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The effect of net metering methods on prosumer energy settlements
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ABSTRACT
Net metering is a well-known mechanism, where only energy exchanges of prosumers with the grid are accounted for in settlements. What is less known is the subtleness of the metering practices of energy suppliers behind the reported energy values. This paper discusses the implications of applying different net metering methods on a prosumer’s energy exchanges with the grid, and subsequently the effect on costs and self-consumption. The methods differ on whether netting is based on each individual phase (or on the overall energy flow) and the netting interval used for settlement. Besides describing and illustrating those differences, real data from a Danish household is used to quantify their impact. Results show that self-consumption increases from 38% to 53%, when moving from instantaneous per-phase netting to hourly summation netting. The corresponding annual energy imports decrease from 1459 kWh to 1087 kWh. The economic implications of applying different netting methods are quantified and discussed, and we show that annual savings of at least €50 can be achieved by simply switching to a summation smart meter.

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1. Introduction

1.1. Background

The practice of energy netting is behind the widespread proliferation of distributed generation worldwide. This allows the owners of generation assets to self-consume their produced energy, and only exchanges with the grid are taken into consideration in any settlements. In countries such as Denmark, where tariffs and taxes comprise more than 80% of the final electricity price for residential customers [1], netting local production and consumption is highly advantageous for the owners. Rooftop photovoltaic (PV) installations are the primary source of generation at a residential level, with a study [2] estimating that they can cover up to 24.4% of the EU electricity consumption. The cost reduction of PV systems in the last two decades has been a major driver behind the expansion of domestic generation [3], turning a large number of customers into prosumers (both producers and consumers of electricity). In the previous decades, governments incentivized the installation of small-scale renewable production (primarily domestic PV systems) mainly via feed-in tariffs or net metering [4]. With feed-in tariffs a favorable price per injected kWh of energy is offered to owners as an incentive for the high installation costs, but this scheme is gradually being abandoned by many countries [5].

While energy netting plays a pivotal role in the development of domestic generation, there is still some confusion regarding the terms net metering and net billing, as recognized by [6] as early as 2004. Under net billing, which is sometimes called net purchase and sale [7], both imports and exports of the prosumer are recorded and they are subsequently charged or compensated at different rates. These values are the “real” exchanges with the network, as they have not been subjected to any processing. Typically, the instantaneous import/export values are not stored in smart meters due to the high data storage requirements, and the accumulated values are reported at a regular reporting interval (RI), usually hourly.

While net billing nets consumption and production only instantaneously, net metering allows prosumers to “use” any energy surplus to cover (partly or fully) their energy deficit over a specified netting interval (NI). In other words, only the accumulated energy exchange with the network is calculated over each NI, and not the exact imports and exports. For example, consider an NI of one hour, with total imports $a$ and total exports $b$ during this period, which are both non-negative by convention. These are the real exchanges with the network, and are equal to $a + b$. If $a > b$, then only an import equal to $a - b$ will be reported, and exports will be zero (similarly, if $a < b$ then exports will be $b - a$ and imports zero). These “processed” energy import and export values will be smaller than the real exchanges with the network. This processing is the main idea behind net metering, and the choice of the NI duration has an impact on energy settlements, as we show in this work. It is worth noting that as the NI becomes sufficiently small (e.g., one second), then practically all exchanges...
with the network are reported; in this case net metering and net billing become the same. For this reason, net billing can be seen as a special case of net metering, called instantaneous netting, with a very small NI [7]. Subsequently, with the exception of literature references that use the term net billing, we will refer only to net metering to simplify the used terminology in our work.

