Effects of smart meter time resolution when analyzing photovoltaic self-consumption system on a daily and annual basis.

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Abstract

The management of photovoltaic self-consumption systems is based mainly on updating energetic parameters such as generation and household power consumption connected via smart devices. The expected rapid increasing volume of data collected with different time resolutions is surely a topic that deserves great attention. The choice of a proper recording interval should balance the amount of monitored data and a proper energy analysis in order not only to take effective and timely decisions but also to help this technology to be more efficient. In the literature, only specific nominal array powers for annual reporting period or an array power range for daily reporting period have been considered. In this context, the error, when matching photovoltaic generation and household power consumption profiles considering different recording intervals (1, 10, 15, 30 and 60 min) and different reporting periods (daily and annual), will be estimated as a function of the array power (up to 10 kW$_p$) for five households and a resident's association. Results depend on the reporting periods and it may be advisable to use one minute and ten minutes of recording intervals in order to estimate performance metrics in this type of system for a daily and annual basis, respectively.

Keywords: Resolution; Averaging effect; Recording interval; Time resolution; Self-consumption;

Abbreviations

E_L	Local energy demand (kWh)
$E_{PV,consumed}$	Photovoltaic energy consumed in-house (kWh)
$E_{PV,generated}$	Photovoltaic energy generated on-site (kWh)
G_I	In-plane irradiance (W/m^2)
H0X	Household
NZEB	Nearly zero energy building
PE	Percentage error (%)
P_L	Load consumption (W)
P_0	Array nominal power (kW$_p$)
PV	Photovoltaic
RA	Resident' association
φ_{sc}	Self-consumption index (%)
φ_{ss}	self-sufficiency index (%)

1. Introduction and background

One of the most important challenges, which Europe is currently facing, is the reduction of energy consumption from non-renewable energies based on fossil resources. Industry and building are generally end-users of global energy and will have a significant influence on this energy transition where distributed energy generation may play a key role. Therefore, European policies promote the use of renewable energies, the reduction of energy consumption and the improvement of energy efficiency in order to promote nearly zero energy buildings (NZEBs) [1]. The NZEBs concept encourage these objectives [2], where thermal and photovoltaic (PV) solar technologies will play an important role [3,4].

1.1. Influence of Smart meters recording interval on household power consumption profile.

Smart meters and energy management controllers are used in NZEBs in order to organize and optimize the electrical energy. Smart meters provide real-time data about household electricity consumption. Electricity load consumption was previously provided by electromechanical energy meters, but during last few years they have been replaced by static energy meters [5] which are being expanded globally [6]. Smart meters provide a high sampling frequency and real-time data, as well as historical data [7]. Although the sampling interval of smart meters may be relatively high, in practice, end-users receive data with a recording interval of half an hour or one-hour as most electric utilities provides household power consumption data with this recording interval [8]. Moreover, ultrashort-term time scales of recording interval for domestic electricity data, as the order of a few seconds, are very scarcely to be found [9]. The recorded parameters for each record should be the minimum, maximum, sum, average or other interested function of the samples acquired during the recording interval [10].

It must be highlighted that sharp peaks may be reduced when data are averaged over its recording interval: the higher averaging period, the more clipped power peak [11]. The sharp peaks reduction can be observed when averaging period is higher than 5 min [12]. **Error! Reference source not found.** shows the daily household power consumption profile with recording intervals of 1, 15, 30 and 60 min. As can be noted, sharp peaks are only represented in the smallest recording interval. On the other hand, the effect of averaging data for the distribution of demand could have less impact than one domestic demand as randomness of aggregate load demand causes smoothness [13]. However, it must be highlighted that one minute of resolution may be sufficient for most common domestic appliances to capture load details [14], as decreasing the sampling period may not considerably improve the simulation of the steady state voltages and power flows in a distribution grid [12]. It may be also possible to obtain good results with a 15 min recording interval for electricity load profiles where the majority of their electricity consumptions are lower than 2kW [9] .

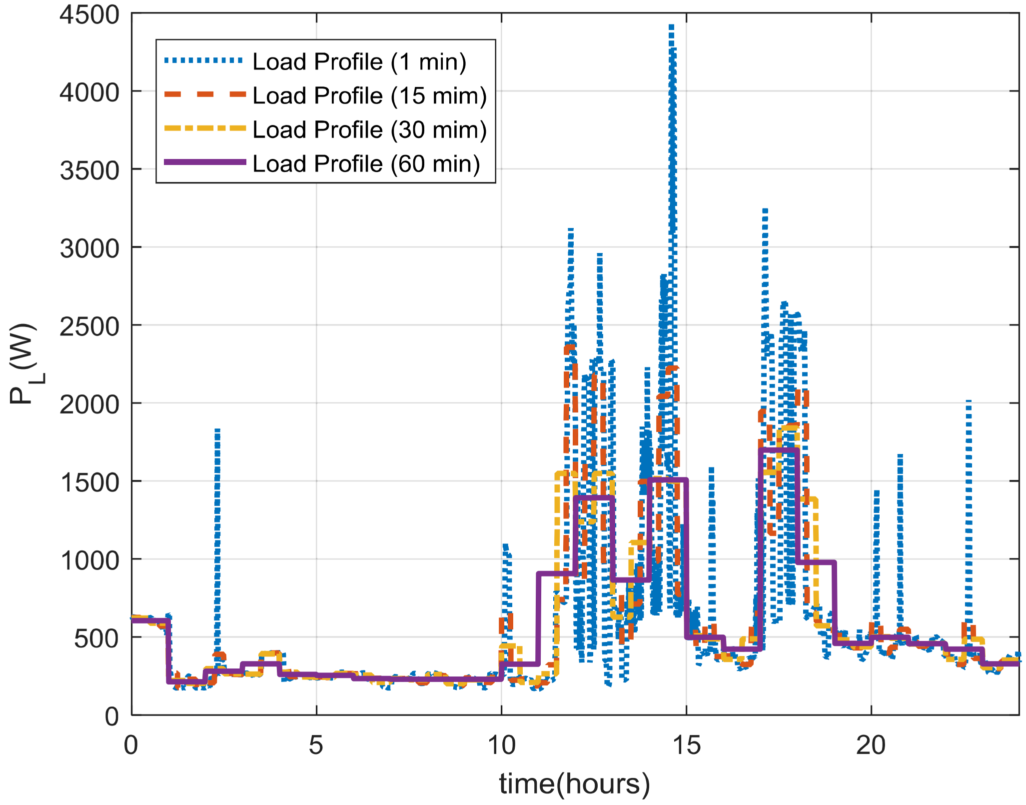

Figure 1 Household power consumption profiles with different recording intervals: 1 min, 15 min, 30 min and one hour. Household#02.

