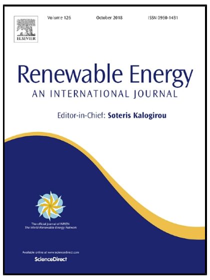

A new approach to sizing the photovoltaic generator in self-consumption systems based on cost–competitiveness, maximizing direct self-consumption.

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PII: S0960-1481(18)30740-7

DOI: 10.1016/j.renene.2018.06.088

Reference: RENE 10244

To appear in: *Renewable Energy*

Received Date: 11 January 2018

Accepted Date: 21 June 2018

Please cite this article as: D.L. Talavera, F.J. Muñoz-Rodriguez, G. Jimenez-Castillo, C. Rus-Casas, A new approach to sizing the photovoltaic generator in self-consumption systems based on cost–competitiveness, maximizing direct self-consumption., *Renewable Energy* (2018), doi: 10.1016/j.renene.2018.06.088

A new approach to sizing the photovoltaic generator in self-consumption systems based on cost–competitiveness, maximizing direct self-consumption.

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Abstract

Applications for sizing Photovoltaic (PV) self-consumption systems have been studied over recent years in order to achieve either an optimization of the cost of energy, the investment cost or any economic profitability criteria. However, PV self-consumption systems at the residential or small business level can be designed with the aims of reducing the electricity consumption from the conventional local grid and achieving competitiveness with grid electricity prices. These criteria will provide not only greater environmental benefits, security and independence of the grid but it will make the cost of PV self-consumption electricity competitive with electricity prices from the power grid. In this sense, this paper proposes a method to size the generator for a PV self-consumption system based on cost-competitiveness, maximizing direct self-consumption. The method will be applied for three different households located in the south of Spain using the household daily consumption and generation profiles for a single year. However, the method here illustrated can be applied to other countries. The results obtained suggest that residential direct PV self-consumption systems with an annual global irradiation at the optimal tilt angle higher than 1000 kWh/(m^2·year) may be a feasible investment to future owners of these systems.

Keywords: photovoltaic, self-consumption, Levelised cost of electricity

1 Abbreviations

C_S	Cost of direct PV self-consumed electricity
d	Nominal discount rate (%).
DES	Distributed energy sources
DEP_n	Annual tax depreciation (€).
DEP_y	Fixed annual tax depreciation (€).
d_{eq}	Annual dividend the equity capital –return on equity- (%).
DSM	Demand Side Management.
DOE	US Department of Energy
$E_{L,\tau}$	Total energy consumption during the reporting period.
EPSS	Energy production and storage simulator
E_{PVC}	Normalized per-kW$_p$ annual direct self-consumed PV energy (kWh/(kW$_p$·year)).
$E_{PV,consumed,\tau}$	Photovoltaic energy consumed during the reporting period.
$E_{PV,generated,\tau}$	Photovoltaic energy generated during the reporting period.
F	Normalized Factor.
g	Annual inflation rate (%).
G_{STC}	Global Irradiance in Standard Test Condition (1 kW/m^2).
HOMER	Hybrid optimization model for electricity renewables)
H_{OPT}	Annual global irradiation at the optimal tilt angle (kWh/(m^2 year)).
i_l	Annual loan interest (%).
K_p	Factor equal to $(1+r_{O\&M})/(1+d)$.
$L(t)$	Direct building power consumption.
LCC	Normalized-per-kW$_p$ life cycle cost of the PV system (€/kW$_p$).
$LCOE$	Levelised cost of electricity (€/kWh).
$M(t)$	Direct photovoltaic power consumed.
N	Life cycle of the PV system, equal to analysis period (years).
N_d	Tax life for depreciation (years).
N_l	Amortization of loan (years).
$P(t)$	Direct onsite power provided by the PV generator.
P_0	PV nominal power (Wp).
PR	Performance Ratio (%).
PV	Photovoltaic
C_S	Cost of direct PV self-consumed electricity (€/kWh).
PV_{AOM}	Annual operation and maintenance cost of a PV system (€).
PV_{OM}	Operation and maintenance costs
PV_{eq}	Amount equal to the portion of the initial investment financed with equity capital (€).
PV_I	Initial investment cost of a PV system (€).
PV_l	Amount equal to the portion of the initial investment financed with loan (€).
PW [$DEP(N_d)$]	Present worth of the tax depreciation (€).
PW[$PV_{OM}(N)$]	Present worth of the PV system operation and maintenance cost (€).
q	Factor equal to $1/(1+d)$.
r_d	Annual degradation rate in the efficiency of the PV panels (%).
$r_{O\&M}$	Annual escalation rate of the operation and maintenance cost of a PV system (%).
S_V	Salvage value of the system at the end of their life cycle (€).
T	Income tax rate (%).
VRES	Variable renewable energy sources
$WACC$	Weighted Average Cost of Capital (%).
WMO	world meteorological organization

Y_F	Annual Final yield of a PV System kWh/(kW$_p$·year)
ZEB	Zero Energy Building.
τ	Reporting period.
τ_r	Recording interval.
φ_{sc}	Self-consumption index.
φ_{ss}	Self-sufficiency index.
C_S	Cost of direct PV self-consumed electricity
d	Nominal discount rate (%).
DEP_n	Annual tax depreciation (€).

1. Introduction

Distributed generation, also known as in-situ generation or decentralized generation, basically consists of the generation of electrical energy by means of many small sources of energy that are connected to the electricity distribution network in places as close as possible to the loads. Systems used as distributed energy sources (DES) are small-scale power generation plants (usually in the range of 3 kW to 10 MW) which provide an alternative or an aid to traditional power generation plants: photovoltaic solar energy, small wind energy systems, fuel cell, cogeneration, microturbines and electric vehicles. In the European Union there are subsidised projects for the optimal design of multi-modal energy systems. Total cost savings by using on-site generation of up to 61% were achieved and photovoltaic energy was a viable option [1].

One of the main sources of distributed energy is photovoltaic solar energy produced by solar panels on building roofs. It is a technology that is growing rapidly, doubling its total installed capacity approximately every two years [2,3]. There is a wide range of photovoltaic systems, from small installations on residential or commercial roofs, integrated installations in buildings, and large-scale grid-connected photovoltaic plants. In recent years, photovoltaic solar energy has improved its energy conversion efficiency and has reduced installation costs, having already achieved grid parity (i.e., PV electricity production at a cost less than or equal to the average price of grid electricity) [4,5]. However, like most renewable energies, and unlike coal or nuclear energy, photovoltaic energy is variable and unmanageable. Moreover, the key challenge of PV technology lies in the fact that, even at infinitely high system sizes, a PV generation profile cannot match the full load profile of a typical household customer as the former cannot supply electricity outside daylight times. This is the reason why in off-grid applications electricity storage must be considered in order to ensure higher power reliability. However, among its advantages are the absence of fuel costs (solar radiation), its zero pollution during the operation phase, as well as its reliability and safety. In [6,7] the use of storage devices is analysed in order to minimize the fluctuations in the power production from variable renewable energy sources (VRES) such as wind and solar energy. Moreover, the most suitable storage characteristics for integrating a high share of VRES into a fully connected European power system are provided.

Photovoltaic self-consumption refers to the individual production of electricity for the consumption through photovoltaic solar panels. The former can be achieved instantaneously which is called direct self-consumption. Moreover, if the PV power generated is higher than the load power consumed, the surplus can be stored for later use. The use of energy storage systems is a strategy that can be used to optimize self-consumption. Increasing self-consumption of PV electricity from grid-connected residential systems could raise the profit of PV systems and lower the stress on the electricity distribution grid [8]. The energy system acquires greater efficiency avoiding transport losses, since the energy is produced closer to the points of consumption. As the use of renewable energies is increased, CO_2 emissions to the atmosphere are reduced. Moreover, for a country that has a very high solar resource and is very dependent on the polluting fossil energies, as is the case of Spain, it would imply an energetic independence, at the same time as the development of a sector that remains stagnant. And last but not least, self-consumption does not constitute an additional cost to the electrical system. On the other hand, and considering direct self-consumption, there is a difficult task of matching the generation and load profiles, the solar resource is not manageable as has been mentioned above, and there may be a dependence on the changing regulations regarding self-consumption, including tolls and rates that hinder profitability and therefore the expansion of this type of energy production.

A brief overview of self-consumption policies can be found in [9] where regulatory framework in most countries supports net balance schemes which directly or indirectly favours photovoltaic self-consumption. However, the case of Spain is quite particular, taking into account the high solar resource available. Spanish self-consumption regulation is set in the Royal Decree 900/2015 and can be summarised as follows [10]: First of all, it must be taken into account that the maximum capacity of the self-consumption installation must be equal or below the contracted capacity. These installations can be classified as: *Type 1*: photovoltaic installations with nominal power below 100 kW_p where there is no compensation for the electricity surplus fed in the grid. These are addressed to small consumers. *Type 2*: installations not included in type 1. It has no limit to the allowed capacity – the surplus can be sold in the wholesale market directly or through an intermediary. A specific grid tax of 0.5 EUR/MWh has to be paid together with a 7% tax on the electricity produced. Moreover, not only are supporting schemes provided but additional taxes should be considered. Self-generated power above 10 kW is charged with a fee per kWh consumed as a “grid backup toll”, also known as the “tax on the sun”. Adding battery storage also implies an additional tax. What is more, geographical compensation and self-consumption for several end customers or a community are not allowed. As can be clearly, seen support policies in the case of Spain are negligible or marginal.

Nowadays, and in some countries, subsidies are no longer needed as the cost of self-produced PV electricity may be lower than the retail price of electricity [5,11]. In this sense, the applications for sizing PV self-consumption systems have been studied over recent years and they are based on very different strategies, where the considered factors are climate, building characteristics and load types [9,12]. The former manage to size PV self-consumption systems based on an optimization of the cost of energy, the investment cost and economic profitability criteria [13-19]. In [13] the method used to size the optimal system configuration is aimed to minimize the total cost of the energy supply. In [14] the authors develop an optimal energy management strategy for a consumer connected to the power grid equipped with a vehicle-to-home power supply and a photovoltaic power generation unit, in order to minimize the total energy cost. In [15] the optimal cost sizing of the main system components and grid interaction is carried out based on a hybrid mixed integer linear programming and a heuristic optimization algorithm. In [16] it is proposed an analytical approach to design an integrated PV-Storage solution for self-consumption purposes optimizing the overall system cost. In [17] the developed techno-economic optimization model for German households allows an evaluation of the net present values for the PV system and the battery storage from a household perspective. In [18] it is developed a techno-economic simulation model that is able to compute the optimal PV and battery size configuration for a given household and its load profile, this model is based on maximizing the net present value. Moreover, there are available software tools, such as HOMER (hybrid optimization model for electricity renewables) which simulate different system configurations and generate results as a list of feasible configurations sorted by net present cost [19]. In this sense, Renewable energy systems with Photovoltaic system and wind system for self-consumption were modelled using the HOMER tool to estimate the levelized cost of electricity and net present cost [20,21]. Other software tools, such as EPSS (energy production and storage simulator) allow the designer to choose between different combinations of nominal power and self-consumption and self-sufficient indices the one which better fits with other requirements, (e.g. minimizing the cost of components [12]).