As we will show in our case study, a typical prosumer with a 6 kW PV system has a large production surplus on a yearly basis and is also self-sufficient on most months of the year. Thus, long NIs typically result in low recorded energy imports, and may disproportionately favor prosumers and lead to a large decrease in tax and grid tariff revenues [8]. For this reason, several grid operators modify their policies and replace net metering schemes that use long NIs with net billing, as is the case with Nevada, Arizona and New York [8]. Another example is Denmark, where yearly net metering was established in 2010 but led to a drastic reduction in tax revenue [9]. Subsequently, all customers that installed a PV after 2012 were subjected to instantaneous netting [10]. In many cases, net metering with long NIs is a necessity due to the lack of appropriate modern metering devices. The existence of old analog meters does not allow system operators to charge prosumers with tariffs on their imports on a volumetric basis, as done for the net billing case [11]. This raises fairness issues [12], as consumers without generating capabilities bear most of the costs of grid operation, unless substantial fixed fees on prosumers are imposed, as done recently in Wallonia, Belgium [13], for prosumers without smart meters.

Regulators and the EU are promoting the rollout of advanced metering infrastructure [14], and in particular energy smart meters [15]. These provide the technical means for employing time-varying prices and short NIs on prosumers, but they can also help at modernizing, automating and improving the management of distribution grids [16,17]. Smart meters are also necessary in the power system to provide flexibility by distributed energy resources [18], such as electric vehicles [19], which if not charged with proper considerations they can potentially stress distribution grids [20]. Adequate metering is thus necessary to provide flexibility, detect operational problems in distribution networks and price customers in a fair manner.

Several aspects of metering infrastructure, and smart meters in particular, have been investigated in the literature, focusing on communication architecture [21,22], cybersecurity [23], or protection and monitoring [24]. In many countries where smart meters are installed, these often report hourly values, based on which settlements with the retailers are carried out. The primary reason behind the hourly RI choice is that this is also the granularity of the wholesale market, and this allows retailers to offer time-varying rates to customers. However, how exactly the reported hourly values are derived is not straightforward, and it is thus important to understand and quantify the economic impact of employing various modes of netting on an hourly basis.

1.2. Related work

The authors of [25–27] examine the effect of hourly netting schemes on the economic performance of residential PV systems by using hourly consumption and production data. Similarly, [28] studies the effects of net metering on policy issues such as cross subsidies and cost recovery, but hourly values are also used in the analysis. However, intra-hourly variations of consumption and production result in concurrent energy imports and exports to/from the grid within each hour. Using hourly average values is not sufficient to capture such energy exchanges.

In [29] net metering schemes are compared considering NIs of 1, 5, 15, 30, 60 min, 1 day and 1 month. However, the analysis largely relies on artificial data and does not examine an interval below the minute scale. As pointed out in [9,10], depending on the smart meter and the utility, netting can also be instantaneous. The meaning of instantaneous netting was discussed in the previous subsection, and it is the case where net power demand (consumption minus production) is sampled instantaneously, and then these samples are accumulated separately as imports and exports. The authors of [30] use smart meter data that record imports and exports of prosumers with instantaneous netting and use an RI of 15-min, but only use them to estimate PV production.

1.3. Contributions

With this paper we intend to clarify how net metering is applied to residential prosumers and present the technical and economic impact of applying different netting methods. We divide the metering methods through two axes: a spatial and a temporal. The first refers to the summation through phases, which is only relevant if the prosumer has a three-phase connection, and which is largely neglected in the literature. Consumption flows unevenly over each phase, as the large majority of domestic appliances are single-phase, while production is usually three-phase and equally distributed. Netting the power flow over the three phases, using the so-called Ferraris method (also known as summation method), will bring different results compared to the measurement performed over each individual phase. The second relates to the time-window that is used to settle consumption and production, ranging from instantaneous to hourly netting. In this paper, the effect of applying summation and per phase metering, and three different NIs (instantaneous, 5 minutes and 1 hour) is assessed. Further, we present results in a case study using real data with fine granularity of a prosumer located in Denmark, where we calculate the economic effect that the different methods have, and also present the implications in terms of the resulting self-consumption.

The rest of the paper is structured as follows. Section 2 focuses on smart metering and how raw values are processed and netted. Illustrative examples to showcase the difference of the various methods are provided, and we also present the mathematical formulations to conduct calculations for each method. Section 3 presents the case study that supports the investigation with numerical results on the impact of the netting method on energy exchanges, economics performance and self-consumption. Section 4 concludes our work.

