A new approach based on economic profitability to sizing the photovoltaic generator in self-consumption systems without storage

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Abstract: *A proper assessment of the cost-competitiveness and profitability of self-consumption systems is crucial to promoting the transition from grid-dependent to energy self-sufficient buildings. Most of the approaches found in the literature may not take into account economic parameters such as taxes, depreciation and the cost of financing, which have a significant effect on the economic profitability of an investment. Moreover, they only focus on discrete array powers and relatively high recording intervals when estimating the self-consumed energy. In order to manage the aforementioned challenges, a new method will be developed to size the PV generator in a PV self-consumption system which provides the NPV curve together with the self-consumption and self-sufficiency indices for a wide range of array powers which suits residential self-consumption systems. Two scenarios will be considered depending on whether the generated surplus electricity is wasted or it is remunerated from the grid operator. Results show that not only the chosen scenario but the electricity tariff may be key parameters when optimizing NPV. Furthermore, the impact of the recording interval may be significant when estimating NPV. Percentage errors of 11.4% and 33.6% may be reached when considering a recording interval of 15 and 60 minutes, respectively.*

Keywords: photovoltaic, self-consumption, profitability, Net Present Value

Terminology

d	Nominal discount rate (%).
DEP_n	Annual tax depreciation in the year n (€).
DEP_y	Fixed annual tax depreciation (€).
d_s	Annual dividend the equity capital –return on equity- (%).
$E_{L,\tau}$	Total energy consumption during the reporting period.
E_{PVcon}	Photovoltaic energy self-consumed (kWh).
E_{PVgrid}	Photovoltaic energy fed into the grid (kWh).
E_{PVgen}	Photovoltaic energy generated (kWh).
F	Normalized Factor.
g	Annual inflation rate (%).
G_{STC}	Global Irradiance at Standard Test Conditions (1 kW/m^2).
H_{OPT}	Annual global irradiation at the optimal tilt angle (kWh/(m^2 year)).
i_l	Annual loan interest (%).
K_{OM}	Factor equal to $(1+r_{O\&M})/(1+d)$.
K_{grid}	Factor equal to $(1+rp_{grid})\cdot(1-r_d)/(1+d)$.
K_{con}	Factor equal to $(1+rp_{con})\cdot(1-r_d)/(1+d)$.

$L(t)$	Load consumption (W).
LCC	Life cycle cost of the PV system (€).
$M(t)$	Direct photovoltaic power self-consumed (W)
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).
$P(t)$	Onsite power provided by the PV generator (W)
p_{con}	Electricity price that is self-consumed (€/kWh).
P_{grid}	Electricity price that is fed into the grid ((€/kWh).
PR	Performance Ratio (%).
PV	Photovoltaic
PV_{AOM}	Annual operation and maintenance cost of a PV system (€).
PV_{OM}	Operation and maintenance costs
PV_s	Amount equal to the portion of the PV system cost financed with equity capital (€).
PV_C	Photovoltaic system cost of (€).
PV_l	Amount equal to the portion of the PV system cost financed with loan (€).
$\mathrm{PW}\ [DEP(\ N_d)]$	Present worth of the tax depreciation (€).
$\mathrm{PW}[PV_{OM}(N)]$	Present worth of the PV system operation and maintenance cost (€).
$\mathrm{PW}[CI\ (N)]$	Present worth of the cash inflows (€).
q	Factor equal to $1/(1+d)$.
r_d	Annual degradation rate of the efficiency of the PV panels (%).
r_{OM}	Annual escalation rate of the operation and maintenance cost of a PV system (%).
rp_{con}	Annual escalation rate of the electricity price that is self-consumed (%).
rp_{grid}	Annual escalation rate of the electricity price that is fed into the grid (%).
S_{con}	Surcharge rate to self-consumed electricity (%)
T	Income tax rate (%).
$WACC$	Weighted Average Cost of Capital (%).
τ	Reporting period.
τ_r	Recording interval.
φ_{sc}	Self-consumption index.
φ_{ss}	Self-sufficiency index.

1. Introduction

The reduction of energy consumption in buildings is one of the challenges that Europe is currently facing. In the European Union, commercial and residential buildings represent over 40% of the total energy consumption [1] and around 55% of electricity consumption [2]. In Europe, this building consumption currently accounts for 24% of the greenhouse gases released into the atmosphere [3]. United States residential energy consumption is very similar to Europe [4] while in China it is about 28%.

In this sense, European policies encourage the improvement inenergy efficiency and the implementation of renewable on-site generation in order to promote nearly zero energy buildings (NZEBs) where photovoltaics (PV) together with solar thermal technology play an important role [5].

Photovoltaics have registered an exponential annual growth, mainly in the grid connected photovoltaic market [6], mainly due to a reduction in price of photovoltaic modules [7]. In 2017, the total PV capacity installed was about 403 GW [8]. Furthermore, the average efficiencies of commercial mono and polycrystalline modules have increased from 12% to 17-17.5% during last decade [9]. Due to the maturity of this technology and its modularity, photovoltaic solar energy offers an interesting option to deal with residential consumption. Moreover, the residential PV system cost has been reduced by 47-78% from 2007 to 2017 [9]. In this sense, building-applied photovoltaic systems have been extensively installed [10] providing a decentralized production where the grid is used to inject the surplus energy when the generated energy exceeds the consumption and, conversely, energy can be obtained from the grid when the generation is lower. Users with these photovoltaic systems could self-produce and self-consume their generated energy on site.

In certain geographical areas residential photovoltaic systems have become a competitive alternative for electricity generation. In this sense, some countries are applying net-metering and self-policies for these types of systems. There are some studies that have addressed this issue [11,12]. In [11] a methodology is presented that identifies the appropriate general net-metering scheme given the particularities and local conditions. In [12] a review is developed in order to investigate the potential of photovoltaics in southern Europe and Middle East/North Africa in terms of PV status and policies/initiatives for PV market development in the region.

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 [13,14] .

It is widely known that photovoltaic self-consumption provides consumers access to renewables energies which represent environment-friendly technologies, contributes to reducing the needs of the electricity grid, generates greater energy independence and reduces greenhouse gas emissions. In addition, it is an employment generating activity linked to the ecological transition, as has already been demonstrated in many countries. In this sense, a proper assessment of the cost-competitiveness and profitability of self-consumption systems is crucial to promote the transition from grid dependent to energy self-sufficient buildings [15].

When analyzing photovoltaic self-consumption systems, it may be defined by the following indices [16]

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

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

Where φ_{sc} and φ_{ss} correspond to self-consumption and self-sufficiency indices, respectively. It must be highlighted that this paper is only focused on self-consumption where no system storage is considered. L(t) and P(t) represent the instantaneous load consumption and the photovoltaic power harvested, respectively. M(t) provides instantaneous overlapping between the load consumption and the photovoltaic power, figure 1.

The sampling interval is defined as the time between samples and the recording interval (τ_r) corresponds to the time between records [17]. In this sense, τ_r provides the time resolution where samples are averaged. It has been reported that high recording interval overestimates the self-consumed energy [18,19]. This fact will be briefly discussed in the next paragraphs. τ defines the reporting period, denoted by t_2 and t_1, [17] and may be generally one year in order to consider seasonal variations and to minimize the influence of short-term random fluctuations.

As can be seen, the self-consumption index is obtained from the photovoltaic energy consumed, E_{PVcon} and the alternating current (AC) energy generated by a PV system in the given reporting period, E_{PVgen}. Whereas, φ_{ss} corresponds to the ratio of E_{PVcon} to the load consumption energy, E_L.

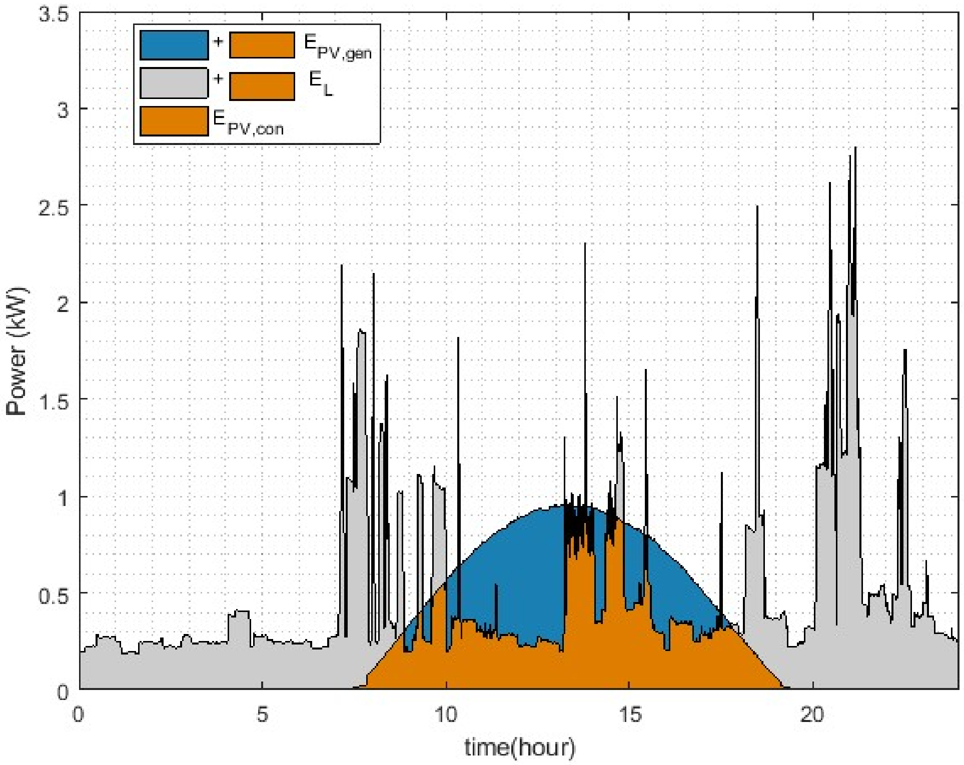


Figure 1. Daily photovoltaic generation and load consumption profiles for a given household in Jaén (South of Spain). The data displayed corresponds to 21 March 2017. The photovoltaic consumed energy is given by the orange area, while, E_{PVgen} and E_L are represented by the blue and orange areas and the grey and orange areas, respectively.

It must be highlighted that, when sizing the photovoltaic generator, the generated energy may be exploited to the maximum while the photovoltaic energy consumed may also represent an important percentage of the total load consumption. However, the economic cost of the photovoltaic self-consumption system must also be considered. In this sense, there are many research studies which intend to size PV self-consumption systems taking into account the economic aspects. In [20] the total cost of the energy supply is minimized when sizing the optimal system configuration. In [21] residential PV self-consumption systems are sized with the aims of reducing the electricity provided by the grid and achieving competitiveness with grid electricity prices. In [22] a method to size a PV self-consumption with storage which optimizes the overall system cost is developed. An economic analysis is carried out in order to compare different solutions and determine the most advantageous ones from an economic point of view. In [23] the developed techno-economic optimization model for German households it is possible to assess the profitability of residential PV systems. This model is based on maximizing net present value (NPV, in €) where power flows are summed up over all time slices ($t \in \{ 1,2 \ldots 35040\}$) of the year (with time slice duration equal to 15 minutes). In [24] a techno-economic simulation model is developed which allows the estimation of the optimal PV system configuration under consideration heterogeneity of electricity consumption profiles. This model is based on maximizing economic profitability and the criterion used is the NPV; the original dataset contains the electricity demand (in kWh) of households with a temporal resolution of 30 minutes. In [25] , a customer-driven investment model is used to examine the feasible market potential of rooftop PV installations in an urban environment. The net present value is used in order to estimate the economic profitability absolute returns for the property owners in the Helsinki urban area. The recording interval considered in this case was of one hour. The methods used to size the PV generator considering profitability criteria use recording intervals of twenty minutes or greater [23,24]. As can be seen, relative high recording intervals when estimating the self-consumed energy are generally considered. The impact of the recording interval does not only affect the analysis performance of this type of system but also on the estimation of different economic parameters such as cash inflows. Furthermore, most of the aforementioned methods provide a profitability analysis only focused on discrete array powers and they do not consider economic parameters such as, taxes, depreciation, escalation rate of operation and maintenance costs and the cost of financing which may have a significant effect on an economic profitability analysis.

2. Aims and scope

This paper will be focused on developing a method to size the PV generator in a self-consumption system with no storage that manages the aforementioned challenges. This approach will maximize the economic profitability considering the aforementioned techno-economic parameters and an array power range that may suit residential self-consumption systems. The recording interval considered either for load demand and photovoltaic generation data has a great impact on the analysis of PV self-consumption systems. The profitability analysis will be developed through a method where power generation, load consumption and price of electricity are considered with a recording interval of one minute [26].

It is worth noting the originality and novelty of this method compared with the one developed in [21] and based on cost-competitiveness as a cost-competitive PV system does not imply that its economic profitability satisfies that which is required by the PV system owners or investors. The cost competitiveness analysis, based on the levelised cost of electricity, is usually used to compare different electricity production technologies, both renewables and conventionals. However, the economic profitability analysis based on the NPV criterion provides a value of the net profit of the PV system throughout its life cycle (i.e. the economic meaning of NPV equals the total net profit in constant currency at the time of evaluation, once the cash inflows have paid the life cycle cost of the PV system). Therefore, the method developed here may be welcomed by future owners or investors interested in self-photovoltaic systems, who demand information on the economic profitability of their investment.

The method developed here manages to optimize the net present value for PV electricity generation so that it maximizes the absolute returns for the owners of a PV self-consumption system. Two scenarios will be considered: Scenario A where the generated electricity surplus is wasted, that is, the latter is not remunerated and Scenario B where the generated surplus electricity is injected into the grid and the PV system owner receives compensation from the grid operator depending on the wholesale market prices. For both scenarios, self-consumed electricity is compensated depending on the retail market prices. Moreover, the method will provide an NPV curve together with the self-consumption and self-sufficiency curves for different array powers ranging from 0 to 7 kWp. In this sense, it may become an interesting and intuitive tool to analyze not only NPV for self-consumption systems but their corresponding self-sufficiency and self-consumption indices as a function of the array power. The method may complement the one developed in [21] which aimed to achieve cost-competitiveness. Furthermore, the method will be illustrated using the load consumption and photovoltaic generation data of three dwellings (Jaén, Spain). The method developed here may be easily replicated as it is widely detailed and may be applied in any country if the corresponding techno-economic parameters are considered.

Finally, it will be shown how the recording interval can affect the estimation of NPV for the three analysed dwellings . Although the effect of this parameter on the estimation of self-consumed energy is widely documented, the effect on economic parameters has not been analysed in the literature. A sensitivity analysis will be conducted to determine the more influential techno-economic parameters when estimating NPV.

The paper will be structured as follows. In the next section, the techno-economic method to analyze the economic profitability of the self-consumption system based on the NPV will be developed. Next, it will be described how to plot the self-consumption and self- sufficiency curves as a function of the nominal array power. The latter together with the aforementioned method will manage to estimate the array power which maximizes the net present value of the self-consumption system. In section 4, in order to illustrate the developed method, the latter will be applied to three dwellings located in the south of Spain. Load consumption and photovoltaic generation data with a one minute recording interval will be considered. Results will be discussed in this section. In section 5 a sensitivity analysis in order to determine the more influential parameters when estimating NPV will be developed and the effect of the recording interval when estimating NPV will be also analysed. Finally, conclusions will be drawn.

3. Methodology

3.1 Data

Three different dwellings located in the south of Spain (Jaén, latitude: 47 deg 46′00′′ N and longitude 3 deg 47′ 0′′ O) have been monitored during a whole year (June 2016-May 2017) considering a sampling interval of one second and a recording interval of one minute, figure 2. A quality control process of the input data has been developed following the recommendations of the IEC 61724 standard [17,27,28] in order to identify invalid and missing data points.