The sizing of the PV self-consumption systems based on an optimization of the cost of energy, net present cost or minimizing the costs of components, does not imply that a PV system is cost-competitive with regard to other sources of electricity generation. Furthermore, a model for optimizing the size of a PV generator based only on economic criteria does not take into account other relevant aspects such as environmental benefits, security and independence of the grid. The latter are in keeping with the European energy policy. In this sense, the main objective of this paper is to provide a new approach to follow when sizing the photovoltaic generator for a PV self-consumption system in order to make a PV self-consumption system cost-competitive with respect to the electricity prices from the power grid, In addition, this method will maximize direct self-consumption, and, therefore, the photovoltaic energy consumed. This new criterion follows the aforementioned European energy policy. Moreover, consumers may become active players of the electricity retail market. In this paper only direct self-consumption will be considered which uses no battery and the surplus generation is wasted.

In order to achieve the aforementioned objective, and for a given annual irradiation, the cost of photovoltaic self-consumed electricity will be estimated as a function of the self-consumption index, i.e. the photovoltaic self-consumed energy. In this way, the self-consumption index that maximizes photovoltaic self-consumed energy achieving cost competitiveness will be obtained. Afterwards, and in order to provide a proper solution to any household, its load consumption time series will be considered during a whole year. These data, together with irradiance time series of the location considered will be used to plot the self-consumption and self-sufficiency indices as a function of the PV array. The latter together with the self-consumption index previously estimated will manage to estimate the proper array size .The method here explained will be applied for the case of Spain, which clearly offers an unfavorable regulatory framework for photovoltaics self-consumption, using real daily consumption and generation profiles for a single year for three different households located in the south of Spain. It will be shown how, even in the absence of subsidies, and considering the case of Spain, the cost of direct self-consumption electricity from a PV system may be lower than the price of electricity obtained from the conventional grid. Therefore, techniques to calculate the cost of PV self-consumption electricity of a system will also be offered. The latter will be expressed as a function of the self-consumption index in order to estimate the value of the cost of PV self-consumption electricity, that manages to achieve cost-competitiveness and that maximizes direct self-consumption. In this sense, it will be illustrated how to determine self-sufficiency and self-consumption indices from the daily load profiles over a whole year as a function of the photovoltaic generator power in order to determine the most suitable one.

It must be stated that self-consumption at the residential or small business level with PV generators below 10 kW_p will be the focus of this paper. Although this method will be only illustrated for Spain, it can be applied to other countries if daily consumption profiles of the household under study are known and the cost of PV self-consumed electricity is estimated. Furthermore, the method here shown can be also applied to self-consumption systems which may use any strategy that improves matching capability between load and generation profiles, such as batteries and demand side management (DSM).

This paper is structured as follows: in section 2, it will be developed the proposed method. In this sense, the main characteristics of three households located in the south of Spain that will be used to illustrate the given methods will be described in subsection 2.1. Their corresponding daily load profiles have been obtained throughout a year and using a one minute recording. Moreover, the parameters used to characterize photovoltaic self-consumption will be presented (i.e. self-consumption and self-sufficiency indices) in subsection 2.2. Likewise, a detailed study of the behaviour of self-sufficiency and self-consumption for these households will be carried out where the relationship between both indices as a function of the PV generator power will be illustrated. The study will be developed from a daily, monthly and annual basis. Afterwards, in subsection 2.3, the mathematic model to be used to calculate the cost of PV self-consumed electricity will be described. Moreover, a review will be developed to estimate the parameters involved in the aforementioned calculation.

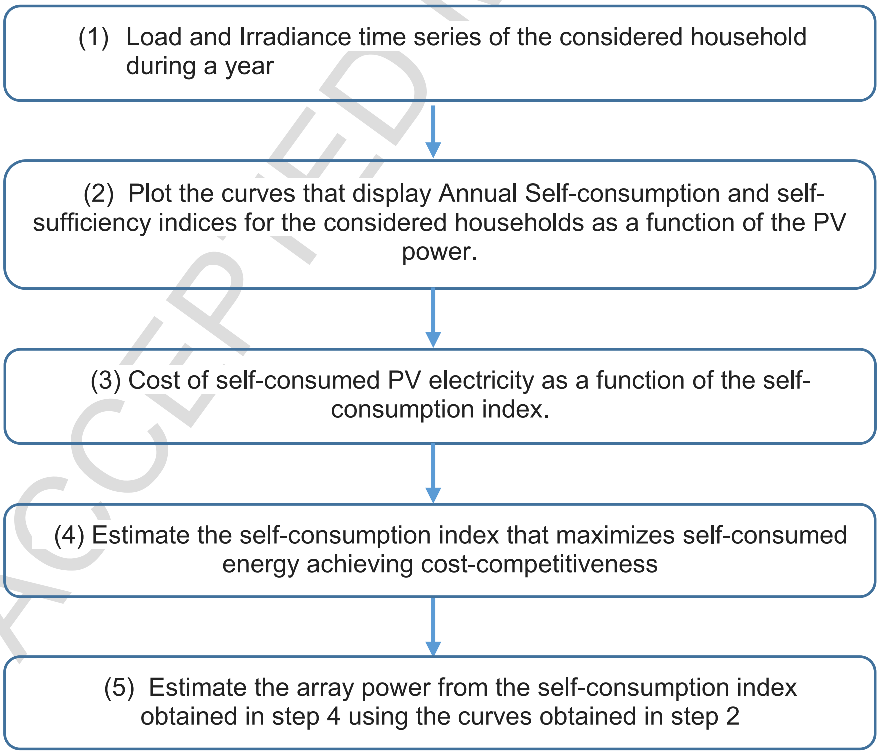


Figure 1. Method to size a photovoltaic generator based on cost–-competitiveness that maximizes self-consumption.

In section 3, different graphs will be offered where the cost of PV self-consumed electricity is calculated as a function of the self-consumption index. The latter, together with self-sufficiency and self-consumption curves as a function of the PV generator, will be used to size the photovoltaic generator. It must be highlighted that the main objective of this paper is to provide a new method to size the photovoltaic generator in a self-consumption system but not to develop a study of photovoltaic self-consumption in south Spain. However, and in order to illustrate the method, the latter will be applied to three households located in this region. Both results concerning the method and some issues about self-consumption systems will be discussed in this section. However, the latter may be not representative, and further analysis which considers a larger number of households should be addressed. Finally, in section 4 conclusions will be drawn.

2. Proposed Method

2.1. Load and Irradiance Time series

Generally, the information on electrical loads is provided by smart counters that are currently being installed in the households. However, the available information on load consumption which is provided by most electric utilities is generally based on a one hour resolution. Nevertheless, for load profiles, as was discussed in [22] there are high fluctuations between high and low power levels whose duration can range from a few minutes to a few seconds (e.g. refrigerator, microwave, lighting and other machinery. When averaging, the load peaks are reduced or disappear as the averaging period is increased: the lower time resolution with averages, the lower peaks. It can be observed that high-frequency cyclic loads are only evident for short logging periods (i.e. 1 min). On the other hand, low load levels are raised when averaging. In this sense, the load consumption for the three different households located in Jaen (South of Spain) and which will be used to illustrate the proposed method have been monitored with a sampling and recording interval of one minute throughout a year, figure 2. Regarding the quality check, the removing of invalid readings and the treatment data has been addressed following the recommendations of the IEC 61724 standard [23]. The main characteristics of the households are summarized in Table 1.

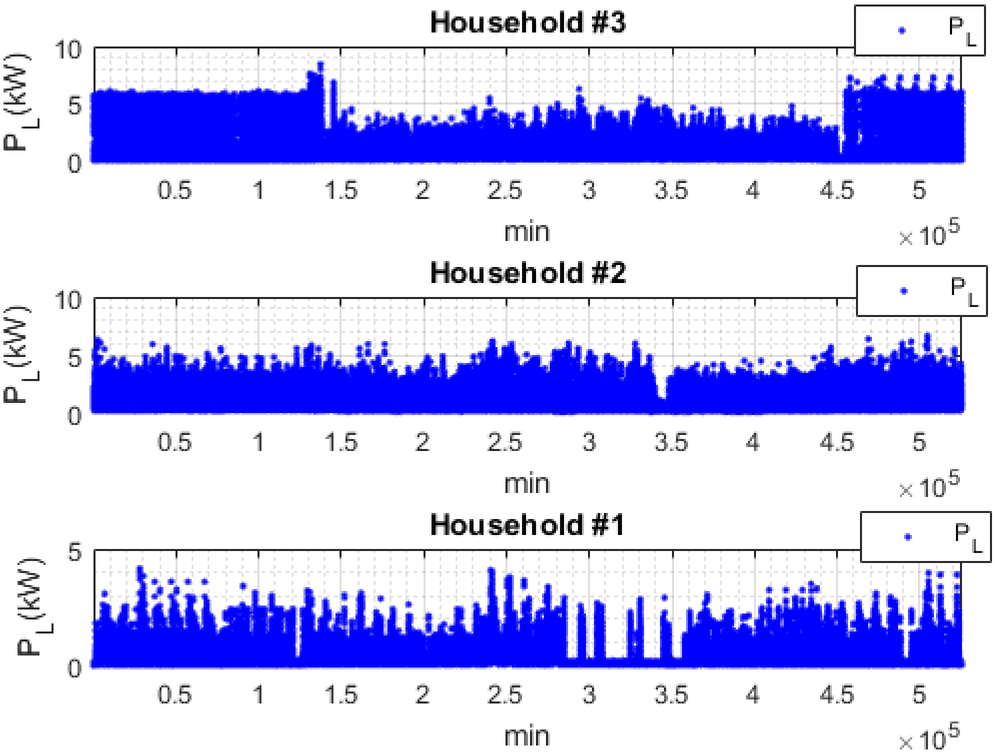


Figure 2. Load consumption time series for the three households considered in this study. Data corresponding from June 2016 to May 2017.

Table 1. Main features of three households located in Jaén (Southern Spain).

	Household#1	Household#2	Household#3
Total annual consumption (kWh/year)	1951	5215	5582
Number of family members	3	4	2
Is there at least an adult during the morning at home?	No	Yes	Yes
Electric Heating	No	No	Yes
Dryer	No	Yes	Yes
Dishwasher	Yes	Yes	Yes

The irradiance data correspond to Jaén (latitude: 47 deg 46´00´´ N and longitude 3 deg 47´ 0´´ O) from June 2016 to May 2017, with a sampling and recording interval of one minute, and they have been obtained thanks to two identical meteorological stations located on different buildings of the University of Jaén. This redundancy together with the IEC 61724 aforementioned guarantees the quality check. The meteorological stations have an Eppley Piranometer which meets the specifications for "secondary standards", from the world meteorological organization (WMO) ISO 9060 standard. The former measures the global irradiance (W/m^2) on a flat surface. From the irradiance data obtained in the horizontal plane, those corresponding to the optimum angle can be obtained [24].

