be derived.

At an aggregate level, the total net demand of the LV feeder under each case considered in Table 12 is shown in Fig. 6. The summary of the incurred losses and the volumetric interaction for all cases are presented in Table 14. These results pertain to the profiles shown in Fig. 6, which are considered representative daily profiles for the test system considered.
Table 13 PV and BESS characteristics

<table>
<thead>
<tr>
<th></th>
<th>Case 0</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>installed capacity, kW</td>
<td>2.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy yield, kWh</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>energy rating – $E_{\text{max}}$, kWh</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BESS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>power rating – $P_{\text{max}}$, kW</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>allowable depth of discharge – DoD, %</td>
<td>60%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minimum state-of-charge – $m$, %</td>
<td>40%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>charging efficiency – $\eta_{c}$, %</td>
<td>97%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>discharging efficiency – $\eta_{d}$, %</td>
<td>97%</td>
<td></td>
<td></td>
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</tbody>
</table>

Table 14 Annual incurred losses and volumetric interaction for each examined case

<table>
<thead>
<tr>
<th>Case</th>
<th>Incurred losses, kWH</th>
<th>Total imported energy, kWH</th>
<th>Total exported energy, kWH</th>
<th>Net sales, kWh</th>
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<tbody>
<tr>
<td>0</td>
<td>5.082</td>
<td>500</td>
<td>0</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>3.656</td>
<td>432.4</td>
<td>112.4</td>
<td>320</td>
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<tr>
<td>2</td>
<td>2.958</td>
<td>406.5</td>
<td>84.4</td>
<td>322.1</td>
</tr>
<tr>
<td>3</td>
<td>2.517</td>
<td>380.6</td>
<td>57</td>
<td>323.6</td>
</tr>
</tbody>
</table>

Table 15 DLF calculation for each case

<table>
<thead>
<tr>
<th>Case</th>
<th>‘One-for-one’ practice (DLF1)</th>
<th>‘One-for-one plus losses’ practice (DLF2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0102</td>
<td>0.0102</td>
</tr>
<tr>
<td>1</td>
<td>0.0114</td>
<td>0.0085</td>
</tr>
<tr>
<td>2</td>
<td>0.0091</td>
<td>0.0072</td>
</tr>
<tr>
<td>3</td>
<td>0.0077</td>
<td>0.0066</td>
</tr>
</tbody>
</table>

3.4 Analysis

The numerical results shown in Table 14 are used to calculate the DLF under the current NEM practice, i.e. using (4), and subsequently under the alternative practice, i.e. using (12). The calculated DLFs are shown in Table 15.

The DLF calculated under the one-for-one and the one-for-one plus losses practices are used to quantify whether the regular, pure consumers in the feeder are facing increased losses charges when compared with their allocated losses in case 0, which quantifies the level of cross-subsidy that occurs under each case and each practice. The corresponding results are shown in Fig. 7.

Fig. 7 shows that pure consumers are allocated increased amounts of losses as the number of NEM prosumers in the feeder is increased. For example, this occurs in the modelled case 1 (+11%), where the number of pure consumers equals the number of NEM prosumers. This in fact corroborates the promise as one-for-one plus losses practice, which does not account for the time diversity between the import and export activities of NEM customers, as in all of the seasonal demands, the incurred energy losses are reduced. More importantly, the results of case 2 and case 3 provide a clear indication that self-consumption may be desirable from an operational point of view. Hence, the fact that the DLFs under the current practice ignore the time diversity between demand and PV generation may result in providing the opposite pricing signals to NEM customers.

 Conversely, the one-for-one plus losses practice presented, which allocates a portion of the incurred energy losses to NEM customers depending on the respective volume of imported energy, is providing an incentive to NEM customers to adjust their consumption in accordance with their self-produced PV energy in order to reduce their imports from the grid. However, in doing so, pure consumers are receiving a benefit even though they exhibit the same behaviour as previously.

It is worth noting that the principles described in the paper can be applied to investigate the seasonal variation of losses-related cross-subsidies that arise from different DLF calculation approaches. For example, the above analysis can be applied to investigate the level of the losses-related cross-subsidies for different timeframes, e.g. monthly, seasonally and so on. Depending on the seasonal demand and PV generation particulars that apply in each power system, the level and direction of the cross-subsidy may vary thus posing a regulatory challenge to be addressed.

3.5 Regulatory challenges

Bearing the above discussion in mind, the arising regulatory challenges relate to how should the costs/benefits that NEM customers bring about in the operation of the distribution network be allocated amongst all retail customers. Some of the key questions that need to be addressed are:

- Is the traditional, one-for-one credit exchange providing the correct price signals to NEM customers?
- Should the grid-imported energy of NEM customers be allocated any losses, similarly to pure consumers?
- Should the behind-the-meter, self-consumption of PV energy from NEM customers be treated differently than the case of pure consumers reducing their consumption, e.g. through energy efficiency measures (e.g. [24])?
• Is the extent of these embedded cross-subsidies adequate to justify the investment and implementation costs of advanced metering infrastructure at the distribution level?

Finally, it should be noted that both fixed and variable (e.g. losses) cost-related cross-subsidies (owing to the integration of NEM customers) are system specific. This is due to the fact that the cost structure of each power system is determined by various factors such as fuel, demand patterns, distributed generation potential, network characteristics, connection topologies, geographical and demographical particulars and so on. Hence, the extent of both cross-subsidies is a direct function of the specific cost and network structures that apply to each power system. For example, a power system with high fixed and low variable cost components will mainly experience fixed cost-related cross-subsidies. Conversely, in a power system with low fixed but high variable costs, the variable/losses related cross-subsidies may be more pronounced. It is worth noting at this point that both fixed and variable cost-related cross-subsidies may be interrelated in certain power systems. The latter is attributed to the fact that DLFs are sometimes used in fixed cost allocation as well (i.e. see, for example, the use-of-system charges in Cyprus [25]). To this extent, if DLFs are affected by NEM customers, this may also distort fixed costs allocation.

4 Conclusion

This paper has demonstrated the hidden financial implication that the traditional NEM practice may impose on utilities in terms of reallocating the incurred energy distribution losses in their distribution systems.

Depending on the import/export activities of NEM customers (i.e. prosumers and/or storsumers) and the network’s characteristics, the incurred losses may be reduced. However, the combined effect of varying losses in conjunction with reduced sales due to the presence of NEM customers affects the losses’ allocation process more erratically. As shown, the traditional, one-for-one credit may lead to cases where absolute losses may be reduced whilst the respective DLF increases. This results in pure consumers subsidising NEM customers. On the other hand, when NEM customers exhibit increased self-consumption (as in the case of NEM storsumers), then pure consumers may receive a benefit even though they do not alter their behaviour. This may be perceived as a cross-subsidy from NEM customers to pure consumers.

To this extent, the limited temporal resolution of the customers’ measured data that utilities possess due to the existing metering infrastructure capabilities poses a major regulatory challenge due to the inability of adopting more sophisticated pricing and loss allocation methods. However, the extent of these embedded cross-subsidies is system specific and should therefore be thoroughly investigated in order to ensure that the efficiency gains outweigh the investment costs of upgrading the metering infrastructure at the distribution level.

5 References

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