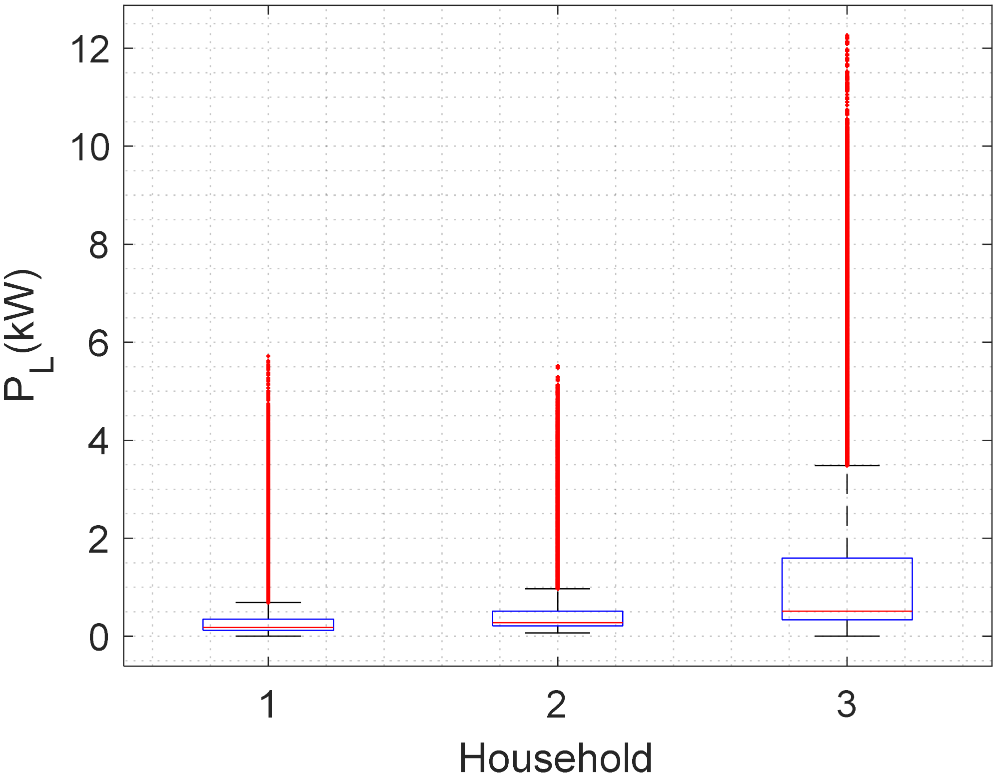


Figure 2. Electricity load consumption boxplot of the three dwellings considered in the manuscript to illustrate the method to sizing the PV generator in self-consumptions systems without storage based on economic profitability.

As shown in table 1, Household #03 has the higher energy consumption, while household #01 has the lowest. The load consumption of Household #03 mainly occurs during the night (the ratio between nigh consumption and total consumption is more than 70%) as it uses electric heating. Household#1 daylight consumption is slightly lower than night consumption (the aforementioned ratio is 52.4 6%). Conversely, Household #02 has more energy consumption during solar hours (44.4%). Meanwhile, the power consumptions range mainly from 0.119 to 0.346, from 0.209 to 0.512, from 0.335 to 1.594 kW in Household

#01, Household #02 and Household #03, respectively. In appendix A, a more detailed load consumption description of the three dwellings can be found.

Table 1. Load consumption of the three dwellings.

Households	**Dates**	**Consumption**						**Occupancy**
		Annual energy consumption (kWh/year)			**Power consumption (kW)**			
		Total	**Daylight hours**	**Night hours**	**25th percentile**	**Mean**	**75th percentile**	
#01	01/04/2017-31/03/2018	2682.6	1277.6	1405.0	0.1190	0.1780	0.3460	3
#02	01/04/2017-31/03/2018	4328.5	2410.3	1918.1	0.2090	0.2780	0.5120	4
#03	01/04/2017-31/03/2018	14297.7	4072.4	10225.3	0.3350	0.5130	1.5940	2

The irradiance data corresponding to the same aforementioned period in Jaén has been also monitored with the same sampling and recording interval considered for load consumption. Two meteorological stations with an Eppley Piranometer have been used which provide the global irradiance (W/m^2) on a horizontal plane in order to estimate the irradiance corresponding to the optimum angle [29]. These can be classified as 'high accuracy' according with the classification of the IEC 61724-1. 'High accuracy" phermopile pyranometers is sorted, in turn, as Secondary standard per ISO 9060 or High quality per WMO Guide no.8. The quality check is guaranteed taking into account the aforementioned redundancy and following IEC 61724.

3.2 Self-consumption and self-sufficiency curves

Different methods to estimate E_{PVgen} [30] can be found. In this paper, the one which considers the Performance Ratio (*PR*) [17], Eq. (3) will be used. This parameter takes into account different losses concerning spectral effects, operating at module temperatures different from 25ºC, dust and soling, inverter efficiency, wiring, etc.

$$E_{PVgen,\tau} = P_0.PR \cdot \frac{H_{OPT}}{G_{STC}} \tag{3}$$

where H_{OTP} (kWh/(m^2·year)) and G_{STC} represents the annual global irradiation at the optimal tilt angle and the global irradiance of 1 kW/m^2 (Standard Test Conditions). P_0 is the nominal power of the photovoltaic array. *PR* typically ranges from 0.70 to 0.80 for conventional PV systems. In this paper, PR values of 0.75 will be considered [31–35].

In figure 3 φ_{sc} and φ_{ss} are plotted against the array nominal power (P_0). As indicated in [21] self-consumption and self-sufficiency indices follow a negative exponential and a logarithmic curves, respectively. The two curves intersect in a particular point called Zero Electrical Energy Point where it may be possible to leave off the grid if it is possible to take advantage of the entire photovoltaic energy generated. In a first approach this is not possible as the generation and the load consumption profiles do not completely match, however, EPV_{con} can be increased and the self-sufficiency index can be maximized as different strategies are considered (i.e storage system and domestic demand-side management (DSM)). In [21] a detailed analysis is given about these types of curves and it is shown how to plot them, figure 4. It must be highlighted that these types of curves may be very useful as will be illustrated in the next sections. They may be used to optimize NPV for PV generation so that it maximizes the absolute returns for the owner/investor of a PV self-consumption system.

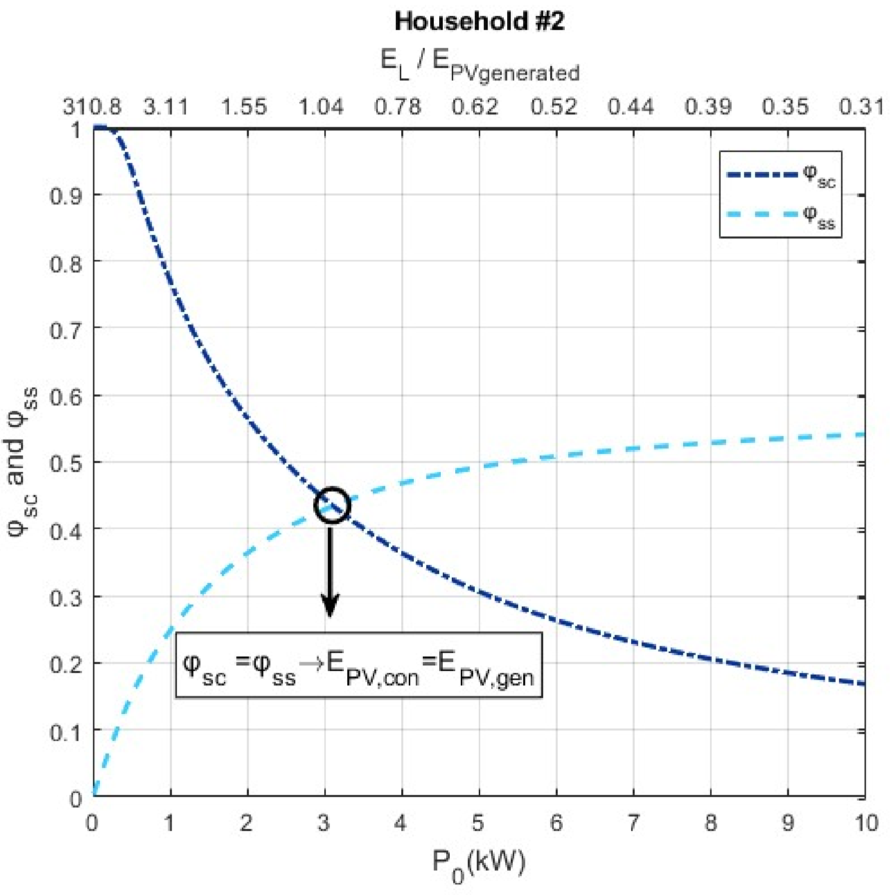


Figure 3. Annual φ_{sc} and φ_{ss} curves for household#2. These two parameters are plotted against the nominal PV power, P_0, and the normalized factor, F.

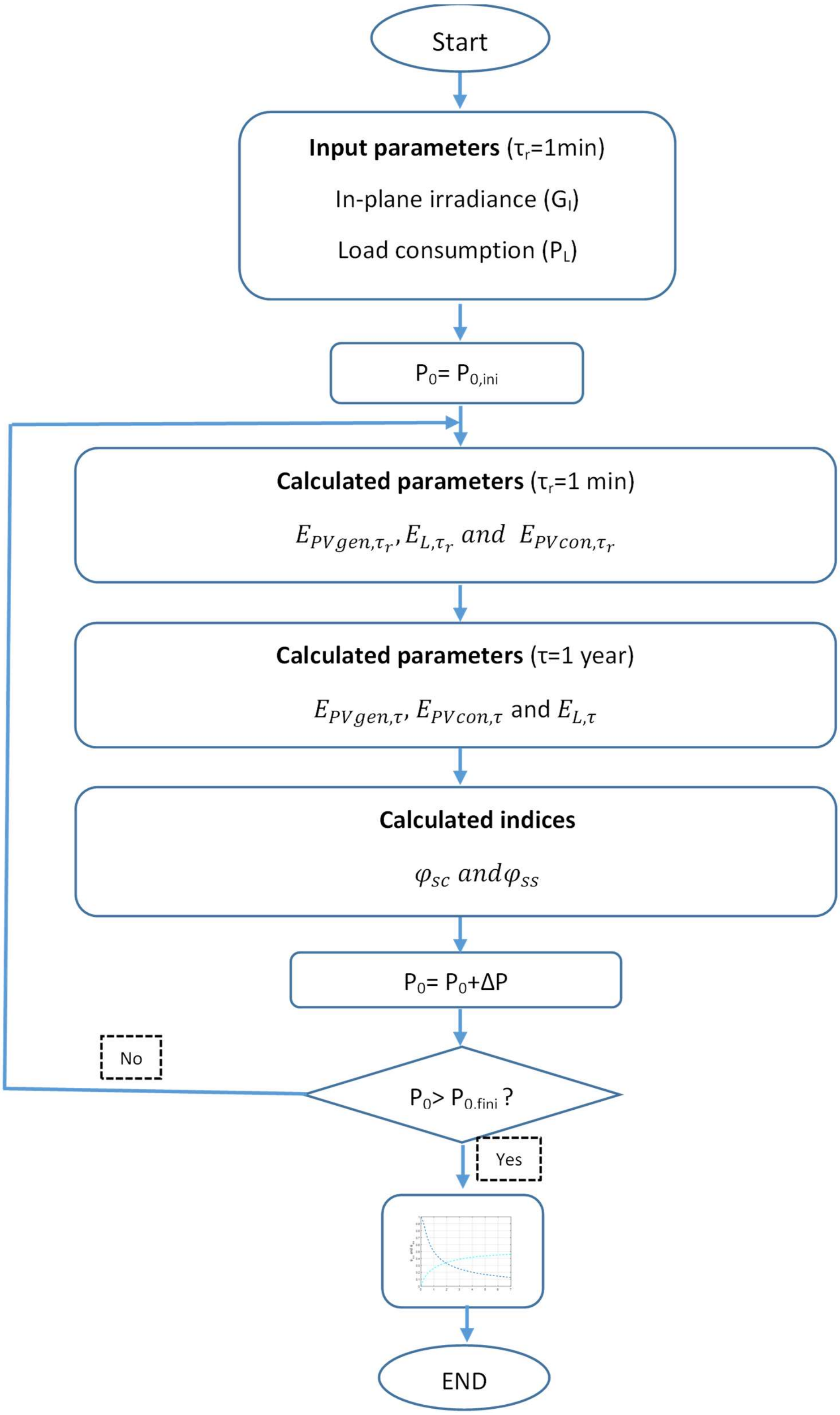


Figure 4. How to plot φ_{sc} and φ_{ss} as a function of the nominal array power, P_0. [21].

3.3 Techno-economic model

In this section, the techno-economic model will be described that maximizes the economic profitability of the self-consumption PV system based on the net present value. This criterion, although it has been used in previous works [36,37], will be improved taking into account not only different electricity retail tariff structures and load profiles but parameters such as self-consumption electricity and electricity fed into the grid.

As is known, the NPV of a project is defined as the difference between the present worth of the cash inflows and the present worth cash of outflows related to the project [38]. Therefore, NPV corresponds to the present worth of the cash inflows from the system minus the life cycle cost. In this way, it may be expressed as:

$$\mathrm{NPV}=\mathrm{PW}\,[\mathrm{CI(N)}]-\mathrm{LCC} \tag{4}$$

PW[CI(N)] represents the present worth of the cash inflows produced over the lifetime of a self-consumption PV system. Cash inflows are related to the regulation for self-consumption of each country (net metering, net billing, among others); the most general case would assume that a portion of the photovoltaic energy generated (E_{PVgen}) is used for self-consumption (E_{PVcon}), while the remaining photovoltaic energy generated is fed into the grid (E_{PVgrid}) and is sold at a given price (p_{grid}). E_{PVcon} avoids buying electricity from the grid at a given price (p_{con}). E_{PVgrid} is calculated as the difference between E_{PVgen} and E_{PVcon}. Taking into account all these considerations, PW[CI(N)] for a self-consumption PV system is provided by the following equation:

$$\mathrm{PW}[\mathrm{CI}(N)] = \left(\sum_{i=1}^{n} p_{con_i}\cdot E_{PVcon_i}\right)(1-S_{con})\cdot\frac{K_{con}\,(1-K_{con}^{N})}{1-K_{con}} + \left(\sum_{i=1}^{n} p_{grid_i}\cdot E_{PVgrid_i}\right)(1-T)\cdot\frac{K_{grid}\,\left(1-K_{grid}^{N}\right)}{1-K_{grid}} \tag{5}$$

Where N corresponds to the cycle life of the system given in years; n is the number of recording intervals in a reporting period of one year; as the recording interval is one minute, n is equal to 525600; S_{con} represents the surcharge rate applied to self-consumed electricity; T is the income tax; K_{con} and K_{grid} are two parameters related to the escalation rate of the electricity price and degradation rate of the power, respectively. They may be written as:

$$K_{con} = (1+rp_{con})\cdot(1-r_d)\,/(1+d) \tag{6}$$

$$K_{grid} = \left(1+rp_{grid}\right)\cdot(1-r_d)\,/(1+d) \tag{7}$$

Where rp_{con} and rp_{grid} stand for the annual escalation rate of the electricity price that is self-consumed and fed into the grid, respectively, while factor r_d is the annual degradation rate in the efficiency of a photovoltaic system and d is referred as the nominal discount rate.

In relation to the cash outflows, they are represented by the life-cycle cost of the PV system (LCC) which is calculated by adding the photovoltaic system cost (PV_C) with the present worth of its operation and maintenance cost ($\mathrm{PW[PV_{OM}}(N)]$) and subtracting the present worth of the tax depreciation $\mathrm{PW[DEP}(N_d)]$ during the system life cycle (N). LCC may be expressed as:

$$\mathrm{LCC} = PV_C + \mathrm{PW}\ [\mathrm{PV_{OM}}(N)] - \mathrm{PW[DEP}(N_d)] \cdot T \tag{8}$$

The term $\mathrm{PW[PV_{OM}}(N)]$ of Eq. (4) can be written as:

$$\mathrm{PW[PV_{OM}}(N)] = PV_{AOM}(1-T) \cdot \frac{K_{OM}\ (1-K_{OM}^N)}{1-K_{OM}} \tag{9}$$

In the previous equation, (PV_{AOM}) stands for the annual operation and maintenance expenditure which is assumed to be constant over the life cycle of the system, with the exception of an annual escalation rate of the operation and maintenance cost (r_{OM}) included in the factor $K_{OM} = (1 + r_{OM})/(1 + d)$.