1.2. Influence of time-resolution smart meters on photovoltaic generation and the household power consumption profiles matching.

During the daytime the load demand and the solar generation peaks are frequently correlated [15]. PV self-consumption systems can be considered as a greener option for dealing with residential building consumption due to the maturity of the PV technology and its modularity. In this sense, this kind of PV systems has experienced a considerable growth [16].

Photovoltaic self-consumption systems provide electrical energy from PV solar generators. Self-consumption and self-sufficiency indices are defined in order to assess the performance metrics of this kind of systems. Self-consumption index, φ_{sc}, is defined as the ratio between photovoltaic energy consumed in-house, $E_{PV,consumed}$, and the photovoltaic energy generated on-site, $E_{PV,generated}$. Meanwhile, self-sufficiency index,

φ_{ss}, corresponds to the ratio between $E_{PV,consumed}$ and the total local energy demand, E_L [17]. $E_{PV,generated}$ and E_L are not affected concerning the total amount of energy by averaging through different recording intervals [18]. On the other hand, it must be highlighted that $E_{PV,consumed}$ may be overestimated when considering greater recording intervals; therefore, both φ_{sc} and φ_{ss} are affected by recording interval.

This overestimation is especially relevant in direct self-consumption energy where storage system is not used [9,19,20]. An analysis of synthetic household power consumption data and measured irradiation data through six recording intervals: 1 h, 30 min, 15 min, 10 min and 1 min for a few days showed an overstatement of both indices and percentage errors range from 0.2% with a 5-min resolution to 82.4% with a 1-h resolution [21]. An overestimation of 8% of φ_{sc} index has also been estimated in a household with a with a 4.9 MWh/year of household power consumption and an PV system of 5 kW_p when two different recording intervals (30 min with 30s) were compared [19]. In a household with 2.6 kW_p PV system, two recording intervals of 60 min and 1 min were compared for an annual reported period in order to estimate φ_{sc} index where hourly recording interval provide an overestimation around 10% [22]. Analysis of a 3 kWp PV system corresponding to zero electrical energy building (ZEB) and monthly average electricity consumption of 10.75 kWh showed that self-sufficiency and self-consumption indices have around 9% difference when hourly instead of 10-s time resolution data is used [23]. Two PV systems with a nominal power of 1 and 2 kW_p were simulated in order to evaluate the influence of averaging interval in the system performance (φ_{sc}, φ_{ss}, energy independence and grid interaction). The results showed also an overestimation of φ_{sc} and φ_{ss} when the recording interval increases. Estimated relative errors of both indexes are lower than 5% when 1 min of time resolution is compared with 15 s when there is no storage elements. However, when recording intervals of 1 hour is used, the estimated relative errors are within -13% and 56%. [24]. It must be highlighted that if a battery storage system is considered, the effect of poor temporal resolution almost vanishes leading to almost negligible effect in case of high φ_{sc} indices [9,12,24]. Table 1 summarizes the previous cases that have been referenced.

Table 1 Relative error in estimated indices.

Ref	**P_0(kW)**	**Parameters**	**Recording interval**		**Reporting period**	**Relative error**
			Reference	**Higher**		
[21]	0.02-10 kW	φ_{sc} and φ_{ss}	1 min	1 h	24 h. 1 Day	Max: 82.4%
[19]	5 kW	φ_{sc}	1 min	30 min	1 year	8%
[22]	2.6 kW	φ_{sc}	1 min	1 h	1 year	10%
[23]	3 kW (ZEB)	φ_{sc}	10 s	1 h	1 year	9%
[24]	1 and 2 kW	φ_{sc} and φ_{ss}	15 s 15 s	1 h 1 min	24 h. 1 Day	Max 56% < 5 %

Photovoltaic energy consumed, $E_{PV,consumed}$, is used to estimate φ_{sc} and φ_{ss}. $E_{PV,consumed}$ may be used not only to evaluate the performance analysis but it is also used for economic analysis when net-metering or net-billing policies are allowed. Therefore, it is very important to know the order of the magnitude of error when $E_{PV,consumed}$, φ_{sc} and φ_{ss} are estimated with different recording intervals. It must be highlighted that the aforementioned studies are addressed for a given array power with an annual reporting period [19,22,23], for a given array power with an daily reporting period [24], or for a range of array powers where only a daily reporting period is considered [21], which may be extremely short, as shown in Table 1. In this way, there is a lack of studies which consider all together the following issues:

- A range of photovoltaic array power (0.01 to 10kWp). It must be highlighted that self-consumption at the residential or small business level with PV generators below 10 kWp are the most common array powers.
- Different recording intervals (1 min, 10 min, 15 min, 30 min and 1 hour)
- Different reporting periods (daily or annual).

Moreover, although there are studies related with resident's association, RA, often referred as housing association, the influence of time resolution when estimating $E_{PV,consumed}$, φ_{sc} and φ_{ss} indices has not been analyzed. As RA load profiles may be smoother than individual household load profiles, it may be interesting to analyze how the estimation of performance metrics in RA is influenced by recording interval. Besides, photovoltaic RA self-consumption is an opportunity within Spanish royal decree (RD 244/219). Motivated by these facts, this work aims to deeply analyse the matching capability of photovoltaic generation and household power consumption profiles. In this sense, the error when estimating the photovoltaic self-consumed energy and derived parameters are provided as a function not only of the recording interval but also of the array power and reporting period (i.e. daily or annual). A better estimation of $E_{PV,consumed}$ will allow to calculate the performance metrics, performance analysis and to make properly decisions on managing and simulating energy resources. In this way, this paper may provide an adequate recording interval for smart meters in order to monitor household power consumption and generation profiles of households with a PV self-consumption system. A proper recording interval would avoid inaccuracy from averaging data in energy estimation and will provide a better performance analysis of this type of systems which will help not only to take appropriate, effective and timely decisions but will help this technology to be more energy efficient. Besides, it may help to evaluate the potential of this technology for residential purposes and to size photovoltaic self-consumption systems.

