A New tool to Analyse Photovoltaic Self-Consumption Systems with Batteries.

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Abstract: *Most of the studies that can be found in the literature for analysing self-consumption systems with storage focus on global self-consumption and self-sufficiency indices and it may be very difficult to define the role of the array power and battery. In this sense, a new approach to analysing this type of systems is provided where direct and battery self-sufficiency and self-consumption indices are defined. The latter represent the direct photovoltaic self-consumed energy and the one provided by the battery. New direct and battery ZEB points are also presented. Furthermore, this type of system is generally analysed using complex 3D plots. Therefore, a new and intuitive 2D contour tool is provided: the iso self-consumption curves. The new approach has been applied to three households located in Spain. Results show that it may be reached a global self-sufficiency of 50% considering array powers and rated capacities below 3.5 kWp and 1 kWh, respectively, where direct and battery self-sufficiency indices may reach 40% and 10%, respectively. This new method together with the graphical tool may help not only to analyse this type of system but to properly size the array power and the rated capacity from either an energetic or profitability approach.*

Keywords: Photovoltaic, self-consumption, batteries, analysis; iso self-consumption curves.

Nomenclature: *List of symbols*

E_L	Load consumption (kWh)
$E_{PV,con}$	Photovoltaic energy self-consumed (kWh)
$E_{PV,generated}$	Photovoltaic energy generated (kWh)
$E_{PV,direct}$	Direct Photovoltaic energy self-consumed (kWh)
E_{TPac}	Photovoltaic energy given to the bidirectional inverter to charge the battery (kWh)
E_{FPac}	Energy given by the bidirectional inverter from the batteries to the loads (kWh)
$E_{PV\text{-}BAT}$	Energy given by the array and the battery to the loads (kWh)
isoSC	Iso self-consumption
isoSS	Iso Self-sufficiency
ZEB_{direct} point	Direct Zero Energy Building point
$ZEB_{battery}$ point	Battery Zero Energy Building point
τ	Reporting period
τ_r	Recording interval
φ_{sc}	Global self-consumption index
φ_{ss}	Global self-sufficiency index
$\varphi_{sc,direct}$	Direct self-consumption index
$\varphi_{ss,direct}$	Direct self-sufficiency index
$\varphi_{sc,bat}$	Battery self-consumption index
$\varphi_{ss,bat}$	Battery self-sufficiency index
η_{BDI}	Bidirectional inverter efficiency
η_{BAT}	charge, storage and discharge efficiency

Acronyms

BDI	Bidirectional inverter
MPPT	Maximum Power Point Tracker
PV	Photovoltaics
PR	Performance Ratio
SC	Self-consumption
SS	Self-sufficiency
ZEB	Nearly zero energy building

1. Introduction

Climate change is a fact and it is necessary that CO_2 emissions should be considerably reduced to mitigate the effect of global warming. In the European Union, commercial and residential consumption represents 40% of total energy consumption and 55% of total electricity consumption [1,2]. Policies that encourage increasing increase energy efficiency as well as the use of renewable energies in order to promote nearly Zero Energy Buildings (nZEBs) should be improved. In this way, a European Union directive requires that all buildings should fall into this category by 2021[3]. In this type of building, photovoltaics solar energy together with thermal solar energy can play an important role.

Photovoltaic solar energy, due to its maturity and its modularity, is a real option to address residential consumption. It should also be noted that the cost of residential photovoltaic systems has been considerably reduced by 48% from 2007 to 2018 [4]. Moreover, it has been shown not only the cost-competitiveness but also the profitability of this type of system has been demosntrated [5,6].

As there is not a complete matching between the generation and consumption profiles (i.e. there is energy consumption outside the generation profile), net zero energy buildings (ZEB) cannot be managed only considering direct photovoltaic self-consumption (i.e. without batteries). However, the matching between the aforementioned profiles in this type of system can be improved through load shifting or Demand side management (DSM) and the use of energy storage systems [7]. In the literature, it is possible to find different control strategies for renewable energy integrated in power grid in order to maximize power delivery capability and manage the electrical grid and load [8,9]. The use of batteries may increase the self-consumption rates in a range of 13-24% for photovoltaic self-consumption systems with batteries between 0.5-1.0 kWh / kWp [10]. Besides, the use of batteries has a prominent role in peak shaving potential [11].

On certain occasions, the injection of excess energy into the network is allowed considering net metering (US) and feed-in tariff policies (Europe, Australia, Asia) providing an economic alternative to this surplus energy. However, grid export rates are decreasing considerably in the PV markets [12,13]. So, it may be the case that the remuneration received is clearly lower than the price of the energy consumed from the grid. Therefore, energy storage is presented as an attractive solution to take advantage of energy that is not directly self-consumed and which may later be used when the generated energy is lower than the consumed energy. Likewise, the increase in self-sufficiency and self-consumption rates while not only prevent energy from being lost or wasted but also limit the delivery of photovoltaic energy to the grid, reducing its stress [14,15].

The topology of a self-consumption photovoltaic system with storage system may have two variants depending on whether a DC or an AC-Bus is used. The topology used in this paper will be the one with an AC-Bus [14,16,17], figure 1.

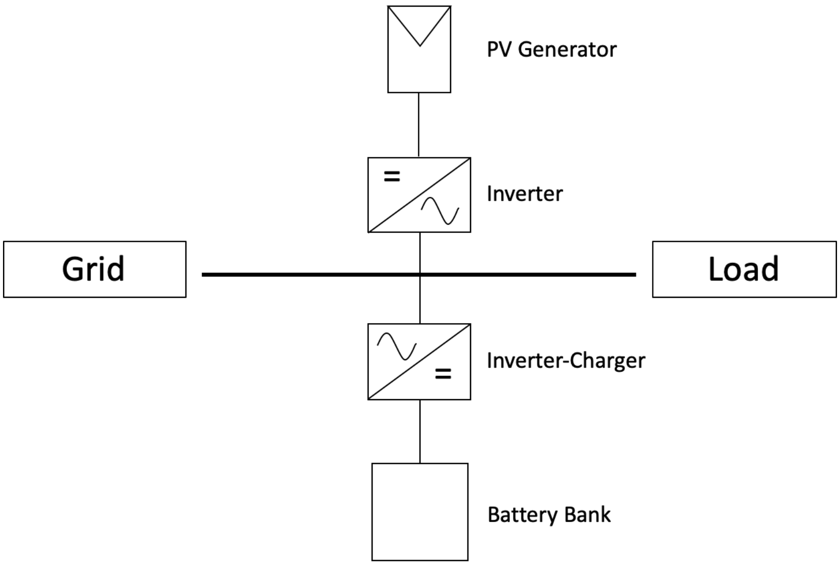


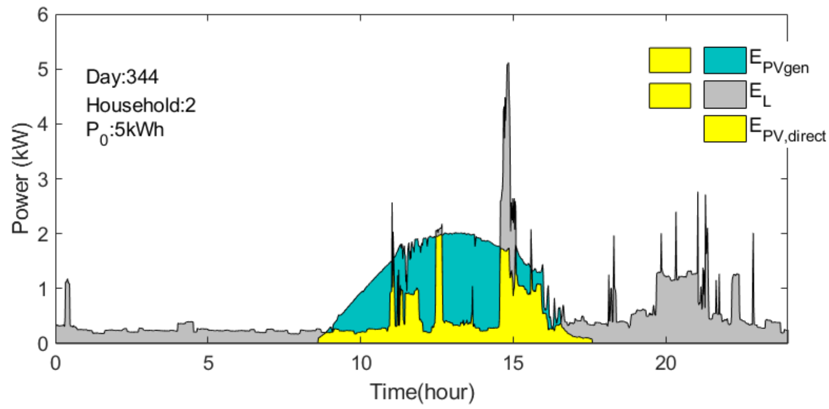
Figure 1. Photovoltaic self-consumption system (a) DC Bus (b) AC Bus.

If batteries are taken into account self-sufficiency (SS) and self-consumption (SC) indices may be defined as:

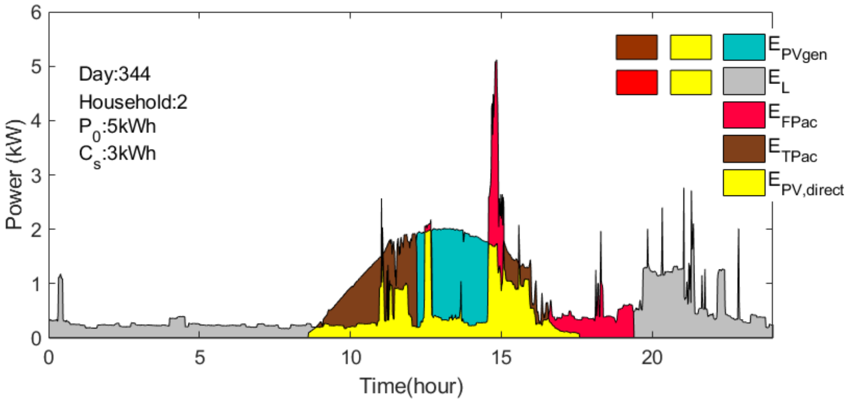
$$\varphi_{SC} = \frac{\int_{t1}^{t2} M(t)dt}{\int_{t1}^{t2} P(t)dt} = \frac{\sum_{t1}^{t2} M(t) \cdot \tau_r}{\sum_{t1}^{t2} P(t) \cdot \tau_r} = \frac{E_{PVcon,\tau}}{E_{PVgen,\tau}} \quad (1)$$

$$\varphi_{SS} = \frac{\int_{t1}^{t2} M_B(t)dt}{\int_{t1}^{t2} L(t)dt} = \frac{E_{PV-BAT,\tau}}{E_{L,\tau}} \quad (2)$$

L(t) and P(t) corresponds to the instantaneous building power consumption and the onsite photovoltaic generated power, respectively. M(t) represents the instantaneous photovoltaic self-consumed power (directly and to storage) while $M_B(t)$ defines the PV power directly self-consumed by the loads together with the power given from the battery to the loads. Figure 2 shows the two types of self-consumption to be considered: direct or with battery, respectively. If batteries are used, $E_{PV,con}$ should consider not only the overlapping part of the generation and load profiles ($E_{PV,direct}$), but the one corresponding to the PV energy given to the charger-inverter or bidirectional inverter (BDI) in order to charge the battery (E_{TPac}) [18]. Moreover, $E_{PV\text{-}BAT}$ should take into account $E_{PV,direct}$ and the energy given by the BDI from the batteries to the loads (E_{FPac}). The reporting period, τ, as stated by the IEC61724, is provided by t2 and t1 and may be daily, weekly, monthly or annual. Generally, an annual basis may be considered so as to take into account seasonal variations and to minimize the influence of short-term random fluctuations. The recording interval, τ_r , provides the time resolution. A proper recording interval that balances matching error, which leads to self-consumption indices overestimation [19,20], and monitoring resources should be considered [21].



(a)



(b)

Figure 2. Daily photovoltaic generation and load profiles. Direct photovoltaic self-consumption without Battery (a) and with battery (b). PV generator=5 kWp and C_S= 3 kWh.

SS and SC indices reported in the literature when analysing photovoltaic self-consumption systems with storage correspond to global indices where the self-consumption due to the array and the battery are gathered together. Moreover, they are generally provided for a given array power and a rated capacity. In [22] indices for different households in different countries as a function of the array and rated capacity are reported. SS and SC indices range from 27 to 87% and from 31 to 91%, respectively. Storage is a good choice when increasing self-sufficiency indices and leaving-off the grid. Moreover, battery prices have been considerably reduced in recent years [23,24]. However, in the literature, global self-consumption and self-sufficiency indices of photovoltaic systems with energy storage for households are widely used [22,25–31]. However, these indices do not discriminate if the self-consumption energy is directly provided by photovoltaic generator or by battery as the monitored data only considers global self-consumed energy. Global self-consumption and self-sufficiency indices are used as output parameters of a sizing method which optimize the cost in terms of photovoltaic generator and battery size [25–28]. Global self-consumption index is also studied to compare individual and shared battery energy storage [31]. It must be pointed out that photovoltaic self-consumption systems have two independent variables (i.e. array power and rated capacity). In this sense, it may be quite interesting to differentiate self-consumption parameters related with the array power and battery as they may help not only to properly analyze this type of system but to improve the sizing methods. Moreover, it may better assess the potential of storage when increasing self-sufficiency index.

Regarding the graphs used to analyse photovoltaic self-consumption systems with storage, some authors plot these indices only for a small number of photovoltaic power peak and specific values of storage capacities in 2-D plots [22,25,27]. 3D plots are also used in order to illustrate these indices [26], which may not be an easy way to interpret the data. Color maps are also used to identify the self-consumption index in a range of photovoltaic power and storage capacities [31]. Moreover, the indices may be also indicated in tables [28], where the tendency of parameters might not be appreciated in a simple and effective way. On the other hand, there are few graphical tools for analyzing photovoltaic and batteries for photovoltaic self-consumption system in buildings. In [22] a graphical approach was proposed in order to analyze the influence of photovoltaic system sizes, batteries and load matching in self-consumption systems. However, as aforementioned, it only considers determined array power and rated capacities. In this sense, it may be very interesting a graphical tool that considers a full range of array power and rated capacities comprising all the information provided in the 3D plots in a simple way.

2. Objectives

Most of the studies regarding photovoltaic self-consumption with batteries focus on global SS and SC indices as indicated in Eq. (1) and (2) and they do not discriminate direct self-consumption (i.e the self-consumed photovoltaic array energy given directly/instantaneously to loads) from self-consumption due to the battery (the self-consumed photovoltaic array energy delivered at first to the battery and then, when necessary, to the loads). This approach may highlight the differentiated role of each one in the self-consumption system in order to make not only a comparison between them but to provide either a proper energetic or a profitability analysis of this type of systems. Moreover, a joint analysis where the direct and battery analysis are considered together may be complex as it is based on 3D plots (there are two independent variables to be considered: the array power and the rated capacity).