The last term of Eq. (8) $\mathrm{PW[DEP}(N_d)]$ represents those scenarios where there is a deductible tax depreciation [39], its impact is considered through the following expression which estimates the present worth of tax depreciation $\mathrm{PW[DEP}(N_d)]$.

$$\mathrm{PW[DEP}(N_d)] = \sum_{n=1}^{N_d} \frac{DEP_n}{(1+d)^n} \tag{10}$$

In this Eq. (10), 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. As the method used in the tax depreciation may differ from country to country, readers should refer to national tax laws. For example, if the tax depreciation is assumed to be linear and constant over a given period of time, the present worth of the tax depreciation can be estimated using the following equation:

$$\mathrm{PW[DEP}(N_d)] = DEP_y \cdot \frac{q\ (1-q^{N_d})}{1-q} \tag{11}$$

where DEP_y is equal to PV_C / N_d and represents the fixed annual tax depreciation for the PV system; q is equal to $1/(1 + d)$.

Finally, the photovoltaic system cost is usually financed by means of debt or equity capital. In the case where the system cost PV_C is financed through a loan (PV_l) —debt— and the remainder by means of the issue of stocks (PV_s) —equity capital— then $PV_C = PV_l + PV_s$. According the previous financing scheme, the photovoltaic system cost may be expressed as:

$$PV_C = \left[PV_l \frac{i_l(1-T)}{1-\left(1+\ i_l(1-T)\right)^{-N_l}} \cdot \frac{q(1-q^{N_l})}{1-q}\right] + \left[d_s \cdot PV_s \cdot \frac{q(1-q^N)}{1-q} + PV_s \cdot q^N\right] \tag{12}$$

The first term in square brackets of Eq. (12) is related to the loan (PV_l), i.e., the amount of the system cost that is borrowed at an annual interest (i_l) to be repaid in N_l years. A possible tax rate (T) influence is also included.

The last term in square brackets of Eq. (12) corresponds to the equity share (PV_s), with an annual retribution in the form of dividends (d_s) as a return on equity. This amount must be paid in full at the end of the system life-cycle (N years).

The right-hand side of Eq. (12) only equals its right-left side if the selected value of d is equal to weight average cost of capital (*WACC*) of the investment, that is, the cost of the chosen financing. A widespread practice consists of setting d equal to the organization's *WACC* [39,40].

In figure 5 the methodology used to develop the techno-economic model here presented is shown.

3.3.1 Techno-economic model parameters

Prior to addressing the estimation of NPV, a review of the inputs parameters used in its calculation will be carried out in this section. This review will lead to the calculation of the different parameters in order to estimate the NPV of the photovoltaic self-consumption systems in the residential segment and for a scenario (2018) in Spain.

In this work, the following two scenarios will be used. Scenario A: self-consumption with surplus electricity injection into the grid, where the generated electricity surplus is wasted, that is, it is not remunerated. Scenario B: self-consumption with surplus injection into the grid, where the surplus electricity is injected into the grid and the PV system owner receives compensation from the grid operator depending on the wholesale market prices. For both scenarios, self-consumed electricity is compensated depending on the retail market prices.

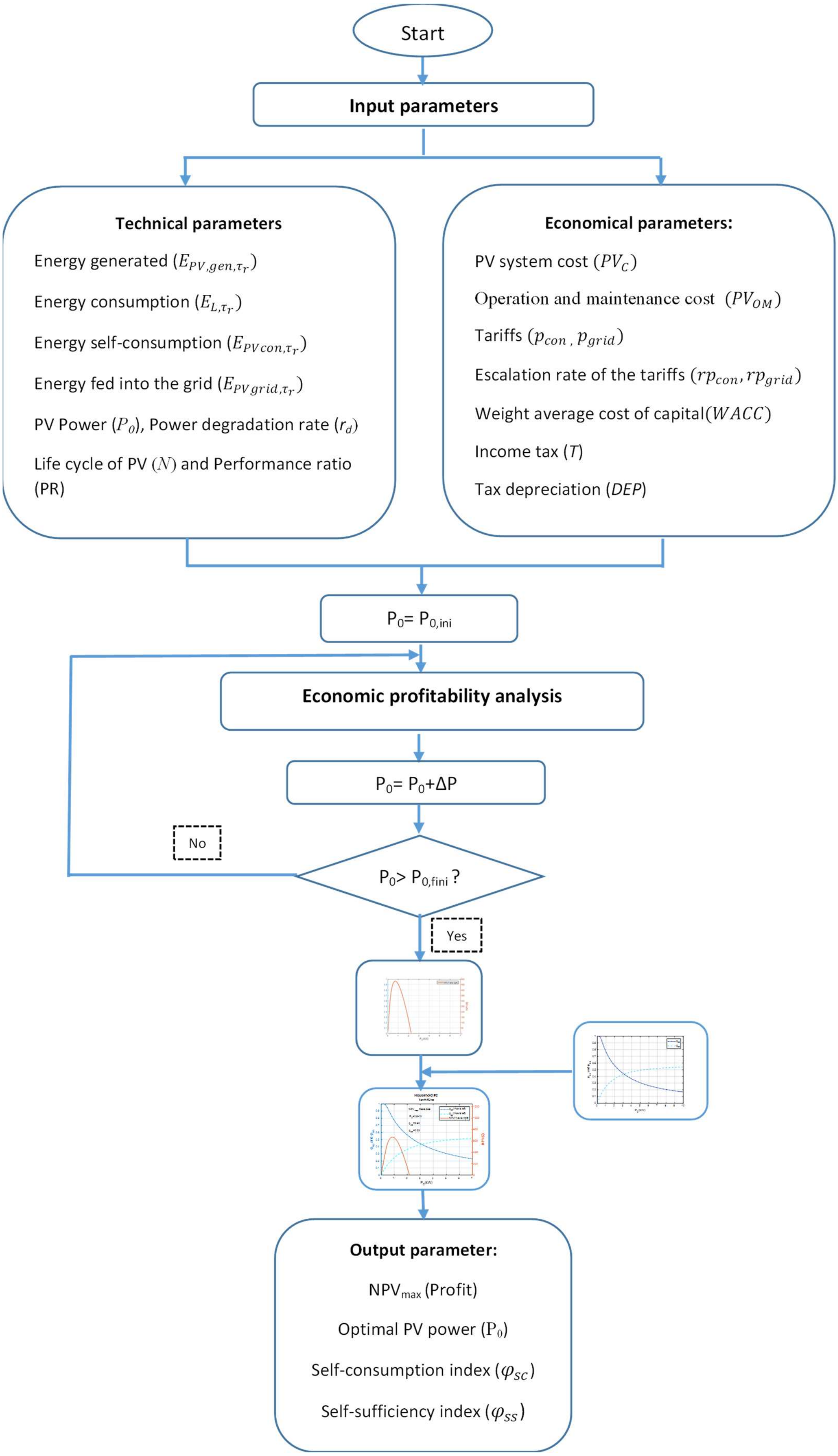


Figure 5. Techno-economic model used to estimate NPV for photovoltaic self-consumption systems for a given power array range.

Currently, the PV system cost per kW_p in PV systems continues to go down, through a decrease in module prices, balance of system, soft costs and margins. Consequently, PV system cost for small rooftops, concretely in the residential sector continued to decline in recent years in several countries. In September 2017, the worldwide average price of a residential system without taxes was given as USD 1.53/Wp (EUR 1.28/Wp) about 20 % higher than in Europe with EUR 1.13/Wp and 30 % higher than in Australia AUD 1.37/Wp (EUR 0.95/Wp) [41,42]. Taking the European price and adding a surcharge of EUR 0.17/Wp for fees, permits, insurance, etc., the installed PV system costs is about EUR 1300/kWp without VAT [43].

In commercial and industrial PV systems, the value-added tax (VAT) is deductible for companies and therefore does not entail a cost. However, to estimate the cost of Residential PV system, the value-added tax VAT should be included (which is nondeductible for consumers).

In the case of Spain 2017, the average cost of a residential PV system can be taken with a variation ranging from 1400 to 1500 €/kW_p (exclude VAT) [44]. However, taking into account the decreasing trend in cost of the PV systems and for a scenario (2018), PV_C may be considered as 1573 €/kW_p, including VAT (21% in Spain).

Cash inflows are related to the regulation for self-consumption of each country (net metering, net billing, among others); the most general case would assume that a portion of the photovoltaic energy generated (E_{PVgen}) is used for self-consumption (E_{PVcon}), while the remaining photovoltaic energy generated is fed into the grid (E_{PVgrid}) and is sold at a given price (p_{grid})

The electricity prices, p_{con} and p_{grid}, depend on the government regulation for self-consumption and electric market of each country. In this work p_{con} is set at the retail price of the market, while p_{grid} is set at the wholesale market price. Electricity price in the residential segment in Spain -powers less than 10 kW-, offered by utilities are shown in table 2 [45–47]. Electricity price in the wholesale market prices in Spain is shown in figure 6 [48]. This figure shows an average price of electricity equal to 45.943 €/MWh in the period 2010-2018.

Table 2. Electricity price in the residential segment in Spain (Load Power less than 10 kW) [45–47] .

Endesa		**Iberdrola**		**Naturgy**	
Type of tariff	Tariffs (€/kWh)	Type of tariff	Tariffs (€/kWh)	Type of tariff	Tariffs (€/kWh)
One	0.159685	Stable Plan	0.173323	Stable Tariff	0.188294
One Night	0.203017 On-peak 0.102296 Off-peak	Night Plan	0.206447 On-peak 0.106281 Off-peak	Night Plan	0.222179 On-peak 0.112149 Off-peak

Tempo Verde Super Off-peak	0.206283 On-peak 0.118315 Off-peak 0.091409 Super Off-peak	Non-available	Three-periods Plan	0.224196 On-peak 0,123441 Off-peak 0.101122 Super Off-peak

- Prices include: VAT (21%) and the electricity tax (5.11%).
- Off-peak hours 14 hours per day: in winter from 22:00h to 12:00 and in summer from 23:00 to 13:00h. Rest of the hours are On-peak
- Super Off-peak: 7 hours per day (between 1:00 and 7:00 h)

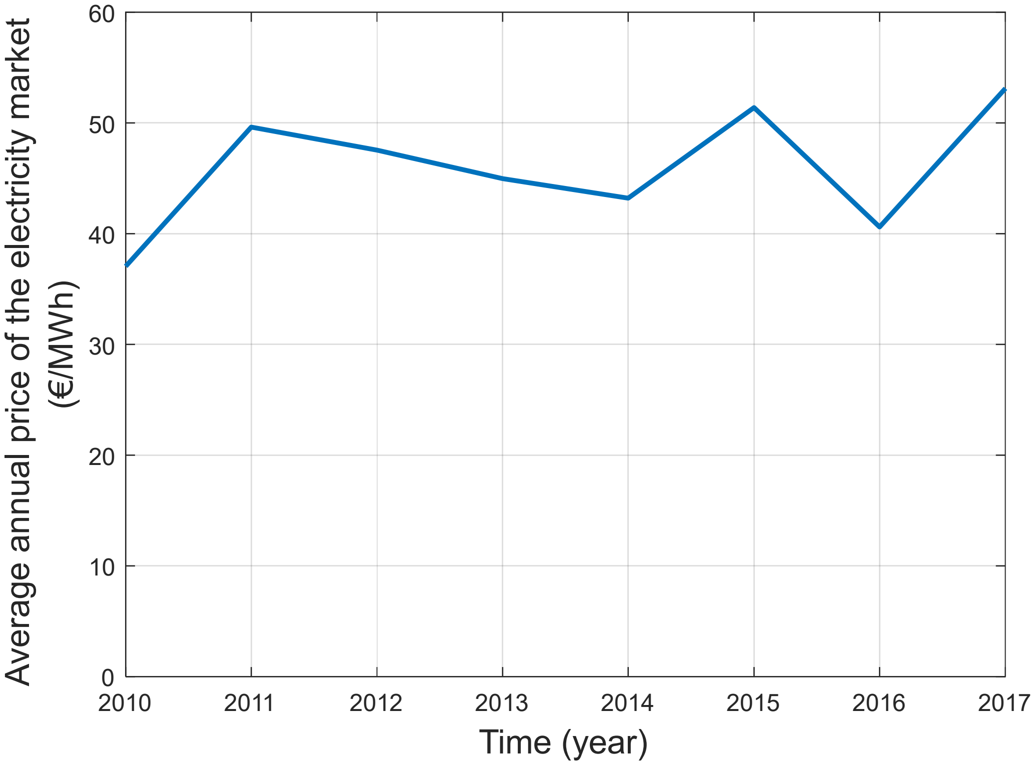


Figure 6. Electricity price in the wholesale market prices in Spain 2010-2017 (prices do not include taxes).

The variation rate of the electricity price, linked to the evolution of electricity markets, is always difficult to forecast. In this paper an escalation equal to the rate of inflation is considered. Thus, in the case of Spain rp_{con} and rp_{grid} is assumed equal to 1.8%.

PV system cost may be financed through long-term debt and equity capital. Thus, 70% of this amount is taken on loan (PV_l) – debt–, while the remaining 30% of the amount is financed by means of stock issue (PV_s); taking into account that commercial banks are generally accepting higher leverage in stable economies with secure property rights [49]. In this study, i_l equal to 5.73% [50] and N_l equal to 20 years are assumed; as regards to equity capital, d_s equal to 9.46% [51] is considered.

The nominal discount rate (d) is assumed equal to the weighted average capital of cost in order to calculate the profitability criteria [39]. In this paper, $WACC$ is equal to 7.2%, given the assumptions stated in the above paragraph. This capital cost will vary depending on how the capital resources are chosen to finance the PV system cost.

The income tax rate *(T)* for the organization or taxpayer, changes depending on each country's regulations. In Spain, the regulatory framework for self-consumption was developed under Royal Decree 900/2015. This Royal Decree established two types of self-consumers: Type I, a maximum capacity installed of 100 kW is established and there is no compensation for the electricity surplus injected into the grid; Type II, no limit to the allowed capacity and the surplus can be sold in the wholesale market directly or through an intermediary. For both types, variable and fixed charges for self-consumed electricity were applied. It should be noted that Type I self-consumption facilities <10 kW are exempt from the variable and fixed charges for self-consumed electricity [52]. A new Royal Decree-Law 15/2018 for the energy transition and the protection of consumers, is currently in force. This Royal Decree-Law eliminates a series of regulatory barriers that, up to now, have discouraged the implementation of electric self-consumption in Spain. The new regulation promoted by the Government is based on three principles: the required bureaucratic and technical procedures are simplified, such as registration in a registry for those facilities not exceeding 100 kW; the right to self-consumption shared by one or several consumers is recognized, which will allow economies of scale to be exploited; and the right to self-consume electric power without tolls or charges. Therefore, repealed the charge imposed on the self-consumer for the energy generated and consumed in its own installation, the so-called "sun tax", remains repealed. Thus income tax rate is assumed equal to 0%.

E_{PVgen} of a system is considered to decrease every year. Normally, an annual degradation rate in the efficiency of the photovoltaic modules equal to 0.5% is assumed, during the lifetime of the system [53,54]. Regarding inflation rate, a value of $g = 1.8\%$ for Spain has been considered. The latter has been obtained from historical data related to annual inflation rates –period 2008-2018– [55].

The annual operation and maintenance costs (PV_{AOM}) should be considered as the percentage of PV_C spent on operation and maintenance tasks on an annual basis. In this case, it has been considered 1.5% of PV_C[56]. Additionally, these costs will also be influenced by an annual escalation rate (r_{OM}). This last parameter is set equal to the value of the inflation rate, so that $r_{OM} = 1.8\%$.

In this sense, the values assumed for every parameter that defines the proposed scenarios are gathered in Table 3.

4. Examples and Discussion

In this section, the techno-economic model will be applied to the three dwellings described in section 3, for each of the aforementioned scenarios.