The manuscript has been organized as follows: introduction and background, context and current state of the research related with the topic have been addressed in section 1. Moreover, the objectives, innovation and novelty are also presented. In section 2, the input data which will be used in the analysis are described. Next, in section 3 the methodology is presented. In section 4, the results are discussed. This section has been spitted in two sub-sections corresponding to daily and annual reporting periods, respectively. Finally, the most relevant conclusions are given in section 5.

2. Input Data

A description of the input data, household power consumption and generation profiles, are provided in this section. Input data has been processed in order to avoid missing and invalid data according the recommendations of IEC 61724-1 [10], IEC 61724-2 [25] and IEC 61724-3 [26].

2.1. Irradiance profile

In-plane irradiance (W/m^2) on a flat surface (G_I) is sampled each second with a recording interval of one minute. The latter is measured with two meteorological stations which are placed in Jaén (latitude: 37º 47' 14.35'' N and longitude: 3º 46' 39.73'' W). Both meteorological stations have Eppley Pyranometers with "Secondary standards" classification per ISO 9060. The G_I measurement campaign was launched in March 2017 until November 2018.

2.2. Household power consumption profiles

Five electric household power consumption profiles were obtained throughout commercial smart meters during a year in five houses located in Jaén (South of Spain). Furthermore, these five electric demand profiles are grouped in order to simulate a resident' association (RA). The smart meters provide a sampling and recording interval of one second and one minute, respectively, and measure active power, voltage and current with an accuracy lower than 2%.

Table 2 Household power consumption of the five dwellings.

Households	Monitoring period	Annual household power consumption (kWh/year)	Occupancy	Contracted power rating (kW)

	Start	*End*	*Total hours*	*Daylight hours*	*Night hours*		
H01	01/04/2017	31/03/2018	2636.7	1419.0	1217.7	3	4,40
H02	01/04/2017	31/03/2018	4651.8	2767.8	1884.0	4	5.75
H03	01/04/2017	31/03/2018	14283.3	4755.7	9527.6	2	8,6
H04	01/02/2018	31/01/2019	3532.3	1891.4	1640.9	2	4,6
H05	01/11/2017	31/10/2018	8061.8	2024.9	6036.9	4	5,196
RA	01/04/2017	31/01/2019	33165.9	12858.8	20307.1	15	4,40-8.6

As can be seen in Table 2, H01 has the lower electrical consumption while H03 provides the higher one. H01 is inhabited by two adults and one child who are out of home during daylight hours. H01, H02 and H04 have the highest electrical consumption from sunrise to sunset. On the other hand, H03 and H05 have the highest electricity consumption during the night, particularly from November to April, because they have installed an electric heating which has been programmed to operate when the electricity prices from the grid is lower (i.e. during the night).

3. **Methodology**

The error when estimating matching capability of annual household power consumption and PV generation profiles will be estimated as a function of the photovoltaic array power, $P_{0,}$ for five households and resident's association. The array power will range from 0.01kW$_p$ to 10 kW$_p$. Load and generation profiles considering different recording intervals (1, 10, 15, 30 and 60 min) and different reporting periods (daily and annual) will be considered.

$E_{PV,generated}$ of the PV system has been estimated from irradiance data. Different methods to estimate $E_{PV,generated}$ can be found [27]. However, in this manuscript, the method which take into account Performance Ratio has been used [10].

A range of P_0 from 0.01 to 10kW$_p$ has been considered in order to evaluate the PV generator. Several steps have been used because of computational needs from massive data. Therefore, from 0.01 to 1 kW$_p$ and from 4 to 5 kW$_p$ an increase step of 0.1 kW has been considered. Meanwhile, from 1 to 4 kW$_p$, an increase of 0.05 kW has been chosen. Finally, from array powers higher than 5 and lower than 10 kW$_{p,}$ the increase step is 0.5 kW. Preliminary simulations have showed that the estimation of self-consumption and self-sufficiency indices provide the highest differences of percentage errors caused by the different recording intervals in the range between 1 and 4 kW$_p$ at individual households.

The performance of photovoltaic self-consumption systems can be evaluated by the parameters and indices which define the generated energy, the electric demanded energy and the energy from generated energy of PV system which is directly consumed by the household. $E_{PV,consumed}$, φ_{sc} and φ_{ss} are estimated against the array nominal power (P_0) following the flowchart indicated in **Error! Reference source not found.** [28].

$E_{PV,consumed}$ has been estimated from household power consumption for each individual household and photovoltaic generated energy data profiles using Eq. 1:

$$E_{PV,consumed,k,\tau_k} = \begin{cases} E_{L,k,\tau_k} & if\ E_{L\,,k,\tau_k} \leq E_{PV,generated,k,\tau_k} \\ E_{PV,generated,k,\tau_k} & if\ E_{L\ k,\tau_k} > E_{PV,generated,k,\tau_k} \end{cases} \qquad \text{Eq. 1}$$

where τ_k denotes the duration of the kth recording interval within a reporting period and k corresponds to the number of recording intervals in the reporting period [10], $E_{PV,generated,k,\tau k}$ is on-site PV generated energy and $E_{L,k,\tau k}$ provides the energy consumption of household for a given recording interval.

$E_{PV,consumed,k,\tau k}$ is considered as $E_{L,k,\tau k}$ when $E_{L,k,\tau k}$ is lower than $E_{PV,generated,k,\tau k}$. On the other hand, $E_{PV,consumed,k,\tau k}$ is $E_{PV,generated,k,\tau k}$ when $E_{L,k,\tau k}$ is higher than $E_{PV,generated,k,\tau k}$ [28,29] Generated energy, load consumption energy and self-consumed energy for a given reporting period can be estimated as:

$$E_{PV,generated,\tau} = \sum_{k=1}^{n} P_{PV,generated,k,\tau_k} \times \tau_k$$

Eq. 2

$$E_{L,\tau} = \sum_{k=1}^{n} P_{PP_{L,k,\tau_k}} \times \tau_k$$

Eq. 3

$$E_{PV,consumed,\tau} = \sum_{k=1}^{n} P_{PV,consumed,k,\tau_k} \times \tau_k$$

Eq. 4

Household power consumption data has been measured every second and with a recording interval of one minute. According to equations 2-4, if the desired recording interval is 15 min and reporting period is one day, τ_k should have a value of 15 and ‘n’ is 96 [18].