2. Methodology

In Section 2.1 the basics of energy metering in relation to the power flows within the prosumer premises and the exchanges with the network are described. In Section 2.2 the effect of considering the flow per phase or as their summation is discussed, and in Section 2.3 the effect of applying different NIs is presented. In Section 2.4 it is shown how energy imports and exports are calculated depending on the applied method.

2.1. The flow of power

Let $g_{\text{PV}}^w$ denote the instantaneous PV generation (in W) at each time step $t$ in each phase $w \in \mathcal{W}$, where $\mathcal{W} = \{a, b, c\}$ is the set containing the three phases. Similarly, let $l_{\text{net}}^w$ denote the instantaneous consumption (in W) and $p_{\text{net}}^w = l_{\text{net}}^w - g_{\text{PV}}^w$ the net power demand (also in W). Typically, a smart meter samples net power demand almost continuously and for practical reasons we consider a sampling rate of 1 s, so that $t \in \{1, \ldots, 86400\}$. Fig. 1 depicts the power flows per phase and the position of the smart meter. Note that the net power demand before and after the smart meter may be slightly different due to losses, but these are usually very small and can be neglected.
Fig. 1. Prosumer installation with a three-phase PV system. Each consumption block represents the load of all appliances supplied by each phase. The PV block represents the PV system and its inverter.

Table 1
An example of the effect of per phase vs summation metering. All values are in kW.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Actual</th>
<th>Per phase metering</th>
<th>Summation metering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>From grid</td>
<td>To grid</td>
<td>From grid</td>
</tr>
<tr>
<td>a</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>c</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Registered</td>
<td>–</td>
<td>–</td>
<td>1</td>
</tr>
</tbody>
</table>

2.2. Spatial dimension — per phase and summation

As discussed in the introduction, there are two metering options: per phase and summation. In the former, energy imports and exports are calculated by sampling $p^{\text{w}}_t$ in each phase separately (as shown in Fig. 1) and then summing up the results. In the latter, these are calculated by sampling the aggregated net power demand $\sum_{w \in W} p^{\text{w}}_t$ of the three phases. The difference of the two options is shown in Table 1 with an illustrative example of symmetric generation of 1 kW per phase and a consumption of 0, 0 and 2 kW per phase, respectively. In the case of summation metering the smart meter registers 1 kW of export to the grid. However, in the case of per phase metering the result is calculated individually on each phase, leading to registering 2 kW of export and 1 kW of import concurrently.

These registered values are converted to the equivalent amounts of energy, and are further processed according to the used NI, as we discuss next.

2.3. Temporal dimension: netting intervals

In this subsection we explain the effect of the NI and for convenience we assume that a summation netting is applied. Fig. 2 presents an illustrative example to highlight the effect of the NI on import/export calculations. Instantaneous netting accumulates all exchanges with the network separately, leading to imports of 1.5 kWh and exports of 0.5 kWh over the hour. An hourly netting (NI of 1 h) considers the overall accumulated exchanges with the networks, which in this case is only imports and 1 kW of import concurrently.

These calculated imports and exports vary significantly depending on the chosen NI, even with hourly reported values. The smaller the NI, the higher the calculated imports and exports from/to the grid.

Table 2
Accumulated energy imports and exports for different NI for the example of Fig. 3.