4.1 Scenario A

As has been previously mentioned, scenario A corresponds to self-consumption where surplus electricity injection into the grid is not remunerated. In figures 7, 8 and 9 annual φ_{sc} and φ_{ss} and net present value are plotted against P_0 for the three analysed dwellings. The Endesa electric utility tariffs known as: One, One night and Tempo (see table 2) have been considered. As can be seen, there is only one maximum value for a given array power which provides the maximum economic profitability of the system. Table 5 shows the maximum value of NPV for each tariff considered, as well as their corresponding array power and self-consumption and self-sufficiency indices.

Table 3. Values of technical and economic parameters assumed for the proposed scenarios.

Parameters	Base case values	Units
PR	75	%
PV_C	1573	€/kW$_p$
r_d	0.5	%
P_{con}	Table 1	€/ kWh
p_{grid}	0[2]	€/ kWh
	45.94375[3]	€/ MWh
rp_{con}; rp_{gid}	1.8	%
PV_{AOM}	1.5[1]	%
r_{OM}	1.8	%
T	0	%
S_{con}	0	%
d	7.2	%
g	1.8	%
i_l	5.73	%
N_l	20	years
d_s	9.46	%
N	25	years

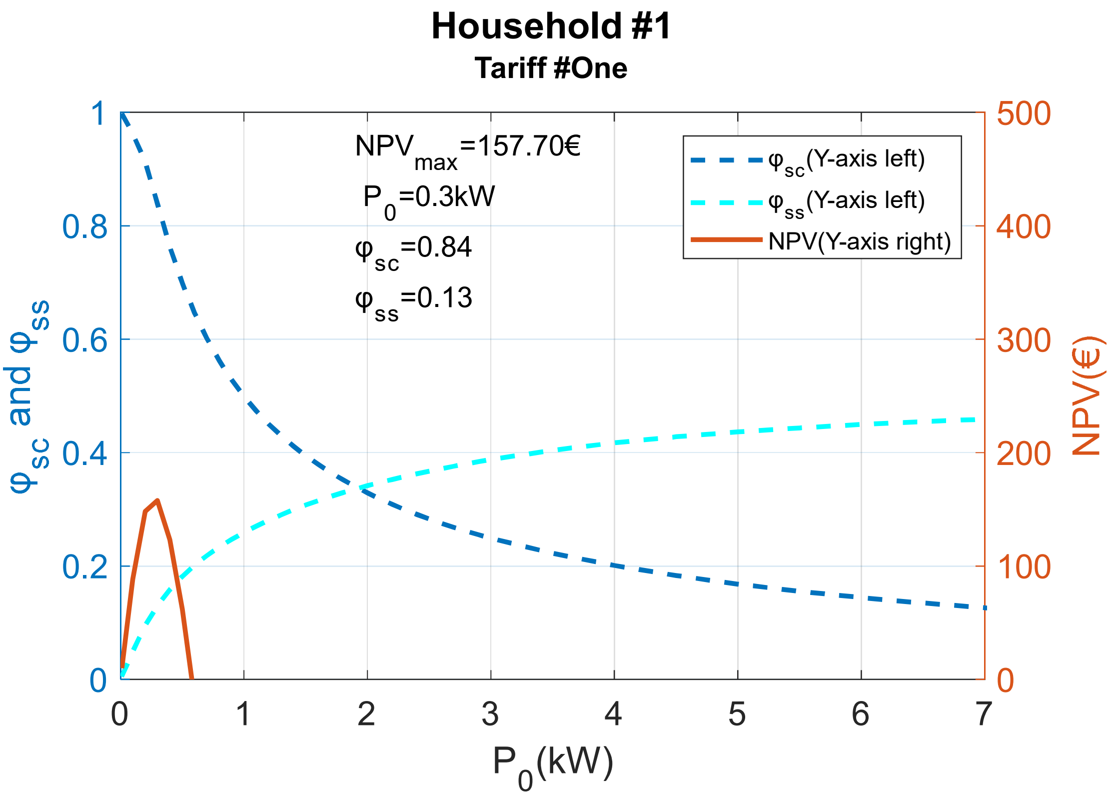
[1] This value should be considered as the percentage of PV_C spent on operation and maintenance tasks on an annual basis. [2] Scenario A. [3] Scenario B.

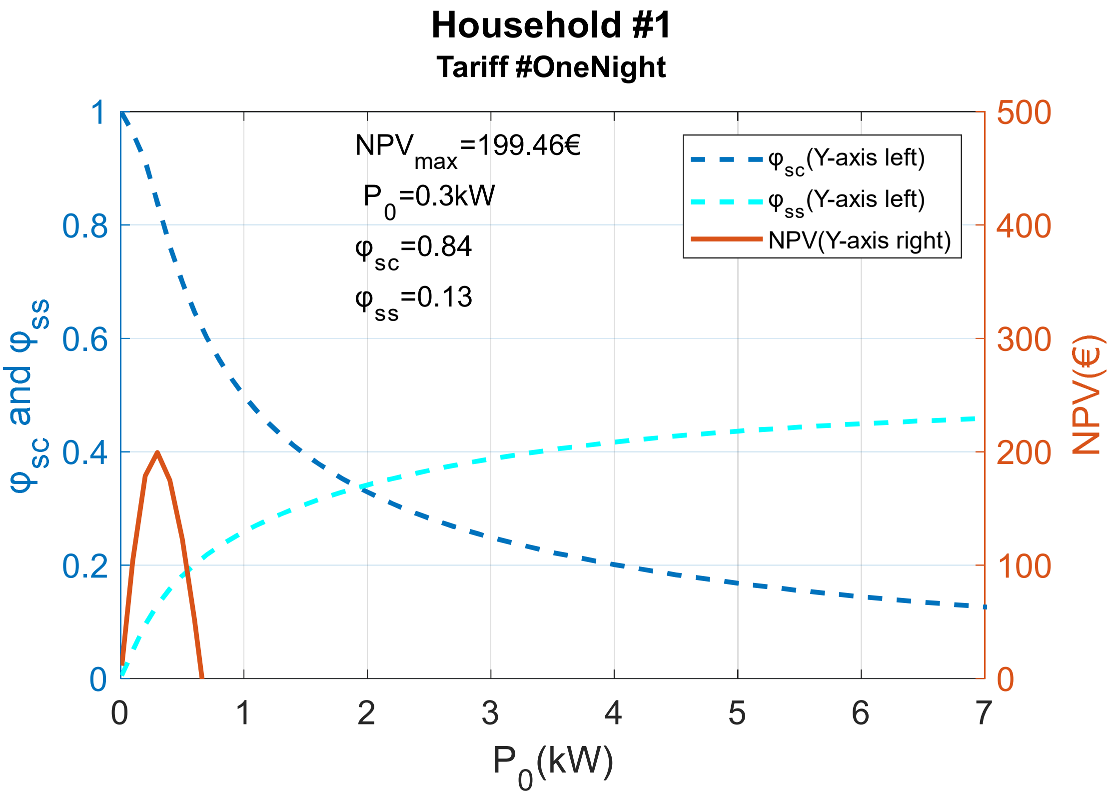
For household#1 it can be observed that this maximum profitability is always reached at 0.3 kWp for the One, One Night and Tempo tariffs. The maximum NPV (233.1 €) corresponds to the tariff of time of use in three periods (Tempo). In table 4 the percentage increase in NPV between the considered Tariffs is shown (i.e. Tempo tariff provides an NPV 48% higher than the one associated to One Tariff for household#1). It must be highlighted that, for the three tariffs, high self-consumption (>83%) and low self-sufficiency (<13%) indices are achieved. This means that relative low array powers should be considered in order to get NPV maxima. Furthermore, as can be seen, NPV increases as the array power does. Once the maximum is reached, NPV decreases, although the array power gets higher. This is due to the fact that the increase in the cost of the system has a greater effect on NPV than the remuneration obtained by the increase in the energy generated. When NPV equals zero it provides an interesting point which determines the highest array power to be considered in order to achieve economic feasibility. In this sense, regarding the array power a profitability window may be defined that ranges between array powers higher than zero and below this upper limit. As can be observed in this window, the more array power, the higher self-sufficiency index. For household#1 this profitability window ranges between 0 and 0.7 kWp.

Regarding Household# 2 (figure 8), the maximum return is obtained for photovoltaic array powers equal to 0.60, 0.70 and 0.70 kW_p for the One, One Night and Tempo tariffs, respectively. As in Household#1 the maximum profitability is achieved in the Tempo tariff (603.5€). As previously mentioned, the chosen tariff is a key parameter when optimizing NPV, Table 4. The percentage increase is very similar to those obtained for household#1. Maximum NPV increases 42% when considering Tempo tariff instead of One Tariff. Regarding the self-consumption and self-sufficiency indices, the former is slightly increased (86-90%) regarding household#1 and the latter ranges between 17-19.5%. The profitability window is found below 1.8kWp. In Household# 3 (figure 9) the power of the photovoltaic generator that maximizes the economic profitability also depends on the considered tariff: 0.80, 0.90 and 0.90 kWp for the One, One Night and Tempo tariffs. Again, the Tempo tariff, as it manages time of use, provides the maximum NPV (777.4€). The low self-sufficiency index achieved must be noted, which is marginal, below 7.6%. As previously noted, this dwelling has a relatively low consumption during sunshine hours. In this case, the profitability window is up to 2 kWp.

Table 4. Percentage increase in NPV maxima when comparing different electricity tariffs. Scenario A.

Tariff	Household#1	Household#2	Household#3
One night/One	1,26	1,23	1,21
Tempo/One	1,48	1,42	1,40
Tempo/ One night	1,17	1,16	1,16


Household #1
Tariff #One
NPV_max=157.70€
P_0=0.3kW
φ_sc=0.84
φ_ss=0.13
φ_sc(Y-axis left)
φ_ss(Y-axis left)
NPV(Y-axis right)
φ_sc and φ_ss
NPV(€)
P_0(kW)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
0
1
2
3
4
5
6
7


Household #1
Tariff #OneNight
NPV_max=199.46€
P_0=0.3kW
φ_sc=0.84
φ_ss=0.13
φ_sc(Y-axis left)
φ_ss(Y-axis left)
NPV(Y-axis right)
φ_sc and φ_ss
NPV(€)
P_0(kW)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
0
1
2
3
4
5
6
7

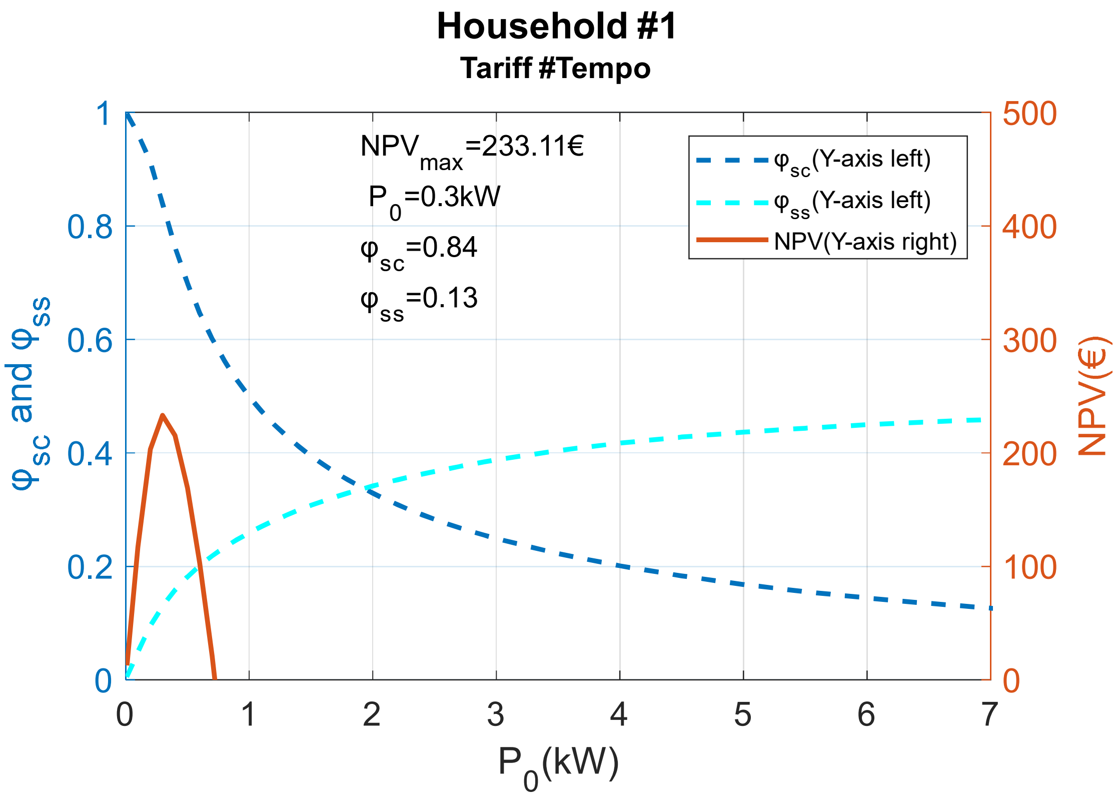
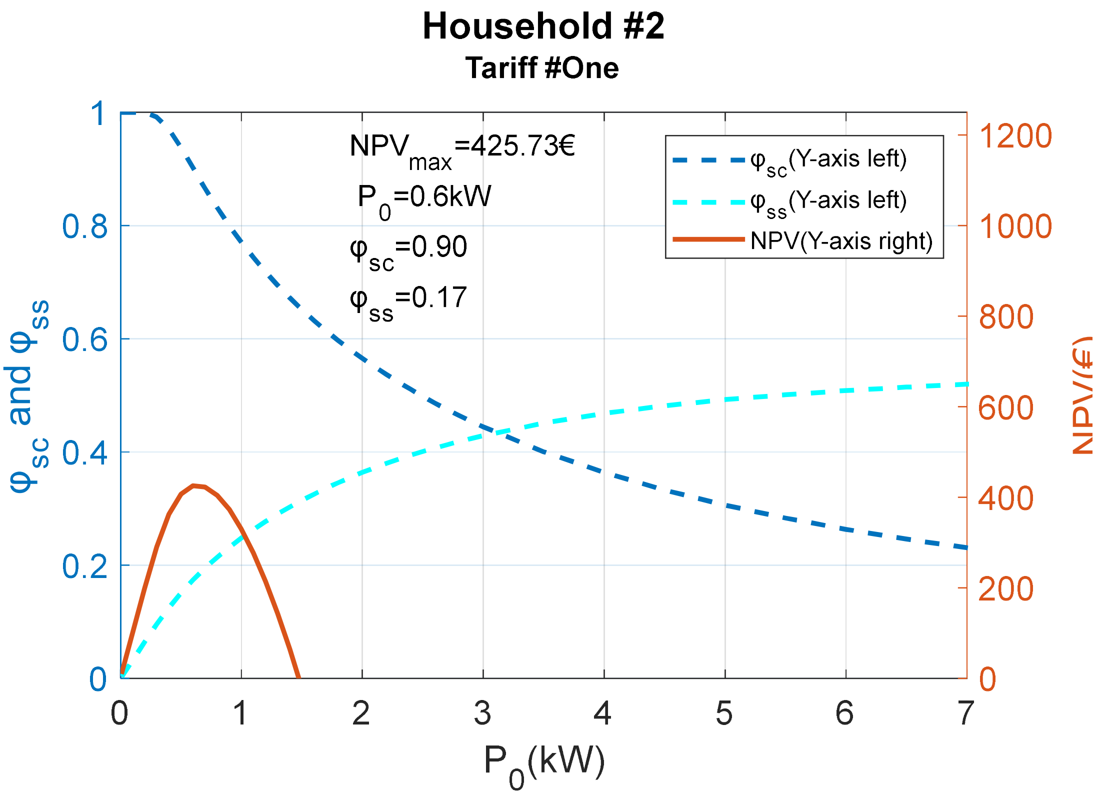


Figure 7. Household#1. NPV considering several tariffs: One (top), One night (middle) and Tempo (bottom). Scenario A. Annual φ_{sc} and φ_{ss} curves have also been plotted.