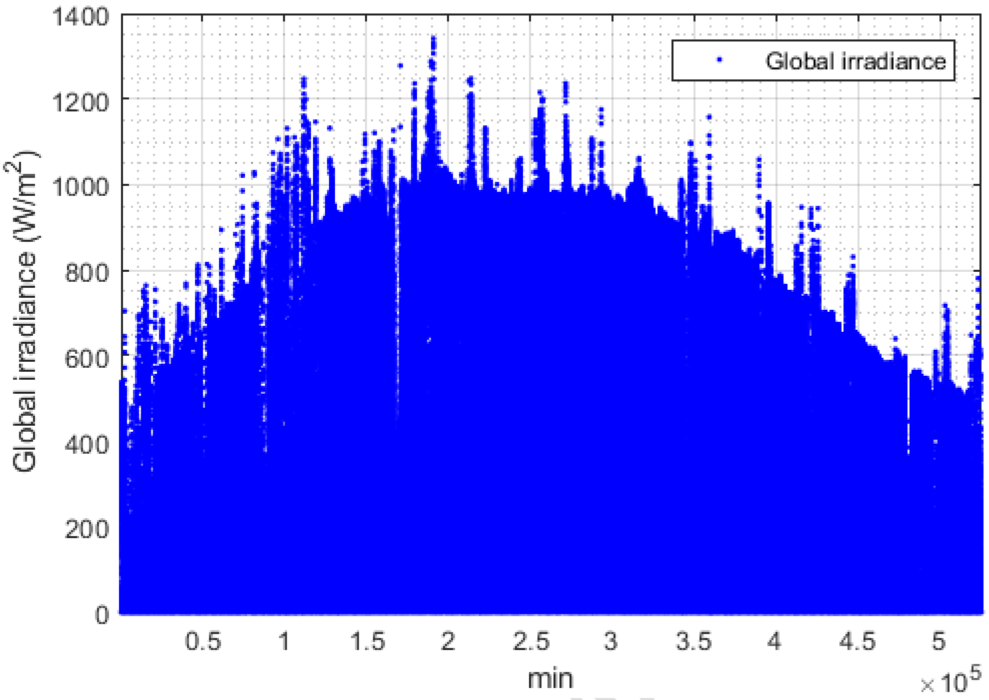


Figure 3. Irradiance Time series for Jaén (latitude: 37 deg 46´00´´ N and longitude 3 deg 47´ 0´´ W). Data corresponding from June 2016 to May 2017.

2.2.Self-consumption and self-sufficiency curves as a function of the photovoltaic generator power

As defined in [9], self-consumption and self-sufficiency indices may be defined as:

$$\varphi_{SC} = \frac{\int_{t1}^{t2} M(t)dt}{\int_{t1}^{t2} P(t)dt} = \frac{\sum_{t1}^{t2} M(t)\cdot\tau_r}{\sum_{t1}^{t2} P(t)\cdot\tau_r} = \frac{E_{PVconsumed,\tau}}{E_{PVgenerated,\tau}} = \frac{E_{PVconsumed,\tau}}{Y_{F,\tau}} \tag{1}$$

$$\varphi_{SS} = \frac{\int_{t1}^{t2} M(t)dt}{\int_{t1}^{t2} L(t)dt} = \frac{\sum_{t1}^{t2} M(t)\cdot\tau_r}{\sum_{t1}^{t2} L(t)\cdot\tau_r} = \frac{E_{PVconsumed,\tau}}{E_{L,\tau}} \tag{2}$$

P(t) and L(t) represent the instantaneous onsite power provided by the PV generator and the building power consumption, respectively. Taking into account that only direct self-consumption will be considered, M(t) corresponds to the instantaneous photovoltaic power consumed, that is, the overlapping part of the generation and load profiles, figure 4. In this figure the load and generation profiles are shown corresponding to three households located in Jaen (south of Spain) which will be further described later. t2 and t1 denotes the reporting period, τ, as indicated by the IEC61724 standard [23]. This reporting period may be generally one year in order to consider seasonal variations and to minimize the influence of short-term random fluctuations. τ_r provides the recording interval and defines the time resolution. The sampled data from each measured parameter shall be processed into time-weighted averages, that is, summed and divided by the recording interval. As has been previously mentioned, a proper recording interval (e.g. 1 minute) should be considered as a low resolution will always lead to an overestimation of the self-consumption indices [25,26].

As can be observed in Eq. (1) and (2) φ_{sc} can be defined as the ratio between the photovoltaic energy consumed, $E_{PV,consumed}$, that is, the absolute self-consumption in Wh and the photovoltaic energy generated, $E_{PV,generated}$ or final yield, Y_F, [23]. Moreover, self-sufficiency index, φ_{ss}, can be stated as the relation between $E_{PV,consumed}$ and the total energy consumption, E_L

There are different methods to calculate the annual final yield of a PV system [27]. In this paper the one based on the performance ratio *(PR)* is considered, which is established in the IEC 61724 standard [23]. In this standard, the annual final yield is defined as the output electrical energy (AC electricity) generated by a photovoltaic system per unit of power installed, and it is expressed in kWh/(kW$_p$·year), Eq. 3.

$$Y_F = PR\frac{H_{OPT}}{G_{STC}} \tag{3}$$

where H_{OPT} (kWh/(m^2·year)) is the annual global irradiation at the optimal tilt angle and G_{STC} the global irradiance at Standard Test Conditions (1 kW/m^2). The value of *PR* for conventional PV systems is typically in the range from 0.70 to 0.80. In this paper, PR values of 0.75 will be considered, based on the experience of this kind of systems [28-32].

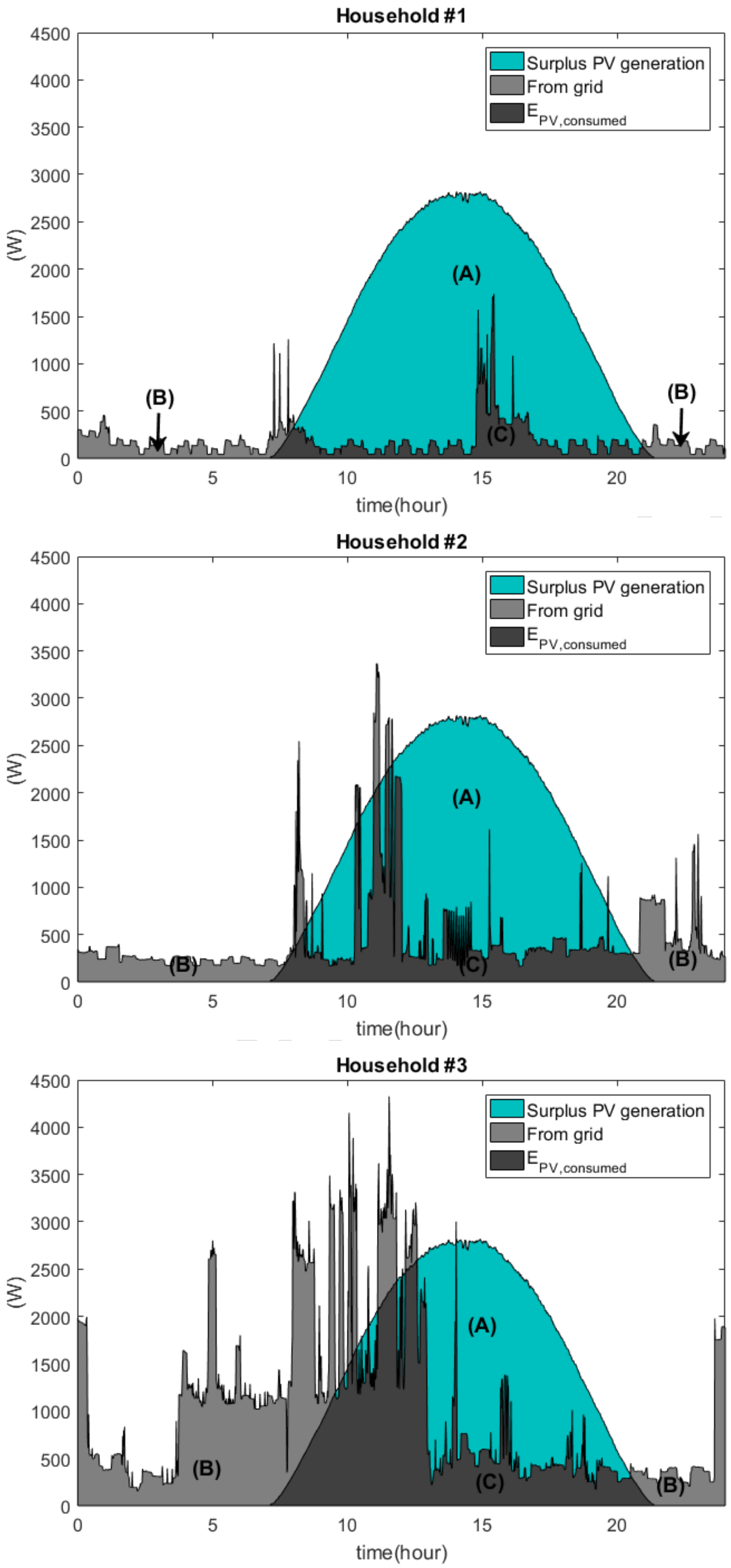


Figure 4. Daily generation and consumption profiles for three different households considering the same generation profile. Data corresponding to 19 May 2017. The sampling and recording interval is one

minute. The photovoltaic energy generated, $E_{PV,generated}$ and total energy consumption, E_L are represented by (A+C) and (B+C), respectively.

As can be seen both in figure 4 and table 1, household#1 provides the lower consumption. Moreover, as the two adults are out of home, there is a marginal consumption during high noon. That´s not the case of household#2 and #3 where there is a higher electricity consumption during the whole day. In the case of household#3 a relevant consumption during the night must be highlighted; this is due to electric heating that operates when the electricity price from the grid is lower, that is, during the night.

In figure 5 self-consumption and self-sufficiency indices are shown for a given household as either a function of the PV power and the yearly electricity consumption normalized by yearly PV production, ($E_L/E_{PVgenerated}$). As can be seen, φ_{sc} evolves following a negative exponential curve, whereas φ_{ss} increases according to a logarithmic response curve reaching an asymptote that for the three households ranges from 0.5 to 0.6. It is necessary to highlight the intersection of the two curves where the two indices are equal. This point defines a special point where the photovoltaic energy generated equals the total load consumption. It provides an approach to Zero Energy Building (ZEB). A ZEB combines highly energy-efficient building designs, technical systems and equipment to minimize the heating and electricity demand with on-site renewable energy generation, typically including a solar hot water production system and a rooftop PV system [33]. However, the mismatch between the electric load and photovoltaic generation profiles need for an exchange of electricity through the public grid that guarantees an annual net-exchange of zero. As can be seen, ZEB point differs from one household to another depending, given a location, on the load consumption profile. In figure 6 it is shown how to get this type of curves that will be used in the following sections in order to size the PV generator that maximizes direct self-consumption.