The main objective of this manuscript is to provide a new approach to analyzing photovoltaic self-consumption systems with batteries. Therefore, indices of direct and battery self-consumption will be defined (i.e. self-sufficiency and self-consumption ones). Likewise, a separate study of the aforementioned indices will be developed based on the photovoltaic array power and the rated capacity. Apart from the new indices, new interesting ZEB points for the analysis of these types of systems regarding direct and battery self-consumption will be defined: ZEB_{direct} and $ZEB_{battery}$. They may be obtained as the intersection of the corresponding self-sufficiency and self-consumption curves. The role of each of one will be studied separately. Furthermore, the ZEB curve (i.e the intersection between the two surfaces associated to the SS and SC indices) can be obtained. Finally, a new and interesting graphical tool to analyze this type of system will be provided: the iso self-consumption and iso self-sufficiency curves (isoSC and isoSS curves). These curves allow a 2D representation of the aforementioned 3D plots and they may also provide, in a simple way, the different SS and SC indices: global, direct and battery ones together with the aforementioned ZEB points and the ZEB curves. This tool may not only manage an analysis of this type of systems but it may make easier and more intuitive the sizing methods based either on energetic and profitability criteria. This new approach will allow selection for a given consumption profile of a household, the necessary array power and rated capacity to get a given self-sufficiency index or to select the array power and rated capacity in a photovoltaic self-consumption system to manage cost-competitiveness. In this sense, a tool may be provided that simplifies the analysis of photovoltaic self-consumption systems with batteries and which may be used not only by designers but also by energy planners to assess the potential of self-consumption systems with storage.

The paper will be structured as follows: in next section load consumption data of three households together with irradiance data to illustrate the new method will be provided. In section 4 the new SS and SC indices together with the direct and battery ZEB points and ZEB curve will be presented. The new approach will be applied to three households described in section 3 considering array power and rated capacities ranging between 0-10 kWp and 0-10 kWh, respectively. In section 5 the isoSC and isoSS curves will be presented. Finally, in section 6, conclusions will be drawn.

3. Data

3.1 Household power consumption data

Three dwellings, which are located in Jaen, Spain, have been used in order to illustrate either the new approach or the new tool to analyse photovoltaic self-consumption systems with storage. These dwellings have a contracted power rating of 4.4 kW (#H01), 5.75 kW (#H02) and 8.6 kW(#H03) and their annual household power consumption are 2636.7, 4651.8 and 14283.3 kWh/year, respectively. The lower annual household power consumption corresponds to household #01, which is inhabited by two adults and one teenager, meanwhile the largest annual household power consumption corresponds tohousehold #03 with two adults. The occupancy of household #02 is two adults and two children. The considerably high electricity consumption of household#3 is due to electricity heating which takes place especially at night.

Their household power consumption was measured from March 2017 to April 2018 by commercial smart-meters which have an accuracy lower than 2%. Missing data were filled by linear interpolation. Further details about the dwellings can be found in [6].

3.2 Irradiance data

Photovoltaic energy generation, $E_{PV,gen}$, is estimated through in-plane irradiance on a flat surface. The measured data were obtained from two meteorological stations, which are placed in Jaén. Both meteorological stations have Eppley Piranometers with "Secundary standards" classification per ISO 9060. The irradiance measurement campaign was launched in March 2017 until April 2018. A recording interval of one minute has been considered in order to obtain the irradiance data which have been processed in order to avoid missing and invalid data according the recommendations of IEC 61724-1 [18], IEC 61724-2 [32] and IEC 61724-3 [33].

$E_{PV,gen}$ will be calculated using the method based on the performance ratio *(PR)* which has been used in other studies regarding self-consumption [5,6,34]. The value of *PR* for conventional PV systems is typically in the range between 0.70 and 0.80 in Spain [35]. In this paper, PR values of 0.75 will be considered, based on the reported values [36–40].

Regarding the battery charge and discharge, different energy management strategies may be implemented according to the parameters to be optimized [14,17]. Here, the one which maximizes the self-consumption index is implemented. Therefore, and considering the state of charge, the battery is charged when PV generation exceeds the household power consumption and it is discharged if the household power consumption is higher than PV generation. It should be noted that the methods to estimate the photovoltaic generation and the battery management are not the main objectives of the paper but the new approach with new SS and SC indices (i.e. direct and battery ones) together with the new graphical tool.

SS and SC indices will be estimated as a function of both the photovoltaic array power, P_0, and rated battery capacity, C_s. The array power will vary from 0.01kWp to 10 kWp with a step of 0.05kWp while battery capacity will vary from 0.01 to 10 kWh with a step of 0.25 kWh.

4. Direct and battery SS and SC indices

As can be observed in Eq. (1) and (2) SC index, φ_{sc}, can be defined as the ratio between the photovoltaic energy consumed, $E_{PV,con}$, that is, the absolute self-consumed energy (the direct self-consumed energy by the loads and the energy provided to the battery, E_{TPac}) and the photovoltaic generated energy, $E_{PV,gen}$. Moreover, SS index, φ_{ss}, can be stated as the relation between the energy given directly by the PV generator to the loads together with the energy given by battery to the loads, $E_{PV\text{-}BAT}$, and the load consumption, E_L. If no batteries are considered $E_{PV,con}$ and $E_{PV\text{-}BAT}$ will be the same. However, if batteries are taken into account when estimating $E_{PV,con}$, the batteries can be seen as an extra load. On the other hand, when determining $E_{PV\text{-}BAT}$, batteries are considered as an extra energy source as the PV generator.

If batteries are considered $E_{PV,con}$ can be defined as:

$$E_{PV,con} = E_{PV,direct} + E_{TPac} \tag{3}$$

$E_{PV,direct}$ as it has been previously mentioned corresponds to the direct PV energy consumed by the loads, that is, the overlapping area between the array power generated profile and the load consumption profile (Figure 2). Furthermore, if the PV power available meets all the load requirements, the remaining power may be used to charge the battery through the BDI (Figure 2b), E_{TPac}.

Moreover, $E_{PV\text{-}BAT}$ can be stated as follows:

$$E_{PV-BAT} = E_{PV,direct} + E_{FPac} \tag{4}$$

Where E_{FPac} corresponds to the energy given by the battery through the bidirectional inverter to meet the load demands. It must be taken into account both the BDI and the battery efficiencies. If the topology with an AC bus is considered E_{FPac} can be expressed as follows, provided that all the stored energy is used to face the load consumption (this may be true on a relative high reporting period such as an annual basis):

$$E_{FPac} = E_{TPac} \cdot \eta_{BDI}^2 \cdot \eta_{BAT} \tag{5}$$

Where η_{BDI} and η_{BAT} provides the BDI and battery efficiencies, respectively. η_{BAT} includes both the charge, storage and discharge efficiencies [41].

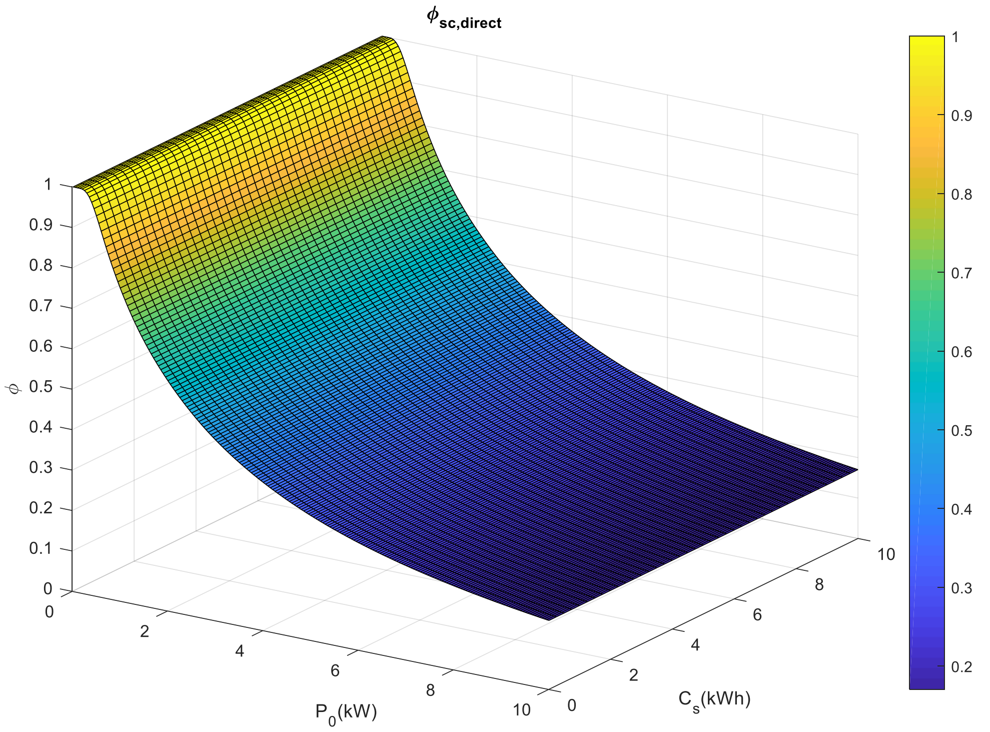
It can be defined new indices in the self-consumption metrics in order to analyse better the role of each type of self-consumption (direct or battery ones). In this sense, the SS and SC indices can be expressed through Equations (6) and (7), respectively:

$$\varphi_{SC} = \frac{E_{PVcon,\tau}}{E_{PVgen,\tau}} = \frac{E_{PV,direct,\tau} + E_{TPac,\tau}}{E_{PVgen,\tau}} = \frac{E_{PV,direct,\tau}}{E_{PVgen,\tau}} + \frac{E_{TPac,\tau}}{E_{PVgen,\tau}} = \varphi_{SC,direct} + \varphi_{SC,bat} \quad (6)$$

$$\varphi_{SS} = \frac{E_{PV-BAT,\tau}}{E_{L,\tau}} = \frac{E_{PV,direct,\tau} + E_{FPac,\tau}}{E_{L,\tau}} = \frac{E_{PV,direct,\tau}}{E_{L,\tau}} + \frac{E_{FPac,\tau}}{E_{L,\tau}} = \varphi_{SS,direct} + \varphi_{SS,bat} \quad (7)$$

It must be highlighted how both the SS and SC indices can be broken down in two differentiated parts: one corresponding to direct self-consumption ($\varphi_{sc,direct}$ and $\varphi_{ss,direct}$) and another related with self-consumption provided by the battery ($\varphi_{sc,bat}$ and $\varphi_{ss,bat}$) through the BDI.

As expected direct indices do not depend on the battery, regardless of its capacity, but only on the rated array power, P_0, figure 3. On the other hand, battery indices depend not only on the rated capacity but on the PV array, Figure 4. Moreover, Figure 5 shows the global SS and SC indices as a function of the array power and the rated capacity (i.e. these indices show the combined effect of the direct and battery indices). As can be seen, it may be quite difficult to analyse these 3D curves, especially if the intersection of the two curves (self-sufficiency and self-consumption) is considered in order to provide the ZEB points, figure 6. In this case, it may be more appropriate to talk about ZEB curve.