<table>
<thead>
<tr>
<th>Net metering method</th>
<th>Instantaneous</th>
<th>5-min</th>
<th>1 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imports [kWh]</td>
<td>0.724</td>
<td>0.473</td>
<td>0</td>
</tr>
<tr>
<td>Exports [kWh]</td>
<td>1.088</td>
<td>0.837</td>
<td>0.364</td>
</tr>
<tr>
<td>Difference [kWh]</td>
<td>0.364</td>
<td>0.364</td>
<td>0.364</td>
</tr>
</tbody>
</table>

In most cases, commercial smart meters either do not provide instantaneous values or the user does not have access to the underlying raw data. Instead, energy imports and exports are provided at a much lower (usually hourly) reporting resolution than that of metering. In reality, load consumption and PV generation present fast fluctuations (in the orders of seconds); such an example is shown in the top plot of Fig. 3 for an hourly snapshot. The reader should note that PV production comes from our experimental facilities of SYSLAB [31], where per second measurements are available. Such variability of PV production is common under cloudy weather conditions. The consumption time-series is constructed based on real data with a 10 second resolution from [32], with the addition of a small noise term.

The middle plot shows the instantaneous imports and exports in kW, and their accumulated values over time in kWh, under instantaneous netting. The bottom plot shows the same results, but for a 5—min netting. Notice that 5—min net metering allows imports and exports to compensate each other to some extent, especially within the 5—min periods where substantial bidirectional exchanges with the grid occur. Notice also that in each period the exchange with the network is calculated as a single value, either import or export. As a result, the total exchanges with the grid are considerably lower within the hour, compared with the instantaneous netting. The results are summarized in Table 2. If hourly net metering is applied, then only exports are recorded and the overall exchanges are reduced by approximately 80%. It is thus evident that the calculated imports and exports vary significantly depending on the chosen NI, even with hourly reported values. The smaller the NI, the higher the calculated imports and exports from/to the grid.

2.4. Energy import/export calculations

In most cases, commercial smart meters either do not provide instantaneous values or the user does not have access to the underlying raw data. Instead, energy imports and exports are provided at a much lower (usually hourly) reporting resolution than that of metering [33]. For example, netting can be done on a per second basis (NI of 1 s) but energy imports and exports may be reported per hour (RI of 1 h). In all cases both the RI and the NI are larger than that of metering/sampling.
in a day, with \( q = 12 \) and \( \Delta T = 1/12 \). We divide each day in a collection of sets \( \mathcal{J}_n \) indexed by \( n \). Each \( \mathcal{J}_n \) contains indices \( k \in \{(n-1)q+1, \ldots, nq\} \).

After introducing the necessary notation, we can calculate the energy imports and exports. The total imported and exported energy during a day \( d \) are given by

\[
\begin{align*}
M_d^+ &= \Delta T \sum_{n \in \mathcal{N}} \left( \sum_{k \in \mathcal{J}_n} p_w^+ \right), \\
X_d^+ &= \Delta T \sum_{n \in \mathcal{N}} \left( \sum_{k \in \mathcal{J}_n} p_w^- \right),
\end{align*}
\]

where \((\cdot)_+\) denotes a positive part function, i.e., \((y)_+ = \max(y, 0)\) for any real number \( y \), and \((\cdot)_-\) denotes a negative part function, i.e., \((y)_- = -\min(y, 0)\). These definitions are used to comply with our convention of non-negative import and export values. To obtain the per phase quantities, summation \( \sum_{n \in \mathcal{N}} \) must be moved outside the \((\cdot)_+\) and \((\cdot)_-\) operations, such that

\[
\begin{align*}
m_d^+ &= \Delta T \sum_{n \in \mathcal{N}} \left( \sum_{k \in \mathcal{J}_n} p_w^+ \right), \\
x_d^+ &= \Delta T \sum_{n \in \mathcal{N}} \left( \sum_{k \in \mathcal{J}_n} p_w^- \right).
\end{align*}
\]

3. Case study

We present a case study from a real Danish household located in the municipality of Roskilde. A description of the household, the available data and the overall study are presented in Section 3.1. We then proceed with an analysis of different billing options based on the duration of the NI and the possibility of per phase or summation metering. The results are reported in Section 3.2. The effect on self-consumption is discussed in Section 3.3 and the economic implications in Section 3.4.