When $E_{PV,consumed,\tau}$ $E_{PV,generated,\tau}$ and E_L are estimated, φ_{sc} and φ_{ss} indices can be calculated as follows [21]:

$$\varphi_{sc,\tau} = \frac{E_{PV,consumed,\tau}}{E_{PV,generated,\tau}}$$

Eq. 5

$$\varphi_{ss,\tau} = \frac{E_{PV,consumed,\tau}}{E_{L,\tau}}$$

Eq. 6

Both indices are related to on-site consumed energy, however φ_{sc} index provides the matching capability between on-site consumed energy and on-site PV generated while φ_{ss} index indicates the matching capability between energy consumption of household and on-site consumed energy.

Different recording intervals (1 min, 10 min, 15 min, 30 min and 60 min) have been used in order to estimate the parameters described above. The percentage error found between recording interval lower than 1 min is smaller than 4.25 % [24], which can be within typical instrumental uncertainty. Moreover, these parameters are analyzed considering different reporting periods: one day and one year.

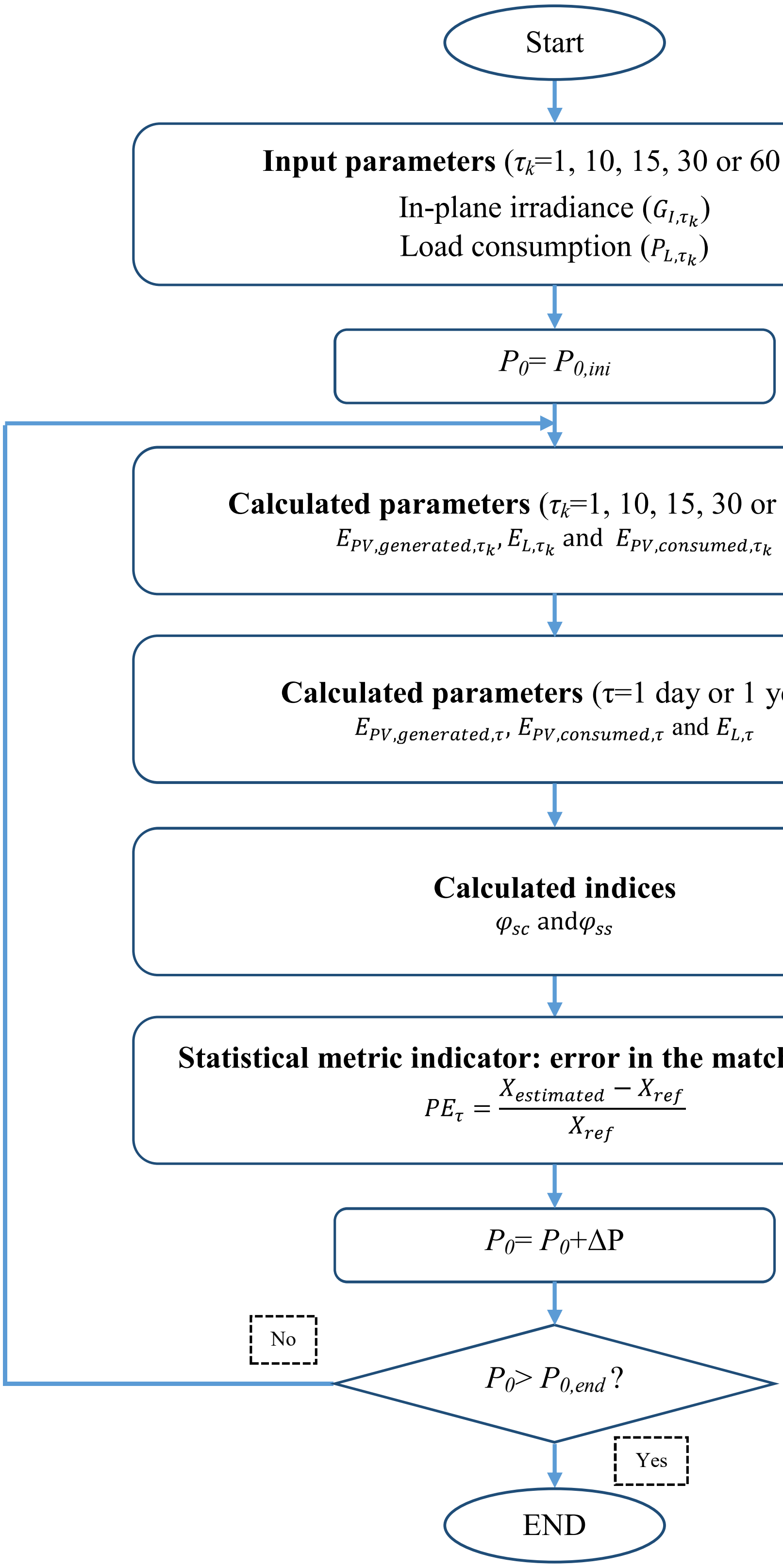

Figure 2 Flowchart to calculate $E_{PV,consumed,\tau}$ $\varphi_{sc,\tau}$, $\varphi_{ss,\tau}$ and PE_τ as a function of P_0.

Percentage error (*PE*) has been used as statistical metric indicator in order to provide the matching capability. *PE* was used in other similar studies [19,21,23,24] .

$$PE = \frac{X_{estimated} - X_{ref}}{X_{ref}} \qquad \text{Eq. 7}$$

where *X* represents the parameter considered and *N* is the number of samples. The recording interval of 1 min has been used as a reference.

In this sense, G_I and E_L have been monitored during one year with one minute of recording interval. Then, the data are checked and filtered in order to identify missing and/or invalid data points. Afterwards, $E_{PV,generated}$ is also estimated from irradiance data and considering a range of P_0 from 0.01 to 10kW$_p$. $E_{PV,consumed}$ is estimated from household power consumption for each individual household and photovoltaic generated power data profiles. These three parameters: E_L, $E_{PV,generated}$ and $E_{PV,consumed}$ are calculated considering different recording intervals (1, 10, 15, 30 or 60 min) and different reporting periods (1 day or 1 year) for each recording interval. Moreover, φ_{sc} and φ_{ss} are estimated over different reporting periods (day and year) for each recording interval. Finally, the matching capability considering different recording intervals (1, 10, 15, 30 or 60 min) within different reporting periods (1 day or 1 year) are analyzed. In this way, percentage error, PE, has been used as statistical metric indicator.