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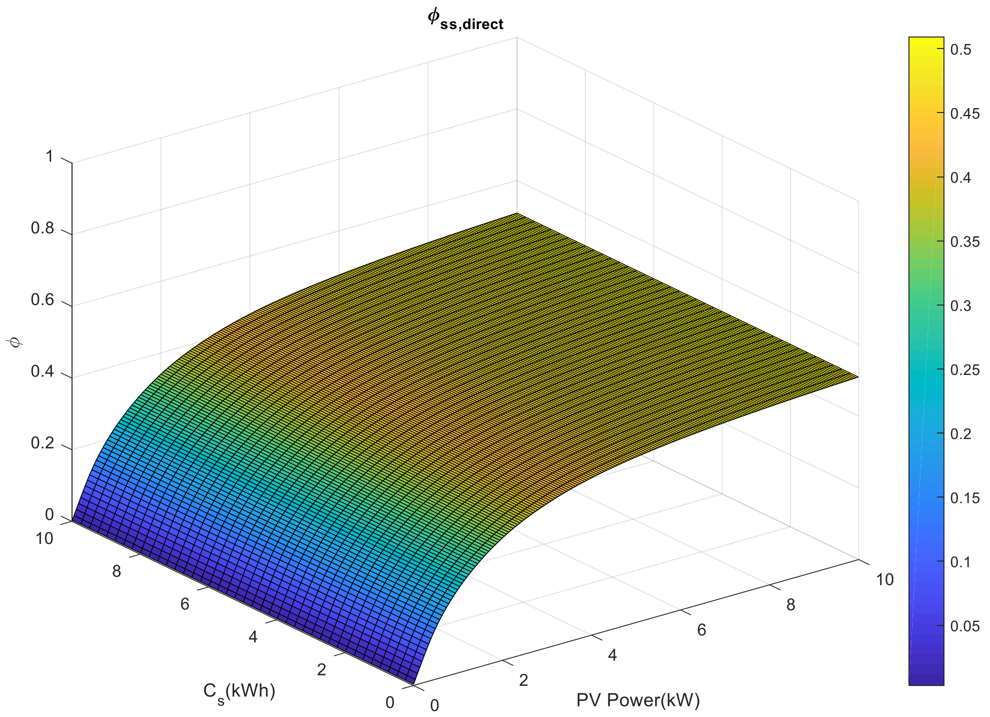
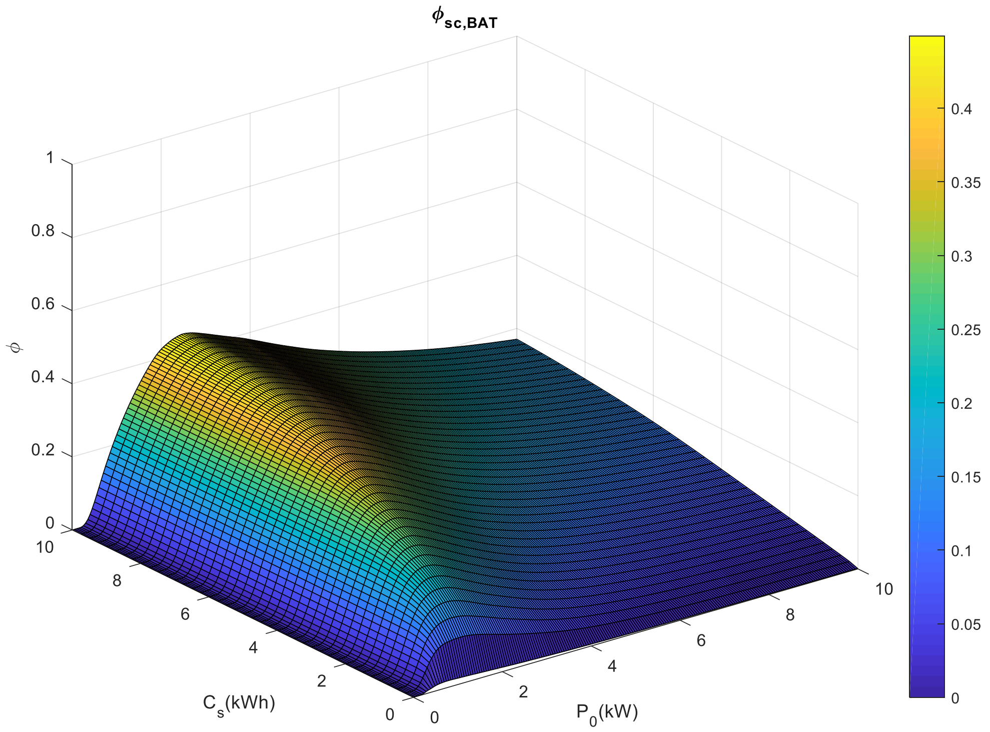


(b)

Figure 3. (a) Direct SC and (b) SS curves as a function of the PV array power and the battery capacity. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.



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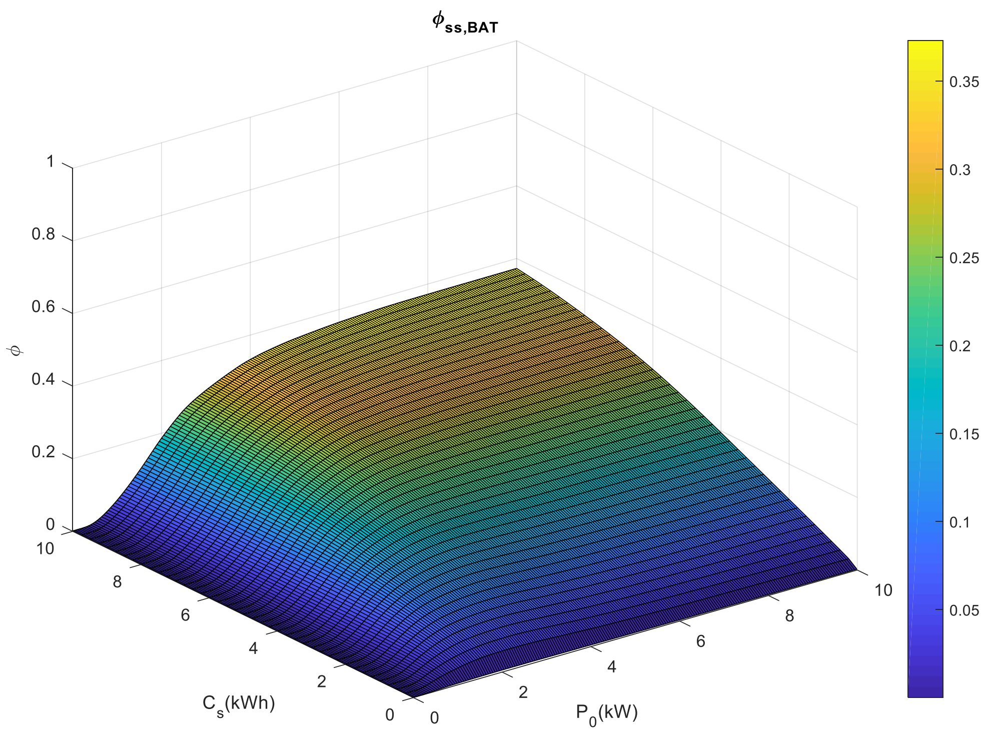
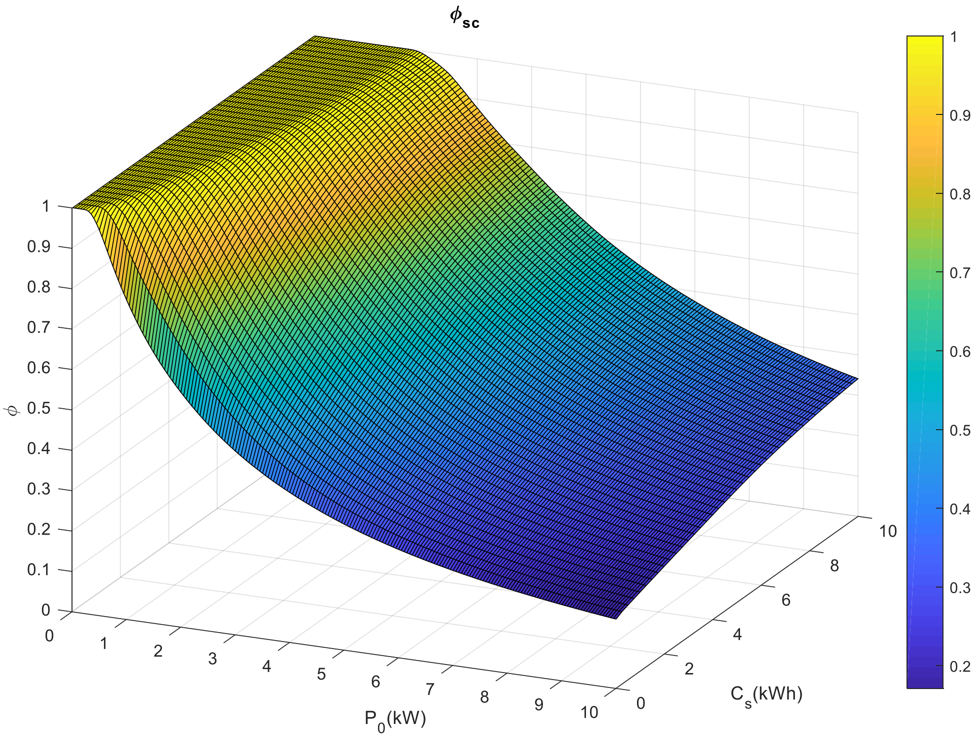


(b)

Figure 4. (a)Battery Direct SS and (b) SC curves as a function of the PV array power and the battery capacity. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.



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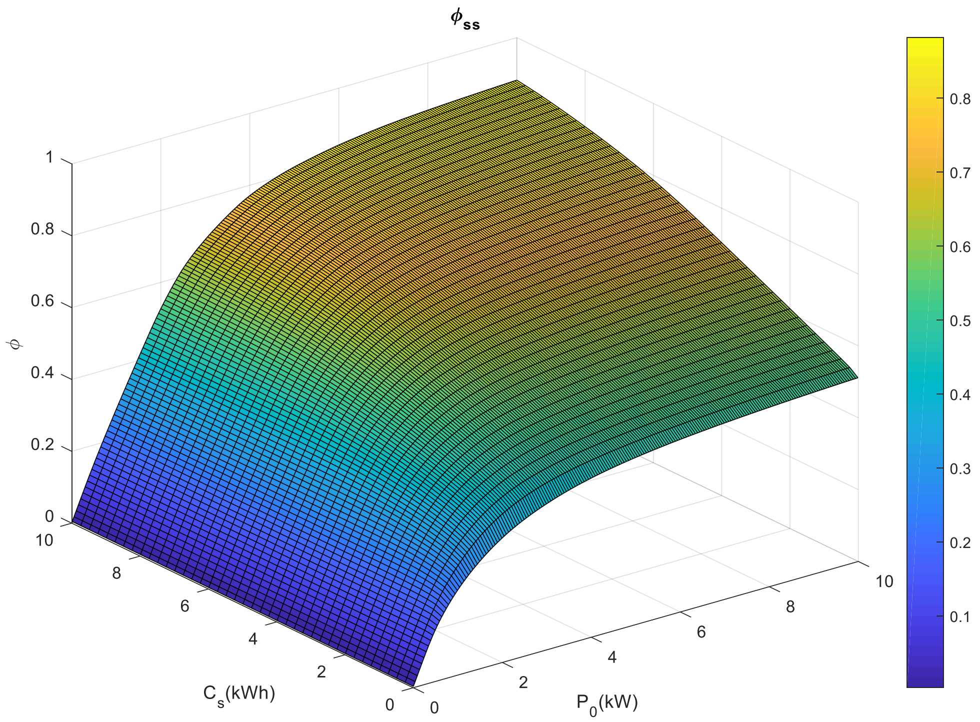
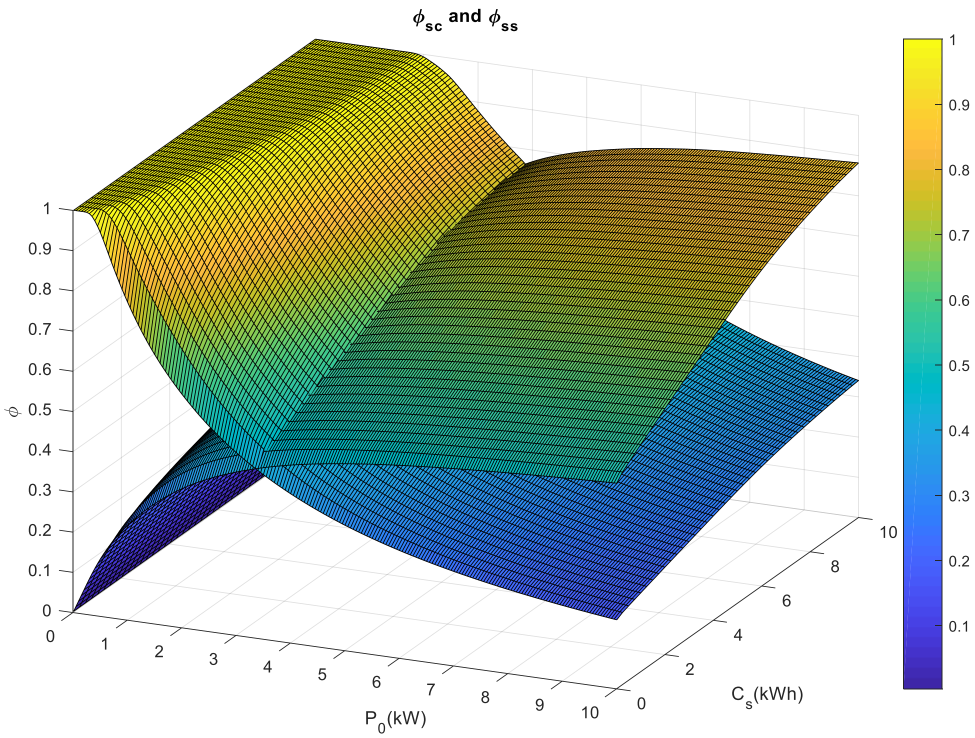


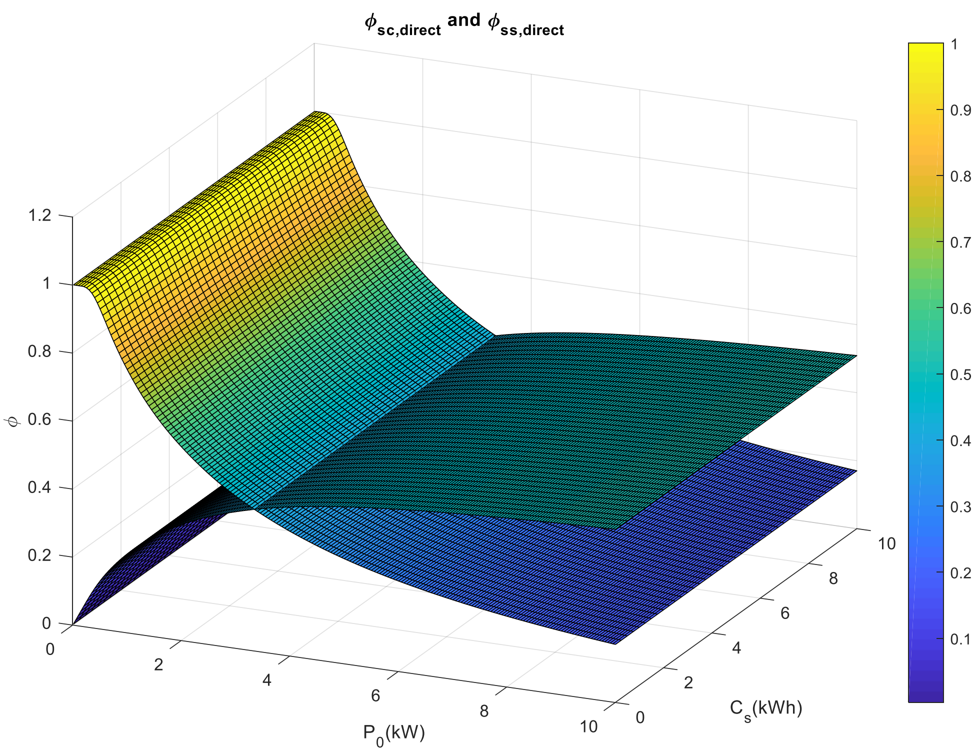
(b)

Figure 5. Global SS and SC curves as a function of the PV array and the rated capacity. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.