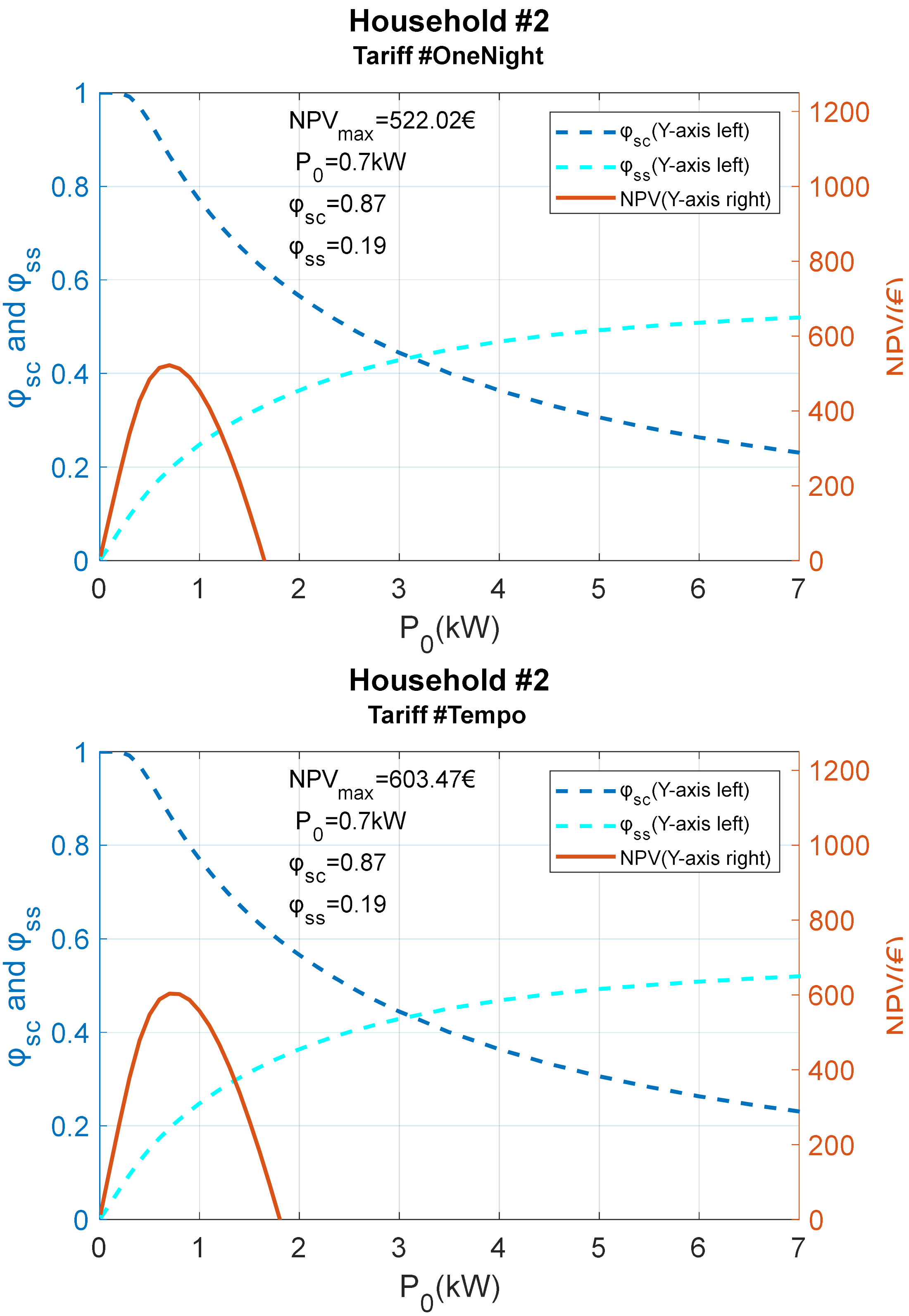
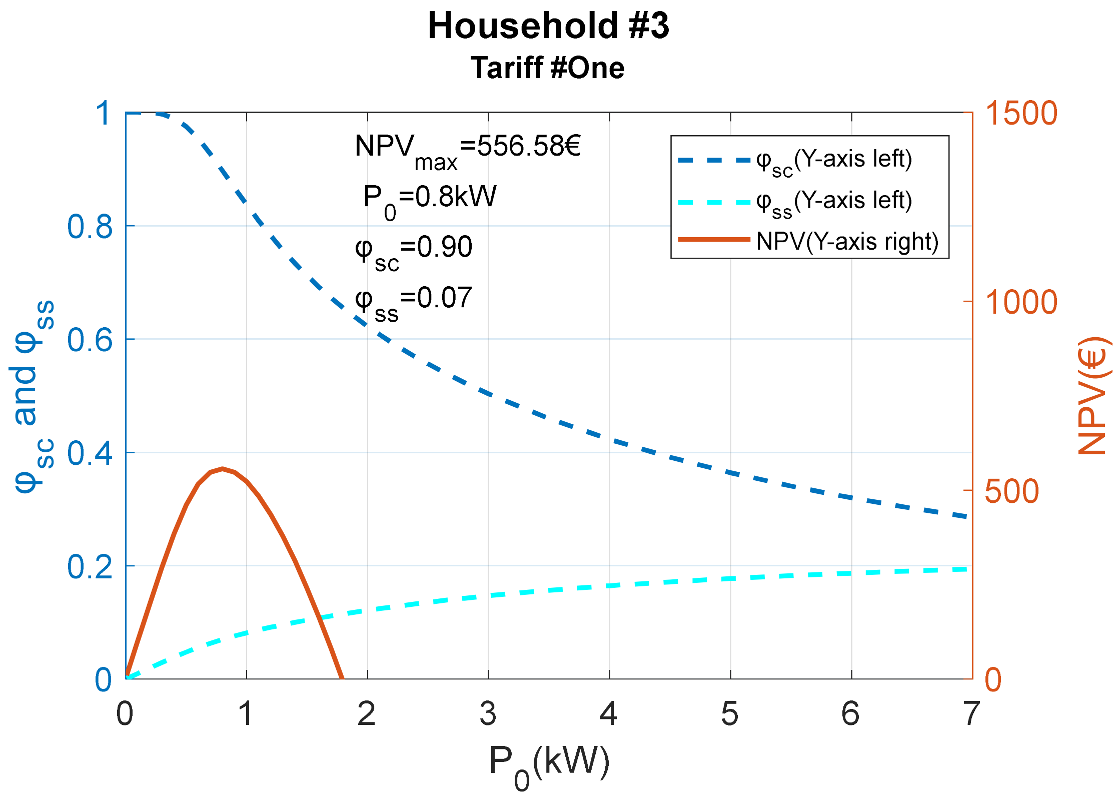
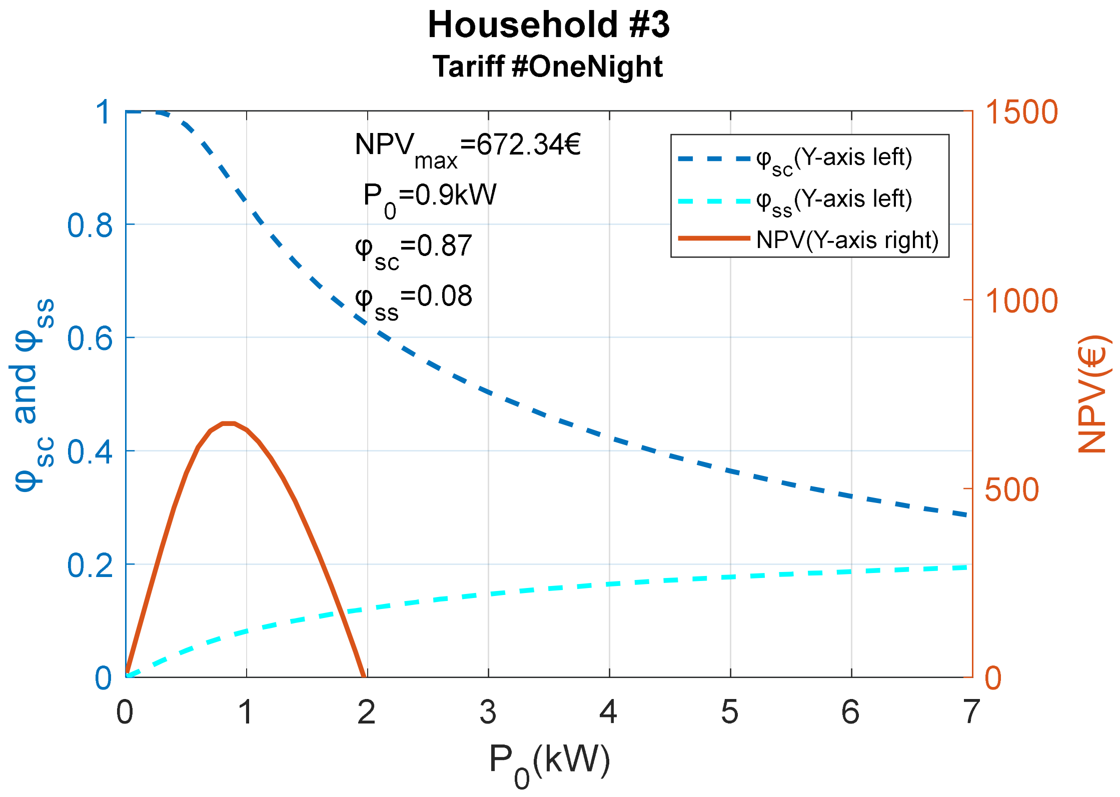


Figure 8. Household#2. NPV considering several tariffs: One (top), One night (middle), Tempo (bottom). Scenario A. Annual φ_{sc} and φ_{ss} curves have also been plotted.


Household #3
Tariff #One
NPV$_{max}$=556.58€
P$_0$=0.8kW
φ$_{sc}$=0.90
φ$_{ss}$=0.07
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
0
0.2
0.4
0.6
0.8
1
NPV(€)
0
500
1000
1500
0
1
2
3
4
5
6
7
P$_0$(kW)


Household #3
Tariff #OneNight
NPV$_{max}$=672.34€
P$_0$=0.9kW
φ$_{sc}$=0.87
φ$_{ss}$=0.08
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
0
0.2
0.4
0.6
0.8
1
NPV(€)
0
500
1000
1500
0
1
2
3
4
5
6
7
P$_0$(kW)

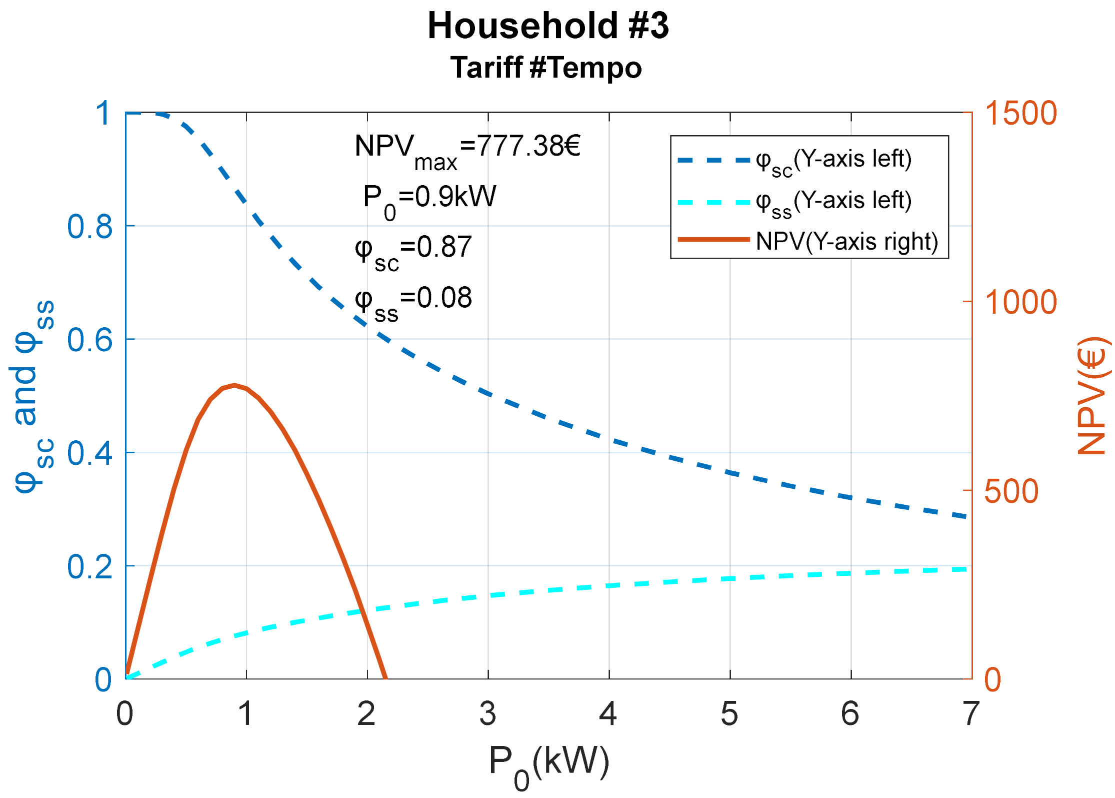


Figure 9. Household#3. NPV considering several tariffs: One (top), One night (middle), Tempo (buttom). Scenario A. Annual φ_{sc} and φ_{ss} curves have also been plotted.

In Table 5 the maxima NPV values for the different tariffs are considered together with their corresponding PV array power and self-sufficiency and self-consumption indices for the three households analysed. As mentioned, regarding profitability, an important parameter to consider when sizing the photovoltaic generator is the tariff. For households#3 and #2 the estimated array power depends on the chosen tariff. Whereas, for household#3 the size of the generator is 0.3 kW$_p$ regardless of the considered tariff. In addition, for this household, the self-sufficient index is the lowest one of the three analyzed households. However, it should be highlighted that household#3 shows the highest economic return due to its high annual consumption (14298 kWh/year) much higher than the those corresponding to household#1 (2683 kWh/year) and household#2 (4329 kWh/year). For NPV maxima, the self-consumption index variability, regardless the household and the tariff, is very low, ranging between 83% to 90%. However, self-sufficiency variability is higher as this index ranges between 7 and 19.5%. These low values are due to the low estimated array powers (0.3 to 0.9 kW$_p$).

Table 5. Summary of results for scenario A.

Tariff		Household#1	Household#2	Household#3
One	P (kW)	0,3	0,6	0,8

	NPV (€)	157,7	425,7	556,6
	φ_{sc} (%)	83,8	90,2	89,7
	φ_{ss} (%)	13,1	17,4	7,0
One night	P (kW)	0,3	0,7	0,9
	NPV (€)	199,5	522,0	672,3
	φ_{sc} (%)	83,8	86,5	86,7
	φ_{ss} (%)	13,1	19,5	7,6
Tempo	P (kW)	0,3	0,7	0,9
	NPV(€)	233,1	603,5	777,4
	φ_{sc} (%)	83,8	86,5	86,7
	φ_{ss} (%)	13,1	19,5	7,6

4.2 Scenario B

As aforementioned, scenario B corresponds to self-consumption where the surplus electricity may be injected into the grid and is remunerated according to the wholesale market prices. It must be highlighted that, in this case, all the array power generated is used as it is either self-consumed or injected into the grid and remunerated. However, regarding self-consumption and self-sufficiency indices, only instantaneous overlapping between the load consumption and the photovoltaic power generated will be considered as indicated in Equations (1) and (2). In figure 10, 11 and 12, and for the three dwellings, the annual self-consumption and self-sufficiency indices together with the net present value are plotted against the nominal power of the PV system. In this scenario, self-consumption electricity is remunerated according to the same tariffs as scenario A, while surplus electricity is remunerated to 45.94375 €/MWh.