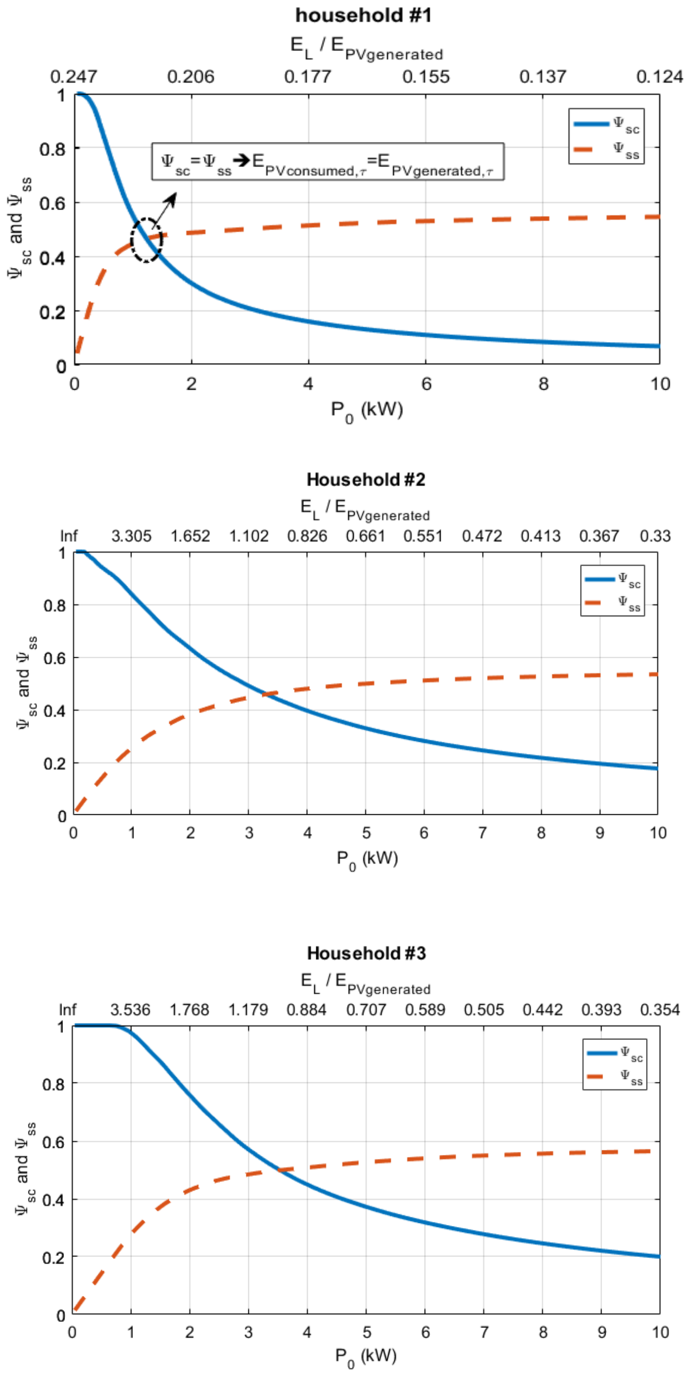


Figure 5. Annual Self-consumption and self-sufficiency indices for the three households analysed either as a function of the nominal PV power, P_0 or the quotient $E_L/E_{PVgenerated}$. Household#1 (top), Household#2 (middle) and Household#3 (bottom).

As can be observed in figure 5, lower PV energy productions related to the load consumption will provide the high self-consumption coefficients. As the ratio between E_L and $E_{PV,generated}$ decreases, so does φ_{sc}, while self-sufficiency becomes higher. This fact is also illustrated in figures 7 and 8 where the self-consumption and self-sufficiency curves are plotted but now on a daily and monthly basis, respectively, instead of an annual basis as was shown in figure 5. Different daily curves for household#2 are shown in figure 7 (a). Although the behavior of the two types of curves follows the same tendency previously mentioned, it is clearly shown how depending on the matching between daily generation and load profiles the asymptotes varies. Taking into account the daily self-sufficiency curves, their asymptotes range between 0.8 and 0.5. In figure 7 (b) the photovoltaic energy consumed is shown for a given day, considering two different nominal PV power for the PV generator: 1 kW_p and 3 kW_p. As can be seen, lower power values provide the best self-consumption values as the most PV energy generated is used. However, the self-sufficiency values are lower. As the size of the PV generator increases, the self-sufficiency index tends to increase at the expense of the self-consumption coefficient that decreases as more PV energy is wasted. Although the 1 kW generation profile is lower than the 3 kW one, it produces less overlapping which implies a high self-consumption coefficient. However, the 3 kW generation profile matches better the load profile which provides better self-sufficiency values, although the associated self-consumption coefficients are lower. It must be noted that when PV energy production related to load consumption is considerably increased, the self-sufficiency increase is marginal. This is due to the poor matching increase obtained when the PV power is considerably augmented. From a determined PV power it is no use increasing the former as the self-sufficiency index will not increase appreciably. So, other strategies should be considered in order to optimize the matching between the two profiles [22]: a) PV panel orientation and inclination, the former can make the generation profiles shift towards the morning or the afternoon, and the latter can enforce the generation in determined months, b) energy storage, mainly using batteries, where the overproduced electricity is shifted to periods with net demand and c) active load shifting, which is an important part of the concept DSM. There are studies that show that it is possible to increase the relative self-consumption by 13-24% points with a battery storage capacity of 0.5-1 kWh per installed kW PV power and between 2% and 15% points with demand side management, both compared to the original rate of self-consumption [9,34]. Moreover, one of the great challenges of distributed generation is to integrate renewable energy sources and electric vehicles into the electric grid in order to create a smart grid where the electric vehicle is used as a power storage device which may increase the self-consumption [35,36]. There are experiences that show the increase of self-consumption of photovoltaic (PV) power by smart charging of electric vehicles and vehicle-to-grid technology. In this sense, self-consumption increases from 49% to 62-87% and demand peaks decrease by 27-67%. These results clearly demonstrate the benefits of smart charging electric vehicles with PV self-consumption [37]. Depending on the revenue of selling/saving PV generated electricity and cost of buying electricity from the grid, increased self-consumption using these options or combinations of them can be profitable for owners of small-scale PV systems.

Figure 8 shows self-consumption and self-sufficiency indices on a monthly basis for hosehold#2. For this household, and as heating is provided by another energy source, monthly load consumption does not differ considerably. In this sense, as irradiation levels differ substantially from one month to another the ZEB point moves. The month with more generation (i.e. irradiation) will provide a ZEB which moves to the left. Meanwhile, months with lower irradiation values will provide ZEB moving towards the right (e.g. January). Special attention must be paid to summer months. The electricity consumption pattern changed in Spain at the end of the 80's. One of the reasons for this was the introduction of cooling systems that increased electricity consumption during hot summer days [38]. Moreover, electricity consumption is still expected to increase during the next decades as more and more households get equipped with cooling systems and summer temperatures are expected to increase with climate change. Unfortunately, the three houses analyzed scarcely use air conditioning. This is because many people in Jaén have a second home in a warmer place where they spend the summer months. However, the effect of cooling systems is an interesting issue that may be further analysed to see how this fact affects the self-consumption and sufficiency curves together with the ZEB point. However, and in our opinion, the use of cooling systems may provide a better matching between the load and generation profiles. In Spain, this type of system generally operates during the day (i.e. when there are high temperatures) which coincides with high levels of irradiance in summer. So the surplus may be not wasted (please see figure 4) and can be exploited providing higher self-consumption and self-sufficiency indices. In principle, the increase in electrical consumption caused by the use of air conditioning can move the ZEB point to the right in the summer months, requiring a greater generator power. However, this shift may be mitigated since the higher consumption will coincide with high levels of irradiance where there may be a considerable generation surplus and may be used to cover a great part of this electricity consumption.

When sizing photovoltaic generators for self-consumption systems, self-consumption and self-sufficiency indices should be plotted on an annual basis in order to take into account seasonal variations as has been previously mentioned. However, if the sizing is focused on a given month or season, their corresponding curves may be considered. Daily curves may not provide enough information in order to manage an appropriate photovoltaic generator sizing.