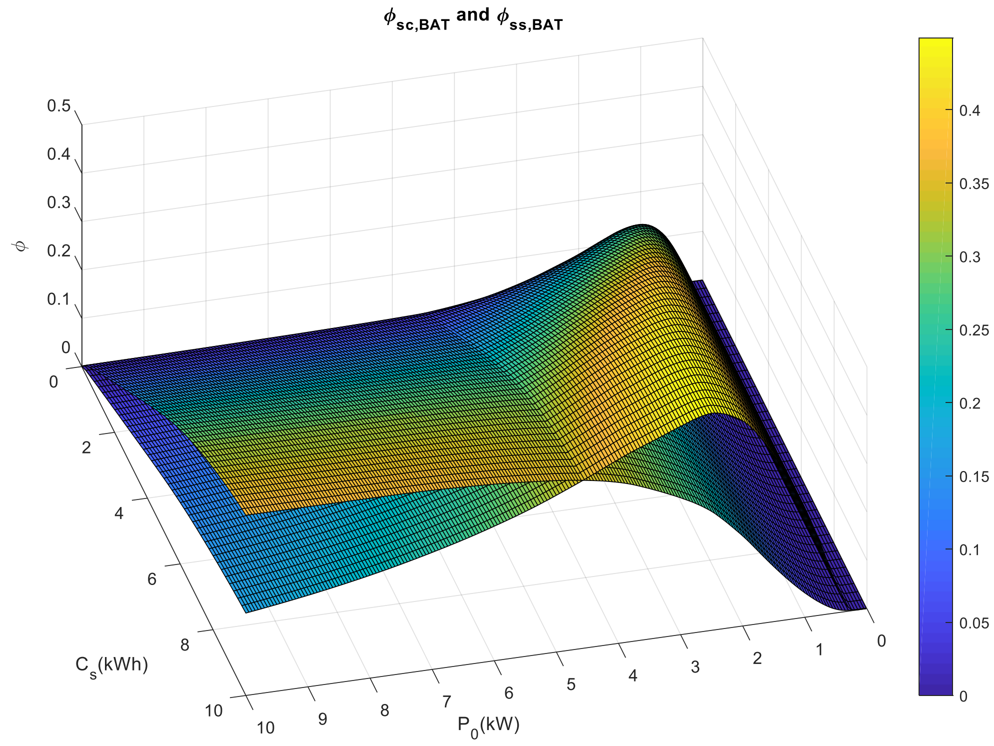
ϕ_{sc} and ϕ_{ss}
ϕ
P_0(kW)
C_s(kWh)

(a)



$\phi_{sc,direct}$ and $\phi_{ss,direct}$
ϕ
P_0(kW)
C_s(kWh)

(b)

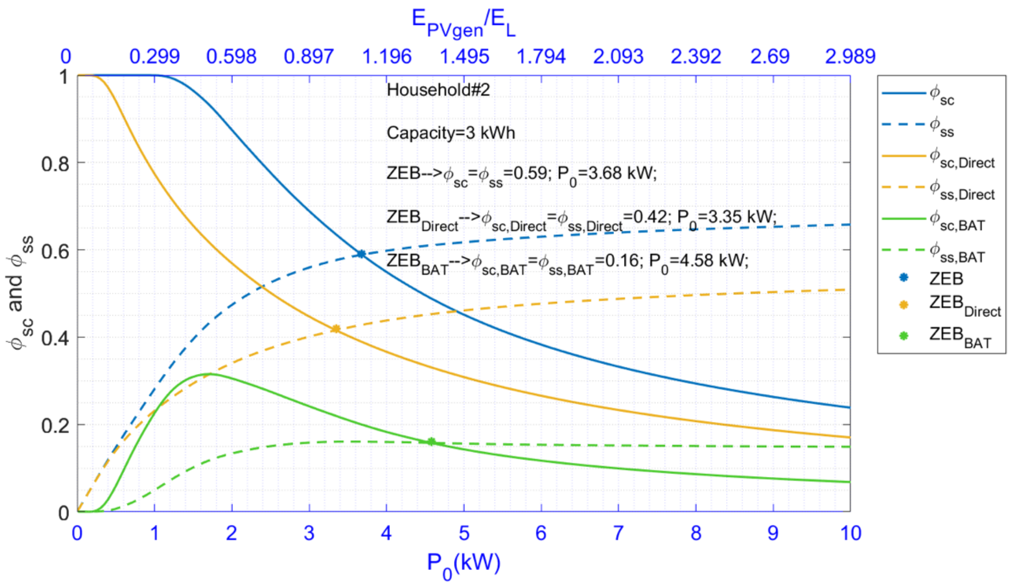


(c)

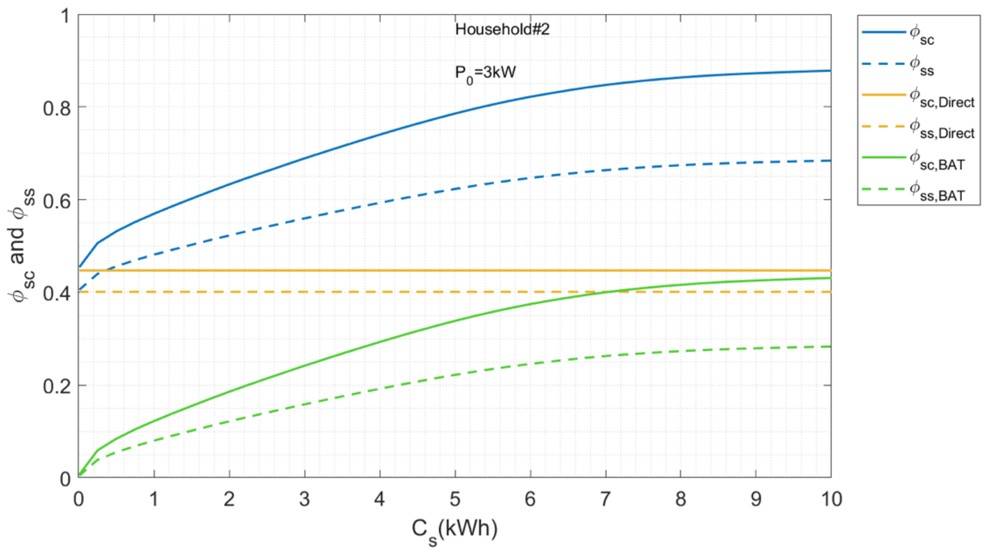
Figure 6. Intersection of SS and SC curves. ZEB points and ZEB curve. (a) global (b) direct and (c) battery. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.

The analysis of these 3D curves may be also achieved combining different 2D curves. In this sense, the different aforementioned indices can be plotted on an annual basis as a function of the PV array for a given capacity, Figure 7(a). Moreover, they can also be plotted as a function of the rated capacity for a given array power, Figure 7(b). As can be seen in Figure 7(a), $\varphi_{sc,direct}$ and $\varphi_{ss,direct}$ corresponds to a negative exponential curve and a logarithmic curve, respectively. A deeper analysis for direct self-consumption is provided in [5]. Regarding battery self-consumption it must be noted that although $\varphi_{ss,bat}$ may have a similar shape to $\varphi_{ss,direct}$, $\varphi_{sc,battery}$ evolves in a particular way: initially it increases with a considerably slope as the PV array power does, it reaches a maximum, and from this point, it decreases following a negative exponential trend. This is due to the considered capacity, in this case 3 kWh. As the array power becomes higher, there is more surplus power that can be used to charge de the battery, so the energy used to charge the battery, E_{TPac}, increases, making the battery self-consumption index higher. However, there is a limit to the energy that the battery can store given a fixed capacity. Once this limit is exceeded, although the array power continues to grow, the surplus cannot be stored. Moreover, $E_{PV,gen}$ continues growing as the array power increases, which will make the battery self-consumption index decrease. On the other hand, $\varphi_{ss,bat}$ presents a similar shape to $\varphi_{ss,direct}$. However, in this case, a maximum is reached. From this point self-sufficiency index slightly decreases with a marginal slope regardless the increase of the array power. As E_{PTac} will be limited by the given capacity so will E_{PFac}. However, in this case, E_L is a fixed value so self-sufficiency index will remain almost constant.

If the array power is now kept fixed and the rated capacity is varied, figure 7(b), as expected direct SS and SC indices do not change regardless the rated capacity. On the other hand, battery self-sufficiency and self-consumption curves do have similar shapes and follow a logarithmic trend. Moreover, global indices also follow this logarithmic trend with a given offset provided by the direct indices.



(a)



(b)

Figure 7. (a) Annual direct and battery SS and SC indices. ZEB, ZEB_{direct} and $ZEB_{battery}$ points. The array power ranges from 0 to 10 kWp. C_S= 3 kWh. (b) Annual direct and battery SS and SC indices. The rated capacity ranges from 0 to 10 kWh. P_0=3kWp. Data corresponding to household#2.

The intersection between global φ_{sc} and φ_{ss} provides the ZEB point where $\varphi_{ss} = \varphi_{sc}$. Furthermore, in figure 7(a) two more ZEB points may be defined: one for *direct self-consumption, ZEB_{direct},* and the other for the battery, *$ZEB_{battery}$*. Direct indices curves intersect in the direct ZEB point. On the other hand, battery indices intersect in the battery ZEB point. Due to the BID and the battery efficiencies, $ZEB_{battery}$ will be shifted to the right in relation to ZEB_{direct}. The more efficient the device, the less displacement. If the BID and the battery were ideal devices, the three ZEB points would be aligned. It must be highlighted how, for the curves shown in figure 7(b) there is no intersection between them, either for direct or battery curves.

In the direct ZEB point:

$$\varphi_{SC,direct} = \varphi_{SSdirect} \Rightarrow \frac{E_{PV,gen,\tau}}{E_{L,\tau}} = 1 \tag{8}$$

In the battery ZEB point:

$$\varphi_{SC,bat} = \varphi_{SSbat} \Rightarrow \frac{E_{TPac,\tau}}{E_{PV,gen,\tau}} = \frac{E_{FPac,\tau}}{E_{L,\tau}} \tag{9}$$

Considering Eq. (5):

$$\varphi_{SC,bat} = \varphi_{SSbat} \Rightarrow \frac{E_{TPac,\tau}}{E_{PV,gen,\tau}} = \frac{E_{TPac,\tau} \cdot \eta_{BDI}^{2} \cdot \eta_{BAT}}{E_{L,\tau}} \Rightarrow \frac{E_{PV,gen,\tau}}{E_{L,\tau}} = \frac{1}{\eta_{BDI}^{2} \cdot \eta_{BAT}} \geq 1 \tag{10}$$

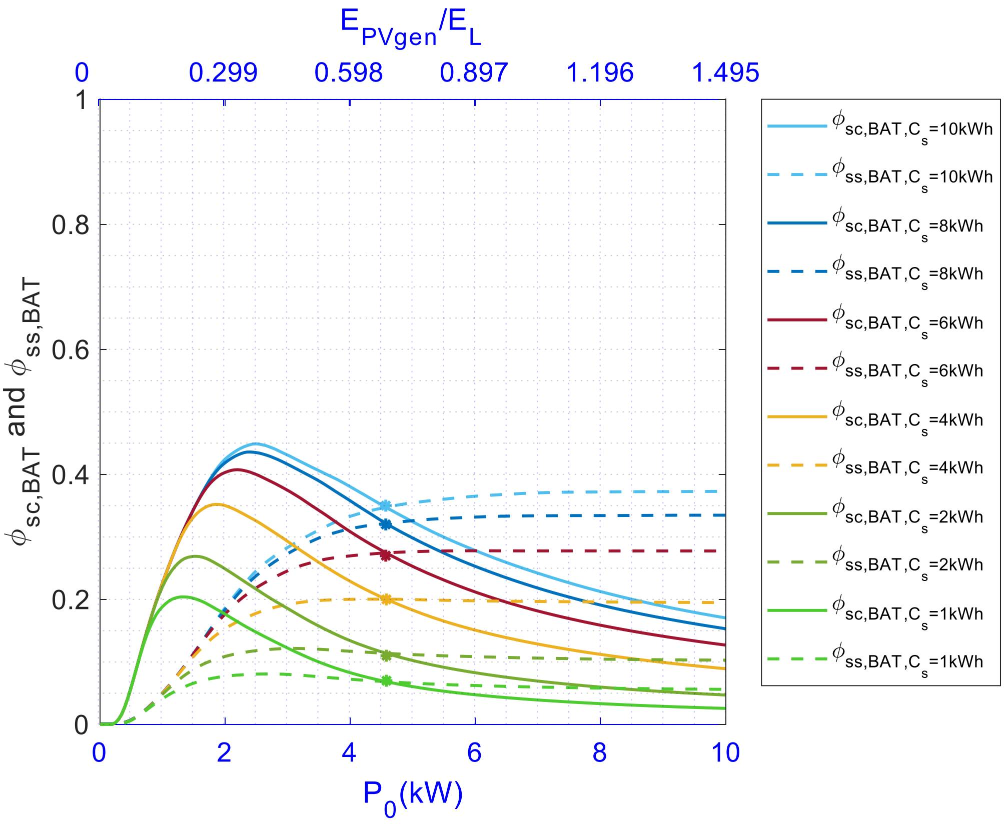
Regarding ZEB point

$$\varphi_{SC} = \varphi_{SS} \rightarrow \frac{E_{PV,direct,\tau} + E_{TPac,\tau}}{E_{PVgen,\tau}} = \frac{E_{PV,direct,\tau} + E_{FPac,\tau}}{E_{L,\tau}} \rightarrow \frac{E_{PV,gen,\tau}}{E_{L,\tau}} = \frac{E_{PV,direct,\tau} + E_{TPac,\tau}}{E_{PV,direct,\tau} + E_{TPac,\tau} \cdot \eta_{BDI}^{2} \cdot \eta_{BAT}} \geq 1 \tag{11}$$

In this way, the use of a battery not only provides higher SS and SC indices but also causes a shift to the right of the global ZEB point in relation to direct ZEB point. Furthermore, the battery ZEB point will be placed in the same abscissa regardless of the array power and the rated capacity (i.e $\frac{E_{PV,gen,\tau}}{E_{L,\tau}} = \frac{1}{\eta_{BDI}^{2} \cdot \eta_{BAT}}$), Figure 8. On the other hand, and taking into account Equation 11, global ZEB point do depend on the array power and the rated capacity, the higher array and capacity the higher E_{TPac} which will provide a higher E_{PVgen}/E_{L} and a more displacement to the right of the global ZEB point, Figure 9.