3.1. Case study description

A single-family house is taken as reference for the investigation. The house is equipped with a 6 kW PV system composed of 20 300 W monocrystalline 60-cell modules assembled by Luxor. The PV system is installed on a south-oriented roof, tilted by 25 degrees. A 6 kW three-phase inverter manufactured by Fronius interfaces the modules with the household’s AC grid (230 V nominal RMS phase-to-neutral voltage).

The appliances in the household are all single-phased. There is an almost continuous base load of approximately 0.1 kW due to the consumption of a modest, environmental monitoring gadgets and a refrigerator. The largest appliances that determine the peak loads are the washing machine (2.3 kW), the dishwasher (1.8 kW) and the cooking stove. The cooking stove, although supplied by three phases, consists of an oven (2.3 kW) supplied by one phase, and two pairs of induction stoves supplied by the remaining two phases. Each induction stove has a different power rating and can consumed a variable power level between 0.4 kW and 1.4 – 1.8 – 2.3 kW. Heating is provided by the district heating co-generation unit of the city, supplemented by a pellet fireplace, both requiring minimal electrical supply. Therefore, the electrical consumption has a weak seasonal variation. It is worth noting that the base-load, despite being only 0.1 kW, accounts for nearly 40% of the yearly energy consumption, and is mostly connected on the first phase.

Two bidirectional meters are installed in the household. The first is the energy meter installed by the electricity supplier,
an Echelon polyphase meter which provides a wide range of measurements. Unfortunately, the user can only access hourly-reported energy import/export values through the Danish energy platform [34,35] managed by the national transmission system operator Energinet. Even though these values are reported on an hourly basis (RI of one hour), a per second netting (NI of one second) is applied. The supplier meter was initially a per phase meter and was replaced with a summation meter at the end of April 2020. Therefore, subsequent measurements are not considering individual flows on each phase but their overall sum.

In order to retrieve more information, an additional smart meter developed by the same company manufacturing the PV inverter was installed [33]. This smart meter offers a range of measurements such as phase currents, voltages and power, reported every 5 minutes as average values. It also records energy flowing from the grid and to the grid with an NI of 1 second (similarly to what the supplier meter does) by applying summation metering. The accumulated values are reported every 5 minutes, which is the RI of the meter. The Fronius smart meter communicates through Modbus to the PV inverter which is equipped with a data-logger that, through the domestic WiFi, transmits data to the Fronius portal.

The available raw data from the two meters that will be used for the netting calculations are listed below:

- **Supplier**: Energy import and export reported per hour (RI 1 h) – Per phase and instantaneous netting (NI 1 s) until April.
- **Supplier**: Energy import and export reported per hour (RI 1 h) – Summation and instantaneous netting (NI 1 s) after May.
- **Fronius**: Energy import and export reported every 5 minutes (RI 5 min) – Summation and instantaneous netting (NI 1 s).
- **Fronius**: Average net power demand and PV production calculated and reported every 5 minutes and per phase (RI 5 min). In the case of production or net power demand no NI is defined.

As seen in Fig. 4, the Fronius smart meter is installed right before the Echelon energy meter, therefore except for the minimal self-consumption of the smart meter (equal to 1.5 W), both meters observe the same power flows. Both meters are class B with a measurement accuracy of 1%, as per European measurement instrument directive [36]. The presence of the Fronius meter makes it possible to assess power flows on each phase and therefore quantify the difference between summation and per phase netting.

Fig. 5 gives an example of daily consumption and production over a high-production and a low-production period. The data for the top plot is taken from a high PV production day and for the bottom plot from a low production day. In the latter it is possible to recognize the base load connected on phase a, along with the cyclic consumption of the refrigerator. The energy production over the analyzed year (September 2019–August 2020) was 6005 kWh. As one should expect given the northern latitude, the solar production varies significantly throughout the year, ranging from 64 kWh in December to 993 kWh in June.