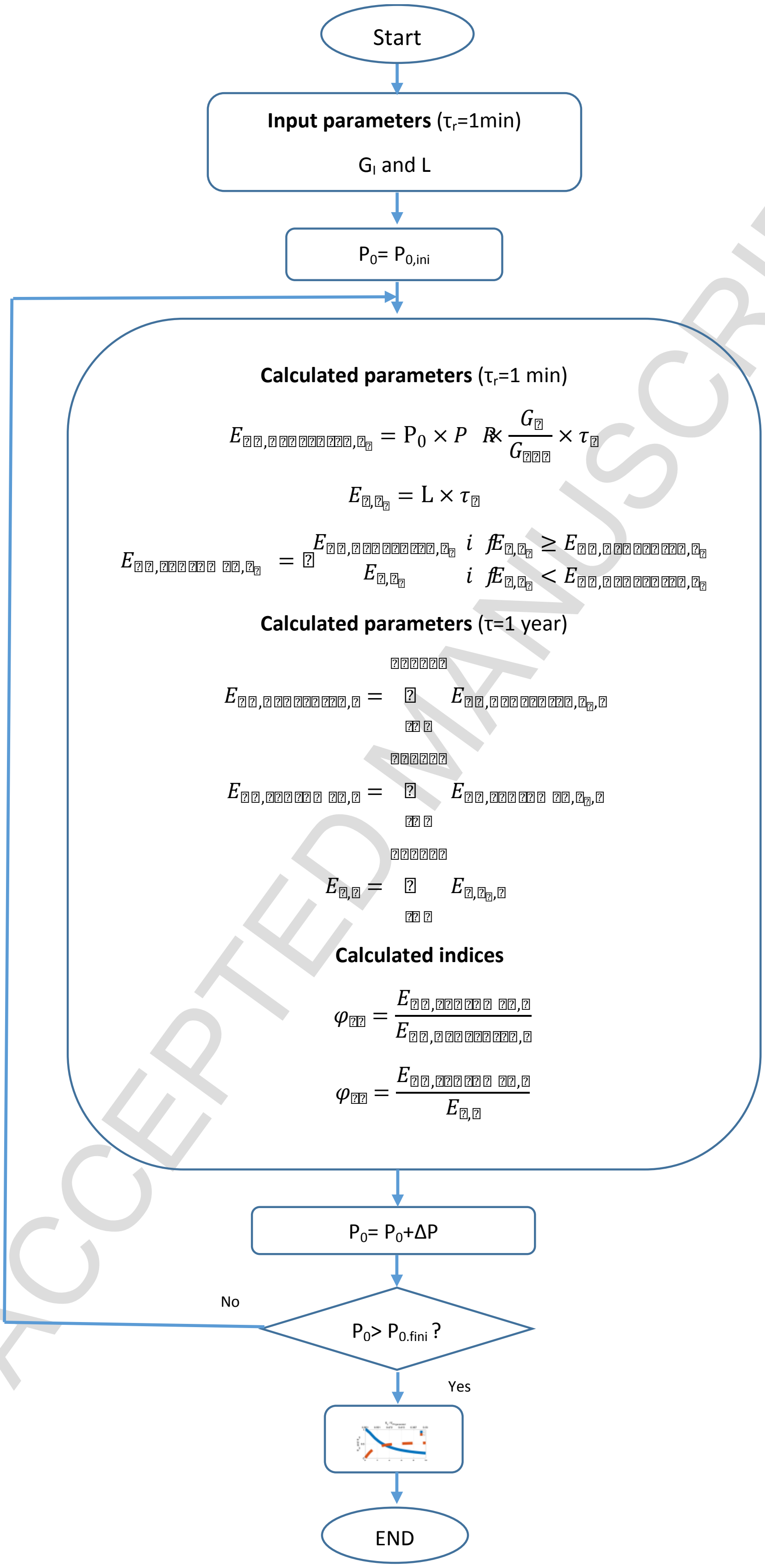
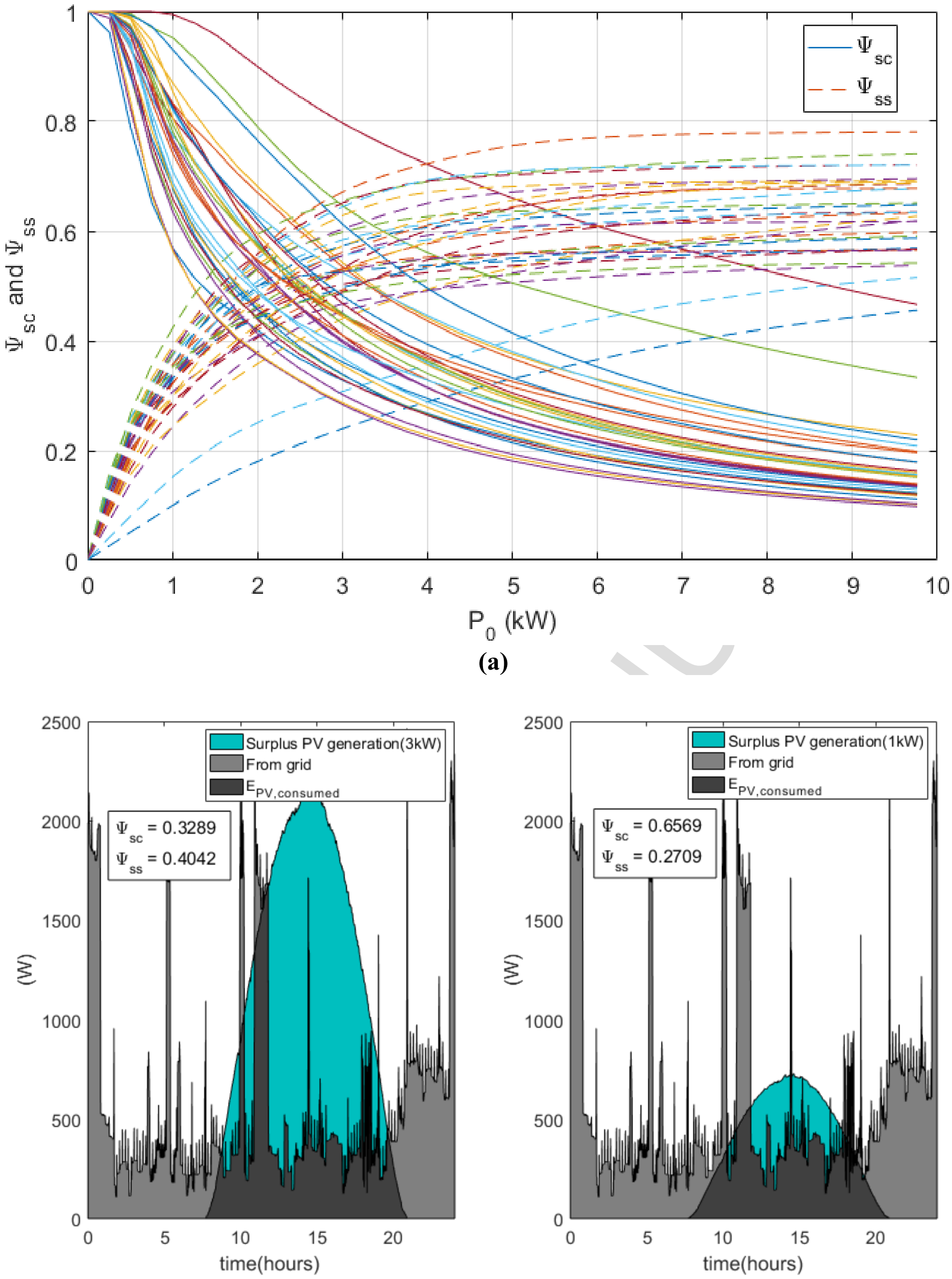


Figure 6. Steps to follow to graph annual self-consumption and self-sufficiency indices as a function of the nominal power. G_I and L correspond, respectively, to in-plane irradiance and load consumption obtained every minute.



(a)

(b)

Figure 7. (a) Daily Self-consumption and self-sufficiency indices as a function of the PV nominal power. Data obtained for household#2. **(b)** Daily generation and load profiles for two different PV generators: 1kW (right) and 3kW (left). Self-sufficiency and self-consumption indices have been included. The generation profiles have been obtained from the irradiance one corresponding to 17 April 2017.

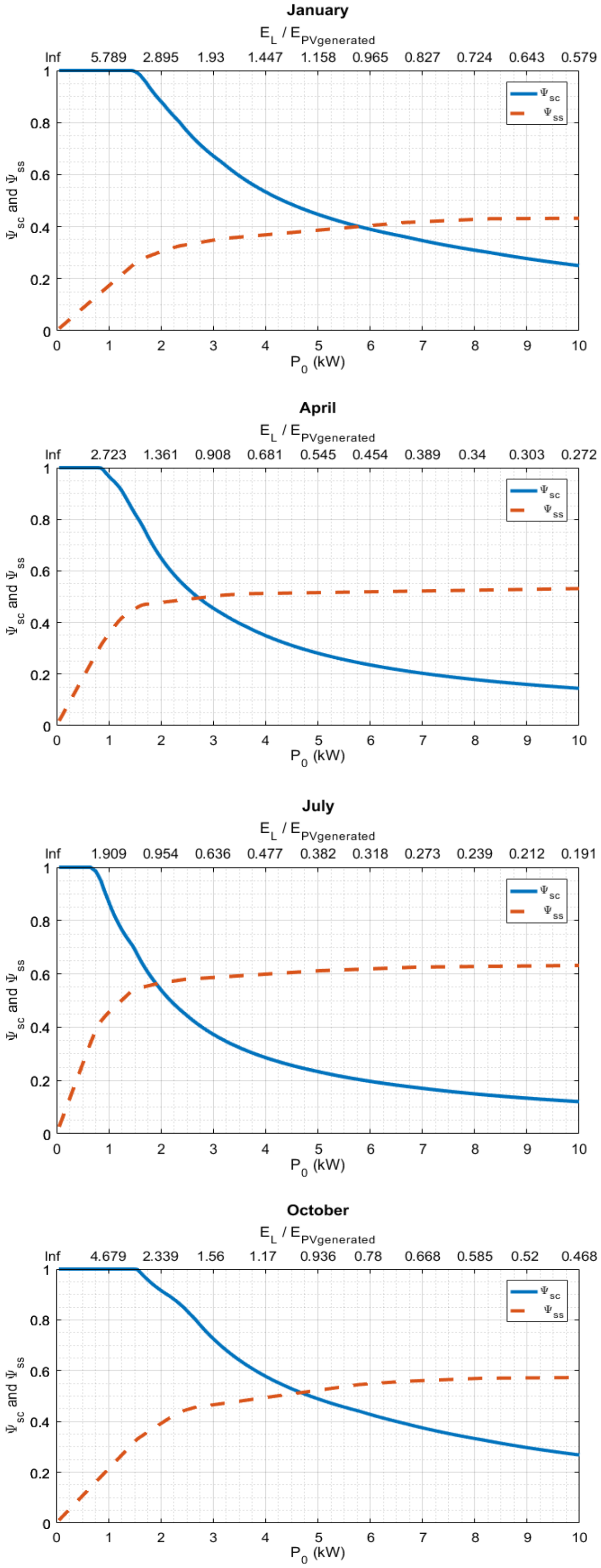


Figure 8. Monthly self-consumption and self-sufficiency indices as a function of the PV nominal power for household#2. Months considered: January, April, July and October.

2.3. Cost of direct PV self-consumed electricity

In this section, the model used to estimate the cost of direct PV self-consumed electricity (C_S) is described. In a PV self-consumption system, C_S is defined as the unitary cost of direct PV self-consumed electricity over its entire lifetime, expressed in €/kWh. Following the procedure introduced in previous works [11,39], the estimation of the cost of electricity generation from the PV system is based on levelised cost of electricity (LCOE), while the cost of direct PV self-consumed electricity can be calculated as:

$$C_S = \frac{LCOE \cdot Y_F \cdot \sum_{n=1}^{N} \frac{(1-r_d)^n}{(1+d)^n}}{E_{PVC} \cdot \sum_{n=1}^{N} \frac{1}{(1+d)^n}} \tag{4}$$

Y_F (kWh/kW$_p$·year) and E_{PVC} (kWh/kW$_p$·year) corresponds, respectively, to the annual final yield of the PV system and the normalized-per-kW$_p$ and the annual direct PV self-consumed energy; d (%) is the nominal discount rate and r_d (%) corresponds to the annual decrease rate of the PV system power due to degradation. *LCOE* is defined as the constant and theoretical cost of PV electricity production over its entire lifecycle, expressed in €/kWh. Additionally, *LCOE* allows to cost comparison of the electricity generated by different technologies. Consequently, the use of *LCOE* estimations is preferred by several institutions –NREL, the US Department of Energy (DOE), the Fraunhofer Institute for Solar Energy Systems ISE, etc.– and is increasingly adopted as a metric by many solar actors. Levelised Cost of Electricity of PV system can be expressed as:

$$LCOE = \frac{LCC}{Y_F \cdot \sum_{n=1}^{N} \frac{(1-r_d)^n}{(1+d)^n}} \tag{5}$$

where *LCC* (€/kW$_p$) represents the normalized-per-kW$_p$ life cycle cost of the PV system. *LCOE* can be expressed either in current or constant currency. This expression of *LCOE* is determined by the type of the discount rate used in the denominator of Eq. (5). If the nominal discount rate is used in the denominator, the resulting *LCOE* is expressed in current (or nominal) values. Current units are often preferred when expressing *LCOE* for making predictions concerning grid parity and they will be used throughout this paper.

The normalized-per-kW$_p$ life cycle cost of the PV system (*LCC*) may be calculated by adding the initial investment cost of the PV system (PV_{IN}) plus the present worth of its operation and maintenance cost (PW[$PV_{OM}(N)$]) and subtracting the present worth of the tax depreciation PW[$DEP(N_d)$] over the system life cycle (N):

$$LCC = PV_I + PW\left[PV_{OM}(N)\right] - PW\left[DEP\left(N_d\right)\right] T \tag{6}$$

where T is the income tax rate.

The present worth of its operation and maintenance cost during the life cycle of the system can be expressed as:

$$PW\left[PV_{OM}(N)\right] = PV_{AOM}(1-T) \cdot \frac{K_p \cdot \left(1-K_p^N\right)}{1-K_p} \tag{7}$$

In the previous equation, (PV_{AOM}, €) is the annual operation and maintenance cost which is assumed constant over the life cycle of the system. K_P is a factor which clusters the annual escalation rate of the operation and maintenance cost of the system ($r_{O\&M}$), so $K_P = (1+ r_{O\&M})/(1+d)$.