4. Results and discussions

4.1. Error estimation on a daily basis

Figures 3, and 4 plot the daily *PE* of $E_{PV,consumed}$, φ_{sc} and φ_{ss} when a recording interval of 60 minutes is used instead of 1 minute in a daily reporting period. The Y-axis provides *PE* and on the horizontal axis it is represented the array power, P_0. Boxplots are used in order to display the distribution of *PE*. Each box comprises groups of P_0 in intervals of one kW$_p$, where the central mark of the box shows the median, and the top and bottom edges of the box represent the 75th and 25th percentiles, respectively. The outliers are plotted as red symbols.

As can be seen from figures 3 to 4, daily *PEs* become higher as recording interval increases. There is a high variability of *PE* not only for the studied households, but also for each one of them for the different days and for P_0 powers considered. The figures show that, for a given recording interval, *PEs* varies depending on the P_0 of the PV generator. The highest *PE* at 75th percentile and median occur for P_0 of 1-3 kW_p in the households H01, H02, H03 and H05. Meanwhile, in H04 and RA this error happens for 0.01-1 kW_p and 6-7 kW_p, respectively. As may be shown in figures 3, 1A, 2A and 3A, the central marks, the bottom and top edges of the boxes from H01, H02, H03, H04 and RA have a similar shape. Firstly, *PE* becomes higher as P_0 increases until the maximum value commented above. Next, although P_0 continues to increase, *PE* decreases. However, H05 has a different shape of the 25th percentile, 50th percentile and 75th percentile *PE* for matching the household power consumption and PV generation profiles in a PV self-consumption system, while P_0 increases, the *PE* decreases. Seventy-five percent of all the matching capability between the household power consumption and PV generation profiles have a value of *PE* lower than 18% in H01, H02, H03 and H05 using a recording interval of 60 min instead of 1 min, table 3. However, in household H04 *PE* is 41% at the 75th percentile. It must be highlighted that for RA, *PE* is lower than 8.5%. RA load consumption is subject to random load coincidence of the five individual household, as Widén indicated, this produces a smoothing effect on the RA load consumption and lower variations [13]. Therefore, as averages will not differ substantially with the data taken at the reference recording interval (i.e. one minute), the error will be considerably lower.

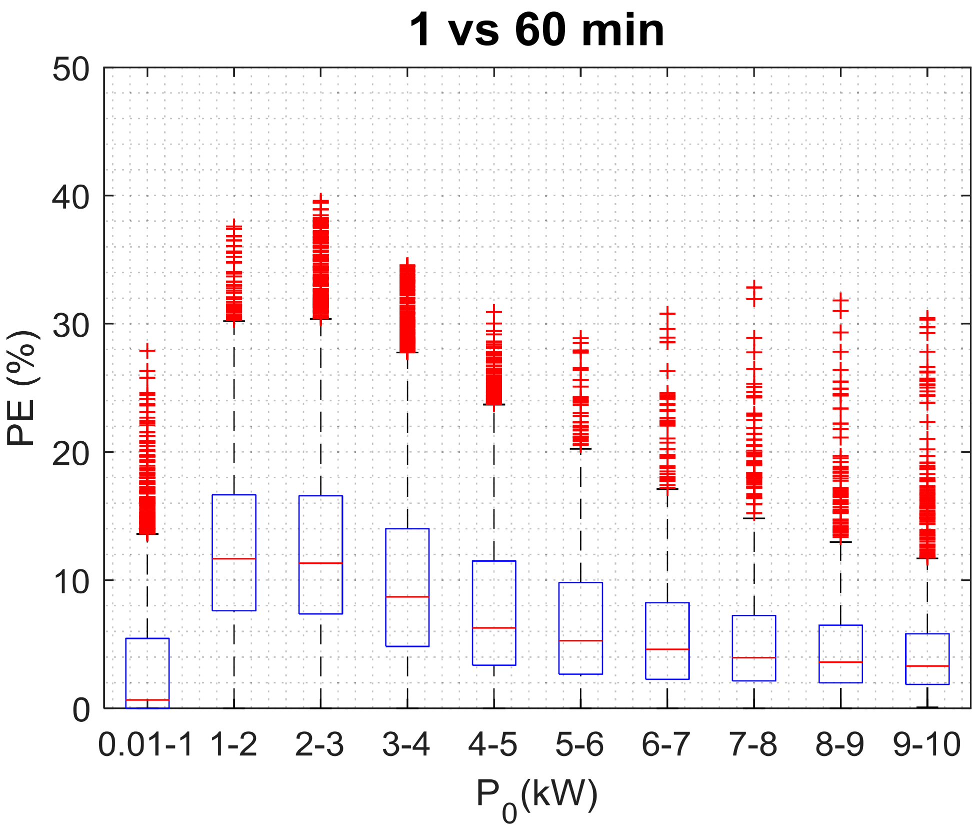

Figure 3 H02 Daily reporting period. Photovoltaic self-consumed energy error considering a recording interval of 60 min. One minute has been taken as a reference when $E_{PV,consumed}$ is estimated.

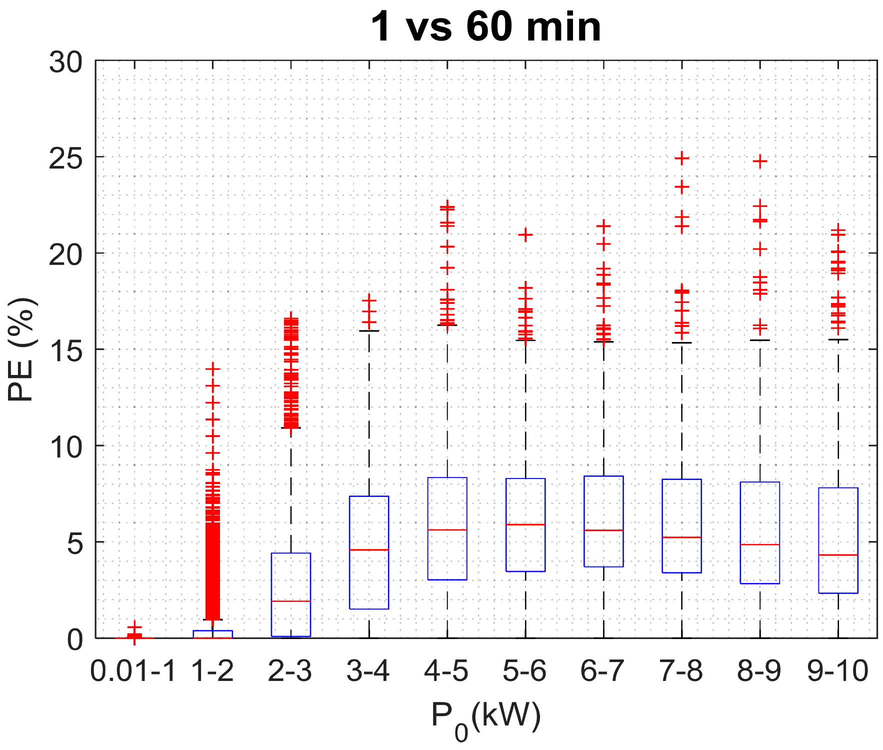

Figure 4 RA. Daily reporting period. Photovoltaic self-consumed energy error considering a recording interval of 60 min. One minute has been taken as a reference when $E_{PV,consumed}$ is estimated.