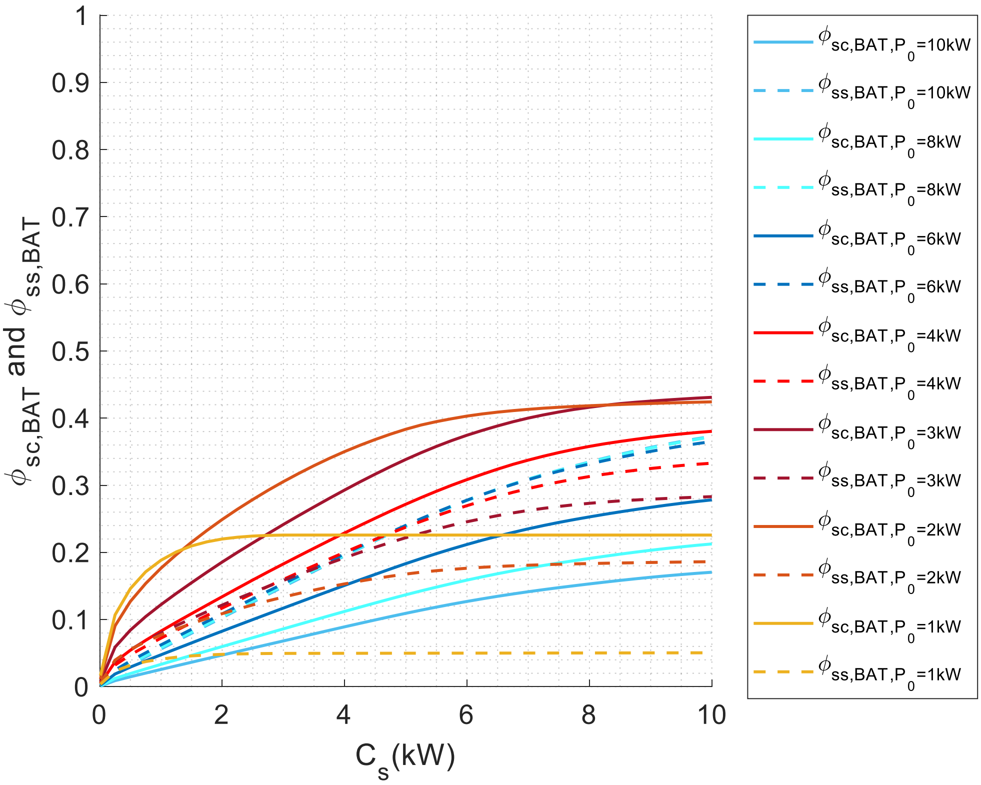
Regarding the battery self-sufficiency index, and for the considered household, it ranges from 0,025 to 0,4 for storage capacities ranging from 0,025 to 10 kWh, Figure 8 (a). As aforementioned, given a rated capacity, self-sufficiency indices tend to increase linearly and then follow a cuadratic curve reaching a maximum. Once reached, the index is kept almost constant decreasing with a marginal slope as the array power increases. In this sense, and provided a determined rated capacity, it may be no use increasing the PV array beyond a given point. Furthermore, the maximum battery self-sufficiency indices do not increase in a proportional way as the rated capacity does. In fact, the higher the capacity the lower the increase in the maximum self-sufficiency index. Moreover, for high capacities, the increase in maximum self-sufficiency index may be marginal. For the considered household, and for the array power and rated capacities considered, battery self-sufficiency index may not exceed 0,4. If the array power is now kept constant and the rated capacity is varied, Figure 8 (b), the battery self-sufficiency index for a given array power increases as the rated capacity does, reaching a maximum. This can be clearly seen, for the capacity range considered, for 1 kWp and 2 kWp curves. Moreover, it must be highlighted how battery self-sufficiency curves for different array powers higher than 3 kWp almost match for capacities lower than 5 kWh. Beyond this capacity the increase may be marginal in battery self-sufficiency when considering either higher array power or rated capacities.

The global curves for φ_{sc} and φ_{ss} are the sum of the direct and the battery indices curves. As can be seen, the global self-sufficiency index that considers the joint work of the photovoltaic generator and the battery becomes higher as the rated capacity increases. For the household considered it may even exceed 85% for rated capacities beyond 8 kWh. High array powers and rated capacities provides such a high index. However, as it can be seen, the associated self-consumption indices are quite low, wasting much of the energy generated. As can be seen, it is very important, for a given load profile, to find the most suitable array power and capacity that balances size with self-sufficiency. Achieving this task using either the 3D curves given in Figures 3, 4, 5 and 6 or using 2D plots such as the provided by Figures 8 and 9 may be quite complex and confusing.



E_PVgen/E_L
0
0.299
0.598
0.897
1.196
1.495
φ_sc,BAT and φ_ss,BAT
P_0(kW)
φ_sc,BAT,C_s=10kWh
φ_ss,BAT,C_s=10kWh
φ_sc,BAT,C_s=8kWh
φ_ss,BAT,C_s=8kWh
φ_sc,BAT,C_s=6kWh
φ_ss,BAT,C_s=6kWh
φ_sc,BAT,C_s=4kWh
φ_ss,BAT,C_s=4kWh
φ_sc,BAT,C_s=2kWh
φ_ss,BAT,C_s=2kWh
φ_sc,BAT,C_s=1kWh
φ_ss,BAT,C_s=1kWh

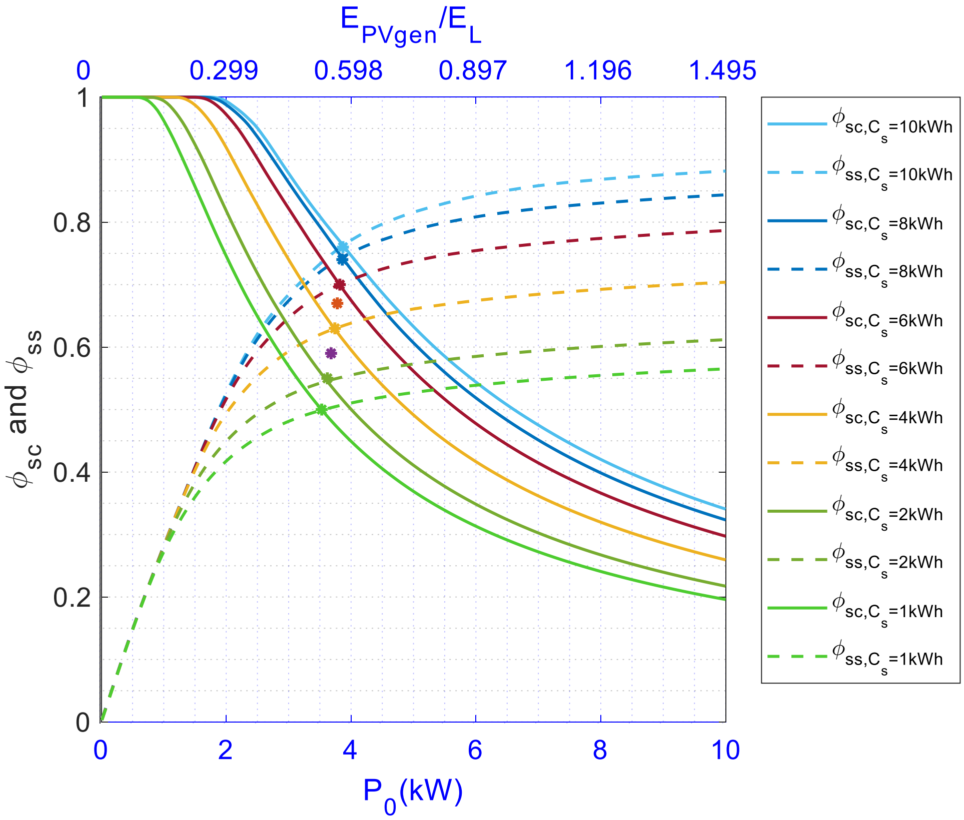
(a)



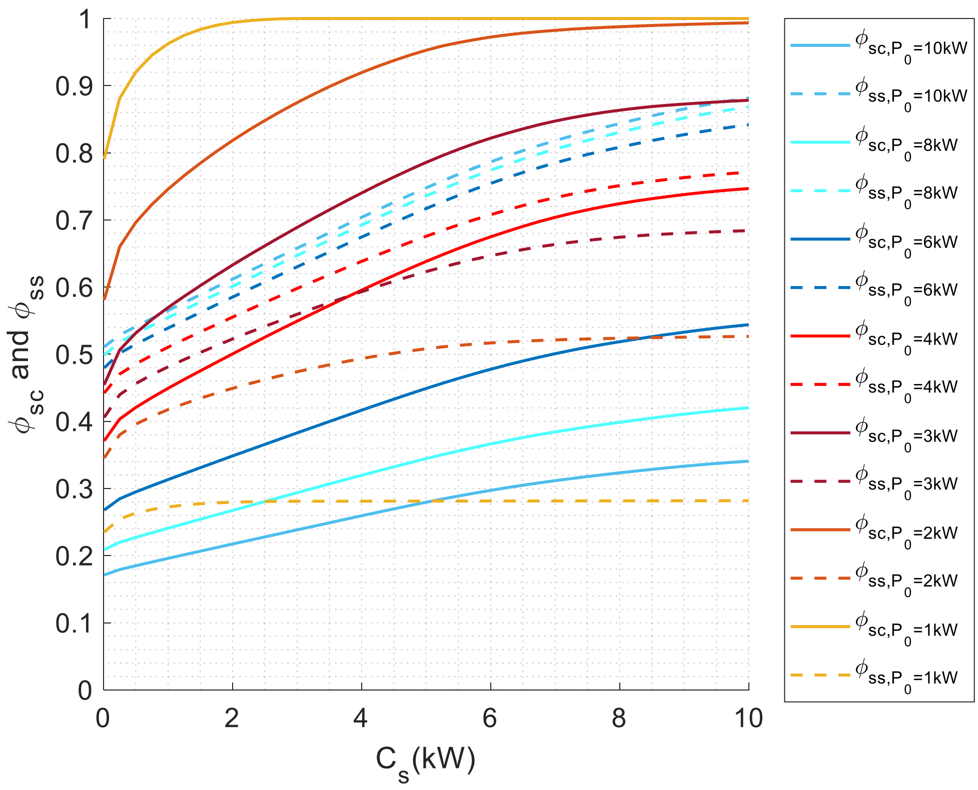
φ_sc,BAT and φ_ss,BAT
C_s(kW)
φ_sc,BAT,P_0=10kW
φ_ss,BAT,P_0=10kW
φ_sc,BAT,P_0=8kW
φ_ss,BAT,P_0=8kW
φ_sc,BAT,P_0=6kW
φ_ss,BAT,P_0=6kW
φ_sc,BAT,P_0=4kW
φ_ss,BAT,P_0=4kW
φ_sc,BAT,P_0=3kW
φ_ss,BAT,P_0=3kW
φ_sc,BAT,P_0=2kW
φ_ss,BAT,P_0=2kW
φ_sc,BAT,P_0=1kW
φ_ss,BAT,P_0=1kW

(b)

Figure 8. (a) Annual battery SS and SC indices as a function of the array power for a given rated capacity. (b) Annual battery SS and SC indices as a function of the rated capacity for a given array power. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.



(a)



(b)

Figure 9. (a) Annual global self-consumption indices as a function of the array power for a given rated capacity. (b) Annual global self-consumption indices as a function of the rated capacity for a given array power. The array power and the battery range from 0 to 10 kWp and from 0 to 10 kWh, respectively. Data corresponding to household#2.