As can be observed in figure 10 which corresponds to household#1, the maximum profitability is reached for greater photovoltaic array powers than the those obtained in scenario A. In this sense, the higher electricity produced by the PV array together with the remuneration of the electricity injected into the grid provide higher NPV values: 208, 260 and 305 € for the One, OneNight and Tempo tariffs, respectively. In Table 6 the percentage increase when comparing different tariffs is shown. As can be seen, the results are very similar to those obtained in scenario A. However, self-sufficiency indices at NPV maxima for scenario B are greater than those for scenario A, reaching 18%. Whereas, self-consumption indices are considerably diminished ranging between 69-76%. This is due to the utilization of the surplus generated electricity injected into the grid which provides more profitability at a higher array power. As can be observed in the self-consumption and self-sufficiency curves, the higher the power, the lower self-consumption index and the higher self-sufficiency index. Furthermore, for this tariff, the upper limit of the array power which provides profitability (1.3 kWp) is almost twice as high as the one that provides NPV maximum for scenario A. Similar results are obtained if we analyze figures 11 (household # 2) and 12 (household # 3). The high self-sufficiency indices obtained for household # 2 must be highlighted. Not only a NPV of 773 € may be achieved for the TempoTariff, but also a self-sufficiency index of around 26%. More than a third of the load consumption is instantly achieved thanks to the PV self-consumption system at the array power given by the NPV maximum. Furthermore, in this case, the profitability window considering the TempoTariff lies between array power above zero and below 3 kWp, providing in this case, a self-sufficiency index up to 45%.

Table 6. Percentage increase in NPV maxima when comparing different Tariffs. Scenario B.

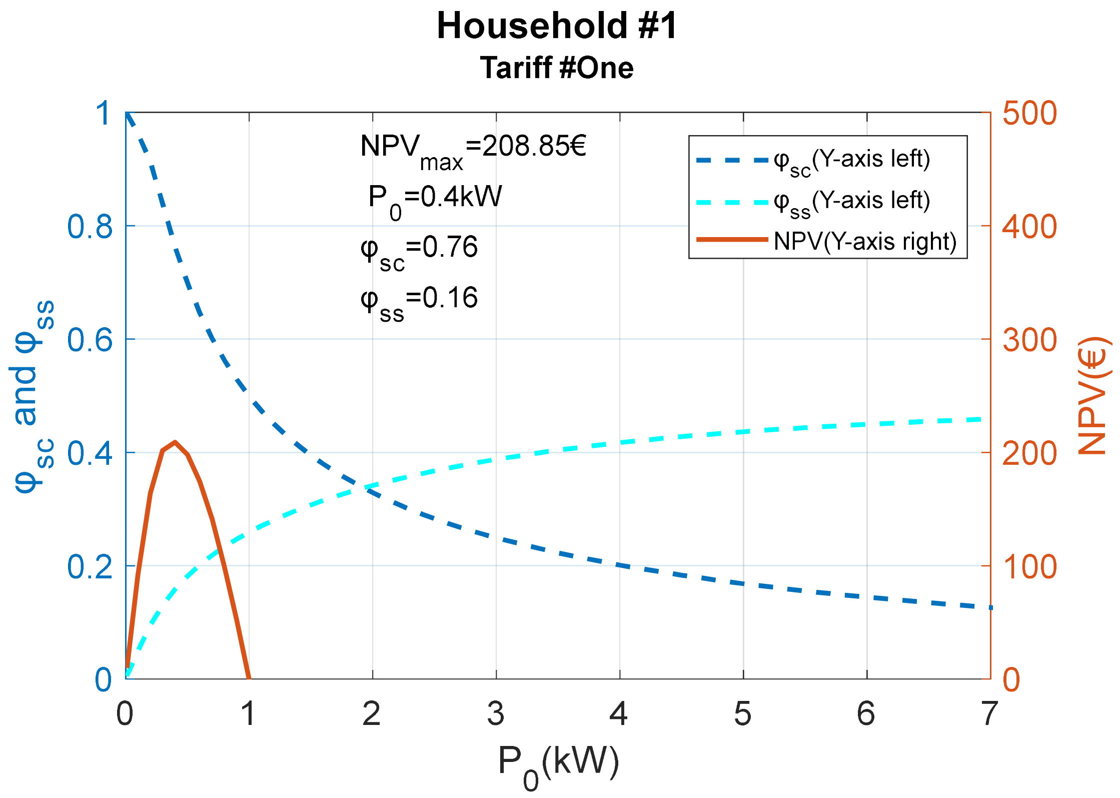
Tariff	Household#1	Household#2	Household#3
One night/One	1,25	1,23	1,21
Tempo/One	1,46	1,44	1,40
Tempo/ One night	1,17	1,17	1,16

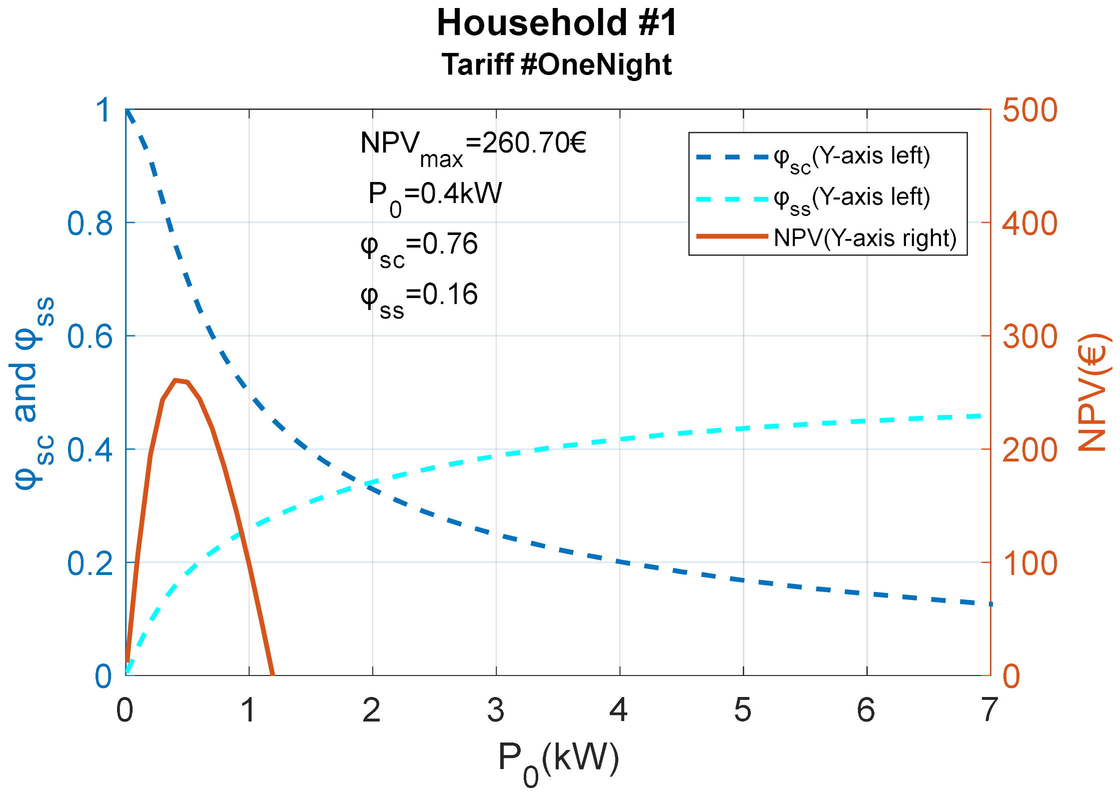
Table 7 shows the values of the PV generator power, NPV, φ_{sc} and φ_{ss} for the three houses studied. If the results of scenario B are analyzed, tariffs are still a relevant parameter for the sizing of the PV generator according to economic profitability criteria. For the three dwellings, the array power which provides the highest NPV varies for flat tariff and some type of tariff with time of use. It can be also observed, as in scenario A, that Household#3 has the lowest self-sufficient index of the households studied due to the aforementioned decoupling of its consumption profile with respect to the maximum photovoltaic generation hours. As can be seen in table 7, the PV power increases along with the load request as the selling energy price is much smaller than the buying one which increases the profitability of this type of system.

Table 7. Summary of results for scenario B.

Tariff		Household#1	Household#2	Household#3
One	P (kW)	0,4	1,0	1,1
	NPV (€)	208,9	537,8	674,7
	φ_{sc} (%)	76,3	77,1	80,9
	φ_{ss} (%)	15,8	24,8	8,7
One night	P (kW)	0,4	1,1	1,2
	NPV (€)	260,7	662,4	817,4
	φ_{sc} (%)	76,3	74,4	78,2
	φ_{ss} (%)	15,8	26,3	9,1
Tempo	P (kW)	0,5	1,1	1,3
	NPV(€)	305,1	772,9	946,9
	φ_{sc} (%)	69,9	74,4	75,7
	φ_{ss} (%)	18,1	26,3	9,6

In table 8 a comparative of NPV maxima between the two considered scenarios is shown. As can be seen, there may be an increase of profitability ranging between 21-33% if different scenarios and tariffs are considered.


Household #1
Tariff #One
NPV$_{max}$=208.85€
P$_0$=0.4kW
φ$_{sc}$=0.76
φ$_{ss}$=0.16
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
NPV(€)
P$_0$(kW)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
0
1
2
3
4
5
6
7


Household #1
Tariff #OneNight
NPV$_{max}$=260.70€
P$_0$=0.4kW
φ$_{sc}$=0.76
φ$_{ss}$=0.16
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
NPV(€)
P$_0$(kW)
0
0.2
0.4
0.6
0.8
1
0
100
200
300
400
500
0
1
2
3
4
5
6
7

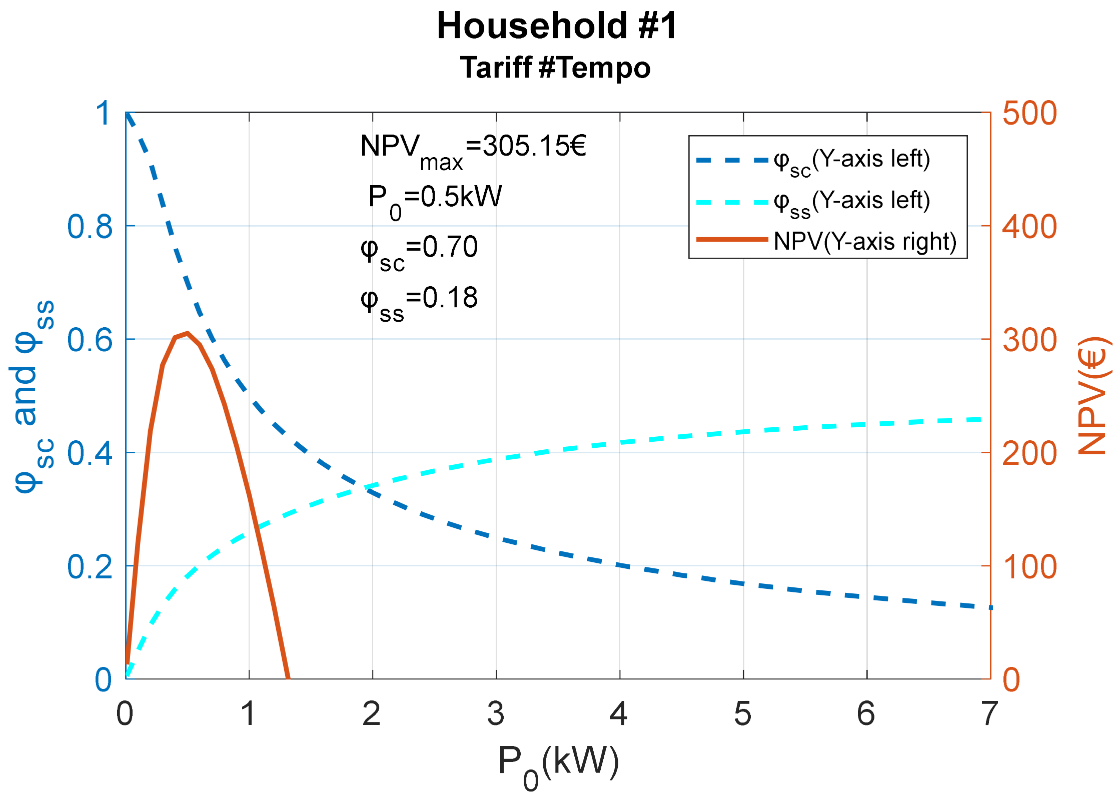
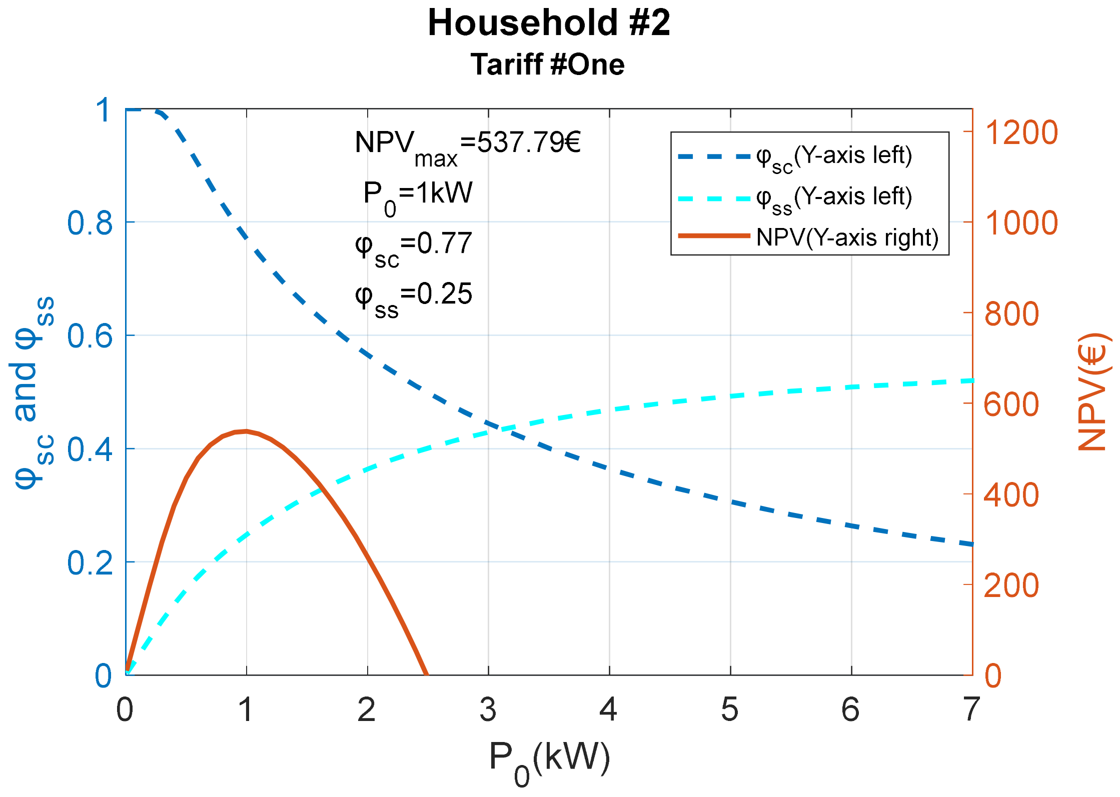


Figure 10. Household#1. NPV considering several tariffs: One (top), One night (middle), Tempo (bottom). Scenario B. Annual φ_{sc} and φ_{ss} curves have also been plotted.