Table 3 Daily reporting period. PE_{Q3} between 10 and 1 min, 15 and 1 min. 30 and 1 min and 60 and 1 min

Recording interval	**1 vs 10 min**		**1 vs 15 min**		**1 vs 30 min**		**1 vs 60 min**	
Households	PE_{Q3} **(%)**	$P_{0, PEQ3}$ **(kW$_{p}$)**	PE_{Q3} **(%)**	$P_{0, PEQ3}$ **(kW$_{p}$)**	PE_{Q3} **(%)**	$P_{0, PEQ3}$ **(kW$_{p}$)**	PE_{Q3} **(%)**	$P_{0, PEQ3}$ **(kW$_{p}$)**
H01	3.96	2-3	5.44	2-3	8.10	2-3	12.31	2-3
H02	5.98	2-3	8.01	2-3	11.93	2-3	16.65	2-3
H03	4.26	2-3	5.73	2-3	9.86	2-3	14.92	2-3
H04	14.12	1-2	20.74	1-2	31.86	1-2	40.94	1-2
H05	5.84	0.01-1	8.07	0.01-1	12.91	0.01-1	17.91	0.01-1
RA	2.95	6-7	3.99	6-7	6.00	5-6	8.42	6-7

Table 4 Daily reporting period. PE_{max} between 10 and 1 min, 15 and 1 min. 30 and 1 min and 60 and 1 min.

Recording interval	**1 vs 10 min**		**1 vs 15 min**		**1 vs 30 min**		**1 vs 60 min**	
Households	PE_{max} **(%)**	$P_{0,PEmax}$ **(kW$_{p}$)**	PE_{max} **(%)**	$P_{0,PEmax}$ **(kW$_{p}$)**	PE_{max} **(%)**	$P_{0,PEmax}$ **(kW$_{p}$)**	PE_{max} **(%)**	$P_{0,PEmax}$ **(kW$_{p}$)**
H01	25.45	1.75	28.24	0.10	35.54	0.10	50.29	0.20
H02	16.95	2.20	19.03	2.30	24.93	1.55	39.59	2.25
H03	15.69	3.05	16.58	3.05	35.91	5.50	55.58	2.75
H04	37.85	2.20	60.70	0.90	96.90	0.60	126.52	0.60
H05	54.29	0.01	77.40	0.01	139.33	0.01	155.32	0.01
RA	17.73	7.00	19.41	7.50	22.76	7.50	24.92	7.50

Conversely, the peak values for *PE* range from 39.6% in H02 with a P_0 of 2.25 kW$_p$ to 155.5% in H04 with P_0 of 0.01 kW$_p$ using a recording interval of 60 min instead of 1 minute, table 4. The largest *PE* for RA is considerably lower than *PE* of individual households: it is always below 25%. It must be highlighted that the peak values are outliers and they are not frequent.

As can be seen, in the load consumption profiles corresponding to H04, figures 5, during the sun hours there is a load power which has a value much larger than generated one for a period of 10-15 minutes, approximately every hour. Moreover, there is an electricity demanded energy much lower than generated energy for the rest of the time. Therefore, when matching PV generation and the household power consumption profiles in a PV self-consumption system with a daily reporting period may occur large *PEs* using recording intervals of 60 minutes instead of 1 minute. These large *PE* may be due to the smoothing effect on the load consumption profiles. As Cao et al observed, when the PV generation curve crosses frequently the intermittent long sharp spikes in the demand profile, the highest *PE* may occur [21]. However, with less than 10 crossings between PV generation and demand profiles the matching error may be higher than 125 %, figure 5.

Most of *PEs* (more than 90%), which are obtained in individual households using recording intervals of 60 minutes and considering a daily reporting period, are within the *PEs* which were observed by Cao et al. and Wolf et al. in their simulations [21,24]. However, for H04 and H05, there are *PEs* that may be twice higher than the observed by these authors and do not show frequently crosses between generation and load profiles.

If 30 minutes of recording interval and a daily reporting period are considered, the third quartile for *PE* has a value lower than 13% for all individual households and RA, with the exception of H04, which has a value of 32%, table 3. Furthermore, *PE* using 10 or 15 minutes of recording intervals instead of 1 minute is not larger than 8% in all households. As expected, H04 has values of *PE* lower than 32%.

Results show that the matching capability is always overestimated when a coarser recording interval than one minute is used for the same array PV generator and load consumption. Furthermore, the results depend on the households profiles and the array power and there is a great variability in the *PE* for each household. Relative high *PEs* in the matching of household power consumption and PV generation profiles have been observed. Therefore, one hour and thirty minutes of recording interval should be avoided with daily basis analysis. Daily basis analysis requires household power consumption and PV generation data with a recording interval as small as possible.