5. A new graphical tool to analysing photovoltaic self-consumption systems with storage

5.1. IsoSC and IsoSS curves

As aforementioned, although the analysis and sizing of a photovoltaic self-consumption system with battery may be achieved using 3D figures or 2D figures which considers together SS and SC indices either as a function of the array power depending on the considered capacity or as a function of the rated capacity depending on the array power, it may be a complex task. In this sense, a useful tool that simplifies not only the analysis but makes the sizing of this type of systems even more simple and intuitive is provided: *iso self-consumption* (isoSC) and *iso self-sufficiency* (isoSS) curves. Iso curves are contour plots containing the iso-lines of SS and SC indices as a function of the array power and the rated capacity. The iso-lines represent the self-sufficiency and self-consumption values on the x-y plane, where 'x' is the array power and 'y' constitutes the rated capacity. The inputs for elaborating iso-curves are SS and SC indices as function of the array power and the rated capacity. The first step to plot them is to search for the maximum and minimum values of both indices. Starting with the maximum value, the next steps manage to find the range of iso-lines from the maximum value to the minimum value with steps of 0.05. The final step is to graph the iso-lines in two dimensions plots, Figure 10.

In figure 11 the isoSS curves are shown given by the dotted curves and isoSC curves for household#1: global, direct and battery ones. They are obtained from the 3D self-consumption curves through the intersection with iso self-sufficiency and self-consumption planes which are parallel to the plane defined by the array and the rated capacity axis. All the information contained in the 3D representation for the considered household is moved to this 2D figure which provides a complete view of the performance of this type of systems considering different array powers and rated capacities given an annual load profile. These curves provide the different combinations of array power and rated capacity that provide a given self-sufficiency or a self-consumption index. The ZEB points (where the iso self-sufficiency and self-consumption curves with the same value intersect) can be easily obtained. Moreover, if the ZEB points are joined together the *ZEB curve* which is the intersection curve between the self-sufficiency and self-consumption 3D surfaces may be achieved. As can be seen, global isoSC curves resemble exponential curves, Figure 11 (a). Their slope increases as the self-consumption index gets higher and they tend to be straight and vertical lines as they approach unity. As expected, the lower the array power, the higher self-consumption index. Regarding global isoSS curves, their shape resembles a decreasing exponential curve.

Figure 11(b) provides direct self-sufficiency and self-consumption curves. As can be seen, they correspond to straight vertical lines, either for self-sufficiency and self-consumption direct indices, that is, direct self-sufficiency and self-consumption do not depend on rated capacity. The information provided by Figure 11(b) is the same as that which is provided by the self-sufficiency and self-consumption curves which are used to analyse photovoltaic self-consumption systems without storage [5] and corresponds to the direct self-sufficiency and self-consumption curves shown in Figure 7. From now on, the latter will be considered to illustrate the performance of direct self-sufficiency and self-consumption. Regarding battery isoSC and isoSS curves, and for household#2, they are shown in Figure 11 (c)

As can be seen, these contour plots may be used either to analyse or to size in a simple and intuitive way the array power and the rated capacity of the photovoltaic self-consumption system if determined SS and SC indices must be achieved.

5.2. Analysis of self-consumption systems with storage for three households using iso SC and SS curves.

In this section the three households located in Spain and described in section 3 are going to be analysed using the aforementioned approach. Regarding household#2, it can be seen that, for the array powers and rated capacities considered (up to 10 kWp and 10 kWh, respectively), a 0,85 global self-sufficiency index may be achieved, Figure 11.a. If a global self-sufficiency index of 50% is to be reached, the corresponding global isoSS curve must be considered. This curve represents all the different solutions (i.e array power and rated capacity) to be considered in order to provide the aforementioned global self-sufficiency index. If other self-sufficiency indices are to be considered the corresponding curve should be taken into account. Now, either energetic or profitability criteria can be applied in order to choose the more suitable combination of array power and rated capacity. To get a global self-sufficiency index of 0,50 and if it is required to take advantage of a great part of the photovoltaic energy generated (i.e self-consumption index higher than 75%) it may be chosen, for the considered household, an array power of 2,5 kWp and a rated capacity of 2,5 kWh may be chosen (these values are obtained as the intersection between 0,75 global iso SC and 0,5 global iso SS curves). Moreover, as can be seen for 0,5 global isoSS curve there may be no use considering higher rated capacities as the curve tends to be vertical. As can be seen in this global isoSS curve, the self-sufficiency index is kept almost constant although the rated capacity is considerably increased and the array power is marginally diminished. On the other hand, if cost-competiveness should be achieved, a higher array power and a lower rated capacity may be considered in the aforementioned self-sufficiency curve (actually the cost of one kWp of array power is considerably lower than one kWh of rated capacity). In this case, an array power of 3.5 kWp and a rated capacity of 1 kWh may be chosen to get a 0,5 self-sufficiency index. Moreover, the global isoSC curve which intersect at this point provides a self-consumption index of 0, 5. Once the global isoSC and isoSS curves have been plotted for a given household, it is only a question of applying the chosen criteria (grid autonomy, cost competitiveness or profitability) when using the aforementioned tool.

Furthermore, these global isoSC curves may be complemented with the associated curves corresponding to the new indices defined in section 4 (i.e direct and battery indices). In this sense, the direct and battery isoSC and isoSS curves for the considered household are shown in figures 11(b) and 11(c), respectively.

Figure 10. Flowchart to plot IsoSC and isoSS curves.

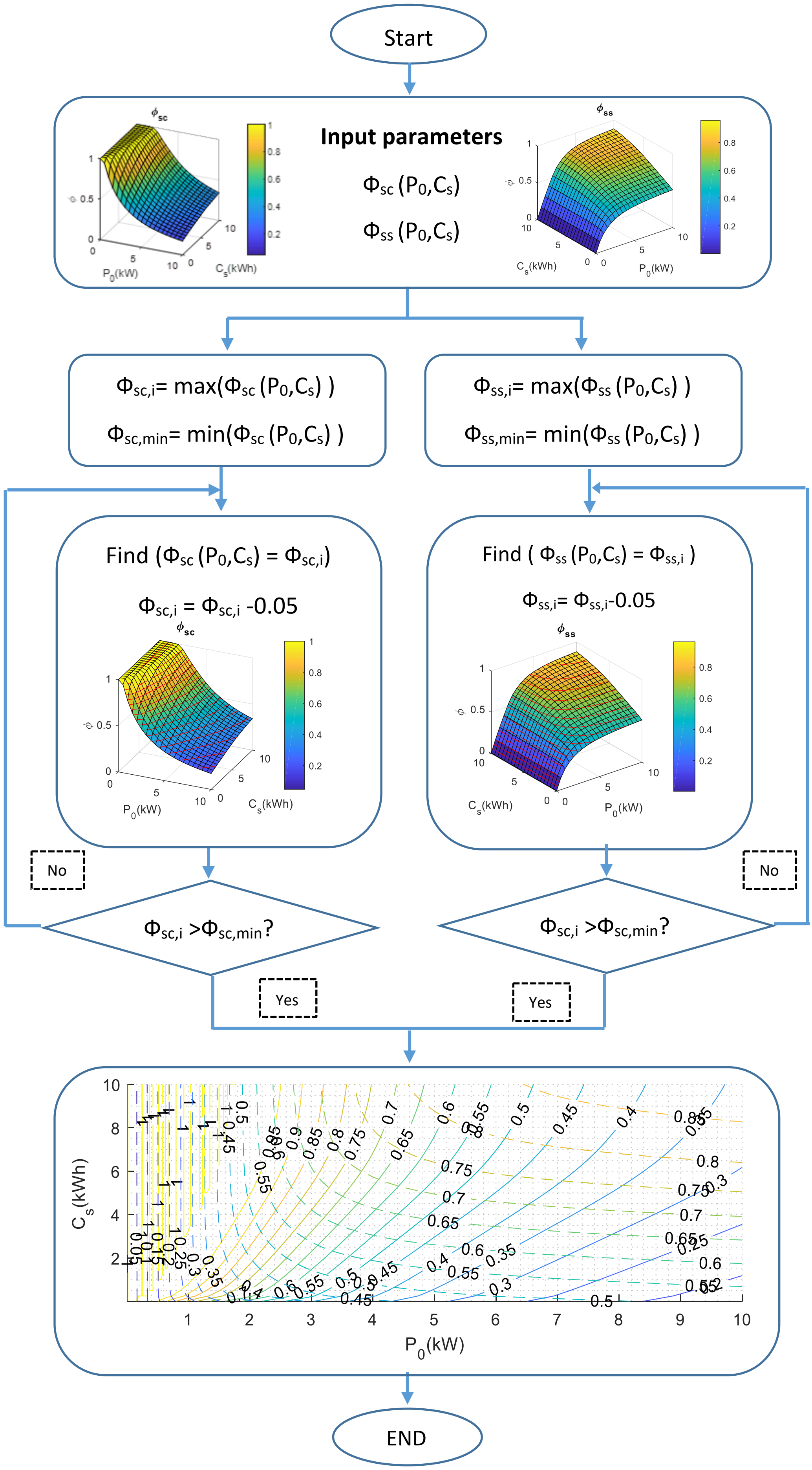
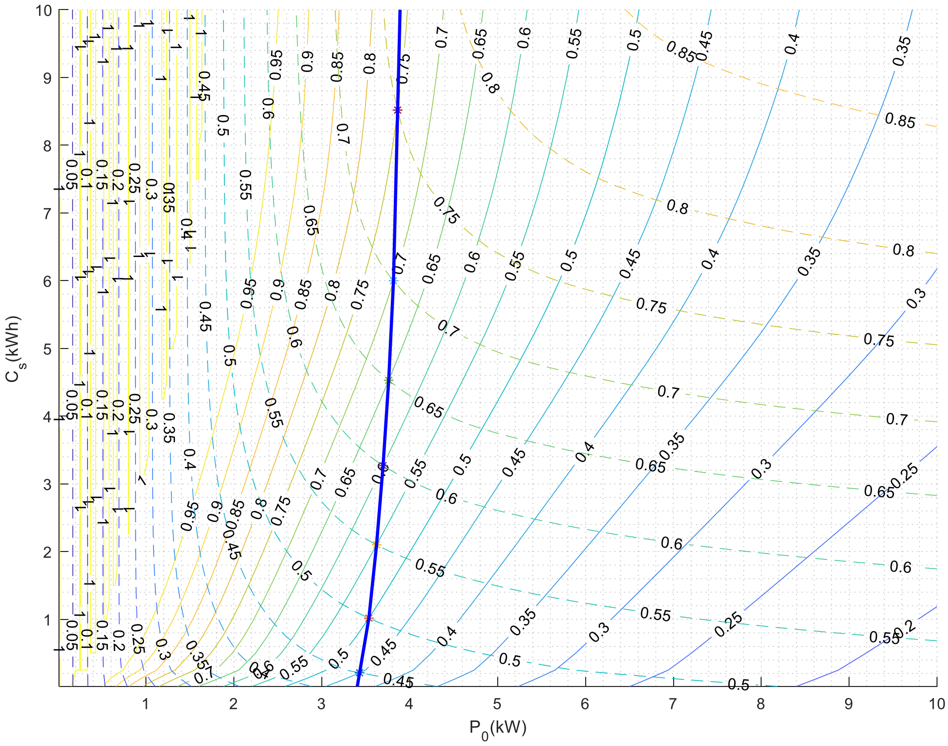
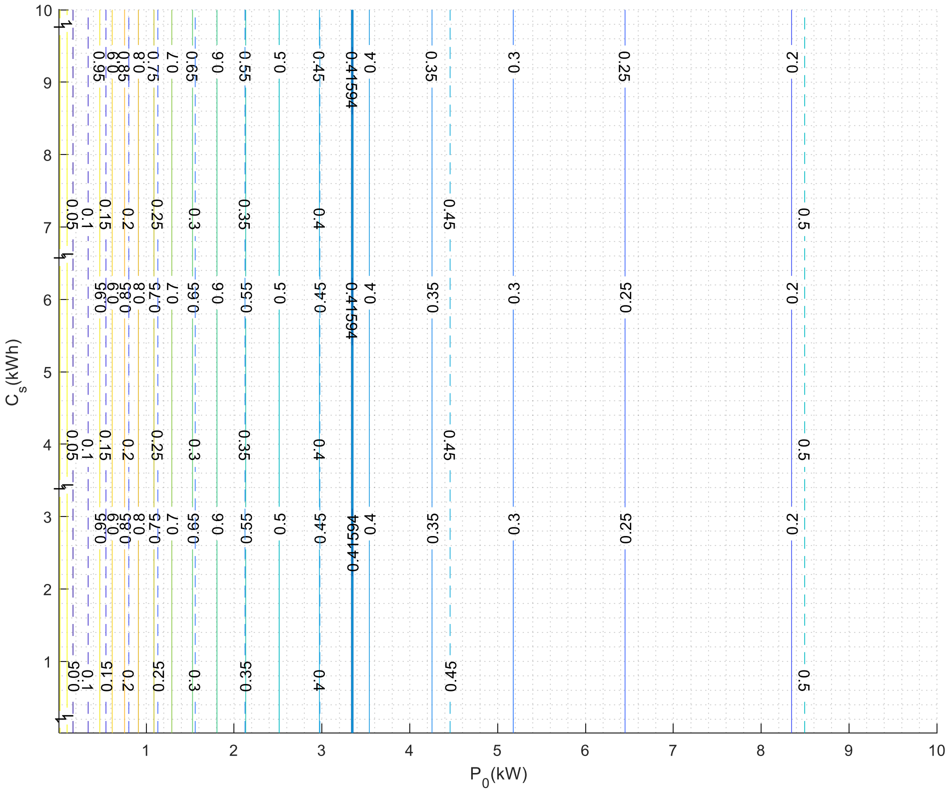

Start
Input parameters
Φsc (P0,Cs)
Φss (P0,Cs)
Φsc,i= max(Φsc (P0,Cs))
Φsc,min= min(Φsc (P0,Cs))
Φss,i= max(Φss (P0,Cs))
Φss,min= min(Φss (P0,Cs))
Find (Φsc (P0,Cs) = Φsc,i)
Φsc,i = Φsc,i -0.05
Find (Φss (P0,Cs) = Φss,i)
Φss,i= Φss,i-0.05
No
No
Φsc,i >Φsc,min?
Φsc,i >Φsc,min?
Yes
Yes
Cs(kWh)
P0(kW)
END