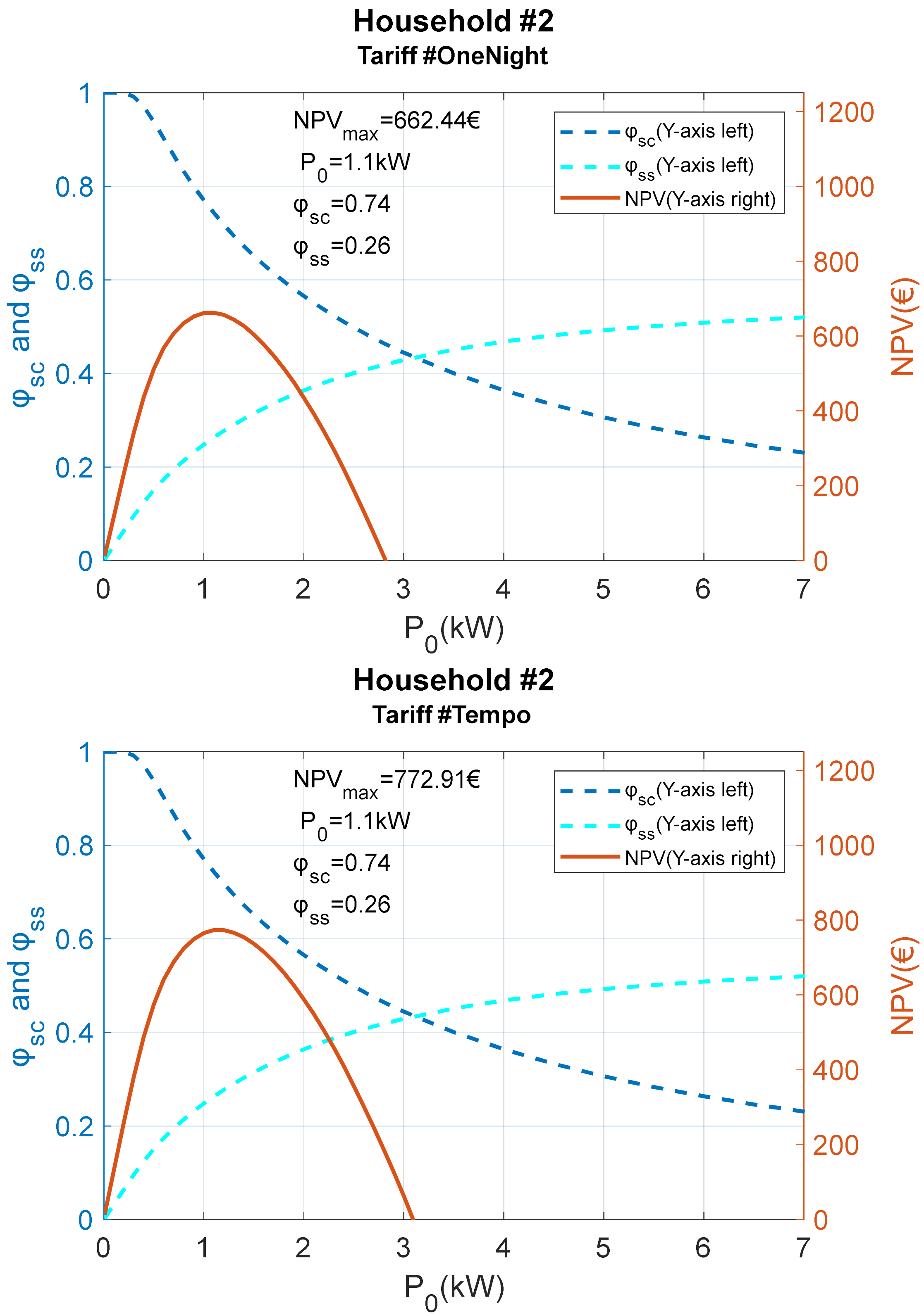
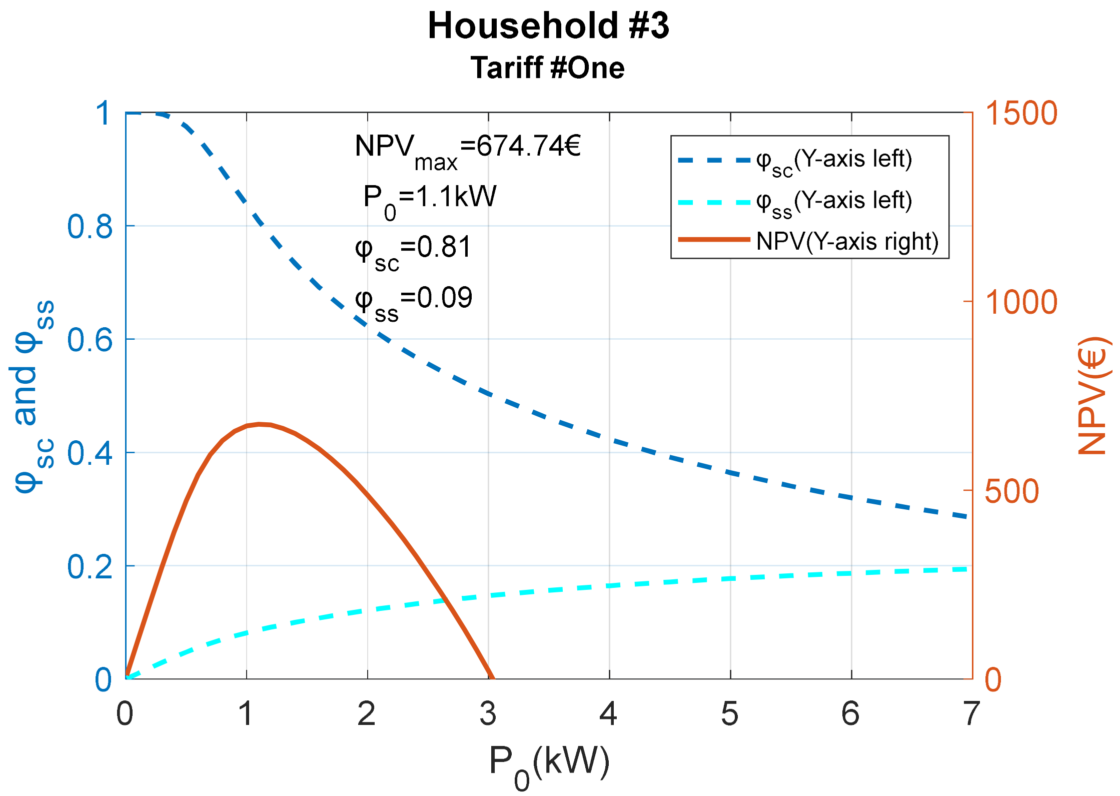
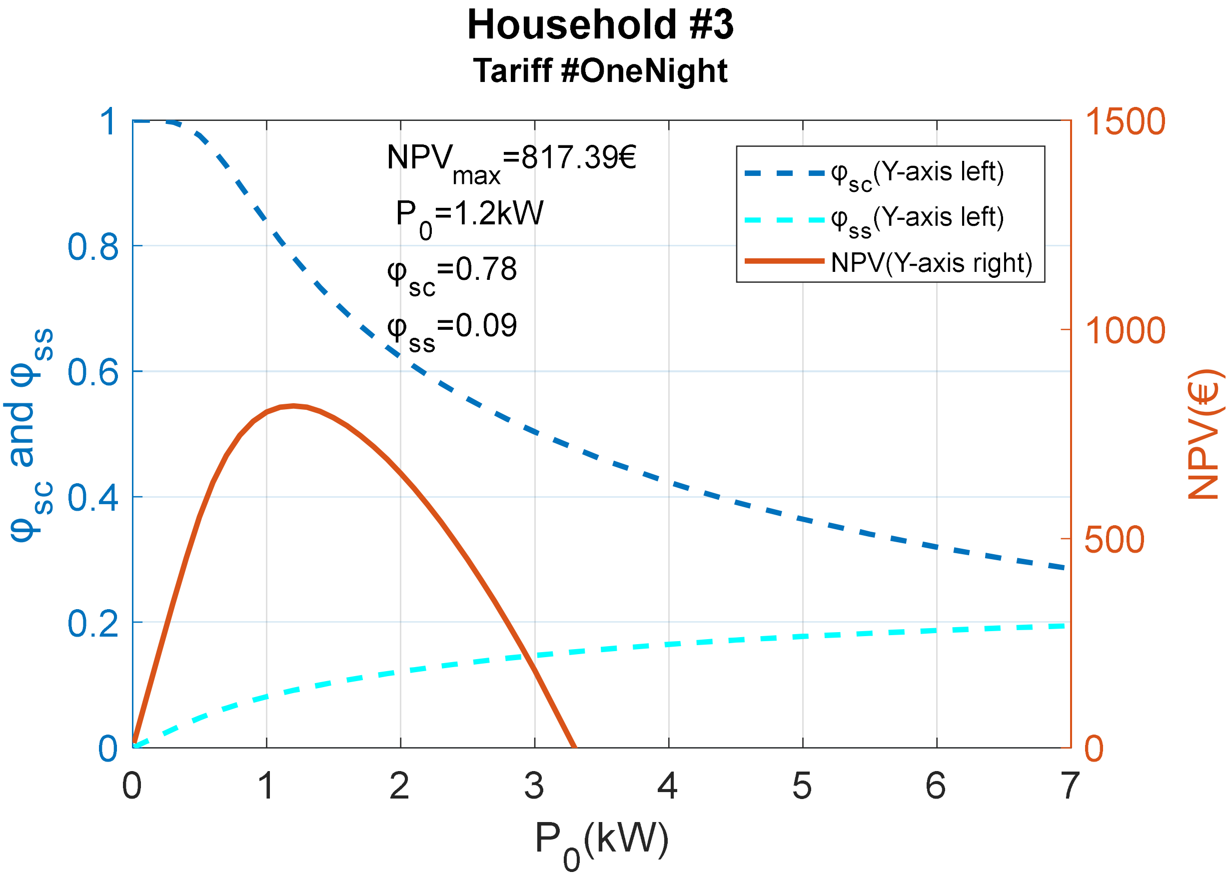


Figure 11. Household#2. NPV considering for several tariffs: One (top), One night (middle), Tempo (bottom). Scenario B. Annual φ_{sc} and φ_{ss} curves have also been plotted.


Household #3
Tariff #One
NPV$_{max}$=674.74€
P$_0$=1.1kW
φ$_{sc}$=0.81
φ$_{ss}$=0.09
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
0
0.2
0.4
0.6
0.8
1
NPV(€)
0
500
1000
1500
0
1
2
3
4
5
6
7
P$_0$(kW)


Household #3
Tariff #OneNight
NPV$_{max}$=817.39€
P$_0$=1.2kW
φ$_{sc}$=0.78
φ$_{ss}$=0.09
φ$_{sc}$(Y-axis left)
φ$_{ss}$(Y-axis left)
NPV(Y-axis right)
φ$_{sc}$ and φ$_{ss}$
0
0.2
0.4
0.6
0.8
1
NPV(€)
0
500
1000
1500
0
1
2
3
4
5
6
7
P$_0$(kW)

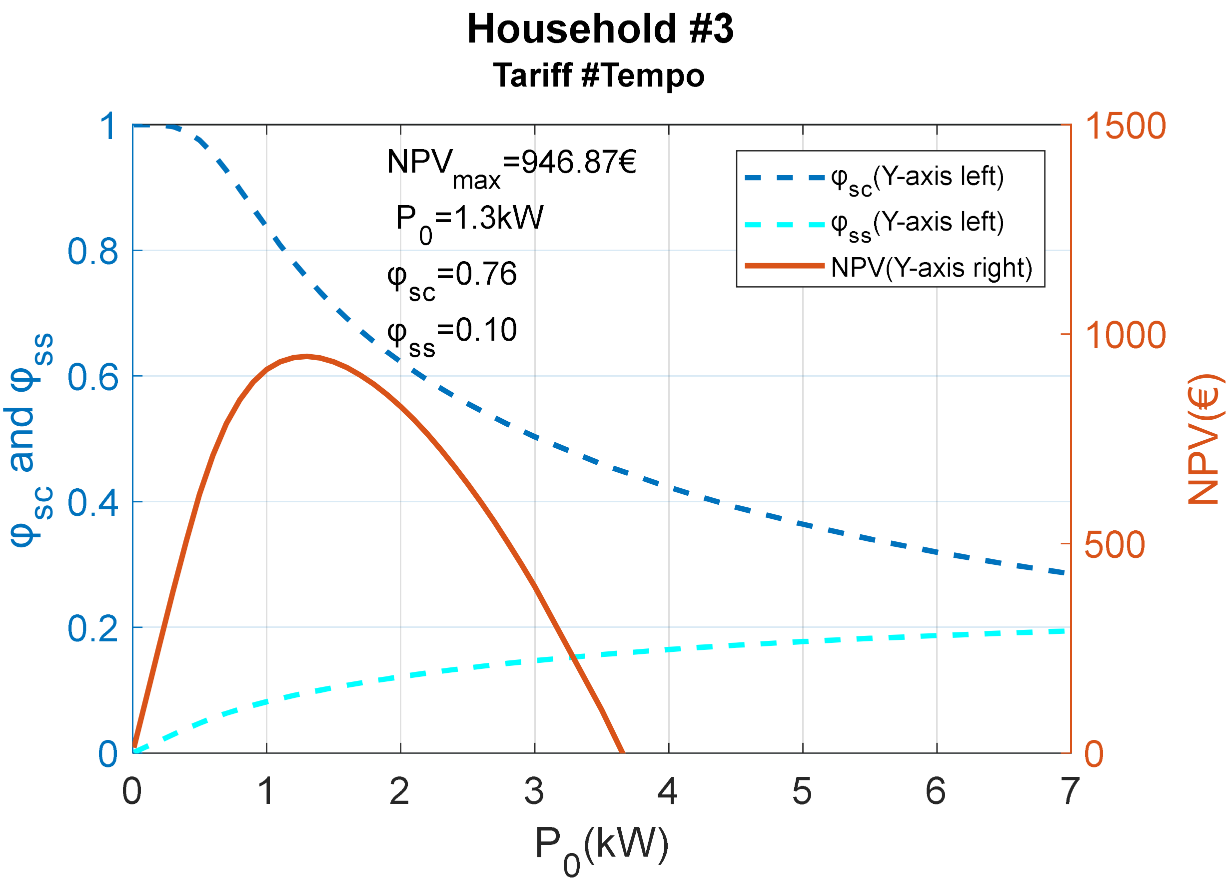


Figure 12. Household#3. NPV considering several tariffs: One (top), One night (middle), Tempo (bottom). Scenario B. Annual φ_{sc} and φ_{ss} curves have also been plotted.

Table 8. NPV maxima. Percentage increase scenario A vs scenario B for different tariffs.

Tariff	Household#1	Household#2	Household#3
One	1,32	1,26	1,21
One night	1,31	1,27	1,22
Tempo	1,31	1,28	1,22

As it previously mentioned in section 1, the optimal PV power may vary significantly and the described cases in the literature depend on many different factors, e.g. climate, consumption profiles, tariffs, etc. In [23] the techno-economic optimization model estimates a peak power for the PV system ranging from 0.5 to 3.9 kWp and an NPV ranging from 700 to 1650 €, which exhibits a high variance between the households studied. The average self-consumption and the self-sufficiency indices are around 55% and 21%, respectively. In [22] an analytical procedure to evaluate the overall cost of the integrated solution of the storage and PV systems has been proposed. It also considers some classical economic indexes in order to compare different solutions from an economic point of view. The results show an array power of 1, 2 and 3 kWp and an NPV of 290, 630 and 910 $, for different scenarios such as low, medium and high load, respectively.

In table 9 and 10 the percentages changes on self-consumption and self-sufficiency indices are shown, respectively, when the scenario A and B are compared. As can be seen, there is a decrease ranging 9-17% in self-consumption index while the self-sufficiency index increase between 21-42%. This is due to the displacement to the right of the NPV curve when scenario B is considered instead of A, see figures 10 and 12.

Table 9. Percentage change of self-consumption index at NPV maximum. Scenario B vs Scenario A.

Tariff	Household#1	Household#2	Household#3
One	0,91	0,85	0,90
One night	0,91	0,86	0,90
Tempo	0,83	0,86	0,87

Table 10. Percentage change of self-sufficiency index at NPV maximum. Scenario B vs scenario A.

Tariff	Household#1	Household#2	Household#3
One	1.21	1.42	1.24
One night	1,21	1,35	1,20
Tempo	1,39	1,35	1,26

It must be highlighted that the results given in this section do not intend to provide a broad view of the profitability of self-consumption systems in Spain but to illustrate the method developed here. Nevertheless, the analysis is currently being expanded with more dwellings in order to provide a more representative study. Moreover, the method may be further developed if different issues such as inclination, orientation of the PV generator and energy storage are considered.

5. Sensitivity analysis

In this section, and taking into account household#2, a sensitivity analysis of the main variables will be conducted in order to provide a comprehensive view of their impact and identify the most influential parameters when estimating NPV. The parameters shown in Table 11 have been considered with their corresponding values which corresponds to the optimal configuration. The changes in the individual parameters range between -40 to 40%.

Table 11. Values of technical and economic parameters assumed for the base case hosehold#2.