The production breakdown per month can be seen in the top plot of Fig. 6. The yearly consumption was 2311 kWh for the investigated period, with a relatively small variation throughout the different months, as visualized by the middle plot of Fig. 6. The bottom plot shows the distribution of the consumption in each phase.
3.2. Netting results

First, we define the hourly summation net metering as our benchmark; in which case, NI is equal to 1 h. Most research works consider average hourly consumption and production values in their investigations and disregard any per phase implications, mainly due to the lack of relevant data. Another reason is that this method results in the smallest energy exchanges with the network when an hourly RI is used. In order to highlight the variations when considering different NIs (1 h, 5 min, 1 s) and summation vs per phase, we will report the differences against the benchmark values per month. Using the available data described in the previous subsection and Eqs. (2)–(5), we calculate energy imports and exports in the benchmark case. These are shown in Fig. 7 for one full year.

In Fig. 8 the increase in imports (which is equal to that of the exports) due to the per phase netting compared to summation is shown per month and for three different NIs. Note that the supplier energy meter switched from per phase to summation at the owner's request at the end of April 2020, and thus per phase values are unavailable after that month for the case of 1 s net metering. As it is obvious by comparing (2)–(3) with (4)–(5), summation metering smooths to some extent the power variations of the individual phases, and results in smaller overall energy imports and exports.

In Fig. 9 we report the same values but normalized against the monthly consumption due to per phase netting for different NI. Data is unavailable after May for the 1 s case because of the change of meter.

![Energy Exports](image1)

![Energy Imports](image2)

Fig. 7. Monthly exports (top plot) and imports (bottom plot) with the benchmark method, i.e., summation hourly net metering, for a typical Danish household.

![Increase in Imports](image3)

Fig. 8. Increase in imports due to per phase (compared to summation) net metering for different NI. Data is unavailable after May for the 1 s case because of the meter change.

![Percentage Increase](image4)

Fig. 9. Percentage increase in imports normalized against the monthly consumption due to per-phase netting for different NI. Data is unavailable after May for the 1 s case because of the change of meter.

![Increase in Imports - Summation](image5)

Fig. 10. Increase in imports due to the NI: summation (top plot) and per phase (bottom plot).

In the first case, the monthly increases in imports are on average 7 kWh for 5 min netting and 10 kWh per second netting. However, no large seasonal variation is observed. In the second case, the increases are similar between October and February. Nonetheless, they show a seasonal variation and are significantly higher during the months of high PV production, i.e., September 2019 and March to August 2020. Changes with the grid increase by approximately 20 kWh and 30 kWh for 5 min and per second netting, respectively, during those months. This can be explained by the fast fluctuations of PV production and consumption (in the order of seconds), along with the uneven phase distribution.

As pointed out in the case study description, the PV yielded 6005 kWh and the household consumed 2311 kWh, leading to a net production of 3694 kWh over the year. While a yearly netting would result in 3694 kWh of exports and zero imports, these figures change substantially depending on the NI. We examine four different methods:
Table 3
Yearly energy imports and exports depending on the NI and summation vs per phase.

<table>
<thead>
<tr>
<th>Energy in kWh</th>
<th>Summation monthly</th>
<th>Summation per h</th>
<th>Summation per s</th>
<th>Per phase per s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imports</td>
<td>371</td>
<td>1087</td>
<td>1204</td>
<td>1459</td>
</tr>
<tr>
<td>Exports</td>
<td>4065</td>
<td>4781</td>
<td>4899</td>
<td>5148</td>
</tr>
<tr>
<td>Difference</td>
<td>3694</td>
<td>3694</td>
<td>3695</td>
<td>3689</td>
</tr>
</tbody>
</table>

- Hourly netting using summation, which is our benchmark case.
- Per second netting on a per phase basis.
- Per second netting using summation.
- Monthly netting using summation.

On Table 3 we provide an overview of the effect of those methods over one year. We should note that for the missing months in the per phase and per second method we used extrapolation based on the available data. We also added the monthly netting in our comparison because it is still quite commonly practiced [37], and to show the significant effect of using long NIs on the results. As discussed earlier, the difference between the imports and exports reflects the overall net production, which is the same, irrespective of the netting method. This is also observed on Table 3, with only some minor deviations which can be attributed to the meters’ accuracy.