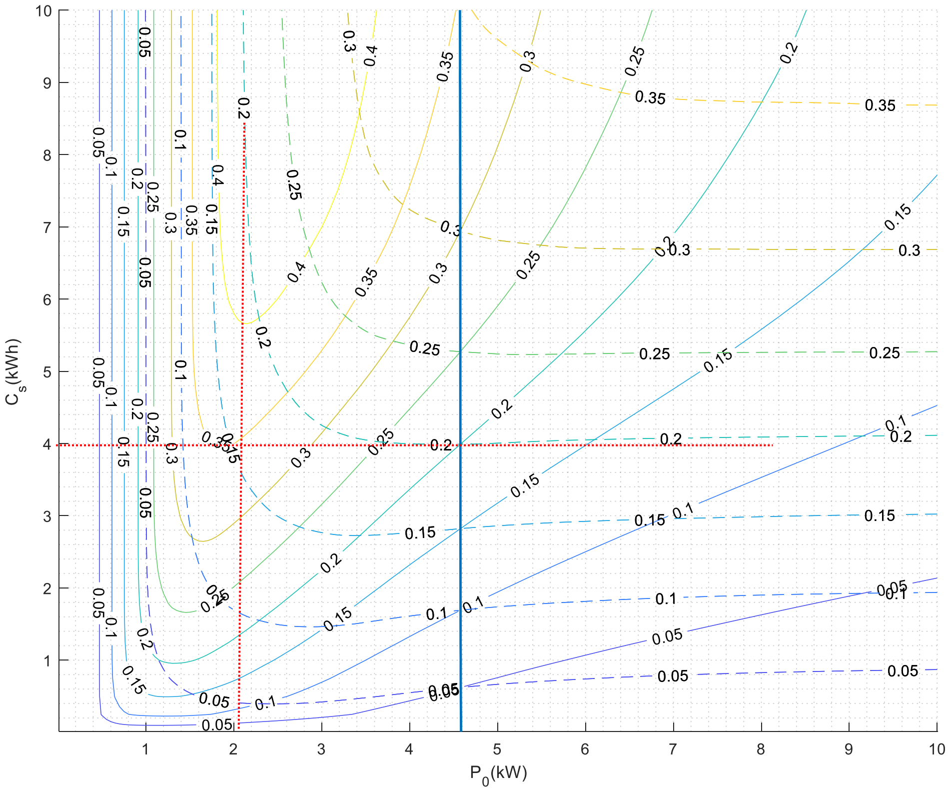
Figure 10. Flowchart to plot IsoSC and isoSS curves.



(a)



(b)



(c)

Figure 11. IsoSC and IsoSS (dotted) curves. (a) global (b) direct (c) Battery. ZEB curve (blue). Household#2

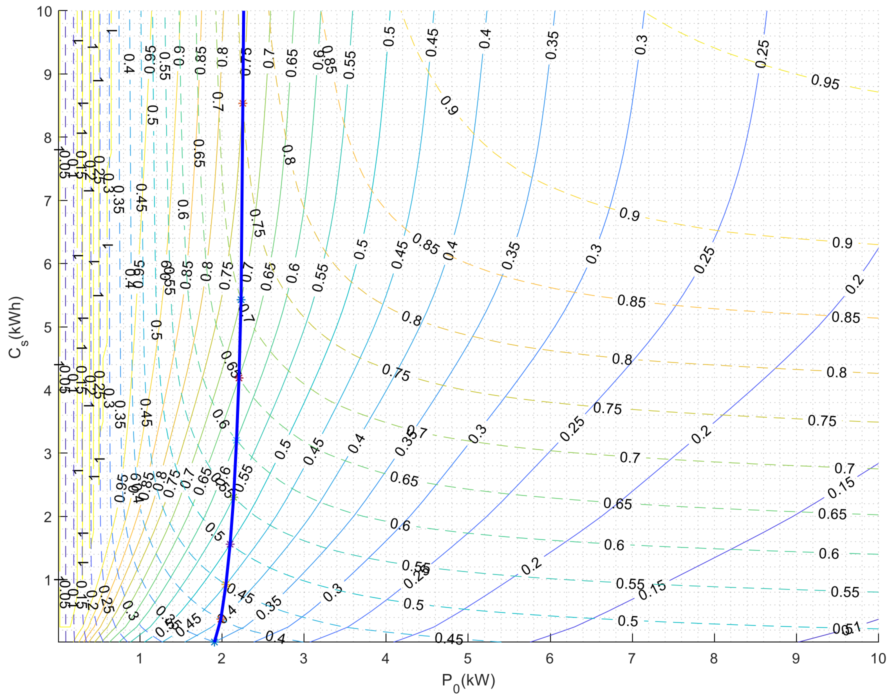
The direct iso SC and SS curves, as it has been aforementioned, do provide the same information as the self-sufficiency and self-consumption curves which are used to analyse photovoltaic self-consumption systems without storage and which are deeply analysed in [5] for the three households here analysed. Regarding the battery iso SC and SS curves, Figure 11.c, the rated capacities considered (up to 10 kWh) may provide a battery self-sufficiency index and, in that way, an increase in the global self-sufficiency index slightly higher than 0,35. Moreover, as can be seen in this figure, battery iso SS curves have two asymptotes, horizontal and vertical, which show that from two given points in the curves there may be no use increasing the array power and the rated capacity, respectively. Moreover, for low self-sufficiency values (i.e lower than 0,2), not only it will be no use increasing the array power but even a high rated capacity will be needed to provide the same self-sufficiency If a given isoSS battery curve is considered for this household (e.g. the one with a battery self-sufficiency index of 0,2), there is a point (P_0=2,1 kWp,

C_S=7 kWh) from which there is no use increasing the rated capacity (i.e. rated capacities beyond 7 kWh do not increase the battery self-sufficiency index and, therefore, the global index). On the other hand, for the aforementioned curve there is also a point (P_0=4 kWp, C_S=4 kWh) from which there is no use considering higher array powers (i.e. array powers higher than 4 kWp provides a marginal increase in the self-sufficiency. The only increase in the global self-sufficiency index, Figure 11 (a) will be provided by the direct self-sufficiency index, Figure 11(b). In this sense, battery isoSS and isoSC curves may provide very important information about the role of storage together with the array power in this type of system, providing, for each battery isoSS curve, a battery sizing window. For the aforementioned battery self-sufficiency curve (0,2) it may range between [2,1 kWp, 7 kWh] and [4 kWp, 4 kWh], Figure 11 (c). This battery sizing window may be obtained with every battery isoSS battery curve and the obtained sizing area may be used in order to narrow the area to consider when sizing the rated capacity. The area outside this sizing area can be also considered, although increasing either the rated capacity or array power may play a negligible role in increasing the battery self-sufficiency and, therefore, the global self-sufficiency. Moreover, global, direct and battery iso curves can be used together in order to determine the role of each element in the system. For example, if an array power of 3,5 kWp and a rated capacity of 1 kWh is finally chosen in order to provide a 0,5 global self-sufficiency index, Figure 11 (a), the direct and battery self-sufficiency indices may be 0,4 and 0,1, respectively, Figures 11(b) and 11(c).

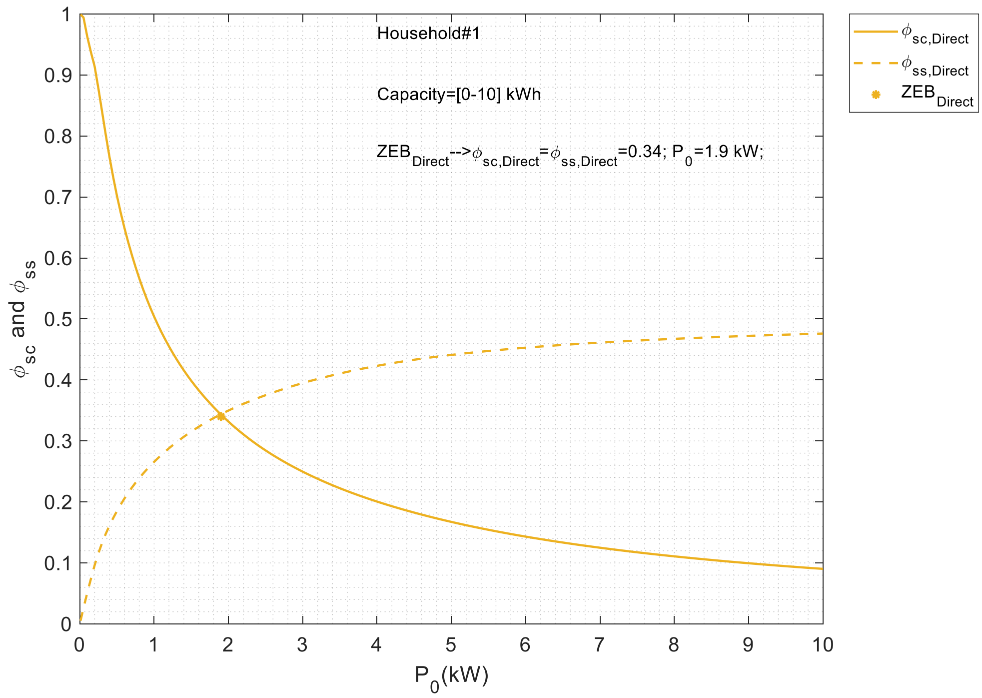
If household#1 is now analysed, different isoSC and isoSS curves should be considered, Figure 12. In this case, and as can be seen, it is possible to achieve a global self-sufficiency index slightly higher than 0,95 with the aforementioned array power and rated capacity ranges, up to 10 kWp and 10 kWh, respectively. A very high autonomy from grid may be achieved in this case. It must also be noted how the global isoSS curves are very similar to those obtained in Figure 11(a) for household#2 although they are more asymptotic. It should be pointed out that more global iso SS curves can be found that do not intersect the x-axis (array power axis) as occurred with household#2 for the given array powers and rated capacities ranges. In order to achieve a 0,5 global self-sufficiency index for this household, and looking for a cost-competitiveness solution, a higher array power and a lower rated capacity may be considered, although this solution involves a lower self-consumption index. In this case, if a rated capacity of 1 kWh is considered, a 3 kWp array power may be chosen to achieve the aforementioned global self-sufficiency index. Direct and battery self-sufficiency indices, as occurred with household#2, may be 40% and 10%. Other combinations may be taken into account where the rated capacity may be slightly decreased but with a considerable increase of the array power. In the same way as occurred for household#2, given a self-sufficiency curve, there is a point from which the self-sufficiency index slightly varies regardless how much the rated capacity is increased: for the aforementioned 0,5 global isoSS curve, it is no use increasing the rated capacity far beyond 4 kWh.

Regarding direct battery indices, it may be noted that the highest direct self-sufficiency index that can be achieved may be higher than 0,45 for the given array power range, Figure 12(b). If attention is now paid to battery isoSS curves, for the array power and rated capacity ranges, the highest battery self-sufficiency may be found between 0,45 and 0,5, Figure 12(c). This value together with the highest direct self-sufficiency index may provide a global self-sufficiency index near unity. Maximum direct and battery indices almost coincide in this case. It must be remembered that for houseuld#2 the maximum battery self-sufficiency index was slightly higher than 0,35. Moreover, these battery isoSS curves are also very similar in shape, not in value due to the load profile, to the ones obtained for household #2. As with household#2, battery iso SS curves have two asymptotes, horizontal and vertical. Now, if a battery isoSS curve of 0,2 is considered, there is a point (P_0=1,1 kWp, C_S=4Kh) from which the effect of increasing the rated capacity beyond 4 kWh is marginal. Moreover, taking into account the horizontal asymptote for this curve, there is a point (P_0=3 kWp, C_S=2,1 kWh) from which there may be no use increasing the array power beyond 3 kWp. In this sense, and for household#1, the sizing window for the aforementioned iso SS curve may lie between [1,1 kWp, 4 kWh] and [3 kWp, 2,1kWh] for an isoSS battery curve of 0,2, Figure 12 (c). The different sizing windows may be obtained for the different isoSS battery curves providing an effective sizing area to focus on which may simplify the sizing process.