Parameters	Base case values	Units
P_0	0.6	kW_p
PR	75	%
PVc	1573	€/kW_p
r_d	0.5	%
p_{con}	0.1597 (tariff One)	€/ kWh
p_{grid}	0	€/ kWh
$rp_{con}; rp_{grid}$	1.8	%
PV_{AOM}	1.5^1	%
r_{OM}	1.8	%
T	0	%
S_{con}	0	%
d	7.2^2	%
g	1.8	%
i_l	5.73	%
N_l	20	years
d_s	9.46	%
N	25	years

[1] This value should be considered as the percentage of PV_C spent on operation and maintenance tasks on an annual basis. [2] In this paper d is assumed equal to WACC.

Accordingly, the influence that deviations from the parameters listed in Table 11 have on NPV analyzed below. Figure 13 shows the impact of deviations from the values of these factors as provided to define the base case. The variations range from -40% to +40% of the value of the factor assumed for the base case.

As shown in Figure 13, percentage changes in self-consumed electricity price exert the biggest impact on NPV. Moreover, the system cost and WACC affects NPV in a very noticeable way. The influence of the different parameters on NPV for a given location and annual load profile may be ordered from the highest impact to the lowest: self-consumed electricity price; system cost; weighted average cost of capital; life cycle and operation and maintenance costs. As can be seen in figure 13, a decrease in electricity price of -

40% (regarding the base case hosehold # 2) provides a decrease of 142% for the NPV, while an increase of 40% imposes a increase of 143% for the NPV. The effect of the WACC on the NPV must be also highlighted: a decrease of the WACC of 40% provide an increase of 99% for the NPV, while an increase of 40% imposes a decrease of 70% For the NPV.

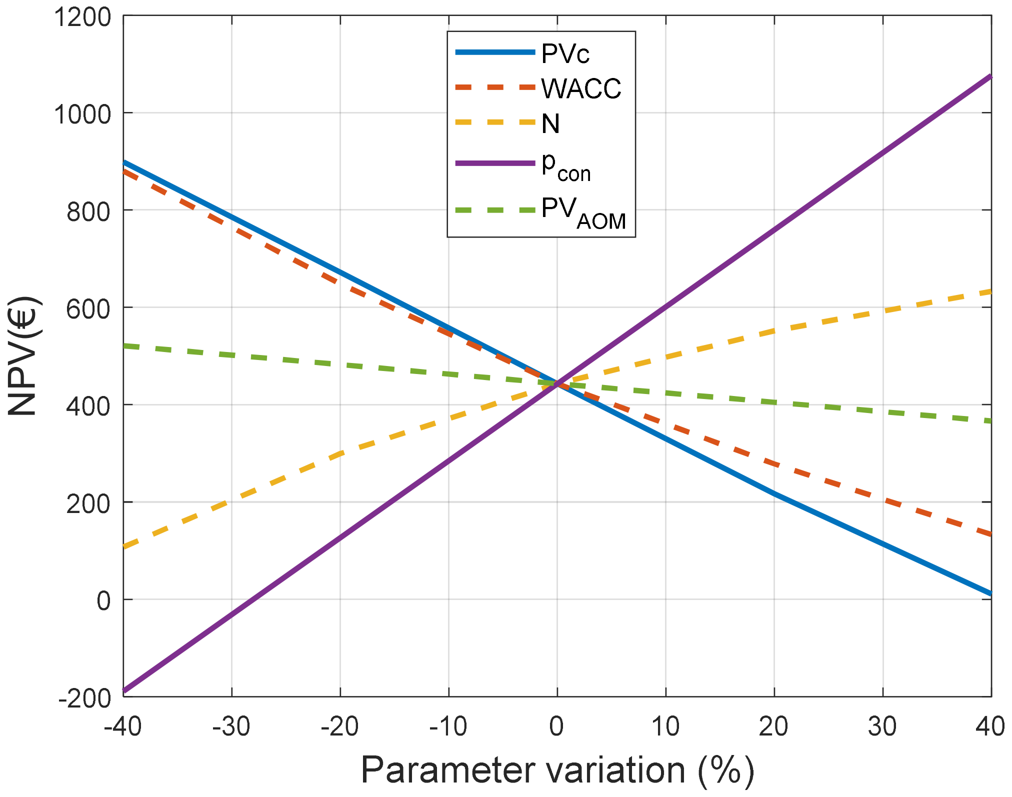


Figure 13. NPV as a function of the percentage of the value of some factors that define the household#2 in scenario A.

6. Effect of the recording interval on the estimation of NPV

The daily load consumption and generation data constitute fundamental information for the performance analysis of self-consumption systems. However, it must be highlighted that the load consumption provided from smart meters by most electricity distribution companies is generally between 15 minutes and 1 hour and it depends on the type of customers [57]. In a household there may be high power fluctuations which may last from a few seconds to a few minutes [58]. If averaged, these fluctuations may be flattened or they may even disappear if the recording interval is considerably larger. On the other hand, low demand power may increase when averaging. Regarding the photovoltaic generation data, a recording interval of 15 minutes may be achieved [59]. In the case of the generation profile, and if there are no moving clouds, averaging has a very small and negligible effect on the distribution of power output levels. In this sense, averaging has a more visible impact on the load profile. Averaging over longer periods has a significant effect on statistics (except the mean), in particular reducing maximum and high percentile values, but increasing the median [18]. In this way, sub-hourly averages should be considered if load profiles are to be characterized. Using recording times of 1 or 2 min is necessary to define the details of the load profiles. As is expected, the sampling period, when averages are considered, has no effect on E_{PVgen} and E_L. However, E_{PVcon} is overestimated when considering larger sample periods which produces the same effect on both indices: the greater the recording period (the lower time resolution), the higher overestimation on both indices [60]. In [19] six recording intervals: 1 h, 30 min, 15 min, 10 min, 5 min and 1 min were considered with synthetic domestic electricity data and real irradiation data during a few days to analyze the influence of time-resolution in the aforementioned indices. The authors found overestimation of both indices, from 0.2% with a 5-min data resolution to 69% with a 1-h data resolution taking into account daily reporting periods. As can be seen in Figure 14, this overestimation can reach high values as reported in [19]. However, in this case, the error provided in the self-consumption and sufficiency indices were obtained considering daily reporting periods. There is no use using such a short reporting period as has been previously indicated in [21]. In this sense, overestimation by 8% of annual self-consumption parameter has been found when the electricity load profile is compared to an averaging period of 30 min or more and 30 s in a household with a 4.9 MWh/year of electrical consumption and a PV system with a nominal power of 5kWp [60]. In a 2.6 kWp PV system, hourly and minute data of PV power and load consumption were used to estimate annual self-consumption index. It was found that hourly data overestimate the index around by 10% [61]. Nevertheless, it must be emphasized that deeper analysis should be made to study if time resolution has a considerable impact on the energy parameters mentioned above, and, therefore, on any energy analysis developed from the latter and the self-consumption and self-sufficiency indices, including economic analysis, specially when monthly or annual reporting periods should be considered. As it is necessary to know accurately both the solar resources and the load consumption and in order to provide a proper analysis [62–64], in this paper load consumption and generation data have been obtained considering a recording interval of one minute.

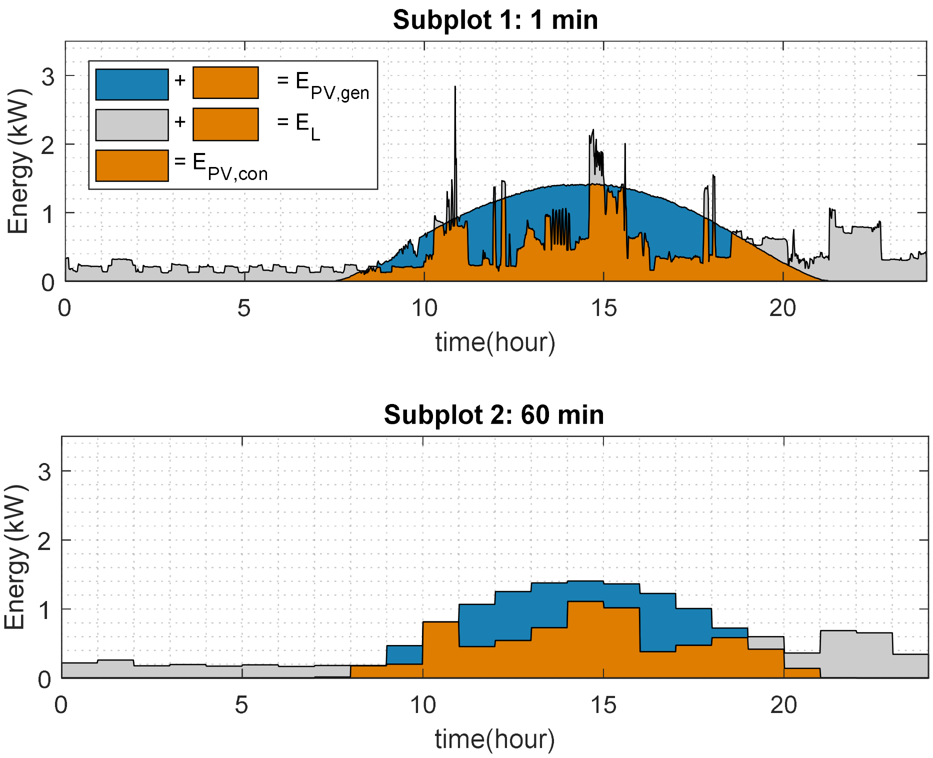


Figure 14. Load consumption and photovoltaic generation matching between 1-min and 1-hour averaging profiles. A daily reporting period has been considered. Data corresponding to 21 March 2017.

In the following paragraphs, it will be shown how the recording interval can affect the economic profitability criteria together with the associated array power and the self-sufficiency and self-consumption indices.

Different recording intervals, 1 minute, 15 minutes and 60 minutes, have been used in order to estimate NPV, P_0, φ_{sc} and φ_{ss} using the irradiance and load consumption data in a photovoltaic self-consumption system in which array power range between 0.01 to 7 kWp as described in figure 5. In order to evaluate the influence of recording interval, percentage error (PE) is calculated, where one minute has been used as a reference value [65]. PE is the error obtained in the matching results when recording intervals higher than one minute:

$$PE_{\tau_r} = \frac{X_{\tau_r} - X_{1\,minute}}{X_{1\,minute}}$$

where X is the analysed parameter.

Table 12 shows the percentage error in the aforementioned parameters: NPV, P_0, φ_{sc} and φ_{ss} at NPV maximum considering 3 different recording intervals: 1, 15 and 60 min. As can be observed, higher recording intervals than one minute may produce an over-estimation of NPV, P_0, and φ_{ss}. For the case of NPV, and for the three households studied, error may vary from 8% to 33% for 15 and 60 minutes, respectively. If P_0 is considered, the percentage error for a 15 minutes recording interval is lower than 17%. However, when the coarser recording interval is used (60 minutes), the PE may even reach 50%. For the self-sufficiency index PE may reach 15% and 45% for 15 and 60 minutes, respectively. Whereas, the influence of recording interval on φ_{sc} has been smoothed as the overestimation of $E_{PV,con}$ compensates the overestimation of $E_{PVgen,}$. Therefore, the results of PEs are between -3% and 4.5% in all cases. The results obtained here show that the effect of the recording interval on the aforementioned parameters is quite relevant and should be taken into account, especially for NPV and the associated array power.

Table 12. Percentage errors with different recording intervals: 1 vs 15 minutes, 1 vs 60 minutes.

Household		1 min	15 min	60 min	PE (%) 1min vs 15 min	PE (%) 1min vs 60 min
Household#1	NPV (€)	157,70	171,27	190,54	8,61	20,83
	P_0 (kW)	0,30	0,30	0,30	0,00	0,00
	φ_{sc} (%)	0,84	0,85	0,88	1,87	4,52
	φ_{ss} (%)	0,13	0,13	0,14	1,87	4,52
Household#2	NPV (€)	425,73	474,39	568,67	11,43	33,58
	P_0 (kW)	0,60	0,70	0,90	16,67	50,00
	φ_{sc} (%)	0,90	0,89	0,88	-1,22	-2,98
	φ_{ss} (%)	0,17	0,20	0,25	15,24	45,53
Household#3	NPV (€)	556,58	601,11	681,33	8,00	22,41
	P_0 (kW)	0,80	0,90	1,00	12,50	25,00
	φ_{sc} (%)	0,90	0,89	0,89	-1,07	-0,56

φ_{ss} (%)	0,07	0,08	0,09	11,29	24,31

7. Conclusions

In this paper a new and interesting techno-economic model based on economic profitability for sizing the photovoltaic generator of a self-consumption system without storage has been developed. It optimizes the net present value for PV electricity generation maximizing the absolute returns for the owners of a PV self-consumption system. The method developed here may become an interesting and intuitive tool for investors and engineers interested in self-consumption systems as it not only comprises NPV and the self-sufficiency and self-consumption indices for a wide range of array powers suitable for residential self-consumption systems but also takes into account economic parameters that have not been considered previously in the literature: taxes, depreciation and the cost of financing. Furthermore, electricity retail tariff structures and two scenarios have been considered: Scenario A where the generated electricity surplus is not remunerated and Scenario B where the generated surplus electricity is injected into the grid and the PV system owner receives compensation from the grid operator depending on the wholesale market prices.

The recording interval for load consumption and irradiance data is crucial when estimating determined economic parameters that are estimated through the self-consumed energy, E_{PVcon}: higher recording intervals may provide an overestimation of E_{PVcon}. As has been shown, errors when estimating self-consumed energy and self-sufficiency index from hourly data may reach 2% and 45% when considering annual reporting periods. This error may extend to the calculation of economic parameters such as present worth of the cash inflows and, therefore, NPV and may provide an erroneous economic analysis which may provide uncertainty and may lead to a loss of confidence in this type of technology. In the different cases studied in this manuscript this error may even reach 33% for a recording interval of one hour. In order to give a proper analysis, load consumption, PV electricity generation, electricity price and irradiance data with a temporal resolution of 1 minute have been considered in this paper.

The method here explained has been applied for the case of Spain, but it can be easily applied to other countries considering their corresponding techno-economic parameters. Annual φ_{sc} and φ_{ss} and net present value are plotted against array power for the three analysed dwellings which have been used to illustrate the method. The Endesa electric utility tariffs known as: One, One night and Tempo have been considered.

As has been shown, there is only one maximum value for a given array power which provides the maximum economic profitability. Generally, for each of the houses, higher NPV are achieved when time of use in the price of electricity is considered instead of a flat rate. As has been shown, NPV can be increased up to 48% regarding the chosen tariff. Moreover, the profitability window (i.e. the array power interval where NPV is higher than zero) is enlarged and greater array powers can be considered which provides higher self-sufficiency indices. In this sense, chosen tariff is a key parameter when optimizing NPV. The NPV maximum depends on each household and on its matching capability between the load consumption and generation profiles.

Regarding the scenario, NPV and its associated array power may range between 157-777 € and 0.3 and 0.9 kWp, respectively for a scenario where the non self-consumed energy is wasted (scenario A). Meanwhile, for scenario B where the non self-consumed energy which is injected into the grid is remunerated, NPV and associated array powers may range between 208-946 € and 0.4-1.3 kWp, respectively. It must be highlighted that, in this case, not only a higher NPV is obtained but the array power profitability window may double. Furthermore, the self-sufficiency indices are considerably increased, and they may reach 40%. Although, as has been shown, self-consumption systems may be profitable without remunerating non self-consumed energy, country policies should encourage this remuneration in order to promote a substantial increase in the production of photovoltaic electric energy in urban areas.

A sensitivity analysis has been also carried out in order to provide a comprehensive view of the impact of different parameters on NPV. The most influential parameters for a given location and annual load profile ordered from the highest to the lowest impact are: self-consumed electricity price; system cost; weighted average cost of capital; life cycle and operation and maintenance costs.

Finally, the method developed here can be used by future owners or investors interested in self-consumption photovoltaic systems, who demand information on the economic profitability of their investment. Also, government officials responsible for formulating policies on these systems can rely on this work to determine the economic framework (type of self-consumption and tariffs), which make investment in these systems attractive.

As this topic may be considered crucial due to the transition of most buildings from being grid-dependent to being energy self-sufficient, further work should be developed in order to extend the aforementioned method to self-consumed systems with storage taking into account batteries. 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. A deeper analysis should be also conducted to study the influence of the recording interval on determined economic parameterss (i.e: internal rate of return, discounted payback time).

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