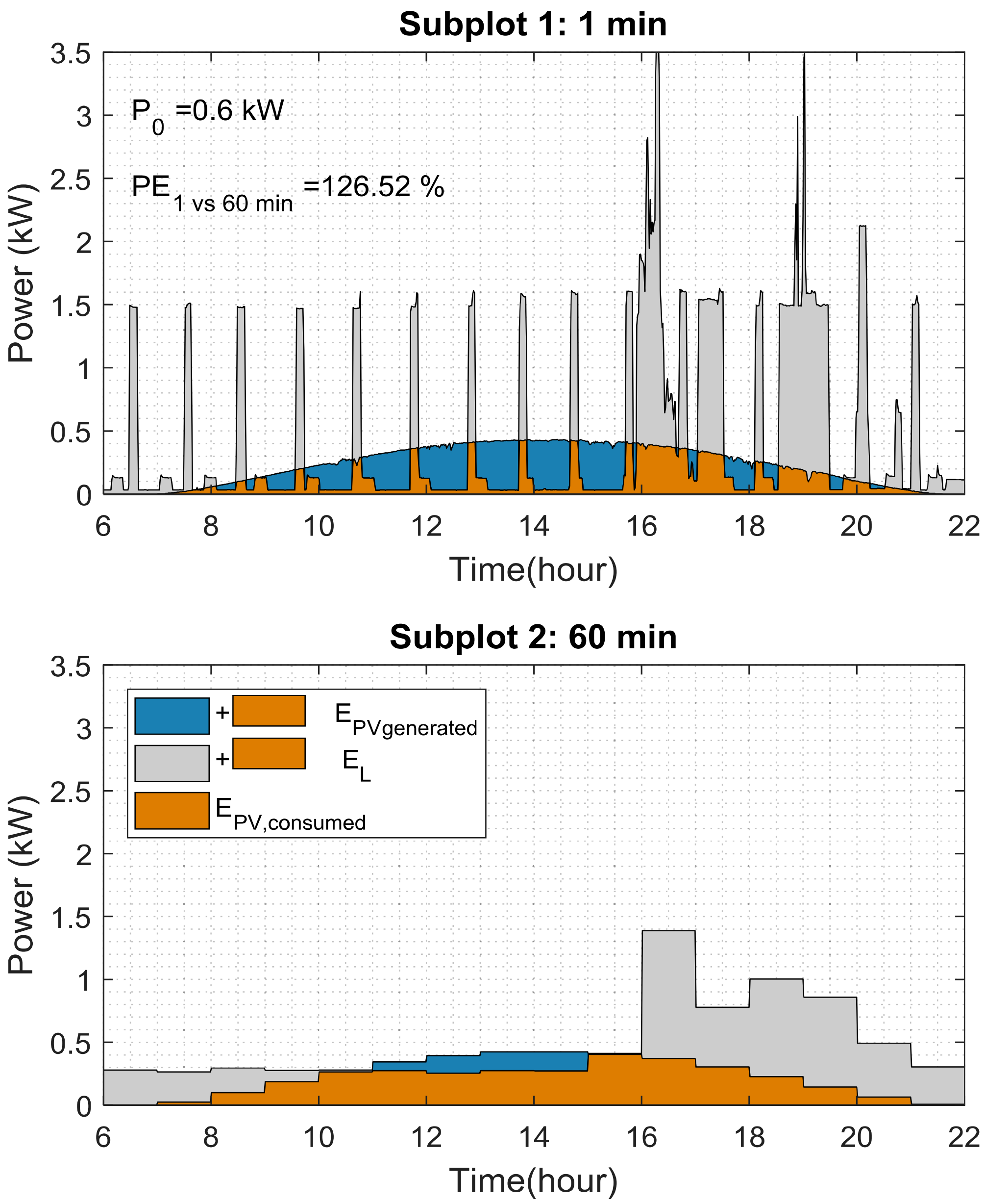

Figure 5 H04. Daily generation, load power consumption and photovoltaic consumption profiles for different recording intervals (1 and 60 minutes). P_0 0.6 kW$_p$. Data corresponding to 4 June 2018. The recording intervals are 1 and 60 minutes.

4.2. **Error estimation on an annual basis**

PE when estimating $E_{PV,consumed}$, φ_{sc} and φ_{ss} with different recording intervals in an annual reporting period is shown in figure 6 and table 5, where one minute recording interval has been used as a reference. As can be seen, annual *PE* increases as recording interval becomes coarser, as it happened on a daily basis. However, much lower *PE* values have been obtained with an annual reporting period and *PEs* are considerably smoothed. Moreover, it must be highlighted that when RA is considered, *PE* becomes almost negligible.

As can be seen in figure 6 and figures 1.B-6.B, *PE* depends on the P_0 considered. Furthermore, curves corresponding to households H01-H04 have a similar shape for all recording intervals. *PE* becomes higher as P_0 increases until it reaches a maximum for the array power that lies between 1.15-2.65 kW_p, where it may be found the maximum PE on an annual basis. Then, *PE* decreases as P_0 continues to grow. RA curve follows a similar pattern as H01-H04 ones where the maximum *PE* is reached not only at a considerably higher array power (5.5-6kWp) but once this maximum is reached, *PE* remains almost unchanged as the slope of the curve is almost negligible. However, as can be seen in figures 6 and 5.B, H05 curves show a different shape from the other analyzed households, the *PE* peak occurs when P_0 is 0.01 kWp. Afterwards, there is a decrease in the value of *PE* between 04-06 kWp. Next, *PE* is increased until P_0 reaches 7 kWp. Finally, *PE* slightly decreases as P_0 continues to increase.

For the cases studied, if 10 and 15 minutes recording intervals are considered, the maximum *PE* is lower than 15.25 %. This peak *PE* corresponds to Household#04. For Household#5 *PE* may reach 10.5%. However, for the rest of the households, *PE*, for the array power range considered, is always below 6.5%. When a 30 minutes recording interval is used on an annual basis, the peak annual *PE* varies from 4.4% to 24.5%. The highest *PE* are 15 and 24.5% and correspond, as it has been previously mentioned, to Household#04 and #05, respectively. For households#01, #02 and #03, *PE* is always below 9%. Finally, the highest *PE* are reached when a 60 minutes recording interval is taken into account. In this case, the peak annual *PEs* range between 6.3 to 32%, although for households#01, #02 and #03, *PE* is always below 13%.

As can be shown in Table 5, for H01, H02, H03 and H04, the PE peak values for the different recording intervals lies between 1.15 and 2.65 kW_p. Meanwhile, the maximum *PE* value for H05 corresponds to 0.01 kW_p. Furthermore, for RA the highest PEs correspond to array powers that can be found between 5.5 and 6 kW_p.

PEs, which were observed by Wyrsch et al, Gusfafsson et al, and Ayala-Gilardon et al, were within the obtained *PE* in the studied households. However, their *PEs* were only provided for one or two specific array powers.

Daily *PEs* are higher than annual *PEs* for all the individuals' households and resident's association. Therefore, one minute or lower recording interval may be used in order to analyse the PV self-consumption system on a daily basis. However, for an annual basis it may be used higher recording intervals such as ten minutes because annual *PE* is substantially reduced in the majority of the households. Moreover, half-hour recording interval may be used for RA.