Finally, if the impact of taxation is taken into account by assuming that tax depreciation is deductible:

$$PW\left[DEP\left(N_d\right)\right] = \sum_{n=1}^{N_d} \frac{DEP_n}{(1+d)^n} \tag{8}$$

where PW[$DEP(N_d)$] is the present worth of tax depreciation, DEP_n (€) represents the tax depreciation corresponding to year n and N_d is the period of time over which an investment is amortized for tax purposes. The method used in the tax depreciation may differ from one country to another. Readers must refer to national taxation laws. For example, if tax depreciation is assumed linear and constant over a given period of time, the present worth of the tax depreciation may be estimated through the following equation:

$$PW\left[DEP\left(N_d\right)\right] = DEP_y \cdot \frac{q \cdot \left(1-q^{N_d}\right)}{(1-q)} \tag{9}$$

where DEP_y (€) is the fixed annual tax depreciation for the PV system and q=1/(1+d).

In order to estimate C_S, the values of the parameters involved have to be determined. When Eq. (4) is thoroughly analyzed, it can be observed that: 1) its numerator depends on levelised cost of electricity and annual final yield of PV system; and 2) its denominator depends on the normalized-per-kW$_p$ annual direct PV self-consumed energy. The values of the parameters influencing Eq. (4), are described in the following section.

2.3.1 Estimation of the parameters involved in the cost analysis

Before addressing the calculations of C_S, a review of the inputs for the equations previously presented will be conducted. This review will lead to the identification of their values for the calculation of C_S in the residential PV systems for a current scenario (second semester 2017) in Spain.

The parameters involved in this analysis are: annual final yield (Y_F), lifetime of the PV system (N), initial investment cost of PV system (PV_I), income tax rate (T), nominal discount rate (d), loan interest rate (i_l), repaying loan (N_l), dividends (d_{eq}), annual degradation rate (r_d), inflation rate (g), annual operation and maintenance costs (PV_{AOM}), annual escalation rate of the operation and maintenance costs ($r_{O\&M}$) and residential electricity price.

Annual final yield

As was previously pointed out, the annual final yield of a PV system is a key parameter for the analysis previously mentioned. There are different methods to calculate the PV generated energy [27,40]. In this paper the one based on the performance ratio (PR) is used, [23] which was defined in Eq. (3). The global annual irradiation at the optimal tilt angle (H_{OPT}) will range between 1000 and 2200 kWh/(m^2·year) in order to take into account, respectively, northern and southern locations in Spain .

Life time

The financeable life of a solar PV system is usually coincident with the manufacturer's guarantee period which is often 20–25 years. However, field experience has shown that the life of solar PV systems spans well beyond 25 years even for the older Si-flat plate technologies, and current ones are likely to extend further their lifetime. However, a conservative criterion has been adopted by assuming a system lifetime of 25 years.

Initial investment cost

The initial investment cost of the PV system (PV_I), especially in the residential segment, continued to decline in 2015 in several countries. Based on an industry and literature survey in Spain 2015, the average initial investment cost per kW_p of a residential PV system < $10kW_p$ may be taken at 1500 €/kW_p with a variation ranging from 1100 to 1700 €/kW_p [4,10]. Due to the decrease trend in system prices and for a current scenario (second semester 2017), in this paper PV_I is assumed equal to 1300 €/kW_p.

Income tax rate

Values of the income tax rate for the owner of the PV system may vary according to each country´s regulations. In the case of Spain, the self-consumer Type 1 exports surplus energy without receiving compensation, thus, T is assumed equal to 0%. It should be noted that the facilities of self-consumption Type 1 below 10 kW are exempt from the variable and fixed charges for self-consumed electricity [41].

Nominal discount rate

Regarding nominal discount rate (d), organizations typically use the value of the organization's weighted average cost of capital ($WACC$) as nominal discount rate [42], for assessment of investment project. Of course, the value of $WACC$ varies depending on how the capital resources are chosen to finance the investment. Initial investment cost of a PV system may be financed by means of debt and/or equity capital. Long-term loans and equity capital are chosen in this work. It has been assumed that 70% of this initial amount is taken on loan (PV_l, in €) –that is, debt– while the remaining investment amount -30%- is contributed with stock issue (PV_{eq}, in €) –that is, equity capital; taking into account that commercial banks are generally accepting higher leverage in stable economies with secure property rights [43]. Given that $PV_I = PV_l + PV_{eq}$ and taking into account taxation, weighted average cost of capital of the initial investment cost of a PV system can be estimated through Eq. 11.

$$PV_I = \left(PV_l \cdot \frac{i_l(1-T)}{1-(1+i_l(1-T))^{-N_l}} \cdot \frac{q\cdot\left(1-q^{N_l}\right)}{1-q} \right) + \left((d_{eq} \cdot PV_{eq}) \cdot \frac{q\cdot\left(1-q^{N}\right)}{1-q} + PV_{eq}\cdot q^N \right) \tag{11}$$

The first term of the right-hand side of Eq. (11) refers to loan: as commented above, PV_l is borrowed at an annual loan interest (i_l) to be repaid in N_l years. The second term refers to equity capital, with an annual payback in the form of dividends (d_{eq}) and it is amortized at the end of the life cycle of the system. It is worth mentioning that the left-hand side of Equation (11) only equals its right-hand side if the selected value of d is equal to the weighted average cost of capital ($WACC$) of the investment.

In this work it is assumed that, regarding the loan, the interest rate (i_l) is equal to 4.3% [44] while N_l is set equal to 20 years; as regards to equity capital, the dividend percentage d_{eq} is assumed equal to 7.3% [45,46] and equity capital is payable in full at the end of the life cycle of the project (N, in years). The value obtained for WACC is equal to 5.6%.

Degradation rate

The annual PV electricity yield generated by the PV system is assumed to decrease every year. A typical annual degradation rate in the efficiency of flat-plate PV modules equals 0.5% [47,48]. This value of r_d leads to a 18.3% decrease of the PV module efficiency after 25 years of operation. Nowadays, flat-plate PV systems have a life cycle of around 25 years and more.

Inflation rate

In order to define the inflation value, taking into account averages of historical data related to annual inflation rates –period 2009-2014− for Spain, the obtained value is g = 1.4% [49]. It is important to mention that, for this study, a salvage value of the system at the end of their life cycle equal to zero has been considered.

Operation and maintenance cost

Regarding operation and maintenance (O&M) cost, for flat-plate PV system this only comprises the expense of cleaning panels and replacing the inverter, in most cases. A typical assumption might be to schedule the replacement of the inverter once during the system's lifetime, with this still representing the majority of the O&M cost. According to the bibliography existing on this issue, an estimation of 1.5% of the initial investment cost dedicated for these annual operation and maintenance cost is normally considered annually [50]. Further, the annual escalation rate of the operation and maintenance costs is set equal to the value of g, so that $r_{O\&M}$ = 1.4%.

Residential electricity prices

Electricity prices (c€/kWh) in the residential or domestic segment for Spain in the period 2008-2016 with all taxes and levies excluded are shown in Figure 9 [51]. In the latter, significant variations can be observed in the electricity price depending on the quantity of the electricity consumption: band DA, consumption < 1000 kWh; band DB, 1000 kWh < consumption < 2500 kWh; band DC, 2500 kWh < consumption < 5000 kWh; band DD, 5000 kWh < consumption < 15000 kWh; band DE, consumption > 15000 kWh. Average electricity prices in the residential segment for band DA, DB, DC, DD and DE are equal to 31.6, 18.4, 16.2, 14.4, 13.2 (c€/kWh), respectively.

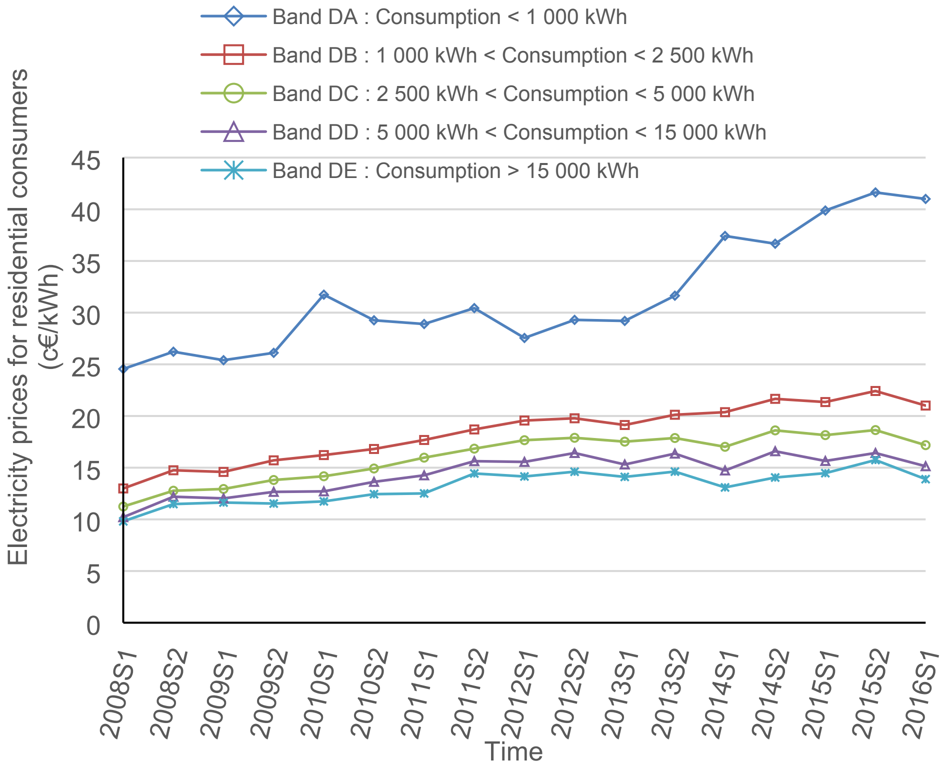


Figure 9. Electricity prices for residential or domestic consumers in Spain - bi-annual data.

A summary of the aforementioned assumptions together with the values assigned to each parameter is gathered in Table 2 for a current scenario in Spain.

Table 2. Values of the parameters assumed for the calculation of the cost of self-consumption PV electricity from residential PV systems < 10 kW_p in the current scenario (second semester 2017) in Spain.

Parameters	Base case	Units
PV_I	1300	€/kW_p
G_{STC}	1	kW/m^2
H_{OPT}	1000-2200	kWh/(m^2·year)
PR	75	%
r_d	0.5	%
PV_{AOM}[a]	1.5	%
$r_{O\&M}$	1.4	%
T	0	%

d	5.6	%
g	1.4	%
i_l	4.3	%
N_l	20	years
d_{eq}	7.3	%
N	25	years

[a] This value should be interpreted as the percentage of PV_I that is spent on operation and maintenance tasks on an annual basis.

3. Examples and Discussion

In order to illustrate the method here shown, the former will be applied to the three households mentioned in section 2.1.