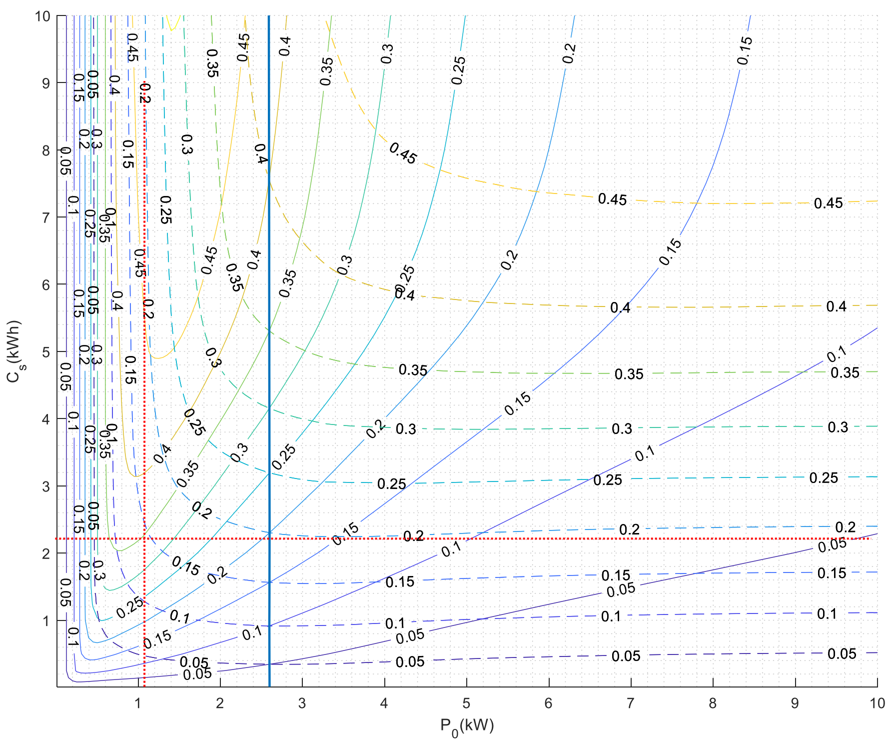
Finally, the global, direct and battery isoSC and isoSS curves for household#3 has been included. As indicated in section 3, the household electricity consumption was higher than the other two houses and it took place mostly at night due to electricity heating. As can be seen the array power range has been enlarged in order to show the ZEB curve. Nevertheless, the global self-sufficiency curves provide the poorest values. Only a global self-sufficiency index slightly higher than 0,35 may be achieved, Figure 13 (a). In Figure 13 (b) the low direct self-consumption index, slightly higher than 0,2 show the poor matching between the generation and load profiles. Moreover, the storage, in this case may only manage a 0,15 battery self-sufficiency index, Figure 13 (c). In this case, neither direct nor battery photovoltaic self-consumption may suit this household. This fact highlights the importance of the aforementioned approach (i.e to provide direct and battery self-consumption indices) and the 2D iso curves which may help to determine not only the suitability of photovoltaic self-consumption for a given household but to properly size the array power and the rated capacity in a simple way.



(a)

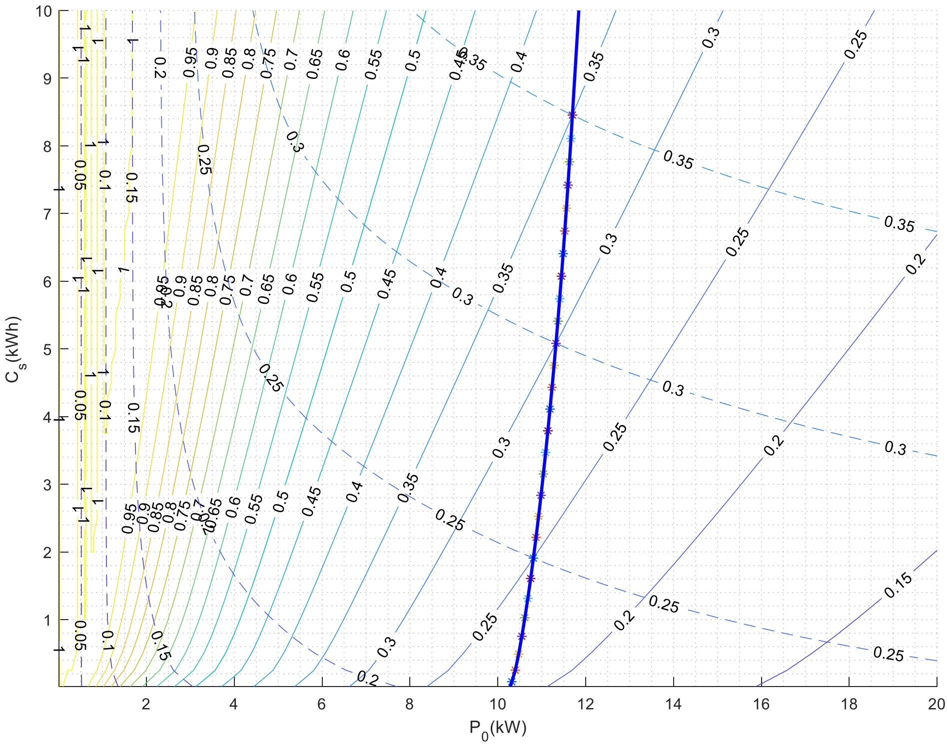

Household#1
Capacity=[0-10] kWh
ZEB_Direct-->φ_sc,Direct=φ_ss,Direct=0.34; P_0=1.9 kW;
φ_sc,Direct
φ_ss,Direct
ZEB_Direct
φ_sc and φ_ss
P_0(kW)

(b)

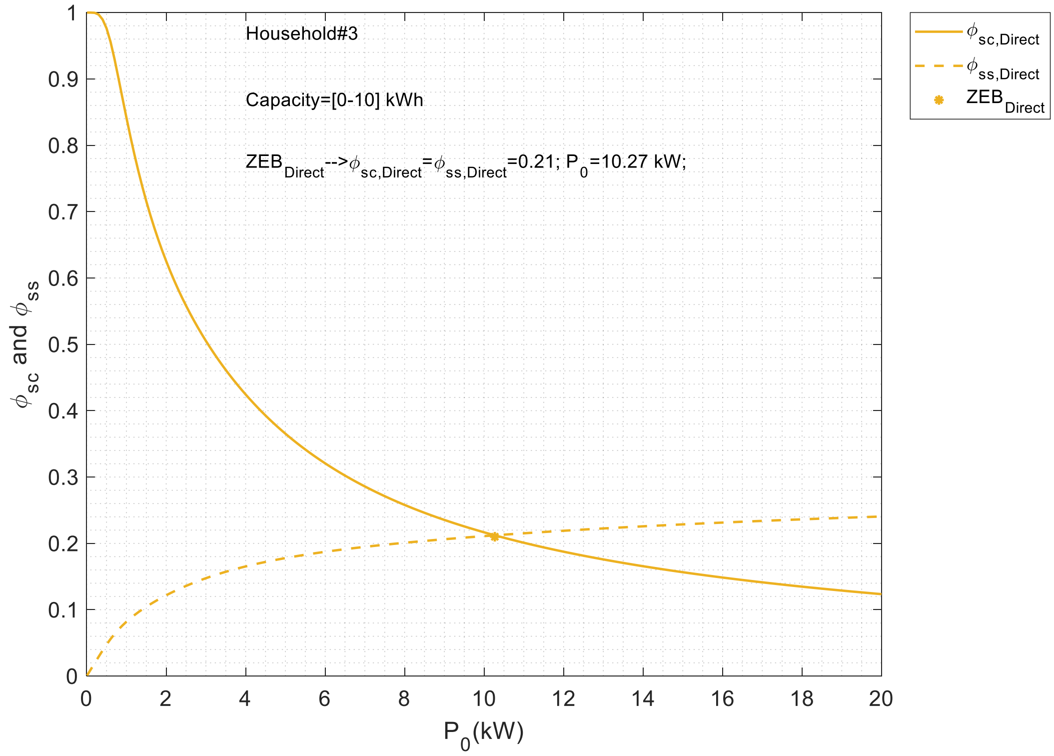

C_s(kWh)
P_0(kW)

(c)

Figure 12. IsoSC (dotted) and IsoSS curves. (a) global (b) direct (c) Battery. ZEB curve (blue)). Household#1.

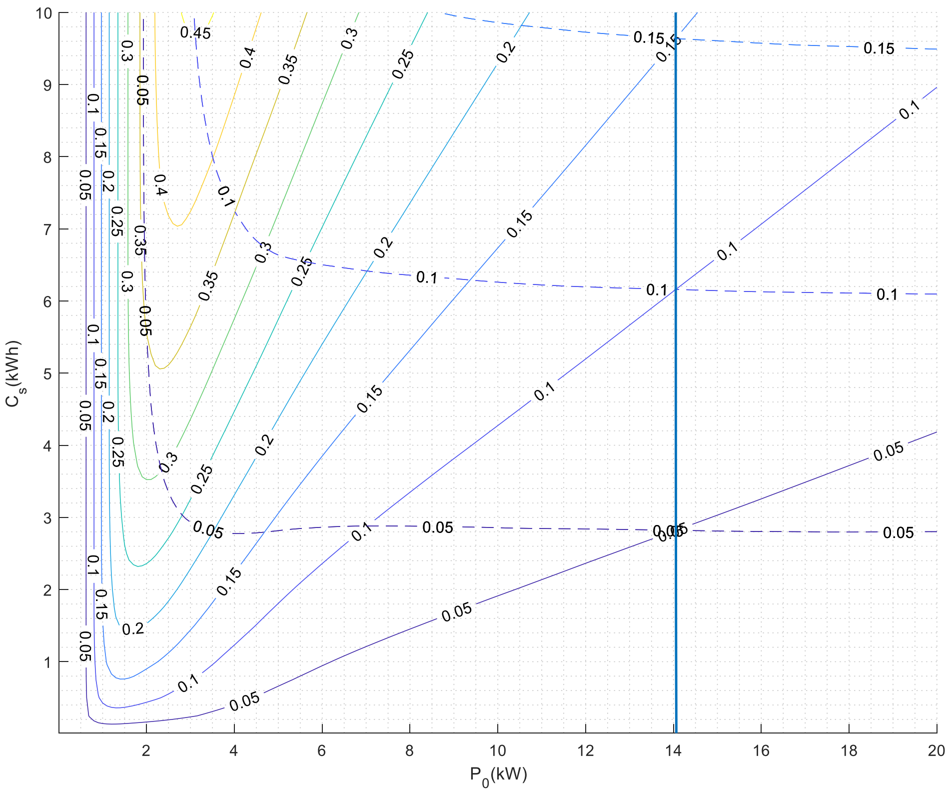


(a)


Household#3
Capacity=[0-10] kWh
ZEB_Direct-->φ_sc,Direct=φ_ss,Direct=0.21; P_0=10.27 kW;
φ_sc,Direct
φ_ss,Direct
ZEB_Direct
φ_sc and φ_ss
P_0(kW)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
2
4
6
8
10
12
14
16
18
20

574

575 (b)



(c)

Figure 13. IsoSC (dotted) and IsoSS curves. (a) direct. (b) Battery. (c) global. ZEB curve (blue). Household#3

6. Conclusions

Global SS and SC indices cannot provide the differentiated role of each element (array power and storage) when analysing the photovoltaic self-consumption system. In this sense, this paper defines new direct and battery self-consumption and self-sufficiency indices for the array generator and the rated capacity. New direct and battery ZEB points are also provided. It has been shown that for a given household, direct indices and direct ZEB point depend only on the array power while battery and global indices and ZEB points depend either on the array power and rated capacity. Due to the inverter-charger and battery efficiencies, battery ZEB and global ZEB points are shifted to the right. The higher the rated capacity the more displacement.

As has been seen, it may be quite difficult to analyse photovoltaic self-consumption systems with batteries when using either 3D plots or combining 2D plots: self-sufficiency and self-consumption indices as a function of the array power given a rated capacity and as a function of the rated capacity given an array power. Therefore, a new concept has been also introduced, the iso self-consumption and iso self-sufficiency curves, isoSC and isoSS curves, respectively. They may be an interesting tool when analyzing and sizing this type of system. They manage to comprise the information of the SS and SC indices as a function of the array power and rated capacity in a single 2D contour plot avoiding either the use of complex 3D figures or a set of 2D plots. Furthermore, they may make easier and more intuitive comparisons of these systems when analysing different households. Considering the aforementioned approach, either the global, direct and battery isoSC and isoSS curves have been provided. Regarding direct curves it must be noted that they do not depend on the rated capacity, so only two curves may be considered: one for the direct self-consumption index and one for the direct self-sufficiency index both depending only on the array power. In this sense, only a direct ZEB point may be considered for a given household. On the other hand, when battery and global indices are considered a set of isoSC and isoSS curves are obtained. Different battery and, therefore, global ZEB points are obtained providing battery and global ZEB curves. The latter are the intersection curves between the self-sufficiency and self-consumption 3D surfaces.

It has been shown how isoSS battery curves for a given household may have either a horizontal or a vertical asymptotes. From a given point there is no use increasing the rated capacity as there is no increase in the battery self-sufficiency index and, therefore, in the global index. On the other hand, for the same curve there is also no use considering higher array powers as a marginal increase in the battery self-sufficiency is provided. In this case, the only increase in the global self-sufficiency index, will be provided by the direct self-sufficiency index. Therefore, each battery isoSS curve may provide a battery sizing window. Putting together all these sizing windows a battery sizing area may be defined to consider when sizing the rated capacity. Values outside this sizing area can be also considered, although increasing either the rated capacity or array power may play a negligible role in increasing the battery self-sufficiency indices. Either energetic or profitability criteria can be applied to this area in order to choose the more suitable combination of array power and rated capacity.

These isoSC and isoSS curves have been used to analyse the role of the array power and the rated capacity in 3 different households located in Jaén (Spain). Array powers and rated capacities up to 10 kWp and 10 kWh, respectively, have been considered. It has been shown how two of them may achieve, for the given array power and capacity ranges, a high degree of autonomy from grid (i.e global self-sufficiency indices higher than 85%) with a battery self-sufficiency index higher than 35%. It may be also reached a global self-sufficiency of 50% considering array powers and rated capacities below 3.5 kWp and 1 kWh, respectively, where direct and battery self-sufficiency indices may reach 40 and 10%, respectively. Another household, due to its load profile may not suit photovoltaic self-consumption systems as considerably high values of either array power or rated capacities are needed to achieve low self-sufficiency values.

It has been proved that isoSC and isoSS curves may help not only to determine the role of each element in the self-consumption system but it may be used by energy planners and designers to properly size the array power and the rated capacity. Moreover, it may assess the potential of this type of system from either an energetic or profitability approach. Further research should be done in order to use these isoSC and isoSS curves when sizing the array power and rated capacity using the aforementioned criteria.

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