A monthly netting results in only 371 kWh of imports and 4065 kWh of exports. With hourly summation these figures increase to 1087 kWh and 4781, respectively. Using per second summation further increases these figures by 117 kWh. A significantly larger increase occurs when per phase netting is used, leading to an overall increase of 372 kWh, compared to the benchmark case. It is also interesting to observe that with per second netting, as is the current practice in Denmark, a switch from a per phase meter to a summation meter decreases the calculated exchanges with the grid by 255 kWh. Obviously, a yearly netting would lead to zero imports from the grid. Using monthly or yearly netting decreases the energy exchanges substantially, as one would expect. Nonetheless, it is interesting to note that even with hourly-reported values, imports can range from 1087 kWh to 1459 kWh, depending on the chosen net metering method.

3.3. Effect of the netting method on self-consumption

The consequences of applying the various netting methods can be also appreciated by looking at the self-consumption in the different cases. Self-consumption is defined as the ratio of the consumed energy which has been produced locally divided by the total consumption. Hourly summation results in the lowest import and thus the highest values in self-consumption, followed by summation per second and lastly per phase and per second netting. As illustrated in Fig. 11, and reported in Table 4, the difference is larger in the months with higher PV production and can reach up to 25 percentage points in July, from 58% to 83%. The overall yearly figure changes from 38% to 53%, with the larger difference attributed to the shift from per phase to summation, rather than from hourly to per second netting.

3.4. Economic implications of the net metering method

The economic impact of the net metering options under hourly-reported values is non negligible. To assess this impact we use Danish tariff values from the owner’s invoices [38], as reported in Table 5. We use average buying and selling prices as reported in the invoices, which correspond to the average yearly spot price in Denmark for 2020 [39] with a small retailer profit margin. The resulting import/export price ratio is approximately 8.

Based on these prices and the previously reported energy exchange values, in Table 6 we present the revenue, energy cost, grid fees, taxes (including VAT) and net cost (total costs minus revenue) for the prosumer, under the three investigated net metering methods. Hourly summation net metering results in the smallest net cost for the prosumer, as this method produces the lowest amount of energy imports. Based on our case study, the impact of using an hourly NI vs instantaneous netting seems to be considerably smaller than that of summation vs per phase netting.
Netting the local production and consumption of prosumers is likely to remain the prevalent settlement practice, because it is essential for the economic viability of investments in the absence of generous feed-in tariffs. It is common for energy suppliers to use hourly intervals for settlement, but the exact way that netting is applied has various implications. In this paper we showed that by using hourly-reported values the yearly energy imports of a typical Danish prosumer can increase by up to 34%, depending on how exactly netting is applied. More specifically, instantaneous netting increases imports by 11% compared to hourly summation, because of the fast fluctuations (intra-minute) of net power demand. Additionally, per phase netting further increases imports by 21% compared to summation, because of the imbalanced nature of the power flows in each phase. Further, self-consumption can also increase from 38%, when applying instantaneous per phase netting, to 53% with hourly summation.

It is worth noting that these large variations are an artifact of how settlement is conducted within the hour, and not how energy actually flows between the prosumer and the grid. Our analysis shows that the choice between summation and per phase netting plays a more important role than applying hourly vs instantaneous netting. A simple change to a summation smart meter reduces tax revenue and grid fees by 17% and results in an annual benefit of more than €50 for the prosumer. Given the considerable impact of the net metering method on tax revenue, grid fees and prosumer costs, our results can be helpful to regulators and system operators in determining an energy settlement policy that does not hamper investments nor significantly reduces critical revenue.

CRediT authorship contribution statement

Charalampos Ziras: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis, Investigation. 
Lisa Calearo: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis, Investigation. 
Mattia Marinelli: Conceptualization, Methodology, Writing – review & editing, Formal analysis, Investigation, Supervision, Funding acquisition, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References