In first place, the annual self-consumption and self-sufficiency indices depicted as a function of the nominal power of the PV system for the three different households must be considered, figure 5. The methodology to be used to obtain the latter has been described in section 2. On the other hand, the cost of PV self-consumed electricity (C_S), and for the considered cases, can be calculated by means of a spreadsheet through the model described in section 2.3 and using the values shown in Table 2. Graphical solutions are shown in figures 10 and 11.

In figure 10, different scenarios for the annual irradiation ranging from 1000 to 2200 kWh/m^{2}year are considered although H_{OPT} corresponding to the location under study is 1800 kW/m^{2}year. It is shown how the annual irradiation together with residential electricity price are decisive when making residential PV systems competitive with regard to other power sources. This figure can be used for any location that has any of the indicated annual irradiations if the residential electricity price for the household considered is known. In this sense, the aforementioned figure manages to estimate the coefficient of self-consumption, φ_{sc}, that must be achieved to make the self-consumption system competitive in generation costs and maximizing self-consumed energy. φ_{sc} will be a function of the annual irradiation and the price of residential electricity both specific to the location.

As can be seen, C_S is depicted as a function of the self-consumption index for variations of the annual global irradiation at the optimal tilt angle (H_{OPT}) and taking into account variations of the self-consumption index from 20 to 100%. Additionally, an average electricity price in the residential segment -band DC, 2500 kWh < consumption < 5000 kWh- equal to 16.2 c€/kWh is considered. If the best case is assumed with a self-consumption index equal to 100% and a H_{OPT} ranging from 1000 to 2200 kWh/(m^2 year), the value estimated of C_S for each one of the values of H_{OPT} is equal to LCOE. Furthermore, in this case, C_S is lower than the electricity price for residential consumers, except for H_{OPT} equal to 1000 kWh/(m^2 year), so the residential PV system begins to be competitive with regard to other power sources. On the other hand, if the case considered provides a self-consumption index lower than 47%, 58% and 74% for H_{OPT} values 2200, 1800 and 1400 kWh/(m^2 years) respectively, the value of C_S is higher than the electricity price for residential consumers, so the residential PV systems are not competitive, regarding other energy sources.

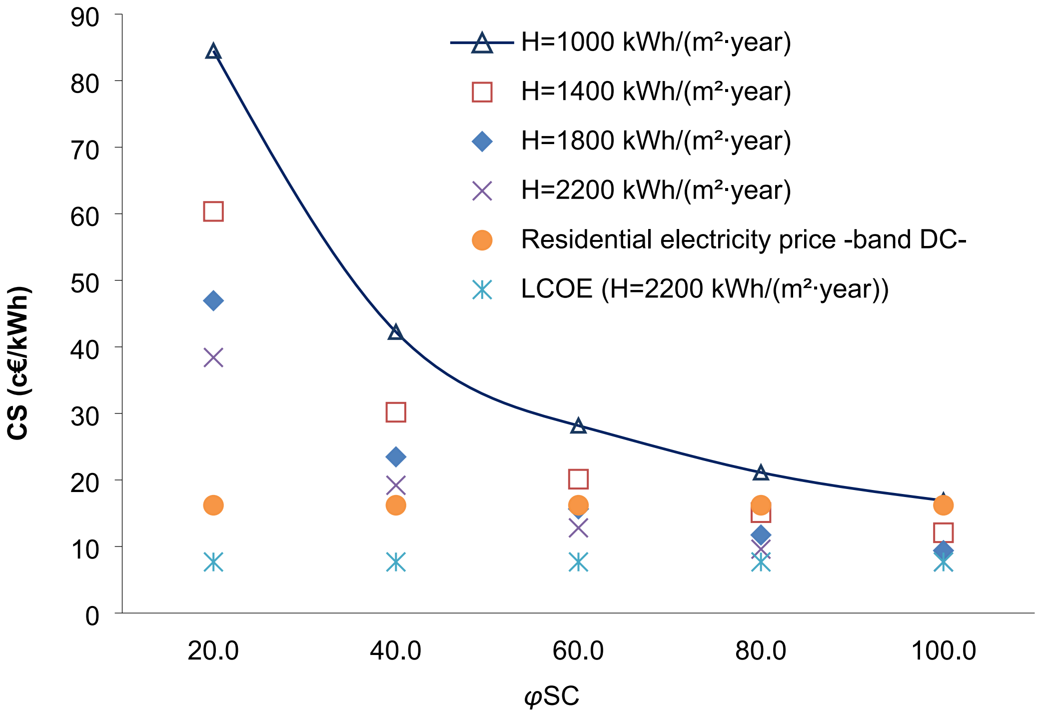


Figure 10. Cost of direct PV self-consumed electricity as a function of the self-consumption index for variations of H_{OPT} ranging from 1000 to 2200 kWh/(m^2 year).

3.1. Household#1

For the household considered, annual self-consumption and self-sufficiency indices as a function of the nominal power of the PV system are shown in figure 5. For the household location (Jaén, southern Spain) an irradiation equal to 1800 kWh/(m^2·year) has been assumed and an annual consumption equal to 1951 kWh/year has been taken into account, Table 1. Moreover, an average electricity price in the residential segment -band DB, 1000 kWh < consumption < 2500 kWh- equal to 18.4 c€/kWh has been considered. In this way, C_S is plotted as a function of the self-consumption index for a H_{OPT} equal to 1800 kWh/(m^2

year), figure 11.

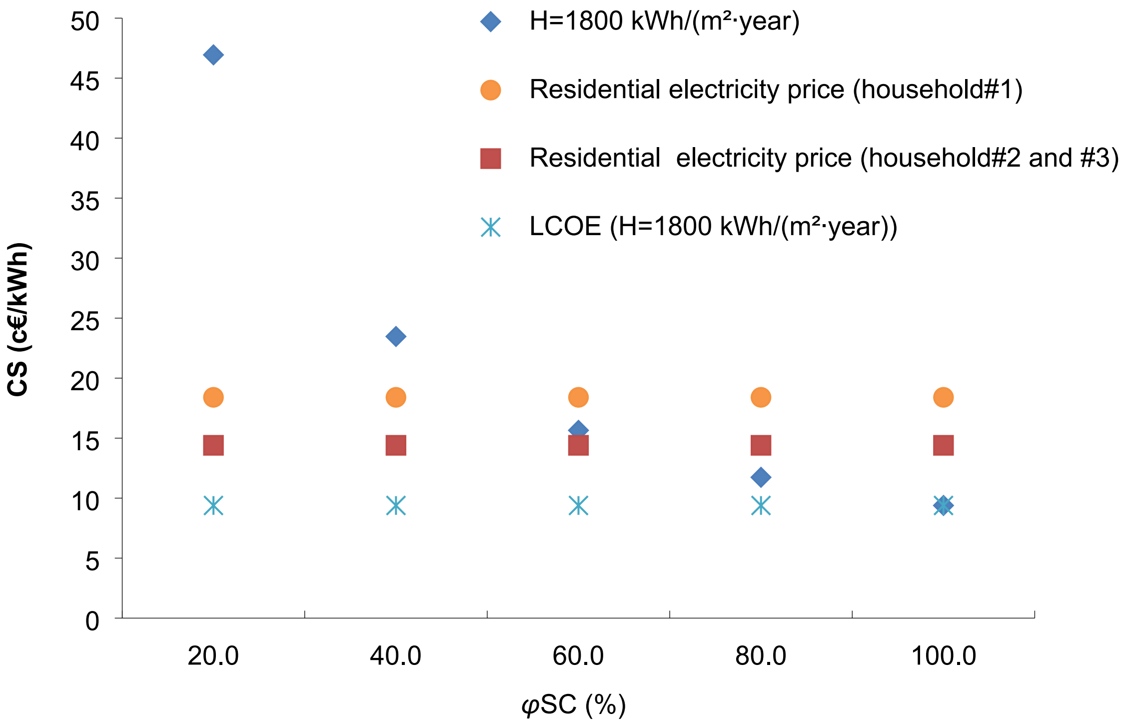


Figure 11. Cost of direct PV self-consumed electricity as a function of self-consumption index for a H_{OPT} of 1800 kWh/(m^2 year).

As can be seen on figure 11, for a self-consumption index equal to 50%, C_S is equal to 18.4 c€/kWh. Furthermore, for a self-consumption index higher than 50%, C_S is lower than the electricity price for residential consumers, following a decreasing trend until it reaches the LCOE value (9.38 c€/kWh). This lowest value is achieved for a self-consumption index equal to 100% when all the harvested energy is used. On the other hand, self-consumption indices lower than 50% make C_S higher than the electricity price for residential consumers. If the self-consumption index is decreased, C_S follows an increasing trend until a maximum of 46.9 c€/kWh is reached. Additionally, in this case, self-consumption indices lower than 50% make the residential PV systems uncompetitive, regarding other energy sources.

In order to size the PV generator of the self-consumption systems, the new criterion followed is based on cost-competitiveness, maximizing direct self-consumption. The latter will provide greater environmental benefits, security and independence of the grid at the same time that it makes C_S competitive with grid electricity prices. This criterion is fulfilled when C_S reaches the same value as electricity price for residential consumers. As has been previously mentioned, for household#1 C_S and the electricity price are equalized when a self-consumption index of 50% is considered. Once the self-consumption index has been calculated, the PV power can be obtained using the figures where the self-consumption and self-sufficiency indices are expressed as a function of the power of the photovoltaic generator for the considered household, Figure 5. For household#1, and for a self-consumption index equal to 50%, a self-sufficiency index and a power of the residential PV system of 45% and 1.2 kW$_p$ are obtained, respectively, Figure 12.

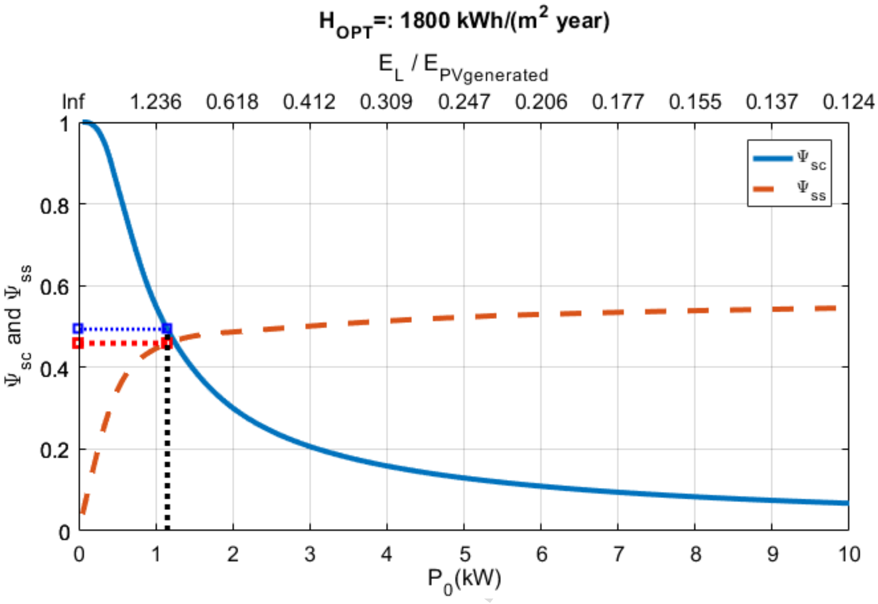


Figure 12. Graphical method to size the PV generator in a self-consumption system from annual self-consumption and self-sufficiency curves as a function of the nominal power of the PVself-consumption system. Case of study: household#1. H_{OPT} =1800

As can be observed in Figure 12, self-consumption indices higher than 50% could be used which will provide a C_S lower than the electricity price for residential consumers but it will not maximize the self-consumption energy. For example, with a self-consumption index higher than 50%, the system remains cost-competitive but a lower self-sufficiency index and a lower power of PV system are obtained, and consequently a lesser amount of direct self-consumption energy is harnessed.