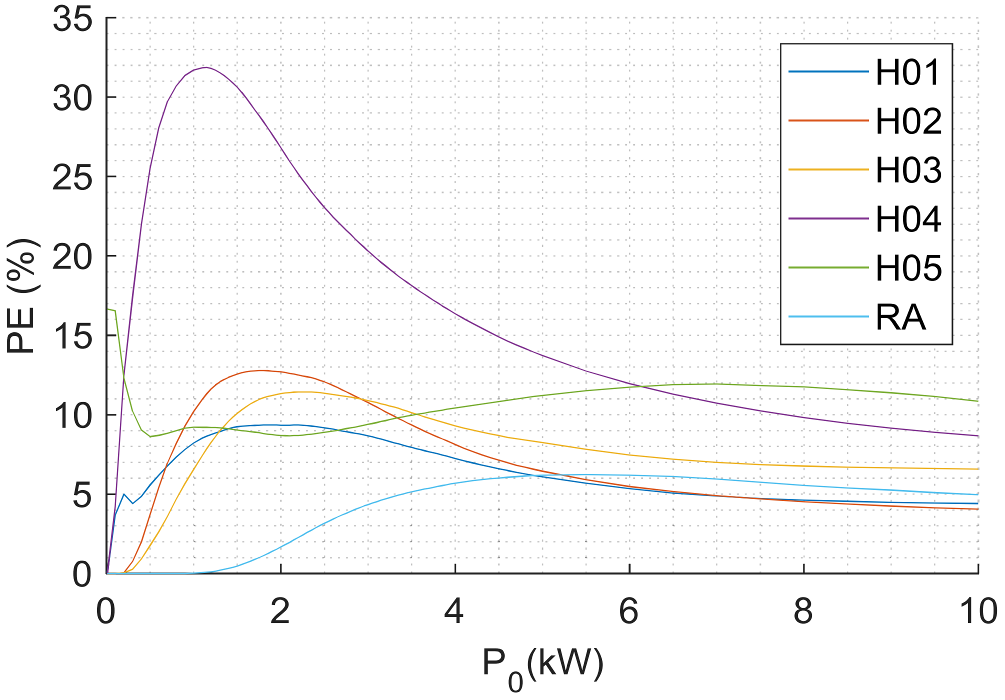

Figure 6 Annual photovoltaic self-consumed energy error as a function of P_0 considering a recording interval of 60 min. One minute has been taken as a reference when $E_{PV,consumed}$ is estimated.

Table 5 Annual reporting period. *PE* between 10 min and 1 min, 15 min and 1 min. 30 min and 1 min and 60 min and 1 min

Recording interval Households	**1 vs 10 min**		**1 vs 15 min**		**1 vs 30 min**		**1 vs 60 min**	
	PE_{max} (%)	$P_{0,PEmax}$ (kW_p)	PE_{max} (%)	$P_{0,PEmax}$ (kW_p)	PE_{max} (%)	$P_{0,PEmax}$ (kW_p)	PE_{max} (%)	$P_{0,PEmax}$ (kW_p)
H01	3.76	2.65	4.56	2.60	6.43	2.35	9.36	1.85
H02	4.78	1.95	6.35	1.95	9.19	1.80	12.78	1.75
H03	3.30	2.35	4.41	2.45	7.25	2.30	11.44	2.30
H04	10.63	1.45	15.25	1.30	24.18	1.15	31.86	1.15
H05	8.01	0.01	10.66	0.01	15.82	0.01	16.66	0.01
RA	2.31	6.00	2.99	5.50	4.40	5.50	6.23	5.50

5. Conclusions

Daily and annual *PEs* of $E_{PV,consumed}$, φ_{sc} and φ_{ss} , when different recording intervals (10, 15, 30 and 60 min) are used instead of 1 minute, have been determined as a function of P_0 for five households and resident's association. Moreover, it has been considered an analysis where the array power ranges from 0.01kWp to 10 kWp.

As has been shown, the influence of recording interval for daily reporting periods is largely dependent on the photovoltaic array power, P_0, and the household power consumption profiles. The peak values for daily *PE* range from 39.6% in H02 with a P_0 of 2.25 kWp to 155.5% in H04 with P0 of 0.01 kWp using a recording interval of 60 min instead of 1 minute. Therefore, there is also a high variability of the *PE* not only for the studied households, but also for the different analyzed days and P_0.

On the other hand, the *PE* when estimating $E_{PV,consumed}$, φ_{sc} and φ_{ss} in a PV self-consumption system with an annual reporting period is considerably smoothed using the same recording interval in comparison with daily recording interval in individual households. The *PE* peak values range from 6.2% to 31% using a recording interval of 60 min instead of 1 minute and *PE* peak values for the different recording intervals lie between 1.15 and 2.65 kW$_p$. Moreover, it must be highlighted that when a RA is considered, *PE* becomes almost negligible, *PE* values lower than 6.2% using a recording interval of 60 min instead of 1 minute.

The obtained results can be very useful to carry out adequate energy analysis in ZEBs with PV self-consumption systems. Moreover, they can be used as a guide for selecting the proper recording interval in smart meters when energy analysis is required. In this regard, despite averaging data through recording interval produces loss of information, one minute or lower recording interval may be used in order to analyze the PV self-consumption system for a daily basis. On the other hand, a ten minutes recording interval may be used for estimating $\mathrm{E}_{\mathrm{PV,consumed}}$,φ_{sc} and φ_{ss} in a PV self-consumption system with annual reporting period as the annual PE is relatively low in the majority of the analysed households. Moreover, a half-hour recording interval may be considered for RA on an annual basis.

As it has been shown, higher recording intervals could provide an overestimation of performance metrics, such as $E_{PV,consumed}$, φ_{sc} and φ_{ss} and may cause a substantial reduction of sharp peaks. A better estimation of $E_{PV,consumed}$ will manage to provide a more accurate energy performance analysis of photovoltaic self-consumption systems. Moreover, it could provide the real matching capability between PV generation and electricity load demand profiles. In this way, a proper recording interval would avoid inaccuracy from averaging data in energy estimation and it may help not only to evaluate the potential of this technology for residential purposes but also to properly size photovoltaic self-consumption systems. Whereas, lower recording interval may generate large amount of data, which may require more storage elements and a more complex data mining.

However, it is necessary to address a deeper investigation that involves a greater number of dwellings. In addition, it would be interesting to investigate the source of the matching error from the consumption and generation profiles. This will allow to define parameters that indicate the magnitude of the error if higher recording intervals are used.

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