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3.2 Household#2 and #3

In figure 5 annual self-consumption and self-sufficiency indices are shown as a function of the nominal power, for household#2 and #3. An annual consumption of 5215 kWh/year and 5580 kWh/year is considered for household#2 and #3, respectively, while an H_{OPT} of 1800 kWh/(m^2·year) is assumed. Additionally, an average electricity price in the residential segment - band DD, 5000 kWh < consumption < 15000 kWh- equal to 14.4 c€/kWh is considered. Then, C_S as a function of the self-consumption index for the given H_{OPT} is shown in figure 11.

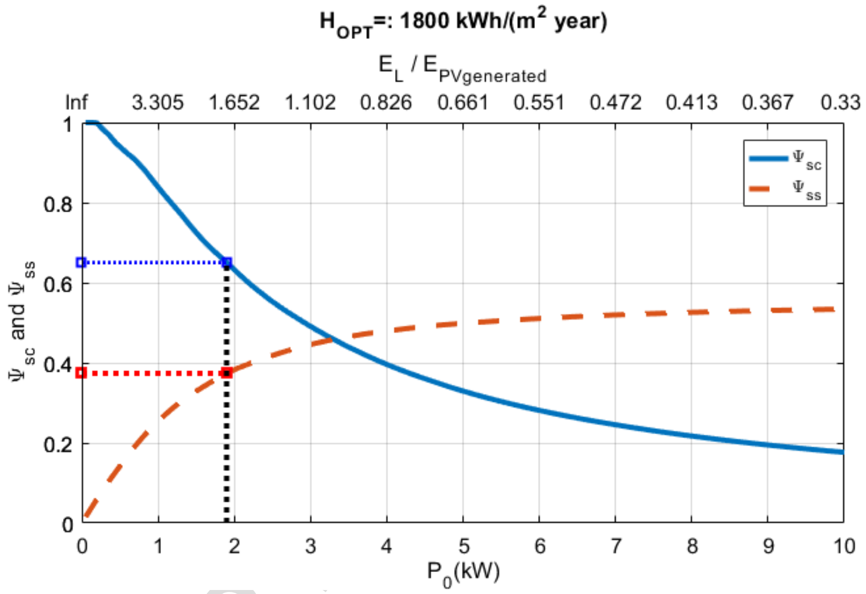

Figure 13. Graphical method to size the PV generator in a self-consumption system from annual self-consumption and self-sufficiency curves as a function of the nominal power of the PV generator. Case of study: household#2. H_{OPT}=1800 kWh/(m^2·year).

As has been previously mentioned, the optimum size of the PV generator is obtained when C_S reaches the electricity price for residential consumers. As can be seen in figure 11, this equality is achieved when a self-consumption index equal to 65% is considered. In this way, and using figure 5 (household#2), a self-sufficiency index and a power of the residential PV system of 37% and 1.9 kW$_p$ are achieved, respectively, for household#2, figure 13. The same methodology is followed for household#3, figure 5 (household#3), where a self-sufficiency index and a power of the residential PV system of 47% and 2.6 kW$_p$ are respectively obtained, figure 14.

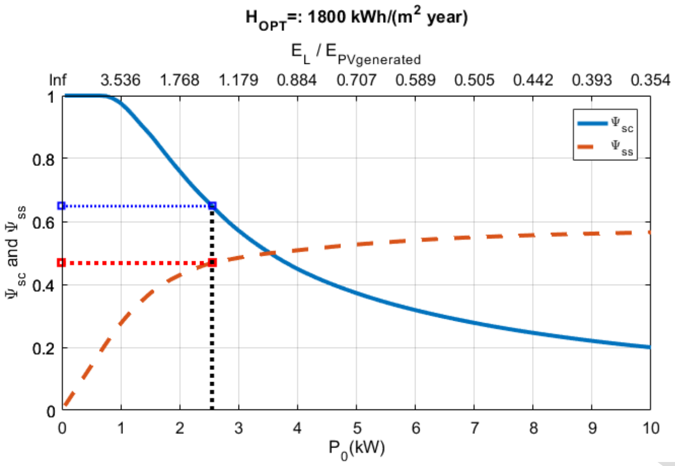

Figure 14. Graphical method to size the PV generator in a self-consumption system from annual self-consumption and self-sufficiency curves as a function of the nominal power pf the PVGCS. Case of study: household#3. H_{OPT}= 1800 (kWh/(m²·year)).

3.3 Discussion

The method here developed estimates C_S and compares it with the residential electricity price. The proper φ_{sc} is calculated when both C_S and residential electricity price have the same value which provides grid parity and maximize direct PV self-consumption electricity. Once φ_{sc} is known and using the self-sufficiency and self-consumption curves, both φ_{ss} and the power of the PV generator of the residential self-consumption system are estimated.

This subsection discuss the results of the cases studied above. The main results obtained for the three households are summarized in Table 3.

Table 3. Self-consumption and self-sufficiency indices for the PV power generator that maximizes self-consumption achieving cost-competitiveness for the three households analysed. H_{OPT} = 1800 (kWh/(m²·year)).

	Houselhold#1	Household#2	Household#3
Total annual consumption (kWh/year)	1951	5215	5580
Self-consumption index (%)	50	65	65
Self-sufficiency index (%)	45	37	47
PV Power generator, P_0 (kW)	1.2	1.9	2.6

For the three households studied, the PV power generator ranges from 1.2 to 2.6 kW$_p$. High self-consumption indices between 50-65% have been achieved which shows a high use of the photovoltaic energy generated. As can be seen in figure 10, and for a given residential electricity price, the lower H_{OPT}, the higher the self-consumption index that must be reached in order to achieve cost-competitiveness. On the other hand, and with respect to the self-sufficiency index, it, it ranges between 37-47% for 1800 kWh/(m^2·year). In this sense, relatively high values can be reached where near half the total energy consumption may be supplied by the PV generator, taking into account that only direct self-consumption has been considered. These values are very similar to those reported in the literature [9] and can be improved if other strategies which increase the profiles matching are used.

The different papers that have been reviewed in section 1 show φ_{sc}, φ_{ss} and PV power generator values that vary significantly as the described cases depend on many different influential factors, e.g. climate, building characteristics, load types, PV system sizes, etc. In [9] a study was developed for self-consumption where different strategies were considered. Taking into account only direct self-consumption, it can be highlighted that φ_{sc} ranged from 26 to 63 % for several locations. In [13] for PV self-consumption systems in Germany, it was obtained that φ_{sc} and φ_{ss} ranged from 28 to 48% and from 20 to 33%, respectively. In [21] for a PV system in Italy, φ_{sc} ranged from 76.5 to 84.9%. In this sense, self-consumption high values may be reached where more than half the total energy production may be consumed.

As can be seen, the casuistry is wide and varied. Moreover, the three households previously described do not provided a representative study making the comparison difficult. In this sense, the latter only manage to illustrate the method here developed, but do not intend to provide a broad view of self-consumption in southern Spain since it would be necessary to increase the number of households under study. Currently, the authors are expanding the study including more households with their corresponding consumption profiles in order to manage a representative study which could increase the potential of comparison. Moreover, the method may be further developed if different issues such as inclination, orientation of the PV generator and energy storage are considered.

4. Conclusions

In this paper, the most characteristic indices which are used in the study of the photovoltaic self-consumption have been analysed from a daily, monthly and annual basis. The analysis has been developed using real load consumption data from three households with different load profiles located in the south of Spain.

For an annual basis, and for the households studied, it has been shown that φ_{ss} follows a logarithmic evolution reaching an asymptote that ranges from 0.5 to 0.6. That is, half the load consumption may be faced with direct self-consumption without batteries. From a determined PV power it is no use increasing the former as φ_{ss} will not increase appreciably. In this way, other strategies should be considered in order to optimize the matching between the generation and load profiles: PV panel orientation and inclination, Demand Side Management (DSM) and energy storage, mainly using batteries, where the overproduced electricity is shifted to periods with net demand.

Moreover, this paper has provided a new method to size the power of the PV generator based on cost-competitiveness, maximizing direct photovoltaic self-consumption. This new criterion will provide greater environmental benefits, security and independence of the grid, and it will make the cost of self-consumption PV electricity competitive with grid electricity prices. Although the method here explained has been applied for the case of Spain, it can be easily extrapolated to other countries.

For the three households used to illustrate the method to size the PV power generator in a self-consumption system, high self-consumption indices have been achieved (50-65%) which shows a high use of the photovoltaic energy generated. Moreover, relative high self-sufficiency indices can be reached (37-45%) where nearly half the total energy consumption may be supplied by the PV generator, taking into account that only direct PV self-consumption has been considered.

In this paper it has been shown than, even in the absence of subsidies, and considering the case of Spain which has an unfavourable regulatory framework, the cost of self-consumed electricity from a residential PV system without batteries may be lower than the residential electricity price from the grid, considering determined self-consumption indices and H_{OPT} higher than 1000 kWh/(m^2 year). Therefore, taking into account both parameters, in Spain the residential PV self-consumption systems may be competitive with regard to other power sources for H_{OPT} higher than 1000 kWh/(m^2 year). Moreover, PV self-consumption systems may be a feasibility investment to future owners interested in these systems where the method here shown can be used.

Further investigations should be addressed applying the techniques here shown to self-consumption systems which use any strategy that improves matching capability between load and generation profiles. In this case, it must be considered the associated costs (e.g. the storage devices) when estimating LCC. In addition, and considering the self-sufficiency and self-consumption curves, it can be developed a method to optimize the size of the PV generator, taking into account profitability criteria for different types of self-consumption (e.g. net metering, net billing, etc.)

Acknowledgments

This research was funded by the Spanish National Plan for Scientific, Technical Research and innovation aimed at the Challenges of Society (Grant No. ENE 2017-83860-R). The authors wish to thank the University of Jaén for the programme: “Plan de Apoyo a la I+D+I 2014-2015. Prorrogado hasta 2016”. We also would like to acknowledge three anonymous reviewers for their kind and interesting comments that have helped us to improve the manuscript.

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Highlights

A method to size PV generators based on the cost of PV self-consumed electricity has been developed

The method is based on cost–competitiveness, maximizing direct self-consumption

Real household load data have been used to illustrate the method

In Spain PV self-consumption may be cost-competitive for irradiation >1000 kWh/(m^2 y)

The method can be also used when considering batteries and Demand side Management